SEA LEVEL RISE

A CRUCIAL CHALLENGE FOR THE FUTURE OF CITIES AND COMMUNITIES, ECOSYSTEMS, AND THE HERITAGE, IN OUR WORLD UPSET BY THE COVID-19 OUTBREAK

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Institute of European Democrats
4 Rue de l'Industrie - 1000 Brussels - Belgium
+32.2.2130010 - info@iedonline.eu
InstituteofEuropeanDemocrats
@IED_IDE
www.iedonline.eu

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Project Coordinator
Elena Giacomin

Editing
Andrea Alicandro

Graphic Design
Riccardo Bizziccari

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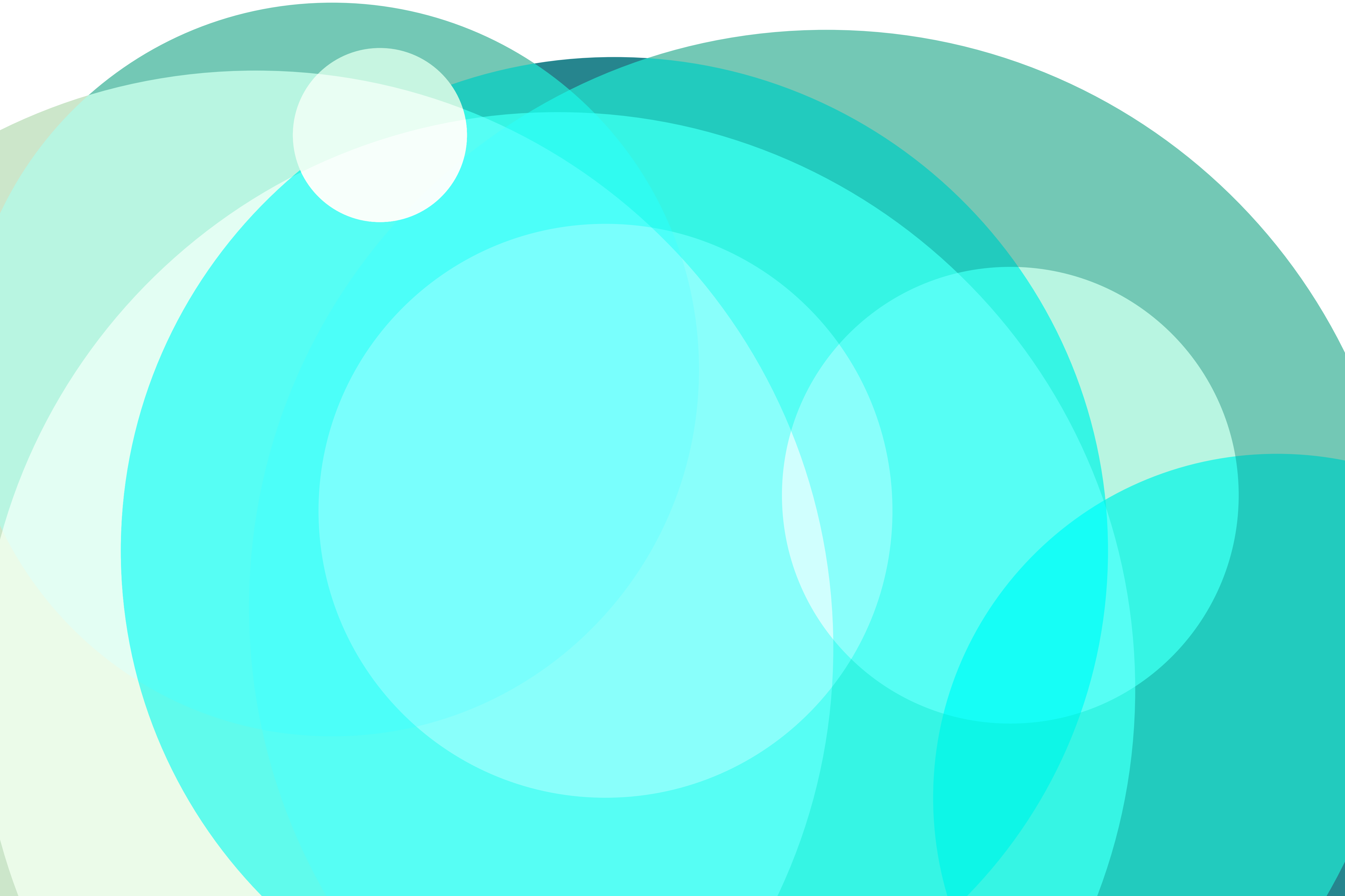


CHAPTER ONE

CLIMATE CHANGE AND SEA LEVEL RISE: WILL BE COVID-19 A GAME-CHANGER?

Francesco Rutelli
President IED, Institute of European Democrats

Countering and limiting the effects of rising sea and ocean levels is an important part of the crucial commitment of our time to mitigate and adapt to Climate Change.

Is it too much of a challenge to be truly engaged with the decision-making and strategic actions of rulers and public actors? Is it too late to issue political agendas pinned to the results of the next elections? How can we leave the vicious circle where matters that affect everybody's future appear negligible compared to the impending emergency that afflicts the international community?

To answer these questions, we need to link the content of this publication with the global COVID-19 emergency. The crisis that has paralysed the world since March 2020 hasn't happened out of the blue: all the conditions for it to arise were in place, and in addition we were caught unprepared, without adequate preventative or counter-measures.

The climate crisis is already underway and it will certainly bring the consequences analysed in this work, among others. Unless we manage to take the necessary, widely-known measures in a rational, planned and shared manner, we will not be able to stop and reverse the current course of events.

Since we started working on this volume, the global context has changed dramatically. As we will see shortly, the contents of these pages are not less, but more relevant and topical than ever.

We had started in the aftermath of the events – and consequent worldwide attention – that struck the iconic and fragile city of Venice in November 2019: an exceptional *Acqua alta,* with serious consequences for the city's life and economy and for a cultural heritage that belongs to Humanity.

A few weeks later, the outbreak of the COVID-19 pandemic changed the terms and perception of global priorities, due to its impact on human lives and the disruptive economic consequences. Europe is having to make life-changing decisions as a political and institutional community.

THREE KEY ELEMENTS STAND OUT IN THE PUBLIC DEBATE:

1. How should the international community interact? The global co-operation remain very weak, weeks after the WHO declaration marking the upgrade of COVID-19 from epidemic to pandemic. The battle for everybody's health, rather than provoking a strong commitment to multilateral collaboration, has been the subject of national strategies and diverse operational approaches, frequently in contrast with each other. This battle is the result of conflicting visions and positions – in the best of cases – and of individual governments' Soft Power to determine who has acted most effectively; most responsibly; most transparently; most collaboratively, etc. These competing narratives, used as self-serving tools during the crisis, are destined to become even more disruptive in the aftermath of the pandemic. And, please, don't forget the risk of new medical and scientific geopolitical competitions, rather than indispensible co-operations.

2. The fast-paced entry of the global community into the era of universally transmissible infections that are capable of temporarily halting social relations, trade, and entire production and services sectors, has also put democratic procedures on hold in various parts of the world. This translates into closed parliaments, elections postponed or suspended, and the centralisation of exceptional and interim powers in the hands of the rulers in office. This is a globally shared need, not only because people are worried or scared, but because the state of emergency is real. It creates an extended mandate, certainly not unrelated to the recent trend of increasing popular support for models other than liberal democracies, and in many cases, towards authoritarian and coercive models.

In a general context of assertive sovereign approaches – albeit conceptually weaker compared with the need to collaborate in finding answers to increasingly supranational, complex and integrated problems – the global governance rhetoric and the narrative of recent decades that is favourable to open economies and open societies are often being disavowed.

3. However, there has been an increase in general awareness about global threats that until a few weeks ago were being passed off as hoaxes. Or rather, even though President Trump gave this definition regarding Climate Change, the global public opinion thinks otherwise. According to international surveys, very few perceived the risk of global viral pandemics, but 68% of the people interviewed considered Climate Change a 'major global threat' (with 20% considering it 'a minor threat'; for a total of 88%).[1]

This leads us to think that the post-COVID-19 period will bring greater attention to the need to face global threats which until recently were indeed considered 'distant'. In fact, they have proven very close to our real, current and daily life, and not only to future scenarios. Global and integrated problems have lasting effects. *Sovereignist* and "*immediate*" narratives have become more contentious now, and are being questioned in light of the effects of global integration.

THERE ARE AT LEAST TWO ESSENTIAL LESSONS TO CONSIDER IN LIGHT OF THE CORONAVIRUS PANDEMIC: ONE IS THE ENVIRONMENTAL ISSUE; THE SECOND IS GOVERNANCE.

Let's go back to the topic of Climate Change.

Recent events are linked to the dynamics the Anthropocene, as Nobel prize winner Paul Crutzen's and the scientific community define it: the new Era that we inhabit, where men are capable of changing the balanced pre-existing ecosystems – in many respects, irreversibly.

The debate is intrinsically connected to: the age of globalisation; the growth of the world population which currently stands at 7.7 billion people; and the involvement and physical interaction through trade, travel and migration among practically every population on the planet. Infections that adapt to humans and are caused by viruses, bacteria, fungi and other agents – some of which transmitted directly, others indirectly – are being closely studied. Wuhan's case is similar, according to scientists, to other epidemics generated by the use of wild species for nutrition and for the preparation of traditional medicines – both in recently urbanised environments with significant and rapid transport connections or, for instance, when human communities have recently moved to areas that are undergoing deforestation.

It should be noted that a vector – as well as a weakening factor of the lung and respiratory defences – is air pollution, with fine particles (PM10; PM2.5) highly suspected of aggravating the situation in the most severely affected Lombard provinces (also in Hubei).

The World Health Organisation itself claims that 'changes in infectious disease transmission patterns are a likely major consequence of climate change'.[2]

This has brought about a deep change in the 'virus ecology' as we know it in human history. Today it is measured by the anthropisation of ecosystems, the urbanisation of billions of people and the globalisation of transport and logistics. In other words, it's not at all true that a virus is itself a killer. But we cannot exclude unexpected results in the coming years, for instance, from the leakage and transmission – and possible adaptation to humans – of viruses 'imprisoned' in glaciers formed millennia ago, or in the vast territories where permafrost will inevitably thaw.[3]

Fiction literature and cinematography have been in charge of anticipating some of these scenarios for some time. It's interesting to see that the disaster movie *Outbreak* (1995, with Dustin Hoffman, Kevin Spacey, Rene Russo, Donald Sutherland, Morgan Freeman) doesn't open with apocalyptic imagery but with a quote, the result of a pioneering life of research and scientific discoveries by Nobel laureate and bacteriologist Joshua Lederberg, who declares that 'The single biggest threat to man's continued dominance on the planet is the virus'[4].

It is unlikely that in future years what Sonia Shah anticipated (she has authored *Pandemic: Tracking Contagions from Cholera to Ebola and Beyond;* and the forthcoming *The Next Great Migration: the Beauty and Terror of Life on the Move)* will actually occur: 'for decades, we've sated our outsized appetites by encroaching on an ever-expanding swath of the planet with our industrial activities, forcing wild species to cram into remaining fragments of habitat in closer proximity to ours. That's what has allowed animal microbes such as SARS-COV2 – not to mention hundreds of others from Ebola to Zika – to cross over into human bodies, causing epidemics. In theory, we could decide to shrink our industrial footprint and conserve wildlife habitat, so that animal microbes stay in animals' bodies, instead'[5]. However, politicians and citizens must focus on the urgent search of a lasting compromise between shared well-being and the environmental sustainability of human growth.

The second lesson is about our democracies. Advocates of democracy and the European integration are gravely concerned about the political faltering, divisions and contradictions with which the 27 EU Member States have tackled the COVID-19 crisis. Future developments will tell us whether this crisis will prove a divisive factor, or to the contrary will rekindle the European Union ability to become involved in a globalised world according to entirely new strategic guidelines.

WHAT IS CERTAIN IS THAT THE WORLD HAS BEEN TESTED IN WAYS THAT NO ONE IMAGINED WOULD OCCUR SO CLOSELY.

The European Parliament's remote sessions and voting are unprecedented, dictated by necessity and motivated by wisdom. But other trials will have to be examined: a mix of choices and constraints when implementing pervasive powers indicates that executive political power can quickly become the expression of healthcare and environmental emergencies.

Until a few months ago, the prospect of interim governments – and related conflicts – was not exclusive to catastrophic literature and films: it was examined in the confidential scenarios laid out by the general staff and intelligence units describing

Photo by Linus Nylund on Unsplash

future global environmental crises. Not because some National Security Council imagined blocking the processes that determine increasing emissions of CO_2 – and equivalent – into the atmosphere; but because emergency and long-term constricting measures were supposed to occur for the phases in which – beyond the *tipping point* – ungovernable environmental phenomena happen such as: floods in inland and coastal areas; uninterrupted drought with loss of water and food supplies; fires on vast territories, including urban areas; submergence of smaller islands, with consequent flows of people and/or unstoppable mass migrations.

The geopolitical analyses and projections that we were aware of this far also concerned the possibility, or rather "the actual risk that, between one and two generations from now, the policies for adapting to climate change implemented with technological measures in specific areas of the Earth – known as geoengineering – become chiefly economic tools, aimed at strategic hegemony and at cornering competing Countries populations"[6]. Among the scenarios deemed plausible – albeit extreme – are for instance a military power launching reflective aerosols into the stratosphere to reduce the impact of solar radiation on its country.

Much more important will be to manage new asymmetric threats – health, cyber - and global threats - Climate Change – through the new approaches of Citizens Science, and Science Literacy.

This is the issue of this volume, in which we try to bring together best practices to help tackle the challenge, which has become an **inevitable trend,** of rising sea and ocean levels. We will also try to provide scientific and policy solutions to help deal with the persistent problem of political inaction.

This is a contentious issue. Again, at the end of this year we will be able to analyse another aspect of the impacts of the COVID-19 pandemic: how much will global CO_2 emissions have decreased in 2020, due to the halt in production and trade activities, transport and international tourism? In an effort to consistently reduce emissions and achieve the Paris Agreement objectives - setting the increase in the earth's average temperature at the end of the century at 1.5°C, and in any case below 2°C

TO WHAT EXTENT WILL THIS YEAR HAVE MARKED A SIGNIFICANT OR EVEN TEMPORARY STEP FORWARD IN THE ATTEMPT TO DECOUPLE ECONOMIC GROWTH AND INCREASING EMISSIONS?

By now, a slowing trend will involve the international Climate negotiations, due to the very critical perspective for complex and crowded gatherings.

As you can see, the issue we're dealing with is very topical and pervasive, as well as strategic.

In the following pages, the introductory text by Alessandro Lanza and Marzio Galeotti illustrates how, by postponing actions to address Climate Change by five years from now, the status quo would lead to an increase by an additional 20 cm in the sea level, close to the 23 cm rise observed from 1880 to this day.

Let's go back to focus, with Renata Codello, on the truly emblematic challenge that is the protection of the city of Venice, which resonates with most European and Mediterranean coastal cities and communities, but not only: for instance, on 31 December last the city of Jakarta was submerged by a flood that killed about 70 people and forced 400,000 residents to flee – just to mention the example of the Indonesian capital, which is physically sinking in large parts due to a series of interconnected causes.

We will describe, with an analysis by ICCROM scholars and a UNESCO document, the devastating impacts that Climate Change and rising water levels will have on the world Cultural Heritage.

We will publish seminal surveys carried out by the institutions and international study centres on the nature of this global issue, together with some economic, technical-scientific and journalistic insights that will be useful to the reader.

The aim is to better understand and assess; to help European and international institutions and the forces of society exercise the true Soft Power needed for the future of our planet, i.e. sharing ideas and solutions.

SEA LEVEL RISE: CAUSES, IMPACTS, AND POLICIES

Marzio Galeotti

Professor of Energy and Environmental Economics DESP - Department of Environmental Science and Policy Università degli Studi di Milano

Fellow, GREEN - Centre for Geography, Resources, Environment, Energy and Networks, Università L. Bocconi Milano

Alessandro Lanza

Università LUISS, Roma

Senior Member of the Strategic Committee of the Fondazione Euro

Mediterranean Center on Climate Change (CMCC) President and CEO CMCC Srl

ENEA, Member of the Board

1. Introduction

Since at least the beginning of the 20th century, the global mean sea level has been rising. Between 1880 and 2020, the sea level rose by approximately 23 cm. According to NASA sea levels are rising at a rate of 3.3 mm/yr. More precise data from satellite radar measurements reveal an accelerating rise and this increase is mostly due to human-induced global warming, which is provoking thermal expansion of seawater and melting of land-based ice sheets and glaciers. More specifically, between 1993 and 2018, thermal expansion of the oceans contributed 42% to sea level rise, the melting of temperate glaciers by 21%, Greenland by 15%, and Antarctica by 8%. Climate scientists expect the rate to further accelerate during the 21st century.

The Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), recently released by the United Nations Intergovernmental Panel on Climate Change (IPCC), expects global mean sea levels to most likely rise between 0.29 mm and 1.1 m by the end of this century. The report paints a very sobering picture of the challenges the world is facing due to sea level, even projecting future sea level is challenging, due to the complexity of many aspects of the climate system.

Even though the oceans are all connected, sea level does not rise or fall uniformly over the planet. Local factors include tectonic effects and subsidence of the land, tides, currents and storms. Rising seas can influence human populations considerably in coastal and island regions. Widespread coastal flooding is expected with several degrees of warming sustained for millennia. Further effects are higher storm-surges and more dangerous tsunamis, displacement of populations, loss and degradation of agricultural land and damage in cities. Natural environments like marine ecosystems are also affected, with fish, birds and plants losing parts of their habitat.

Societies can respond to sea level rise in three different ways: to retreat, to accommodate and to protect. Sometimes these adaptation strategies go hand in hand, but at other times choices have to be made among different strategies. Ecosystems that adapt to rising sea levels by moving inland might not always be able to do so, due to natural or artificial barriers.

2. Data and Measurement

How do scientists know that sea levels are rising? Different ways have been followed. Since 1992, NASA has collected data from satellites. Scientists also use tide gauges in many parts of the world to get a global average. Date on tides are always checked against satellite observations. Finally, there is review of rock formations. Scientists use this method to determine the sea level millions of years ago. They look for fossils of ocean organisms, sedimentary deposits, and even the actions of waves.

Global mean sea level has risen by about 21–24 cm since 1880, with about a third occurred during just the last two and a half decades. The rising water level is mostly due to a combination of meltwater from glaciers and ice sheets and thermal expansion of seawater as it warms. In 2018, global mean sea level was 8.1 cm above the 1993 average, the highest annual average in the satellite record (1993-present).

The global mean water level in the ocean rose by 3.6 mm per year from 2006–2015, which was 2.5 times the average rate of 1.4 mm per year throughout most of the twentieth century. By the end of the century, global mean sea level is likely to rise at least 0.3 m above 2000 levels, even if greenhouse gas emissions follow a relatively low pathway in coming decades.

In some ocean basins, sea level rise has been as much as 15-20 cm since the start of the satellite record. Regional differences exist because of natural variability in the strength of winds and ocean currents, which influence how much and where the deeper layers of the ocean store heat. Past and future sea level rise at specific locations on land may be more or less than the global average due to local factors: ground settling, upstream flood control, erosion, regional ocean currents, and whether the land is still rebounding from the compressive weight of Ice Age glaciers.

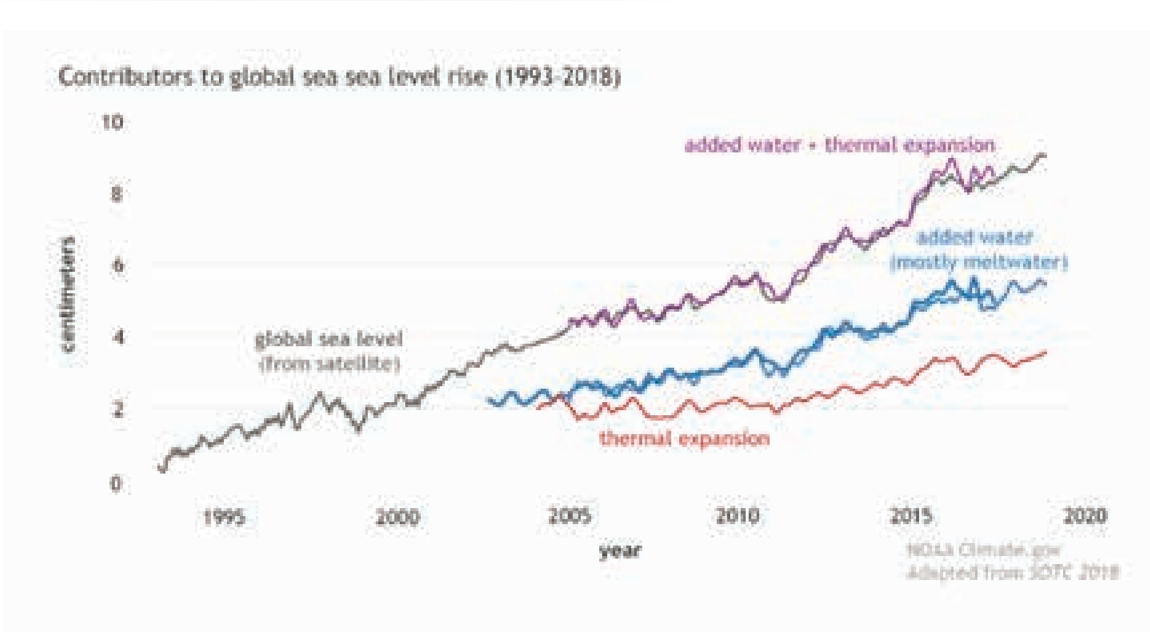
3. Causes

Sea levels rise due to global warming in two ways. First, as the ocean warms, it takes up more space. That alone has caused half of the sea level rise in the past century. Second, a warmer temperature melts Greenland's ice sheets and the polar ice caps. Specifically:

1. Thermal expansion: When water heats up, it expands. About half of the sea-level rise over the past 25 years is attributable to warmer oceans simply occupying more space.

2. Melting glaciers: Large ice formations such as mountain glaciers naturally melt a bit each summer. In the winter, snows, primarily from evaporated seawater, are generally sufficient to balance out the melting. Recently, though, persistently higher temperatures caused by global warming have led to greater-than-average summer melting as well as diminished snowfall due to later winters and earlier springs. That creates an imbalance between runoff and ocean evaporation, causing sea levels to rise.

3. Loss of Greenland and Antarctica's ice sheets: As with mountain glaciers, increased heat is causing the massive ice sheets that cover Greenland and Antarctica to melt more quickly. Scientists also believe that meltwater from above and seawater from below is seeping beneath Greenland's ice sheets, effectively lubricating ice streams and causing them to move more quickly into the sea. While melting in West Antarctica has drawn considerable focus from scientists, especially with the 2017 break in the Larsen C ice shelf, glaciers in East Antarctica are also showing signs of destabilizing.



These trends are cause of great concern. Since 2007 Antarctic melting has tripled: at that rate, it will increase sea levels another 15 cm by 2100. Andrew Shepherd, a professor of earth observation at the University of Leeds, said that translates into flooding in Brooklyn around 20 times a year. The worst losses occurred along the West Greenland coast. If the Greenland ice sheet melts completely, it would raise sea levels by 4,9 to 7 m. That's enough to put New Orleans, Miami, and Amsterdam underwater.

As to the future, timing is critical. A five-year delay in addressing climate change would increase sea levels by another 20 cm. That is almost as much as the nearly 23 cm increase that has occurred since 1880.

4. Impacts

Even a small increase in sea levels can have devastating impacts on coastal habitats farther inland, it can cause destructive erosion, wetland flooding, aquifer and agricultural soil contamination with salt, and lost habitat for fish, birds, and plants. Flooding in low-lying coastal areas is forcing people to migrate to higher ground, with millions people vulnerable to flood risk.

Although flooding is the obvious consequence of rising sea levels, other adverse effects follow from sea level rise.

1. Drinking water contamination: rising seas in many places will seep into the freshwater sources in the ground many coastal areas rely on for their drinking water. These aquifers are crucial springs of the planet's freshwater. Saltwater is unsafe to drink and removing the salt from water is technically feasible but expensive. The desalination plants some communities are already relying on are also energy-intensive. Because of these reasons this may not be a viable option for many coastal communities on a large scale.

2. Farming: not only are freshwater sources used for drinking but also for irrigation. The problem is the same as before: saltwater can harm or even kill crops and obtaining freshwater from saltwater is a costly and unsustainable practice.

3. Subsidence: recent research and increasing evidence suggests that pumping freshwater from the ground for human use – together with hydrocarbon extraction - may be contributing to a rise in sea levels. In addition, after its use groundwater is often discarded into the ocean, where it adds to the already-growing volume of water lapping at our shores.

4. Coastal plant life: shores hit by more saltwater will change the chemistry of the soil on the coast, with serious implications for plant life. Plants are sensitive to their environments: air temperature, access to water, and the chemical characteristics of soil are all factors that influence whether a plant can thrive in a given location. As the soil near the coast gets saltier, some plants may be fatally affected by the change in soil salinity.

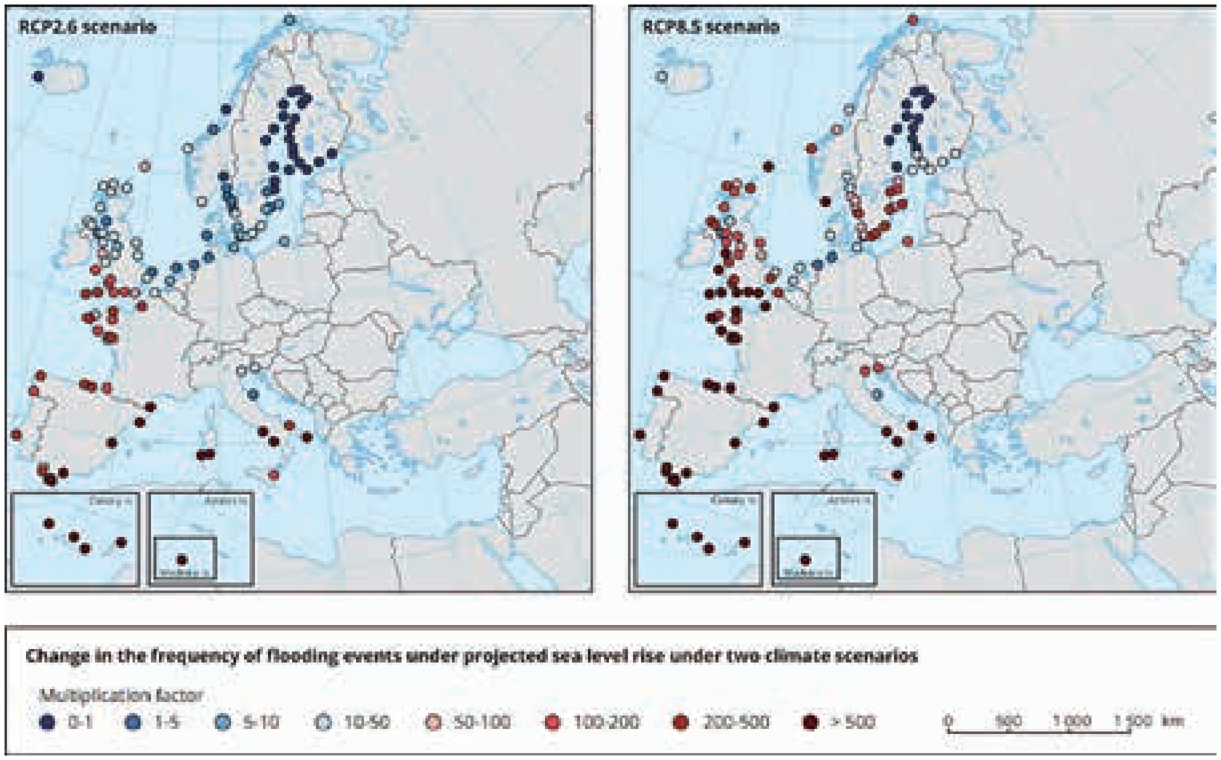
5. Wildlife populations: shores and beaches are habitat to many forms of wildlife. As the rising ocean erodes the shoreline and floods the areas in which coastal animals live, animals like shorebirds and sea turtles will suffer. Their delicate nests may be swept away by flooding, an especially big problem for endangered animals like sea turtles that can't afford to lose any offspring. Their habitats may be so damaged by flooding or changes in the surrounding plant life that they can no longer survive in the environment.

6. The economy. Tourism and real-estate industries are likely to be hit first by sea level rise. In coastal areas beachfront properties and recreational areas are directly threatened by rising waters. Perhaps less apparently, basic services such as Internet access and much of the underlying communications infrastructure which lie in the path of rising seas will be affected. A very recent study by Schinko et al. (2020) for the first time assesses the economy-wide effects of sea level rise globally and in particular in G20 countries, a group that includes both advanced and emerging countries, big emitters and countries affected by climate change. Two scenarios are considered by the study: one with warming well below +2° (a Paris Agreement scenario) and one exceeding this target by the end of the century. The central result is that by 2100, without further mitigation and adaptation and assuming continued sea level rise, projected annual global economy-wide losses can amount to more than 4%. With ambitious mitigation and adaptation, this percentage can be reduced to less than 0.5% of global GDP loss. This confirms the importance and economic efficiency of adaptation in the long term: making sure that coastal communities and their infrastructure are climate-resilient will affect economies across the globe much less than persistent climate impacts in the absence of climate action. The highest levels of annual GDP impacts in relative terms are projected for China and India, where in 2050 and with no further adaptation economic losses amount to 0.8-1.0% and 0.5-0.6%, respectively. Other regions with severe economy-wide damages by 2100 under no adaptation are Europe and Japan.

5. Impacts in Europe and Italy

According to a recent analysis of the European Environmental Agency, all coastal regions in Europe have experienced an increase in absolute sea level, but with significant regional variation. The rise in sea level relative to land along most European coasts is projected to be similar to the global average, with the exception of the northern Baltic Sea and the northern Atlantic coast, which are experiencing considerable land rise as a consequence of post-glacial rebound. Extreme high coastal water levels have increased at most locations along the European coastline. This increase appears to have been predominantly due to increases in mean local sea level rather than changes in storm activity.

Projected increases in extreme high coastal water levels are likely to be primarily the result of increases in local relative mean sea levels in most locations. However, several recent studies suggest that increases in the meteorologically driven surge component could also play a substantial role, in particular along the northern European coastline. All available studies project that damages from coastal floods in Europe would increase many fold in the absence of adaptation, although the specific projections depend on the assumptions of the particular study.



In Italy there are forty areas at risk if the sea rises, not just Venice. From north to south, the tides represent a risk for an area as large as Liguria. Half of the world's metropolitan areas are located on the coast, with a population of almost 2 billion people. In Italy the flooding scenarios of the Italian coasts developed by Enea, in collaboration with CNR and other Italian and foreign university research centers, show that there is an area equal to that of Liguria at risk of flooding. Forty coastal areas at risk of flooding were identified for our country, thirteen of these areas were mapped, for a total of 384.8 km of flooded coast, corresponding to the loss of territory equal to 5686.4 sq km.

Especially threatened are the areas of the northern coast of the Adriatic Sea, between Trieste and Ravenna, where in addition to the increase in sea level, the slow and inexorable sinking of the lands ranging from Romagna to Veneto must also be accounted for. It is not only Venice, therefore, already accustomed to the phenomenon of high water, but hundreds of coastal cities are in danger.

Central Italy does not do well either, with the plains of Versilia, Fiumicino, the Piane Pontina and Fondi, those of the Sele and Volturno rivers are at risk. Even the coastal area of Catania in Sicily and Cagliari and Oristano in Sardinia could see their physiognomies distorted. The data of ENEA are clear: in the last thousand years, the Mediterranean has risen by 30 centimeters. A tripling of the average level is expected in the next hundred years. This means that in the course of a few years we could see the most beautiful beaches in the world and the cities that overlook the sea devoured with periodic floods . If we look at an even more remote future, it is not difficult to imagine coastal cities and towns disappearing completely among the waves.

6. Coping Policies

There are policies and solutions that can be adopted to cope with the problem of sea level rise. If we look at the consequences, these solutions consist of adaptation measures.

1. One option is to plant trees and other vegetation to halt deforestation and to prevent flooding. In addition, restoring peatland and wetland areas is a low-cost carbon sequestration solution. Peatlands are the compressed remains of plants in waterlogged areas. They contain 550 gigatons of carbon. Governments must develop plans to identify, conserve, and restore the world's peatlands. Planting mangroves or other vegetation to absorb water are also being undertaken.

2. Soil management by farmers must be improved. Plowing which releases carbon into the atmosphere has to be reduced. Carbon-absorbing plants such as daikon can be planted. The roots break up the earth and become fertilizer when they die. Governments could subsidize these methods to make them cost-effective with traditional methods that rely on fertilizers.

3. Drainage systems and building up seawalls are already being installed by coastal cities. In Jakarta, a $40 billion project will aim to protect the city with an 80-foot-high seawall. Rotterdam has built barriers, drainage, and innovative architectural features such as a "water square" with temporary ponds. Island populations are starting to move, while tourists are flocking to visit popular vacation spots, like the Maldives before they are underwater. Urban planning and building practices are being revised to take into account the possibility of flooding.

6. Conclusions

Most predictions indicate that the warming of the planet will continue and is likely to accelerate, causing the oceans to keep rising. This means hundreds of coastal cities face flooding. But forecasting how much and how soon seas will rise remains an area of ongoing research.

While several measures are being adopted, in the end coping and adaptation solutions do not address the root cause of the sea level rise problem, which is global warming. The most cost effective solution is mitigation of planet-heating emissions. While progress is underway, the switch from fossil fuels to clean alternatives to reduce greenhouse gas emissions is far from the rate that is necessary to prevent temperature to rise above +1.5/2°C. The strategy to obtain this goal is to price carbon through carbon taxes or carbon trading. Subsidizing the adoption of green energy technologies and of carbon capture and storage are also policies that can be implemented.

VENICE'S CASE: A HISTORIC ICON AND CLIMATE CHANGE'S DESIGNATED VICTIM; THE CITY'S EXEMPLARY HISTORY POINTS THE WORLD TOWARDS MORE EFFECTIVE SOLUTIONS

Renata Codello

Former Superintendent of the Architectural and Landscape Heritage of Venice and the Lagoon

The protection and conservation of cultural heritage in a city like Venice is an absolute priority not only for the city's universally valued historical and cultural significance, but also for the social and economic development that this heritage is capable of generating. Potentially irreparable losses are not only linked to the many risks to which the heritage is exposed, but also to its extreme vulnerability, due to various permanent factors. These include particularly aggressive environmental conditions; frequent flooding phenomena due to tides; the especially pliable nature of the land which brings instability to buildings; the settlement features of the historical centre's urban fabric, which increase the vulnerability of buildings in the event of fires.

AS FERNAND BRAUDEL WROTE: 'IN VENICE, WATER IS AS IMPORTANT AS STONE.

It meant security and at the same time an ancestral curse, limitless wealth and daily torment: to this day it is a combination of rare beauty and deadly threat. Venice could die because of water.'[1]

This is a powerful, universal metaphor. From the outset this city-state was born on the principle of physical instability. It guaranteed its survival by equipping itself with councils that managed and controlled building work. This special and brave attitude of the Venetian *Magistratures* allowed them to make choices and carry out conservation work while studying the areas' specific features. Yet they also observed new phenomena and the existing balances with tireless analytical and decision-making skills. This is one of the most interesting topics: where balance is unstable by definition, there can be no effective resistance tout court. Above all, there can be no resistance arising from conflicting forces, so much so that nature always has the upper hand. Perhaps we should go back to read the far-sighted policy implemented by the Serenissima. It aimed at keeping the special habitat of its internal waters in balance, describing it as 'the lagoon that lead Venice to become a prime maritime centre, but that a set of overpowering, natural and social forces tended to bury, turning it into a malaria-breeding swamp and threatening the city with depopulation and abandonment.'[2] Nonetheless, although deviating some of the largest rivers in Italy prevented the land from covering the lagoon, this produced imbalances in vast areas, which as a consequence were periodically flooded. This story isn't only one of successes, yet undoubtedly, the fact that the world can still enjoy the charm of this extraordinary city is an incredible achievement.

Therefore, it can be useful to rediscover Venice's historical modernity. Its many historical accomplishments, discoveries and achievements have often been ignored, underestimated or removed. Nonetheless, the city's deep physical and social complexity has always been managed as it extended through time. The cultural heritage proper, i.e. the entire historical city and its lagoon, are emblematic of a new reflection.

In recent decades, for example, the usual ways to prevent damage and protect the city from high waters and earthquakes alike have been based on previous experience, acquired during critical past events and on the basis of a probabilistic analysis of situations that are more likely to happen in the life cycle of our heritage. The life span of a common artefact is easily estimated, but with cultural heritage the issue is much more complex. In fact, the conservation of a cultural asset should have no time limits and should account for the worst case scenario. This inevitably leads to implementing hefty protection measures which, at times, have such an impact as to jeopardise conservation. Therefore, it seems logical to choose and consider only the events that could determine the loss of Venice as a legacy, taking risky actions only when they cause ultimately reversible damage.

In general, restoration experts speak of a balance between safety and conservation needs: a position with wide margins of discretion and error. This is why we believe that the issue can also be addressed differently.

IN RECENT YEARS, EXPERIENCES IN VENICE HAVE OFFERED A SIGNIFICANT CONTRIBUTION.

Although the historic centre of the lagoon city is classified as a low seismicity zone, the structural condition of buildings is complex[3]. Venetian buildings, in general, show significant damage mechanisms triggered by non-uniform foundation subsidence, which occurred both over long periods of time and at specific moments, so much so that the elevated walls show them very clearly. Inside the same building or in adjacent buildings there have been collapses of 20 to 30 cm and in the largest monuments they have reached 50 to 60 cm. It follows that many buildings are affected by significant overhangs, wall disconnections and damage, and this could pose a serious risk for the conservation and safety of the entire building heritage of the City. Therefore, Venice is an extraordinary field of study and experimentation given that, due to its constructive nature, it obliges us to reason in terms of historical resilience. Resilience is 'the ability of a system and its components to prevent, absorb, welcome and recover from the effects of a dangerous event in a timely and efficient manner, in particular by ensuring the conservation, restoration or improvement of its basic and essential structures and of its functions.' (*Managing Extreme Events and Disasters to Advance Climate Change Adaptation*).

The urban configuration of the historic centre of the city of Venice implies, from a structural point of view, that most of the buildings cannot be defined as isolated since the building fronts aren't continuous and lack building joints to separate them. It's difficult to ascertain if and how the various structural units are clamped and/or juxtaposed, making it necessary to study historical archives and cross-check them with accurate on-site inspections. Often in Venice, as in many other historical centres, it's therefore equally necessary to determine the vulnerability of adjacent buildings, whose ties to other buildings are unknown. This leads to the fundamental idea of a system, by which investigating the complexity of historical buildings becomes a formidable investigative tool.

The studies conducted by scholars of construction history and science such as Edoardo Benvenuto, Salvatore D'Agostino and Antonino Giuffrè have radically innovated the way we study old buildings. They developed surveys and checks on cultural heritage – including buildings that are subjected to seismic events and natural disasters – bringing value to the static qualities of ancient buildings and therefore reconsidering their resistance to stress. By adopting appropriate analytical methods, we can see, for instance, that one of the most extraordinary buildings by Andrea Palladio in the convent of Santa Maria della Carità in Venice – home to the Gallerie dell'Accademia museum – has its entire historical foundations already set up to effectively counter the high water phenomenon; or it would need minimal intervention to meet the requirements of a good seismic improvement. In this case, as in many other architectures of similar construction quality, the traditional stiffening criteria used in engineering would create an unsustainable structural impact on the sixteenth-century building, with uncertain results for the overall effectiveness of the intervention, given that it would result in a clear contrast with the foundation system and the peculiar elastic characteristics of the lagoon subsoil.

UNDOUBTEDLY, TODAY WE CAN RETRIEVE A LARGE AMOUNT OF DATA IN THESE ANCIENT BUILDINGS

from the surveys and the study of layered materials. We need to make the most of the design process, favouring concise actions and assigning wider responsibilities to designers. Great analytical capacity gained over the years shouldn't be a reason for impediment, but a source of operational improvement concerning the techniques, methods and time frame of intervention plans. Perhaps this is the exact moment in which project activities can exceed the standard made up of the sum of the various specialist activities, and could be configured as an inclusive outcome of various disciplines.

In 2014, the Superintendence of the Architectural and Landscape Heritage of Venice and the Lagoon concluded a field trial, together with the Prefecture of Venice, to stipulate a *Memorandum of Understanding for the safety of Cultural Heritage located in the Province of Venice in case of emergency situations due to hydro-geological phenomena (floods, river floods and high tide)*. The Memorandum was complemented by the monitoring plan of the Venice bell towers and the development of prevention and risk reduction measures for the entire area of St. Mark's Square, which was shared with universities and local authorities. Even more extensive, in-depth and challenging, was the work carried out for the construction of the integrated management system of the city of Venice, required for the 2012-2018 Management Plan of the UNESCO site – VENICE AND ITS LAGOON.

The results were appreciated during the exceptional tide of 12 November 2019, when damage to the books in the Marciana Library and to the movable assets of state and municipal museums was very limited. Even the damage to the buildings in the

Marciana area, considering the strength of the rising water, was minimal. The exception is the Church of St. Mark which, despite being invaded by high water for centuries, has suffered greatly from the repeated violence of flooding.

These projects are aimed at overcoming the habit of intervening on heritage only when necessary and urgent, mostly ex-post. Instead, they are aimed at putting in place preventative actions by triggering an independent cognitive process. This is the essential prerequisite for assessing various types and degrees of danger and risk, ranging from occasional disasters to the degradation due to phenomena such as the continuous wear produced by uncontrolled tourism to which the heritage is exposed[4].

KNOWLEDGE, THE CENTRAL AND FOUNDING MOMENT OF CONSERVATION PROJECTS, IS ALSO A TOOL TO PREDICT POTENTIAL DAMAGE TO HERITAGE

in various ways, namely by providing information on: the nature and strength of the events that threaten the integrity of the buildings; the physical, chemical and mechanical properties of assets at risk; and on the behaviour and reaction of buildings subjected to harmful events.

Knowledge makes active conservation possible by exploiting the peculiarities of buildings to minimise the damage caused by disasters and by making the resilience of buildings explicit. Knowledge guides and consciously directs conservation choices; it lets us measure preventative and protective interventions in a timely and localised way, avoiding widespread and as such invasive operations; and it lets us identify intervention techniques and materials that are compatible with the building's behaviour. Knowledge provides measurable data with respect to the behaviour of buildings during previous disasters. For example, in the case of seismic events, the knowledge of the damage suffered by the building gives us information on its structural behaviour during dynamic stresses and therefore on its vulnerability or, rather, its resilience. And again, the knowledge of the construction features and traditional techniques used precisely to respond to particular climatic and environmental conditions (e.g. the yielding soils of Venice), allows us to avoid incompatible interventions that produce damage and potential losses. This is the case with reinforced concrete consolidating structures which – as we have seen during seismic events – have caused damage or foundational subsidence by becoming rigid joints in buildings that were conceived with specific elasticity and shape-changing feat

Photo by Jack Ward *on* Unsplash

URBAN HERITAGE
& CLIMATE RESILIENCE

Rohit Jigyasu
Project Manager on Urban Heritage, Climate Change and Disaster Risk Management, ICCROM

Aparna Tandon
Project Manager Collections Unit, ICCROM

Introduction

Floods, fires, droughts or pandemics-adverse impacts of climate are pervasive and affect every aspect of life including cultural heritage. From 1988 to 2007, 76 per cent of all disaster events were hydrological, meteorological or climatological in nature and have adversely affected cultural heritage (UNISDR 2008). A concern that received attention worldwide, when last year, Venice suffered prolonged flooding induced by high tides. The flood caused extensive damage affecting several palaces, churches and libraries including its beloved St. Mark's Basilica. A 3 billion Euro plan was announced for its recovery, while the Italian Ministry of Culture provided Euro 190,000 as crisis fund to stabilize the heritage places and clear the debris in the immediate aftermath (Rodenigo 2020). This is just the tip of the iceberg.

RECOVERING FROM THE FLOOD AND MITIGATING THE IMPACTS OF RECURRENT FLOODING WOULD REQUIRE CONCERTED AND TARGETED ACTION, COSTS FOR WHICH COULD RUN INTO BILLIONS.

Yet the threat is global. Recent projections from the UN point that global warming could rise upto 3.2C by 2100, which is higher than the limit of 2C set by the Paris Agreement. Consequences include existential threat to several major cities across the globe including ancient ones like Alexandria in Egypt (Holder, Commenda and Watts 2017)

The case of forest fires in Eastern Europe in 2008, which posed a high risk to the archaeological site of Olympia in Greece is yet another example. Flash floods due to unprecedented heavy rains in India's Uttarakhand State in 2013 destroyed many heritage structures in the region, while in Leh in August 2010, it caused caused destruction of vernacular adobe heritage.

Due to high intensity rainfall, increased instances of urban flooding have been reported in recent decades in nearly every part of the world, while storms in Western Europe in 2010 inundated historic centres of Rome, Paris and Lison in Europe. Heavy rains in Thailand caused the World Heritage Site of Ayutthaya to remain submerged in water thereby causing insurmountable loss to the foundations of historic built structures.

If these trends continue, many disaster scenarios may unfold in the future due to climate change. Increased frequency of high precipitation in some regions will trigger floods and landslides, with potentially large losses of life and assets. These may increase the number and intensity of very strong cyclones (typhoons and hurricanes). Sea level rise, coupled with coastal storms, will increase the impacts of storm surge and river flooding. Higher temperatures and melting glaciers may cause glacial lake outbursts that could flood downstream settlements.

Besides catastrophic events, climate change is also posing risks to heritage due to slow and progressive factors. For example, increased temperature may thaw permafrost, causing destabilization of heritage buildings and infrastructure. Variability in precipitation and humidity may result in increased efflorescence by capillary action in walls, frescoes, wall paintings, mosaics, and statues or cause wet-frost that may damage porous materials. Moreover, increased wind or changes in its direction may increase abrasion and degradation of rock art and damage to archaeological sites and historic buildings. Similarly, in areas that were arid before are experiencing increased rain fall and as a consequence, heritage places in such areas have to deal with recurrent pest infestations. Preventing infestations would require investments in maintenance programmes to include periodic checks.

Equally important is the consideration how processes and structures created to manage as well as regenerate heritage may, albeit unintentionally, contribute to global warming and human induced climate change. These may range from use of green-house gases or unfriendly materials for conservation and exhibition in museums to polluting of waterbodies and/ or cutting of forests for sustaining crafts (Bibby 2019). Moreover Environmental and climate change are removing and altering animals' habitat, changing how they live, where they live and who eats whom.

WITH INCREASED URBANIZATION, HUMANS ARE MORE SUSCEPTIBLE TO PATHOGENS CARRIED BY WILD ANIMALS AS HAS BEEN THE CASE OF CURRENT COVID19 PANDEMIC (BENTON 2020).

Understanding climate change induced risks for heritage

While climate change is indeed major threat, it is important to consider all those vulnerability factors that are increasing the susceptibility of cultural heritage to its effects.

Physical vulnerability of cultural heritage with respect to climate change related hazards may be structural, non-structural or material. For example, sandstone may be increasingly vulnerable due to changed humidity conditions or coastal erosion exacerbated by sea level rise may destabilize the foundations of historic buildings. Besides, social, economic, institutional, and attitudinal vulnerabilities may also directly or indirectly increase risks associated with climate change. The attitudinal vulnerabilities result from lack of awareness or blind faith among the local people causing little or no proactive action for reducing risks.

In many instances, different types of vulnerabilities merge overtime to exacerbate both, progressive and disaster risks.

A pertinent example here is that of Venice, where in order to attract more tourists, canals have been dug up, enabling ships to enter. This inadvertently has increased the risk of recurrent flooding. Recurrent flooding has led to depopulation. Residents feel that their coping capacities are tested time and again by recurrent shocks and stresses. Consequently, in 2013 the population of the historic city had dropped down to 56000 about one-third of its size, a generation ago (De Rossi 2015). Depopulation has further contributed to neglect of the historic city and the delicate ecosystem of the Venetian lagoon.

It is important to mention here that risks to cultural heritage are not only limited to monuments but also extend to urban areas in which these monuments are located historically. In fact, urbanization is one of the key factors that is increasing the vulnerability and risks to people, properties, and economy. The world is passing through great urban upsurge. The number of people living in cities equalled those in villages in 2007 and has been rising ever since. Since people, properties, infrastructure, and capital stock are concentrated in cities, the impact of climate change related hazards in urban areas can be catastrophic.

One of the impacts of rapid urbanization is that traditional boundaries are breaking up due to unplanned development, thereby disturbing delicate ecological relationships and exposing these areas to increasing risks from external hazards. Moreover, local communities are losing control over their own resources as traditional management systems are getting eroded and increasingly replaced by alien systems, which in many cases prove to be ineffective in reducing risks to local communities inhabiting these areas. Another consequence of these factors is the gradual disappearance of traditional skills, crafts and cultural practices, putting living aspects of heritage at risk. The likelihood of increased weather extremes in future, therefore, gives great concern that the number or scale of weather-related disasters will also increase, thereby dramatically increasing their impact on urban heritage in not too distant future.

Contribution of urban heritage in building resilience

Although cultural heritage is increasingly vulnerable to climate change, it should not be seen merely as a passive victim. Through enduring past disasters, communities in historic cities and traditional settelements often develop a vocabulary of resilient features in the urban environment that could contribute towards adapting to climate change, controlling carbon emissions and mitigating the impacts on heritage fabric as well as communities.

As mentioned before, traditional urban planning based on local geography and available natural resources have also served to build the resilience of traditional urban communities. For example, traditional planning of Ayutthaya with networks of canals and check dams as well as houses built on stilts ensured that local communities have adapted their way of life to live with the risk of floods. Cities such as Amsterdam, Venice (as also mentioned before) or Srinagar in India, also called the "Venice of Asia" provide similar cases of human settlements in close proximity to water (Byerly 2010). They provide us with valuable insights on how to balance delicate ecosystems exist in form of cities.

RECOVERING TRADITIONAL KNOWLEDGE SYSTEMS IN URBAN PLANNING AND MANAGEMENT AND IDENTIFYING THEIR POTENTIAL ROLE IN DISASTER RISK REDUCTION IS CRUCIAL FOR ENHANCING SAFETY AND RESILIENCE OF HISTORIC URBAN AREAS.

This calls for people centred development model uses traditional knowledge to achieve sustainable and equitable growth. Such models are crucial in Pacific island countries like Kiribati which have an imminent existential threat (Farran 2014).

Last but not the least, traditional management systems also have tremendous potential in securing collective action among communities for recovery following climate related disasters. The rich expression of heritage is also a powerful means to help victims recover from the psychological impact of the disaster. In such situations, people search desperately for identity and self-esteem. Traditional social and religious networks that provide mutual support and access to collective assets often represented by urban heritage are an extremely effective coping mechanism for community members (UNISDR 2013). This was well demonstrated following 2015 Nepal earthquake as networks of traditional guthi (communal trusts) provided support to local communities in their transition from response to recovery phase.

Mitigating Impacts of climate change for urban heritage

The challenges of urban heritage management are critical as well as context specific. Moreover, there are limitations of human and financial resources. In such situations, it becomes even harder to give exclusive consideration to climate change impacts, thereby recognizing the need of dovetailing climate actions with larger policies and plans for urban heritage conservation and management.

Various initiatives for climate change adaptation and disaster risk reduction seem to be on parallel tracks with very little synergy between them. Even some terms such as mitigation that are used in both the fields have different connotations leading to siloed on -the -ground implementation.

Nonetheless, it is important to develop interface between the two initiatives and this would require connecting global with local (macro-climate with micro-climatic factors which may or may not be linked and it is difficult to ascertain to what extent). At the same time, human actions need to unify strategies for climate change mitigation and adaptation with those for disaster risk reduction.

This implies that long-term risks need to be connected to short- term or immediate risks although it is difficult to prioritize keeping both long and short-term considerations in mind. The Hyogo Framework for Action" (2005) also calls for promoting the integration of risk reduction associated with existing climate variability and future climate change into the strategies for the reduction of disaster risk and adaptation to climate change. Therefore rather than seeing climate change adaptation and Disaster Risk Reduction as two parallel activities, climate change impacts should be factored in disaster risk assessment and mitigation practices. In other words, disaster risk reduction strategies for cultural heritage should be viable in a climate altered future.

It is equally crucial to mainstream heritage concerns in national, provincial and urban policies for climate change and disaster risk management. On the other hand, cultural heritage policies should also address disaster and climate change risks. That such policies should also seek to integrate traditional knowledge and increase participation of the local populations cannot be highlighted enough.

However, it is often difficult to collect and access meteorological data of sufficiently high resolution and continuity that is crucial for detecting important local and regional scale climatic trends as well as validating regional projections of climate models. Thereby, reducing uncertainties in the predictions, translating and disseminating scientific data in a form that facilitates decision-making processes is another related challenge. Considering these issues, it would be helpful to create a comprehensive yet easy to use information base that would facilitate assessment of risks to historic urban areas. At the same time, it could provide information on aspects such as assets and liabilities of residents and traditional knowledge systems as well as mechanisms to cope with urban disasters.

IN ORDER TO BUILD RESILIENCE AGAINST CLIMATE RELATED DISASTERS THERE IS A NEED TO DEVELOP DIFFERENT MEASURES FOR ADAPTING TO CLIMATE VARIABILITY,

reducing the carbon footprint and mitigating other direct as well as indirect impacts of climate change. This would necessitate developing viable options to upgrade, retrofit and manage physical growth of historic urban areas in a way that vulnerability of these areas to climate change is reduced. This will essentially involve introducing improved building materials and methods in a way that structural integrity and heritage values of these areas are maintained. This would also call for upgrading of urban infrastructure to include 'mitigation furniture' – dykes and levees, windbreaks, raised walkways, and platforms that will protect vulnerable areas and offer safe haven as required for the future without distorting heritage values of these areas.

Effective climate action for urban heritage also calls for territorial planning approach extending over the larger ecological footprint of the historic city rather than conventional master planning approach restricted to urban jurisdiction is needed to address the vulnerabilities and risks that are created in the larger urban ecosystem and landscape.

Heritage management practices should include monitoring indicators and performance guidelines, which will help in understanding short-and long-term changes to cultural heritage due to various factors including climate change and reporting preventive and corrective actions in heritage sites to address climate impacts, to reduce carbon footprint and to maintain and/or enhance the biosphere carbon sinks and to evaluate their effectiveness. Ensuring that heritage associated industries such as tourism or arts and crafts contribute to overall risk mitigation and adaptation would be crucial in achieving resilience outcomes.

Most importantly, a fundamental shift in heritage conservation is required from reactive to a more proactive approach aimed at addressing the change rather than mere static preservation in the 'original' state defined by a particular time period.

ICCROM's efforts for building climate resilience of heritage

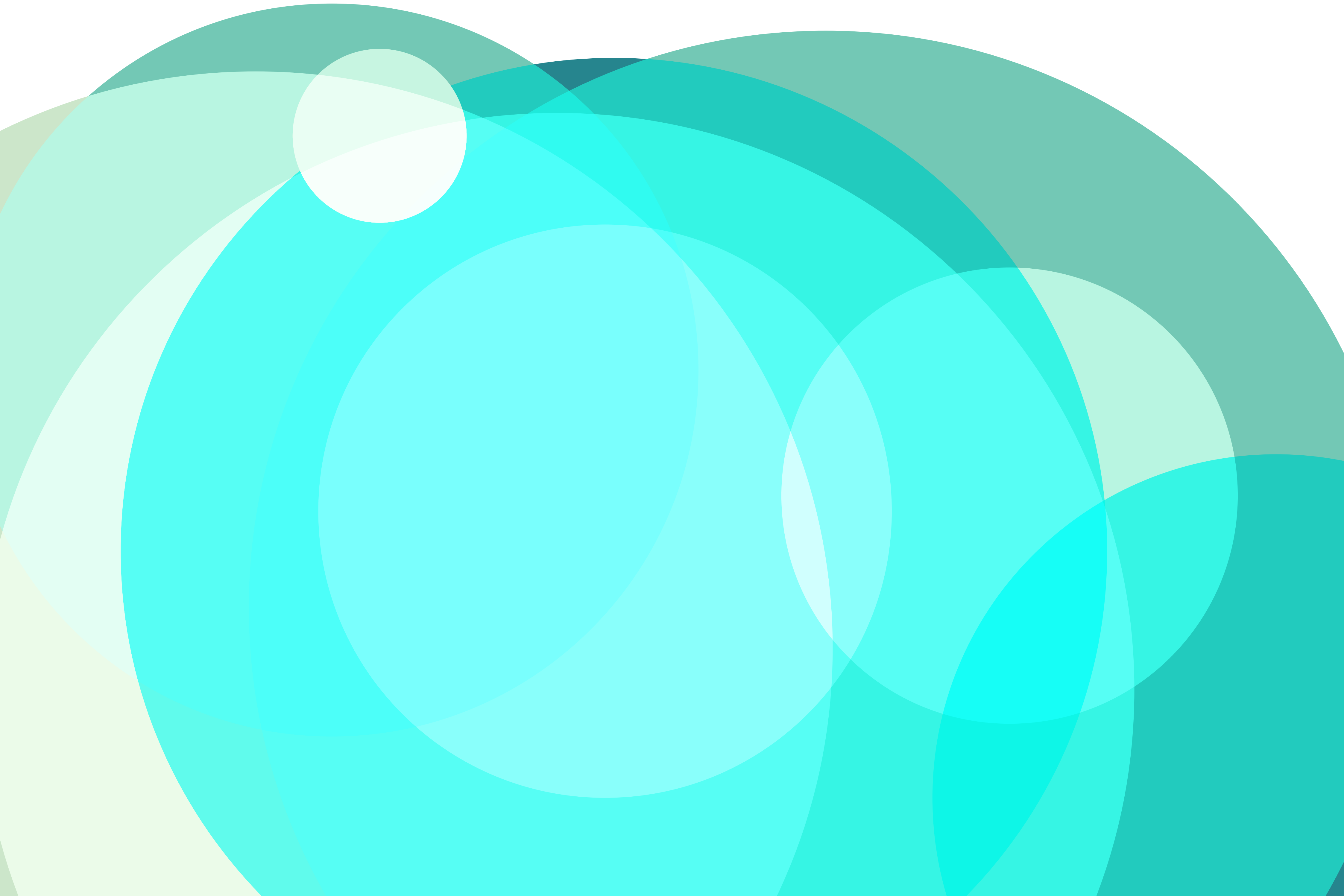
Recognizing the urgency of action due to exponential increase in climate risks to cultural heritage, ICCROM has been at the forefront of developing various activities aimed at capacity building and advocacy in disaster risk management and climate change adaption for cultural heritage. In collaboration with Ritsumeikan University in Kyoto, Japan, ICCROM has been organizing an International Training Course on Disaster Risk Management of Cultural Heritage since 2006. This pioneering multidisciplinary course brings together professionals from heritage, disaster risk management and environment sectors to build their capacity in risk assessment, mitigation, preparedness, response and recovery of cultural heritage. Among other aspects, the course takes into consideration climate related hazards. Recently ICCROM has also partnered with SEAMEO SPAFA, an inter-governmental organization for South East Asian region to deliver training courses in this area.

ICCROM's flagship programme on First Aid and Resilience for Cultural Heritage in Times of Crisis (FAR) espouses a multi hazard approach for all types of heritage and offers training as well tools for enhancing adaptive and coping capacities of communities in high risk zones. It emphasises coordinated approaches for risk reduction including climate change adaptation and mitigation. A proactive action of the programme focuses on developing common methods and procedures for manging risks to heritage and embedding them in regional, national and local systems for disaster risk reduction and climate change adaptation. In particular, ICCROM together with Italian Department for Civil Protection, the French Ministry of Interior, The Spanish Ministry of Culture and Sport and AFAD - Disaster and Emergency Management Presidency in Turkey is developing mechanisms for inter-agency coordination and cooperation within Europe that will address multiple and varied risks to cultural heritage and at the same time enhance coping and adaptive capacities of the local populations.

IN ORDER TO BUILD RESILIENCE AGAINST CLIMATE RELATED DISASTERS THERE IS A NEED TO DEVELOP DIFFERENT MEASURES FOR ADAPTING TO CLIMATE VARIABILITY,

that aims to mainstream climate action in conservation and management practices in Heritage Sites.

ICCROM acknowledges that a climate altered future requires unified action across sectors. It aims to continue efforts in this area through development of new tools, guidelines, training and awareness programmes for various target audiences, building bridges between heritage and non-heritage sectors to address the common challenge for a safer and sustainable future of heritage and people.



CHAPTER TWO

IPCC – INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE: SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE 2019

* Michael Oppenheimer (USA),
Bruce C. Glavovic (New Zealand/South Africa)
www.ipcc.ch

CHAPTER 4: SEA LEVEL RISE AND IMPLICATIONS FOR LOW-LYING ISLANDS, COASTS AND COMMUNITIES

EXECUTIVE SUMMARY

This chapter assesses past and future contributions to global, regional and extreme sea level changes, associated risk to low-lying islands, coasts, cities, and settlements, and response options and pathways to resilience and sustainable development along the coast.

Observations

Global mean sea level (GMSL) is rising (virtually certain1) and accelerating (high confidence2). The sum of glacier and ice sheet contributions is now the dominant source of GMSL rise (very high confidence). GMSL from tide gauges and altimetry observations increased from 1.4 mm yr–1 over the period 1901–1990 to 2.1 mm yr–1 over the period 1970–2015 to 3.2 mm yr–1 over the period 1993–2015 to 3.6 mm yr–1 over the period 2006–2015 (high confidence). The dominant cause of GMSL rise since 1970 is anthropogenic forcing (high confidence). {4.2.2.1.1, 4.2.2.2}

GMSL was considerably higher than today during past climate states that were warmer than pre-industrial, including the Last Interglacial (LIG; 129–116 ka), when global mean surface temperature was 0.5°C–1.0°C warmer, and the mid-Pliocene Warm Period (mPWP; ~3.3 to 3.0 million years ago), 2°C–4°C warmer. Despite the modest global warmth of the Last Interglacial, GMSL was likely 6–9 m higher, mainly due to contributions from the Greenland and Antarctic ice sheets (GIS and AIS, respectively), and unlikely more than 10m higher (medium confidence). Based on new understanding about geological constraints since the IPCC 5th Assessment Report (AR5), 25 m is a plausible upper bound on GMSL during the mPWP (low confidence). Ongoing uncertainties in palaeo sea level reconstructions and modelling hamper conclusions regarding the total magnitudes and rates of past sea level rise (SLR). Furthermore, the long (multi-millennial) time scales of these past climate and sea level changes, and regional climate influences from changes in Earth's orbital configuration and climate system feedbacks, lead to low confidence in direct comparisons with near-term future changes. {Cross-Chapter Box 5 in Chapter 1, 4.2.2, 4.2.2.1, 4.2.2.5, SM 4.1}

Non-climatic anthropogenic drivers, including recent and historical demographic and settlement trends and anthropogenic subsidence, have played an important role in increasing low-lying coastal communities' exposure and vulnerability to SLR and extreme sea level (ESL) events (very high confidence). In coastal deltas, for example, these drivers have altered freshwater and sediment availability (high confidence). In low-lying coastal areas more broadly, human-induced changes can be rapid and modify coastlines over short periods of time, outpacing the effects of SLR (high confidence). Adaptation can be undertaken in the short- to medium-term by targeting local drivers of exposure and vulnerability, notwithstanding uncertainty about local SLR impacts in coming decades and beyond (high confidence). {4.2.2.4, 4.3.1, 4.3.2.2, 4.3.2.3}

Coastal ecosystems are already impacted by the combination of SLR, other climate-related ocean changes, and adverse effects from human activities on ocean and land (high confidence). Attributing such impacts to SLR, however, remains challenging due to the influence of other climate-related and non-climatic drivers such as infrastructure development and human-induced habitat degradation (high confidence). Coastal ecosystems, including saltmarshes, mangroves, vegetated dunes and sandy beaches, can build vertically and expand laterally in response to SLR, though this capacity varies across sites (high confidence). These ecosystems provide important services that include coastal protection and habitat for diverse biota. However, as a consequence of human actions that fragment wetland habitats and restrict landward migration, coastal ecosystems progressively lose their ability to adapt to climate-induced changes and provide ecosystem services, including acting as protective barriers (high confidence). {4.3.2.3}

Coastal risk is dynamic and increased by widely observed changes in coastal infrastructure, community livelihoods, agriculture and habitability (high confidence). As with coastal ecosystems, attribution of observed changes and associated risk to SLR remains challenging. Drivers and processes inhibiting attribution include demographic, resource and land use changes and anthropogenic subsidence. {4.3.3, 4.3.4}

A diversity of adaptation responses to coastal impacts and risks have been implemented around the world, but mostly as a reaction to current coastal risk or experienced disasters (high confidence). Hard coastal protection measures (dikes, embankments, sea walls and surge barriers) are widespread, providing predictable levels of safety in northwest Europe, East Asia, and around many coastal cities and deltas. Ecosystem-based adaptation (EbA) is continuing to gain traction worldwide, providing multiple co-benefits, but there is still low agreement on its cost and long-term effectiveness. Advance, which refers to the creation of new land by building into the sea (e.g., land reclamation), has a long history in most areas where there are dense coastal populations. Accommodation measures, such as early warning systems (EWS) for ESL events, are widespread. Retreat is observed but largely restricted to small communities or carried out for the purpose of creating new wetland habitat. {4.4.2.3, 4.4.2.4, 4.4.2.5}

Projections

Future rise in GMSL caused by thermal expansion, melting of glaciers and ice sheets and land water storage changes, is strongly dependent on which Representative Concentration Pathway (RCP) emission scenario is followed. SLR at the end of the century is projected to be faster under all scenarios, including those compatible with achieving the long-term temperature goal set out in the Paris Agreement. GMSL will rise between 0.43 m (0.29–0.59 m, likely range; RCP2.6) and 0.84 m (0.61–1.10 m, likely range; RCP8.5) by 2100 (medium confidence) relative to 1986–2005. Beyond 2100, sea level will continue to rise for centuries due to continuing deep ocean heat uptake and mass loss of the GIS and AIS and will remain elevated for thousands of years (high confidence). Under RCP8.5, estimates for 2100 are higher and the uncertainty range larger than in AR5. Antarctica could contribute up to 28 cm of SLR (RCP8.5, upper end of likely range) by the end of the century (medium confidence). Estimates of SLR higher than the likely range are also provided here for decision makers with low risk tolerance. {SR1.5, 4.1, 4.2.3.2, 4.2.3.5}

Under RCP8.5, the rate of SLR will be 15 mm yr–1 (10–20 mm yr–1, likely range) in 2100, and could exceed several cm yr–1 in the 22nd century. These high rates challenge the implementation of adaptation measures that involve a long lead time, but this has not yet been studied in detail. {4.2.3.2, 4.4.2.2.3}

Processes controlling the timing of future ice shelf loss and the spatial extent of ice sheet instabilities could increase Antarctica's contribution to SLR to values higher than the likely range on century and longer time scales (low confidence). Evolution of the AIS beyond the end of the 21st century is characterized by deep uncertainty as ice sheet models lack realistic representations of some of the underlying physical processes. The few model studies available addressing time scales of centuries to millennia indicate multi-metre (2.3–5.4 m) rise in sea level for RCP8.5 (low confidence). There is low confidence in threshold temperatures for ice sheet instabilities and the rates of GMSL rise they can produce. {Cross-Chapter Box 5 in Chapter 1, Cross-Chapter Box 8 in Chapter 3, and Sections 4.1, 4.2.3.1.1, 4.2.3.1.2, 4.2.3.6}

Sea level rise is not globally uniform and varies regionally. Thermal expansion, ocean dynamics and land ice loss contributions will generate regional departures of about ±30% around the GMSL rise. Differences from the global mean can be greater than ±30% in areas of rapid vertical land movements, including those caused by local anthropogenic factors such as groundwater extraction (high confidence). Subsidence caused by human activities is currently the most important cause of relative sea level rise (RSL) change in many delta regions. While the comparative importance of climate-driven RSL rise will increase over time, these findings on anthropogenic subsidence imply that a consideration of local processes is critical for projections of sea level impacts at local scales (high confidence). {4.2.1.6, 4.2.2.4}

Due to projected GMSL rise, ESLs that are historically rare (for example, today's hundred-year event) will become common by 2100 under all RCPs (high confidence). Many low-lying cities and small islands at most latitudes will experience such events annually by 2050. Greenhouse gas (GHG) mitigation envisioned in low-emission scenarios (e.g., RCP2.6) is expected to sharply reduce but not eliminate risk to low-lying coasts and islands from SLR and ESL events. Low-emission scenarios lead to slower rates of SLR and allow for a wider range of adaptation options. For the first half of the 21st century differences in ESL events among the scenarios are small, facilitating adaptation planning. {4.2.2.5, 4.2.3.4}

Non-climatic anthropogenic drivers will continue to increase the exposure and vulnerability of coastal communities to future SLR and ESL events in the absence of major adaptation efforts compared to today (high confidence). {4.3.4, Cross-Chapter Box 9}

The expected impacts of SLR on coastal ecosystems over the course of the century include habitat contraction, loss of functionality and biodiversity, and lateral and inland migration. Impacts will be exacerbated in cases of land reclamation and where anthropogenic barriers prevent inland migration of marshes and mangroves and limit the availability and relocation of sediment (high confidence). Under favourable conditions, marshes and mangroves have been found to keep pace with fast rates of SLR (e.g., >10 mm yr-1), but this capacity varies significantly depending on factors such as wave exposure of the location, tidal range, sediment trapping, overall sediment availability and coastal squeeze (high confidence). {4.3.3.5.1}

In the absence of adaptation, more intense and frequent ESL events, together with trends in coastal development will increase expected annual flood damages by 2-3 orders of magnitude by 2100 (high confidence). However, well designed coastal protection is very effective in reducing expected damages and cost efficient for urban and densely populated regions, but generally unaffordable for rural and poorer areas (high confidence). Effective protection requires investments on the order of tens to several hundreds of billions of USD yr-1 globally (high confidence). While investments are generally cost efficient for densely populated and urban areas (high confidence), rural and poorer areas will be challenged to afford such investments with relative annual costs for some small island states amounting to several percent of GDP (high confidence). Even with well-designed hard protection, the risk of possibly disastrous consequences in the event of failure of defences remains. {4.3.4, 4.4.2.2, 4.4.3.2, Cross-Chapter Box 9}

Risk related to SLR (including erosion, flooding and salinisation) is expected to significantly increase by the end of this century along all low-lying coasts in the absence of major additional adaptation efforts (very high confidence). While only urban atoll islands and some Arctic communities are expected to experience moderate to high risk relative to today in a low emission pathway, almost high to very high risks are expected in all low-lying coastal settings at the upper end of the likely range for high emission pathways (medium confidence). However, the transition from moderate to high and from high to very high risk will vary from one coastal setting to another (high confidence). While a slower rate of SLR enables greater opportunities for adapting, adaptation benefits are also expected to vary between coastal settings. Although ambitious adaptation will not necessarily eradicate end-century SLR risk (medium confidence), it will help to buy time in many locations and therefore help to lay a robust foundation for adaptation beyond 2100. {4.1.3, 4.3.4, Box 4.1, SM4.2}

Choosing and Implementing Responses

All types of responses to SLR, including protection, accommodation, EbA, advance and retreat, have important and synergistic roles to play in an integrated and sequenced response to SLR (high confidence). Hard protection and advance (building into the sea) are economically efficient in most urban contexts facing land scarcity (high confidence), but can lead to increased exposure in the long term. Where sufficient space is available, EbA can both reduce coastal risks and provide multiple other benefits (medium confidence). Accommodation such as flood proofing buildings and EWS for ESL events are often both low-cost and highly cost-efficient in all contexts (high confidence). Where coastal risks are already high, and population size and density are low, or in the aftermath of a coastal disaster, retreat may be especially effective, albeit socially, culturally and politically challenging. {4.4.2.2, 4.4.2.3, 4.4.2.4, 4.4.2.5, 4.4.2.6, 4.4.3}

Technical limits to hard protection are expected to be reached under high emission scenarios (RCP8.5) beyond 2100 (high confidence) and biophysical limits to EbA may arise during the 21st century, but economic and social barriers arise well before the end of the century (medium confidence). Economic challenges to hard protection increase with higher sea levels and will make adaptation unaffordable before technical limits are reached (high confidence). Drivers other than SLR are expected to contribute more to biophysical limits of EbA. For corals, limits may be reached during this century, due to ocean acidification and ocean warming, and for tidal wetlands due to pollution and infrastructure limiting their inland migration. Limits to accommodation are expected to occur well before limits to protection occur. Limits to retreat are uncertain, reflecting research gaps. Social barriers (including governance challenges) to adaptation are already encountered. {4.4.2.2, 4.4.2.3., 4.4.2.3.2, 4.4.2.5, 4.4.2.6, 4.4.3, Cross-Chapter Box 9}

Choosing and implementing responses to SLR presents society with profound governance challenges and difficult social choices, which are inherently political and value laden (high confidence). The large uncertainties about post 2050 SLR, and the substantial impact expected, challenge established planning and decision making practises and introduce the need for coordination within and between governance levels and policy domains. SLR responses also raise equity concerns about marginalising those most vulnerable and could potentially spark or compound social conflict (high confidence). Choosing and implementing responses is further challenged through a lack of resources, vexing trade-offs between safety, conservation and economic development, multiple ways of framing the 'sea level rise problem', power relations, and various coastal stakeholders having conflicting interests in the future development of heavily used coastal zones (high confidence). {4.4.2, 4.4.3}

Despite the large uncertainties about post 2050 SLR, adaptation decisions can be made now, facilitated by using decision analysis methods specifically designed to address uncertainty (high confidence). These methods favour flexible responses (i.e., those that can be adapted over time) and periodically adjusted decisions (i.e., adaptive decision making). They use robustness criteria (i.e., effectiveness across a range of circumstances) for evaluating alternative responses instead of standard expect-

Photo by Kelly Sikkema on Unsplash

ed utility criteria (high confidence). One example is adaptation pathway analysis, which has emerged as a low-cost tool to assess long-term coastal responses as sequences of adaptive decisions in the face of dynamic coastal risk characterised by deep uncertainty (medium evidence, high agreement). The range of SLR to be considered in decisions depends on the risk tolerance of stakeholders, with stakeholders whose risk tolerance is low also considering SLR higher than the likely range. {4.1, 4.4.4.3}

Adaptation experience to date demonstrates that using a locally appropriate combination of decision analysis, land use planning, public participation and conflict resolution approaches can help to address the governance challenges faced in responding to SLR (high confidence). Effective SLR responses depend, first, on taking a long-term perspective when making short-term decisions, explicitly accounting for uncertainty of locality-specific risks beyond 2050 (high confidence), and building governance capabilities to tackle the complexity of SLR risk (medium evidence, high agreement). Second, improved coordination of SLR responses across scales, sectors and policy domains can help to address SLR impacts and risk (high confidence). Third, prioritising consideration of social vulnerability and equity underpins efforts to promote fair and just climate resilience and sustainable development (high confidence) and can be helped by creating safe community arenas for meaningful public deliberation and conflict resolution (medium evidence, high agreement). Finally, public awareness and understanding about SLR risks and responses can be improved by drawing on local, indigenous and scientific knowledge systems, together with social learning about locality-specific SLR risk and response potential (high confidence). {4.4.4.2, 4.4.5, Table 4.9}

Achieving the United Nations Sustainable Development Goals (SDGs) and charting Climate Resilient Development Pathways depends in part on ambitious and sustained mitigation efforts to contain SLR coupled with effective adaptation actions to reduce SLR impacts and risk (medium evidence, high agreement).

SEA-LEVEL RISE WILL CAUSE MORE THAN FLOODING

Sea-level rise will cause more than flooding

As global temperatures continue to rise, ice in the polar regions and glaciers will melt, dumping tons of extra water into the ocean. Warmer water temperatures will also lead the oceans to expand.

These factors will cause sea levels to increase and swamp coastal areas all over the world.

Although flooding is the obvious consequence of rising sea levels, there are plenty of other effects to consider – none of them good.

Here are five of those effects you probably haven't thought about:

1. It will contaminate our drinking water

As the rising sea crawls farther and farther up the shore, in many places it will seep into the freshwater sources in the ground that many coastal areas rely on for their drinking water. These underground water sources, called aquifers, are crucial springs of freshwater – in fact, groundwater accounts for most of the planet's freshwater.

Saltwater is unsafe to drink, and while it is possible to remove the salt from water, doing so is an expensive and complicated process. Some communities are already investing in costly desalination plants in anticipation of hard times ahead. San Diego County in drought-stricken California is building the largest seawater desalination plant in the western hemisphere, and the MIT Technology Review reports that the plant will cost about $1 billion.

These kinds of costly projects may be unrealistic for coastal communities on a large scale.

2. It will interfere with farming

Those same freshwater sources we use for drinking also supply the water we use for irrigation. The problems here are the same: The intruding sea could make these groundwater sources saltier. Saltwater can stunt or even kill crops, but creating freshw ater from saltwater is a costly and unsustainable practice.

In a twist of irony, recent research has suggested that pumping freshwater from the ground for human use may actually be contributing to a rise in sea levels. After the groundwater has been used – for drinking, irrigation, or other industrial purposes – it is often discarded into the ocean, where it adds to the already-growing volume of water lapping at our shores.

3. It will change our coastal plant life

More saltwater hitting our shores will change the chemistry of the soil on the coast, meaning the plant life there will most likely change as well.

Plants are really sensitive to their environments. Air temperature, access to water, and the chemical characteristics of soil are all factors that influence whether a plant can thrive in a given location.

As rising ocean water seeps into the ground, the soil near the coast will become saltier. Some plants will simply be unable to cope with the change in soil salinity and may disappear from the shoreline.

According to Climate Central, a nonprofit organization dedicated to communicating climate science to the public, trees will have an especially difficult time. Climate Central reports:

Trees have to work harder to pull water out of salty soil; as a result, their growth can be stunted – and if the soil is salty enough, they will die, a common sign of sea level rise. Even trees that are especially suited to salty soil can't survive repeated flooding by seawater.

4. It will threaten wildlife populations

Many forms of wildlife make their home on the beach. As the rising ocean erodes the shoreline and floods the areas in which coastal animals live, animals like shorebirds and sea turtles will suffer.

Their delicate nests may be swept away by flooding, an especially big problem for endangered animals like sea turtles that can't afford to lose any offspring. Their habitats may be so damaged by flooding or changes in the surrounding plant life that they can no longer survive in the environment.

5. It will hurt the economy

The tourism and real-estate industries in coastal areas are likely to take a hit as prime beachfront properties and recreational areas are washed away by rising waters. This is a fact that some involved in these industries are finding hard to swallow.

RISING SEA LEVEL EFFECTS, PROJECTIONS, AND SOLUTIONS

HOW THE RISING SEA LEVEL AFFECTS YOU

The average global sea level has risen 8.9 inches between 1880 and 2015. That's much faster than in the previous 2,700 years.

The table below shows the specifics per decade. It shows how the pace is quickening. It added 1.84 inches between 2000 and 2010. If it adds the same amount, between 2010 and 2020, it will have risen by 9.2 inches by 2020.

Year	Since 1880	Per Decade
1880	0	0
1890	0.4	0.44
1900	1.1	0.69
1910	1.3	0.15
1920	1.9	0.63
1930	2.1	0.16
1940	2.6	0.56
1950	3.6	0.98
1960	4.5	0.91
1970	4.7	0.17
1980	5.6	0.92
1990	6.2	0.63
2000	6.9	0.67
2010	8.1	1.16
2015	8.9	0.88
2020	9.2	1.16

Source: "Global Average Absolute Sea Level Change, 1880-2015," Environmental Protection Agency. 2020 estimate based on the current rate of change.)

How Scientists Know the Sea Level Is Rising

Scientists accurately measure global sea level increases in three ways.

1. Since 1992, NASA has collected data from satellites. Here's a link to the data.

2. NASA also uses tide gauges in many parts of the world to get a global average. The gauges block out the impact of waves and tides to get an accurate reading.

3. The third method is reviewing rock formations. Scientists use this method to determine the sea level millions of years ago. They look for fossils of ocean organisms, sedimentary deposits, and even the actions of waves.

Effects of the Rising Seas

The rising sea level is affecting coastal areas all over the world. It increases flooding, worsens hurricane damage, and leaches saltwater into tidal areas. It increases migration, weakens military preparedness, and threatens historical sites.

Local governments are spending billions to defend against these effects.

Flooding will affect eight of the world's largest coastal cities. It will impact 40% of Americans who live in coastal counties.

Floods have hit U.S. coastal towns three to nine times more often than they did 50 years ago. From 2005 to 2017, sea level rises cost eight coastal states $14.1 billion.

Another study showed that the number of coastal flood days in 27 U.S. locations has increased dramatically. They flooded 2.1 days a year between 1956 and 1960. That exploded to 11.8 days annually between 2006 and 2010.

Between 1978 and 2015, at least 30,000 homes flooded multiple times. The federal government bought out fewer than 9% and only paid 75% of the home's value. Federal disaster funds help people rebuild their homes in the same spot. In 2012, Congress phased out subsidies for federal flood insurance. That makes it too expensive for many homeowners.

U.S. sea level rise affects three areas the most. Here are specifics on its impact.

Eastern Seaboard:

• Flood-prone areas in New York, New Jersey, and Connecticut lost $6.7 billion in home values.

• Atlantic City, New Jersey, regularly floods when it rains. A four-foot storm surge would flood 50% of it.

• Boston is near the fastest warming body on Earth the Gulf of Maine. Storm damage affects the $8 billion Waterfront District.

• Annapolis, Maryland, now floods from high tide several days a week. Floor vents were installed to drain floodwaters from historic buildings. If sea waters rise 3.7 feet, the U.S. Naval Academy will be underwater.

• Charleston, S.C., floods 50 days a year, up from four days a year in the 1980s. By 2050, it will flood every third day. North Carolina is losing six feet of coastal land every year. The Outer Banks are eroding away.

Florida and Gulf States:

• In Miami, Florida, streets flood during high tide. The City of Miami Beach launched a five-year, $400 million public works program. It's raising roads, installing pumps, and redoing sewer connections. By 2070, Miami streets will flood every single day That threatens $136 billion of real estate.

• By 2048, the residents of 64,000 Florida homes will have to deal with chronic flooding.

• Home prices in lower-lying areas of Miami-Dade County and Miami Beach are being affected. Properties at risk of rising sea levels sell at a 7% discount to comparable properties. By 2030, Miami Beach homes could pay $17 million in higher property taxes due to flooding. By 2100, that could rise to $760 million.That's if property owners, many of whom are from overseas, don't abandon the market.

• In Louisiana, rising sea levels are flooding the Mississippi Delta. Louisiana is losing one acre an hour of wetlands. These areas nourish fisheries and protect New Orleans from hurricanes. They also absorb the greenhouse gases that cause global warming.

West Coast:

• Rising sea levels combined with sinking land will flood many areas around San Francisco by 2100. The land is sinking because of groundwater pumping. Parts of the airport, as well as large sections of Union City, Foster City, and Treasure Island would be underwater.

• San Diego County, California, is building the largest seawater desalination plant in the western hemisphere. The plant will cost $1 billion.

• Most of the property in these cities are financed by municipal bonds or mortgages. Their destruction will hurt the investors and depress the bond market. Real estate markets could collapse in these regions, especially after severe storms.

Rising sea levels worsen damage from hurricanes. The 17 most destructive U.S. storms in history occurred after 2000, with three in 2017. Their damage cost the economy $700 billion.

About 1.2 million Americans live in coastal areas at risk of "substantial damage" from hurricanes. Most of this densely populated area lies less than 10 feet above sea level, according to the National Hurricane Center. A 23-foot storm surge would flood 67% of U.S. interstates, including 57% of arterial highways. It would cover almost half of the rail miles, 29 airports, and almost all ports in the Gulf Coast area.

Hurricane storm surges threaten 12 of the world's busiest airports. Hurricane Sandy inundated all three New York City airports. As a result, La Guardia Airport is using a $28 million federal grant to build a flood wall, rainwater pumps, and a new drainage system.

• Saltwater leaches into underground aquifers and the soil. It disrupts the chemical balance of estuaries, destroying oyster beds and bird habitats. Increased salinity in Bangladesh, Vietnam, and other South Asian coastal countries threatens rice production. In Egypt, up to 12.5 miles inland from the shoreline have become saline, threatening billions of dollars in farming losses.

• U.S. military preparedness is being compromised. There are 1,774 military sites on 95,471 miles of coastline at risk of flooding from sea level rise. More than 30 sites are already impacted. Extreme weather affects all bases, but especially those in the Pacific region. They are hubs for disaster relief efforts. There is also a huge nuclear fallout container on the Marshall Islands. Rising sea levels and storms could easily damage the dome, releasing nuclear debris into the ocean.

• Migration is increased as residents flee from flooding coastal areas. Low-lying island nations, such as the Maldives and Seychelles, will soon be underwater. By 2050, 17% of Bangladesh would be flooded, displacing 18 million people. Forty percent of Jakarta, Indonesia, home to 30 million people, lies below sea level.

• Tourism and historical sites are threatened. On Easter Island, the famous Moai statues will be destroyed if the sea rises six feet. The Marshall Islands are disappearing already. They are less than six feet above sea level, but changing sea winds have raised sea levels a foot over the past 30 years. The nation's 70,000 residents will probably emigrate to the United States, thanks to a 1986 agreement.

Causes Behind the Rising Seas

Global warming causes rising sea levels in two ways. First, as the ocean warms, it takes up more space. That alone has caused half of the sea level rise in the past century.

Second, a warmer temperature melts Greenland's ice sheets and the polar ice caps. Between 2002 and 2016, Antarctica lost 125 gigatons of ice annually. It contributed 0.013 inches of sea level rise per year. Most of this loss occurred in the West Antarctic Ice Sheet. Antarctica holds 90% of the world's ice. If it all melted, sea levels would rise 200 feet.

The rate of ice sheet melting is accelerating. Between 1992 and 2017, Antarctica shed 3 trillion tons of ice. It increased sea levels by three-tenths of an inch. But 40% of that occurred during the last five years, from 2012 to 2017.

Looked at another way, Antarctic melting has tripled since 2007. At that rate, it will increase sea levels another six inches, or 15 centimeters, by 2100. Andrew Shepherd, a professor of earth observation at the University of Leeds, said that translates into flooding in Brooklyn around 20 times a year.

Even more recently, an additional concern has been added. Between 2010 and 2016, the Antarctic grounding line has receded 600 feet per year. The grounding line is the last place where the ice meets bedrock. A receding line means warmer ocean water is melting the underside of the glacier while a warmer air temperature attacks the top layers. It creates a river under the glaciers that ferries them more quickly into the ocean.

That could raise sea level another 10 feet by 2100. It's enough to put FDR Drive and 1st Avenue on the Upper East Side in Manhattan underwater.

During the same period, Greenland lost 280 gigatons of ice per year. It's melting at the fastest rate in the past 450 years. The melting ice added 0.03 inches each year to rising sea levels. The worst losses occurred along the West Greenland coast. If the Greenland ice sheet melts completely, it would raise sea levels by 16 feet to 23 feet. That's enough to put New Orleans, Miami, and Amsterdam underwater.

The loss of polar ice also affects the many species that live there. Polar bears are just one of the 17 species that will go extinct as a result.

Predictions for the Future

Timing is critical. A five-year delay in addressing climate change would increase sea levels by another 7.8 inches. That's almost as much as the 8.9-inch increase that's occurred since 1880. Here's a timeline of what will happen if nothing is done.

• By 2033, rising sea levels will flood 4,000 miles of fiber optic cables that deliver the internet and telephone services. Relocating the cables would be expensive and only buy a little time. At first, New York, Miami, and Seattle would be affected the most. Over time, everyone will be impacted by a disruption in these services.

• By 2038, 170 U.S. coastal cities and towns will be "chronically inundated" according to the Union of Concerned Scientists. They will see 10% of their area flooded at least twice a month. By 2100, more than half of the communities along the Eastern Seaboard and Gulf Coast will experience it.

• By 2045, another study found that 300,000 coastal properties will be flooded 26 times a year. The value of that real estate is $136 billion.

• By 2100, that number will rise to $1 trillion. At most risk are homes in Miami, New York's Long Island, and the San Francisco Bay area. For example, San Francisco would experience $62 billion in property damage by a four-foot rise in sea levels. It would also put the headquarters of Facebook and Yahoo underwater.

• The Intergovernmental Panel on Climate Change predicted sea levels will rise between one and two feet by 2100. That's 52 cm to 98 cm. The IPCC made this forecast in 2007. A two-foot rise would flood tens of millions of people living in low-lying areas. It would swamp many U.S. East Coast cities.

Other, more recent, studies have issued more dire warnings.

In February 2018, NASA found that sea levels are rising faster than the IPCC forecast. NASA predicts sea levels will be three to four feet higher by 2100. That's 91 cm to 122 cm. It based this on recent measurements of melting ice in Greenland and Antarctica. They warn this is a conservative estimate. A May 2019 study confirmed this estimate.

A 2010 North Carolina study also confirmed that ocean levels will rise three feet by 2100. That would flood 50,000 residents of the state. It would also damage tens of thousands of expensive beach-front properties. Nationally, a three-foot rise would displace 4.2 million people according to a Harvard study.

In 2017, researchers led by the University of Melbourne, Australia predicted sea levels could rise as much as six feet by 2100. That's 183 cm. As Antarctica melts, it will reach the larger sheets that are more inland. Their weight will make them melt faster than smaller ice sheets have in the recent past. A six-foot rise would put Atlantic City underwater. A six-foot rise would flood 100,000 homes in New York City, causing $39 billion in property damage.

In Miami, 54,000 homes costing $14 billion would be flooded.

The worst predictions are based on what happened the last time the temperature was this high. That was 116,000 years ago, and the sea level was 20 to 30 feet higher. Why isn't the sea level that high now? Warming has happened so fast that the ice hasn't had time to fully melt yet. It's like putting an ice cube in hot coffee, it doesn't melt instantly. Over thousands of years, ice will continue to melt unless the temperature is reduced.

The worst prediction of all comes from looking at the Earth the last time greenhouse gas emissions were this high. Carbon dioxide is 411 parts per million. The last time it was this high was during the Pliocene era. Back then, the sea level was 66 feet higher. Again, it takes time for the temperature to rise in response to greenhouse gases. It's like turning on the burner to heat the coffee. Until greenhouse gases are reduced, the temperature will continue to climb.

Potential Solutions to the Problem

There are three types of solutions to sea level rise. The most widely-discussed are coping solutions. Coastal cities are installing drainage systems and building up seawalls. Island populations are moving. Tourists are flocking to visit popular vacation spots, like the Maldives before they are underwater.

In Boston, developers are planning ahead. Skanska Commercial Development constructed an elliptical office tower designed to withstand fierce wind storms. The building's electrical infrastructure is located 40 feet above the 100-year floodplain. It also has a 40,000-gallon water reclamation tank, and a raised ground floor.

But coping solutions don't address the root cause of global warming. Nations are focused on the second type of solution, reducing future greenhouse gas emissions. They are switching from fossil fuels to clean alternatives. These include solar energy, wind energy, and geothermal energy sources.They are instituting carbon taxes to raise the cost of burning carbon. Carbon emissions trading rewards businesses that adhere to carbon caps.

The third solution is the most critical, but less widely discussed. Existing greenhouse gases must be removed from the atmosphere. Carbon sequestration captures and stores CO2 underground. To meet the Paris Agreement goal, 10 billion tons a year must be removed by 2050 and 100 billion tons by 2100. In 2018, only 60 million tons of carbon was sequestered according to Princeton University's Professor Steven Pacala.

One of the easiest solutions is to plant trees and other vegetation to halt deforestation. The world's 3 trillion trees store 400 gigatons of carbon. There is room to plant another 1.2 trillion trees in vacant land across the earth. That would absorb an additional 1.6 gigatons of carbon. The Nature Conservancy estimated that this would only cost $10 per ton of CO2 absorbed. California is planting trees to prevent flooding. Seattle encourages developers to add rooftop gardens or walls covered by vegetation to new building projects.

Restoring peatland and wetland areas is another low-cost carbon sequestration solution. Peatlands are the compressed remains of plants in waterlogged areas. They contain 550 gigatons of carbon. Governments must develop plans to identify, conserve, and restore the world's peatlands.

Second, farmers must manage their soil better. For example, they could reduce plowing which releases carbon into the atmosphere. Instead, they could plant carbon-absorbing plants such as daikon. The roots break up the earth and become fertilizer when they die. The government can subsidize these methods to make them cost-effective with traditional methods that rely on fertilizers.

Third, power plants can efficiently use carbon capture and storage because CO2 makes up 5% to 10% of their emissions. The government should subsidize the research as it did with solar and wind energy. It would only cost $900 million, far less than the $15 billion Congress spent on Hurricane Harvey disaster relief.

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CLIMATE CHANGE: GLOBAL SEA LEVEL

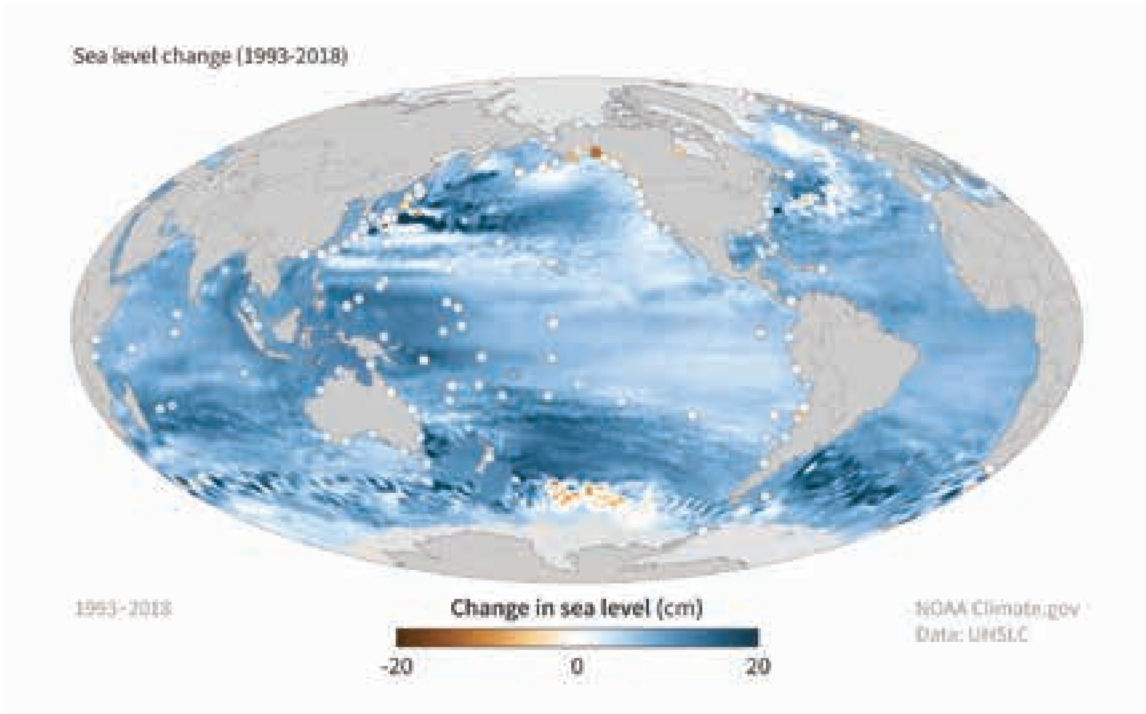
Rebecca Lindsey
www.climate.gov

Global mean sea level has risen about 8–9 inches (21–24 centimeters) since 1880, with about a third of that coming in just the last two and a half decades. The rising water level is mostly due to a combination of meltwater from glaciers and ice sheets and thermal expansion of seawater as it warms. In 2018, global mean sea level was 3.2 inches (8.1 centimeters) above the 1993 average–the highest annual average in the satellite record (1993-present)

SEA LEVEL SINCE 1880

The global mean water level in the ocean rose by 0.14 inches (3.6 millimeters) per year from 2006–2015, which was 2.5 times the average rate of 0.06 inches (1.4 millimeters) per year throughout most of the twentieth century. By the end of the century, global mean sea level is likely to rise at least one foot (0.3 meters) above 2000 levels, even if greenhouse gas emissions follow a relatively low pathway in coming decades.

In some ocean basins, sea level rise has been as much as 6-8 inches (15-20 centimeters) since the start of the satellite record. Regional differences exist because of natural variability in the strength of winds and ocean currents, which influence how much and where the deeper layers of the ocean store heat.



Between 1993 and 2018, mean sea level has risen across most of the world ocean (blue colors). In some ocean basins, sea level has risen 6-8 inches (15-20 centimeters). Rates of local sea level (dots) can be amplified by geological processes like ground settling or offset by processes like the centuries-long rebound of land masses from the loss of ice age glaciers. NOAA Climate.gov map, based on data provided by Philip Thompson, University of Hawaii.

Past and future sea level rise at specific locations on land may be more or less than the global average due to local factors: ground settling, upstream flood control, erosion, regional ocean currents, and whether the land is still rebounding from the compressive weight of Ice Age glaciers. In the United States, the fastest rates of sea level rise are occurring in the Gulf of Mexico from the mouth of the Mississippi westward, followed by the mid-Atlantic. Only in Alaska and a few places in the Pacific Northwest are sea levels falling, though that trend will reverse under high greenhouse gas emission pathways.

“In some ocean basins, sea level rise has been as much as 6-8 inches (15-20 centimeters) since the start of the satellite record in 1993.”

WHY SEA LEVEL MATTERS

In the United States, almost 40 percent of the population lives in relatively high population-density coastal areas, where sea level plays a role in flooding, shoreline erosion, and hazards from storms. Globally, 8 of the world's 10 largest cities are near a coast, according to the U.N. Atlas of the Oceans.

South Beach, Miami on May 3, 2007. Photo by Flickr user James WIlliamor, via a Creative Commons license.

Nuisance flooding in Annapolis in 2012. Around the U.S., nuisance flooding has increased dramatically in the past 50 years. Photo by Amy McGovern.

In urban settings along coastlines around the world, rising seas threaten infrastructure necessary for local jobs and regional industries. Roads, bridges, subways, water supplies, oil and gas wells, power plants, sewage treatment plants, landfills–the list is practically endless–are all at risk from sea level rise.

Higher background water levels mean that deadly and destructive storm surges, such as those associated with Hurricane Katrina, "Superstorm" Sandy, and Hurricane Michael–push farther inland than they once did. Higher sea level also means more frequent high-tide flooding, sometimes called "nuisance flooding" because it isn't generally deadly or dangerous, but it can be disruptive and expensive. (Explore past and future frequency of high-tide flooding at U.S. locations with the Climate Explorer, part of the U.S. Climate Resilience Toolkit.)

In the natural world, rising sea level creates stress on coastal ecosystems that provide recreation, protection from storms, and habitat for fish and wildlife, including commercially valuable fisheries. As seas rise, saltwater is also contaminating freshwater aquifers, many of which sustain municipal and agricultural water supplies and natural ecosystems.

WHAT'S CAUSING SEA LEVEL TO RISE?

Global warming is causing global mean sea level to rise in two ways. First, glaciers and ice sheets worldwide are melting and adding water to the ocean. Second, the volume of the ocean is expanding as the water warms. A third, much smaller contributor to sea level rise is a decline in the amount of liquid water on land–aquifers, lakes and reservoirs, rivers, soil moisture. This shift of liquid water from land to ocean is largely due to groundwater pumping.

Pedersen Glacier, at Aialik Bay in Alaska's Kenai Mountains, in 1917 (left) and 2005 (right). In the early 20th century, the glacier met the water and calved icebergs into a marginal lake near the bay. By 2005, the glacier had retreated, and the lake had become a small grassland. Photos courtesy of Louis H. Pedersen (1917) and Bruce F. Molina (2005), obtained from the Glacier Photograph Collection, Boulder, Colorado USA: National Snow and Ice Data Center/World Data Center for Glaciology. Large images: 1917 | 2005

Melt streams on the Greenland Ice Sheet on July 19, 2015. Ice loss from the Greenland and Antarctic Ice Sheets as well as alpine glaciers has accelerated in recent decades. NASA photo by Maria-José Viñas

From the 1970s up through the last decade or so, melting and heat expansion were contributing roughly equally to observed sea level rise. But the melting of mountain glaciers and ice sheets has accelerated:

- The decadal average loss from glaciers in the World Glacier Monitoring Service's reference network quintupled over the past few decades, from the equivalent of 6.7 inches (171 millimeters) of liquid water in the 1980s, to 18 inches (460 millimeters) in the 1990s, to 20 inches (-500 millimeters) in the 2000s, to 33 inches (850 millimeters) for 2010-2018.
- Ice loss from the Greenland Ice Sheet increased seven-fold from 34 billion tons per year between 1992-2001 to 247 billion tons per year between 2012 and 2016.
- Antarctic ice loss nearly quadrupled from 51 billion tons per year between 1992 and 2001 to 199 billion tons per year from 2012-2016.

As a result, the amount of sea level rise due to melting (with a small addition from groundwater transfer and other water storage shifts) from 2005–2013 was nearly twice the amount of sea level rise due to thermal expansion.

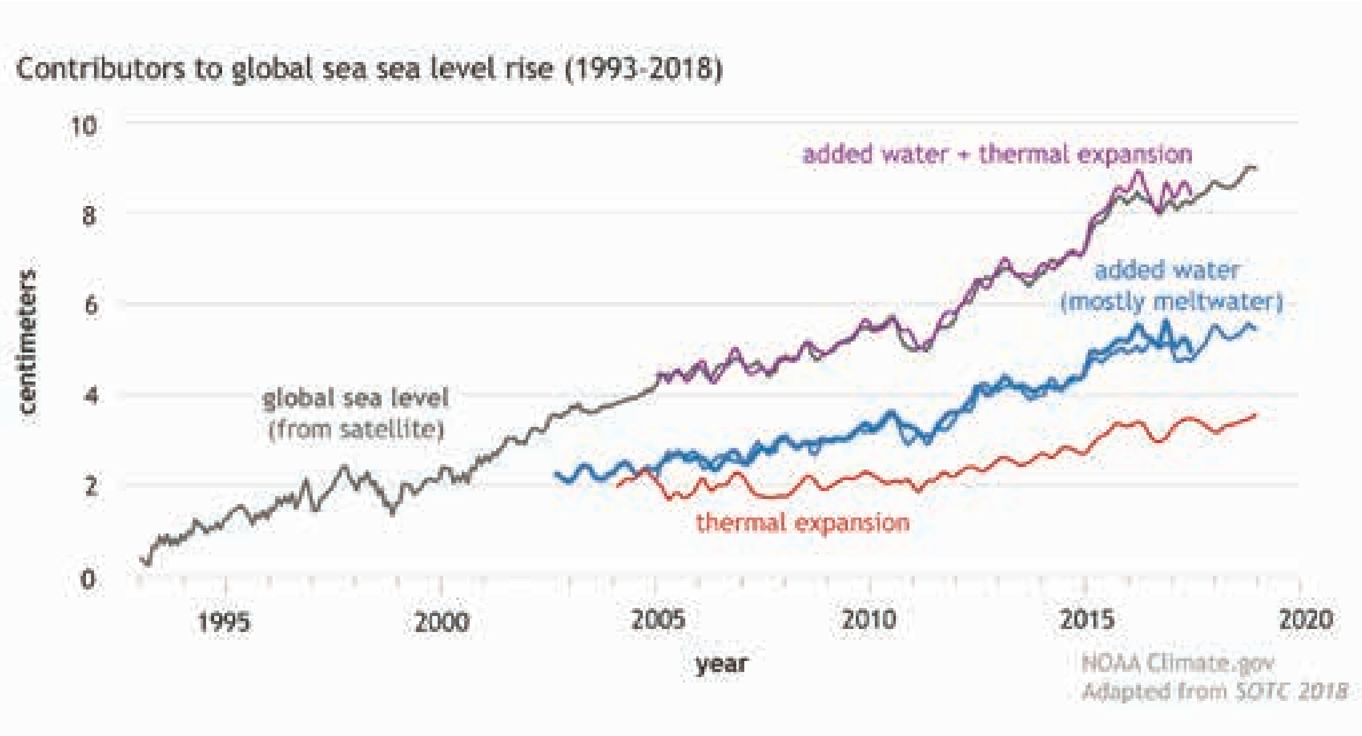
"The pace of global sea level rise more than doubled from 1.4 mm per year throughout most of the twentieth century to 3.6 mm per year from 2006–2015."

MEASURING SEA LEVEL

Sea level is measured by two main methods: tide gauges and satellite altimeters. Tide gauge stations from around the world have measured the daily high and low tides for more than a century, using a variety of manual and automatic sensors. Using data from scores of stations around the world, scientists can calculate a global average and adjust it for seasonal differences.

Since the early 1990s, sea level has been measured from space using radar altimeters, which determine the height of the sea surface by measuring the return speed and intensity of a radar pulse directed at the ocean. The higher the sea level, the faster and stronger the return signal is.

To estimate how much of the observed sea level rise is due to thermal expansion, scientists measure sea surface temperature using moored and drifting buoys, satellites, and water samples collected by ships. Temperatures in the upper half of the ocean are measured by a global fleet of aquatic robots. Deeper temperatures are measured by instruments lowered from oceanographic research ships.



Observed sea level since the start of the satellite altimeter record in 1993 (black line), plus independent estimates of the different contributions to sea level rise: thermal expansion (red) and added water, mostly due to glacier melt (blue). Added together (purple line), these separate estimates match the observed sea level very well. NOAA Climate.gov graphic, adapted from Figure 3.15a in State of the Climate in 2018.

To estimate how much of the increase in sea level is due to actual mass transfer–the movement of water from land to ocean–scientists rely on a combination of direct measurements of melt rate and glacier elevation made during field surveys, and satellite-based measurements of tiny shifts in Earth's gravity field. When water shifts from land to ocean, the increase in mass increases the strength of gravity over oceans by a small amount. From these gravity shifts, scientists estimate the amount of added water.

FUTURE SEA LEVEL RISE

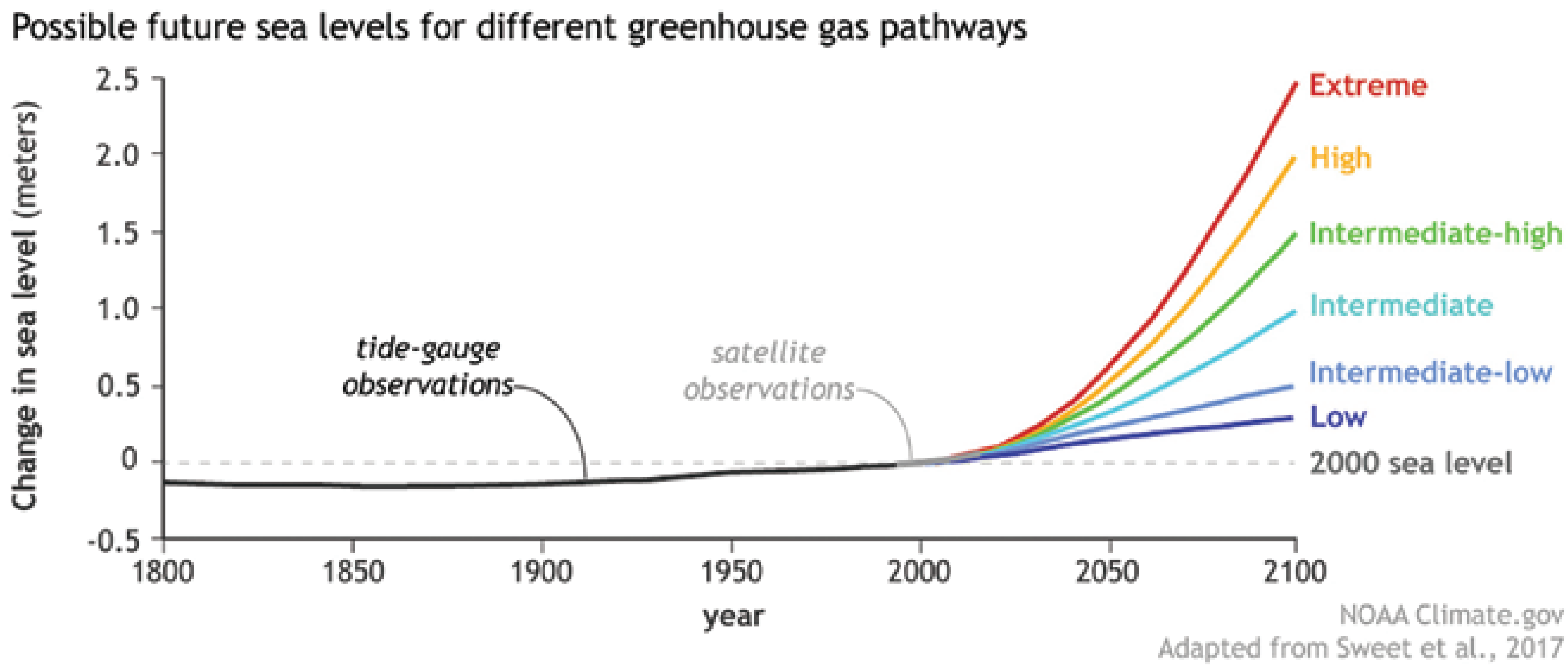
As global temperatures continue to warm, sea level will continue to rise. How much it will rise depends mostly on the rate of future carbon dioxide emissions and future global warming. How fast it will rise depends mostly on the rate of glacier and ice sheet melting.

The pace of sea level rise accelerated beginning in the 1990s, coinciding with acceleration in glacier and ice sheet melting. However, it's uncertain whether that acceleration will continue, driving faster and faster sea level rise, or whether internal glacier and ice sheet dynamics (not to mention natural climate variability) will lead to "pulses" of accelerated melting interrupted by slowdowns.

"By the end of the century, global mean sea level is likely to rise at least one foot (0.3 meters) above 2000 levels, even if greenhouse gas emissions follow a relatively low pathway in coming decades."

In 2012, at the request of the U.S. Climate Change Science Program, NOAA scientists conducted a review of the research on global sea level rise projections. Their experts concluded that even with lowest possible greenhouse gas emission pathways, global mean sea level would rise at least 8 inches (0.2 meters) above 1992 levels by 2100. With high rates of emissions, sea level rise would be much higher, but was unlikely to exceed 6.6 feet higher than 1992 levels.

Both the low-end and "worst-case" possibilities were revised upward in 2017 following a review by the U.S. Interagency Sea Level Rise Taskforce. Based on their new scenarios, global sea level is very likely to rise at least 12 inches (0.3 meters) above 2000 levels by 2100 even on a low-emissions pathway. On future pathways with the highest greenhouse gas emissions, sea level rise could be as high as 8.2 feet (2.5 meters) above 2000 levels by 2100.



The higher worst-case scenario–which is extremely unlikely, but can't be ruled out–is largely due to new observations and modeling on ice loss from Antarctica and Greenland. Since the 2012 report report, new research has emerged showing that some of the more extreme estimates of how quickly those ice sheets could melt were more plausible than they previously seemed.

Along almost all U.S. coasts outside Alaska, the 2017 projections indicate that sea level rise is likely to be higher than the global average for the three highest sea level rise pathways, thanks to local factors like land subsidence, changes in ocean currents, and regional ocean warming. For the densely populated Atlantic seaboard north of Virginia and the western Gulf of Mexico, sea level rise will likely be higher than the global average for all pathways. On the bright side, if future energy choices keep us on one the three lowest pathways, Alaska and the Pacific Northwest are likely to experience local sea level rise that is less than the global average.

In all cases, however, rising sea levels are increasing coastal flood risk. High-tide flooding is already a serious problem in many coastal communities, and it is only expected to get much worse in the future with continued rising seas.

Observed sea level from tide gauges (dark gray) and satellites (light gray) from 1800-2015, with future sea level through 2100 under six possible future scenarios (colored lines). The scenarios differ based on potential future rates of greenhouse gas emissions and differences in the plausible rates of glacier and ice sheet loss. NOAA Climate.gov graph, adapted from Figure 8 in Sweet et al., 2017.

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https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

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MEDITERRANEAN UNESCO WORLD HERITAGE AT RISK FROM COASTAL FLOODING AND EROSION DUE TO SEA-LEVEL RISE

* Lena Reimann, Athanasios T. Vafeidis,
Sally Brown, Jochen Hinkel & Richard S. J. Tol
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ABSTRACT

UNESCO World Heritage sites (WHS) located in coastal areas are increasingly at risk from coastal hazards due to sea-level rise. In this study, we assess Mediterranean cultural WHS at risk from coastal flooding and erosion under four sea-level rise scenarios until 2100. Based on the analysis of spatially explicit WHS data, we develop an index-based approach that allows for ranking WHS at risk from both coastal hazards. Here we show that of 49 cultural WHS located in low-lying coastal areas of the Mediterranean, 37 are at risk from a 100-year flood and 42 from coastal erosion, already today. Until 2100, flood risk may increase by 50% and erosion risk by 13% across the region, with considerably higher increases at individual WHS. Our results provide a first-order assessment of where adaptation is most urgently needed and can support policymakers in steering local-scale research to devise suitable adaptation strategies for each WHS.

higher LIG sea levels (14). While an isotopic signature of a relatively cool LIG climate preserved in the Mount Moulton blue ice field (16) may be explained by substantial WAIS mass loss (17), no direct

INTRODUCTION

Since 1972, the United Nations Educational, Scientific and Cultural Organisation (UNESCO) designates the world's common heritage under the World Heritage Convention[1]. The World Heritage List of 2018 comprises a total of 1092 cultural and natural heritage sites, based on their Outstanding Universal Value (OUV)[2]. Over 77% of these sites are cultural World Heritage sites (WHS) which have high intangible value as they represent icons of human civilisation[3,4]. A large share of cultural WHS are located in coastal areas as human activity has traditionally concentrated in these locations[5,6]. As the risk of coastal hazards such as flooding and erosion increases with sea-level rise (SLR)7, a considerable number of coastal WHS will gradually be exposed to these hazards in the future[7,8], threatening the OUV of affected sites[9,10,11,12] and potentially leading to losses in economic revenue as WHS are popular tourist destinations[12,13]. This is particularly true for the Mediterranean region as several ancient civilisations have developed in the region4,6,[14], resulting in a high concentration of cultural WHS in coastal locations. Due to the small tidal range and steep topography in coastal areas, ancient and current settlements are often located directly at the waterfront and hardly above sea level6,[15]. Furthermore, adaptation methods and protection standards vary considerably across Mediterranean countries[16] due to large socioeconomic differences between northern, eastern and southern parts of the region14,[17], therefore leaving most WHS with limited protection from coastal hazards.

Although WHS are protected under the World Heritage Convention, countries themselves are responsible for their management, which includes adaptation to climate change[18]. However, WHS management plans rarely consider adaptation to SLR impacts11,[19]. Although climate change has been acknowledged as a threat to WHS in recent years[3,9,19,20], few studies have explored this aspect, leaving heritage managers and policymakers with little information on potential adaptation options. Therefore, previous work has called for more research identifying WHS at risk to inform adaptation planning and to ensure that their OUV is preserved[9,10,11,18,20,21]. It has expressed the need for more robust data and modelling approaches on local to regional scales, as adaptation planning takes place at a national level and specific adaptation measures are implemented at a local level[9,11,22]. The results of assessments based on these methods can support adaptation planning, especially in prioritising adaptation strategies with limited financial resources[3,8,12,19,22,23].

Previous studies have primarily focused on local-scale assessments of various climate change impacts on UNESCO WHS11,[12,19,22,24,25,26] or on natural hazards, such as landslides and river floods, without directly considering climate change[13,27,28,29,30]. To our knowledge, only one large-scale study has analysed the long-term impacts of SLR on cultural UNESCO WHS7. This study was based on aggregate WHS data provided on the UNESCO website, where every WHS is depicted by a point that represents its approximate centre, even if the WHS consists of a number of so-called serial nominations[31]. Consequently, the location of the point can substantially deviate from the location of the actual WHS. Further, none of the above-mentioned studies assessed the risks of coastal flooding due to extreme sea levels (ESL) or to coastal erosion due to SLR.

To address the current research gap, we assessed Mediterranean UNESCO cultural WHS at risk from coastal flooding and erosion under four SLR scenarios from 2000 to 2100. We used an index-based approach that allows for ranking and comparing WHS at risk. For this purpose, we produced a WHS dataset containing spatially explicit representations of all Mediterranean WHS located in low-lying coastal areas. Results show that the vast majority of WHS at risk from either of the two hazards until 2100 are already at risk under current conditions. Risk will increase in the course of the century, its magnitude depending on the rate of SLR, with particularly high increases in coastal flood risk and at individual WHS. Our results can support adaptation planning in determining potential risk thresholds (tipping points) based on the temporal evolution of the indices. Additionally, based on the WHS most at risk policymakers can designate priority areas for further analysis in order to devise specific adaptation strategies.

RESULTS

UNESCO World Heritage in coastal areas

The modified and extended WHS dataset[32] comprises 159 data entries that represent inscribed (main) WHS (49) along with their serial nominations (110) located in the Mediterranean Low Elevation Coastal Zone (LECZ), which is defined as all land with an elevation of up to 10 m in hydrological connection to the sea[33]. The data comprise attributes adopted from the original dataset and newly added attributes (e.g. heritage type, elevation, WHS location in urban settlements, distance from the coast). See Supplementary Table 1 for a complete list of attributes. Our analysis focuses on an aggregated version of the dataset that contains the 49 main WHS. Figure 1 shows the 49 main WHS located in the Mediterranean LECZ. Approximately one third of these WHS are located in Italy (15), followed by Croatia (7), Greece (4), and Tunisia (4). In most instances, only certain parts of the WHS (on average 35%) fall into the LECZ; five sites are fully located in the LECZ (see dataset).

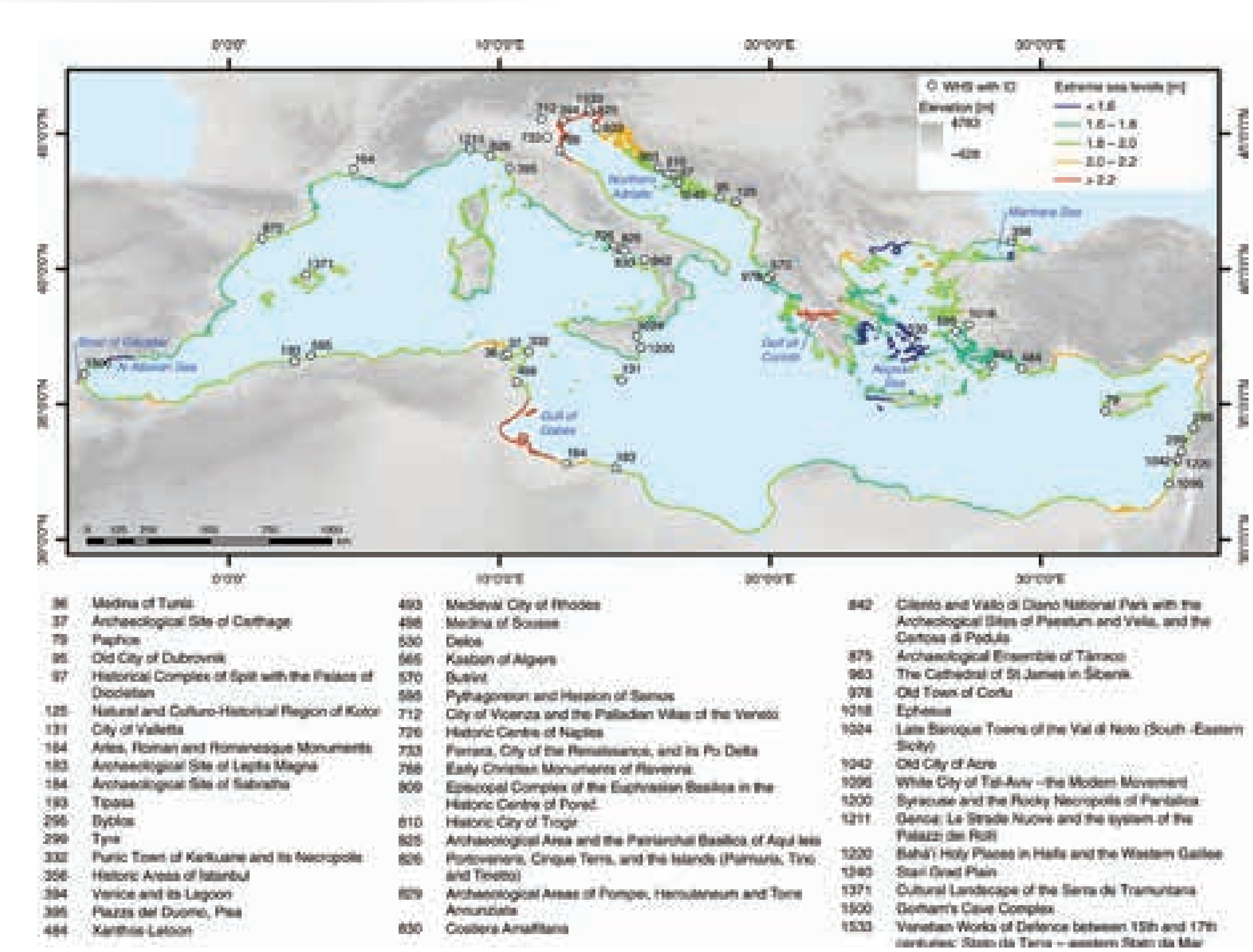

Fig. 1 UNESCO cultural World Heritage sites located in the Mediterranean Low Elevation Coastal Zone (LECZ). All sites are shown with their official UNESCO ID and name. The map also shows extreme sea levels per coastal segment based on the Mediterranean Coastal Database[108] under the high-end sea-level rise scenario in 2100

Flood risk

Under current conditions (base year 2000), 37 WHS are at risk from ESL, defined as the 100-year storm surge (including tides) plus the amount of SLR for the respective scenario and year (see Methods), which corresponds to 75% of all sites located in the LECZ. This number increases to 40 WHS at risk under the high-end (HE) scenario. The flood area ranges from 0.03% of the total WHS at Archaeological Site of Leptis Magna (183) and Cultural Landscape of the Serra de Tramuntana (1371) to 97% at Venice and its Lagoon (394), with a mean of 11.3%. The average flood area increases to over 14% in 2100 under the HE scenario, corresponding to an increase of 24% compared to 2000. Under Representative Concentration Pathway 2.6 (RCP2.6), RCP4.5 and RCP8.5, the average flood area increases to around 12% in 2100 (Fig. 2a). In 2000, the highest flood depth of 1.2 m can be found at Archaeological Area and the Patriarchal Basilica of Aquileia (825) while the mean of maximum flood depth for all sites amounts to roughly 0.4 m. The maximum flood depth increases by approximately 70% to a mean of more than 0.6 m under RCP2.6, 92% (over 0.7 m) under RCP4.5, 121% (approximately 0.8 m) under RCP8.5 and 290% (roughly 1.5 m) under the HE scenario (Fig. 2b), where the highest flood depth of 2.5 m can be found at Venice and its Lagoon (394). The flood risk index that results from combining flood area and flood depth (see Methods) has a mean of 3.7 in 2000, which increases by 25% to 4.6 under RCP2.6 and by almost 50% to 5.5 under the HE scenario (Fig. 2c).

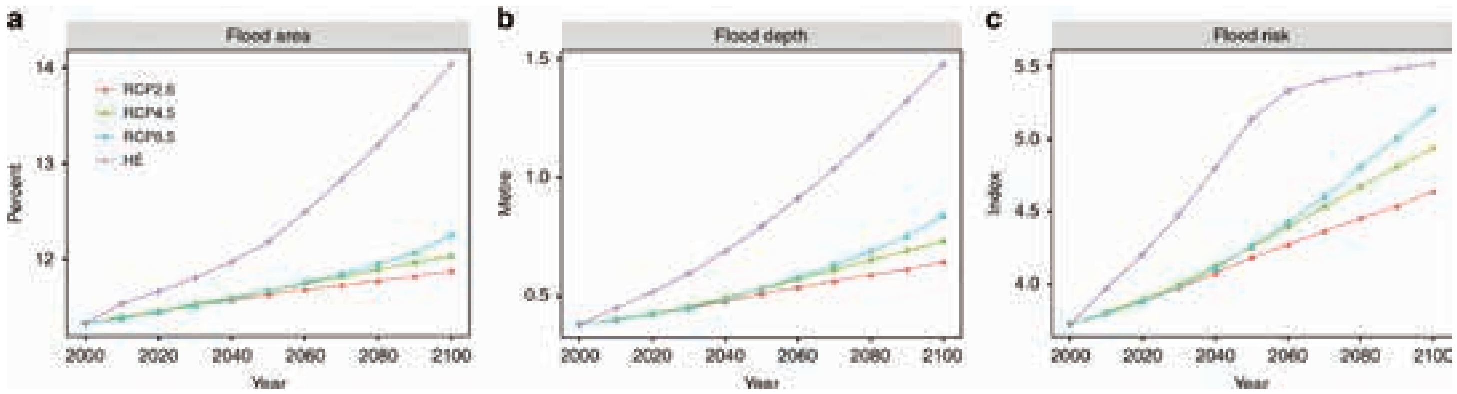

Figure 2 Temporal evolution of the flood risk indicators at each World Heritage site, averaged across the Mediterranean region. Results are shown from 2000 to 2100 for RCP2.6, RCP4.5, RCP8.5 and the high-end (HE) scenario. a Mean area flooded (in %), b mean flood depth (in m) and c mean flood risk index

In the base year, the risk index ranges from 0 for those sites that are not at risk to a maximum of 10 at Venice and its Lagoon (394), Ferrara, City of the Renaissance, and its Po Delta (733) and Archaeological Area and the Patriarchal Basilica of Aquileia (825). These WHS are located along the northern Adriatic Sea where ESL are highest as high storm surges coincide with high regional SLR (Fig. 1 and Supplementary Figure 1). Under the HE scenario, a total of six WHS have the highest risk index of 10, four of which are located in Italy and two in Croatia (Fig. 3). In 16 Mediterranean countries (including Gibraltar), at least one WHS is at risk under at least one of the four scenarios. The highest number of WHS at risk can be found in Italy (13), which corresponds to 87% of the Italian WHS located in the LECZ, followed by Croatia (6; 86%) and Greece (3; 75%). See also Supplementary Figure 2 for the flood risk indicators at each WHS and Supplementary Data 1 for the raw data of the indicators.

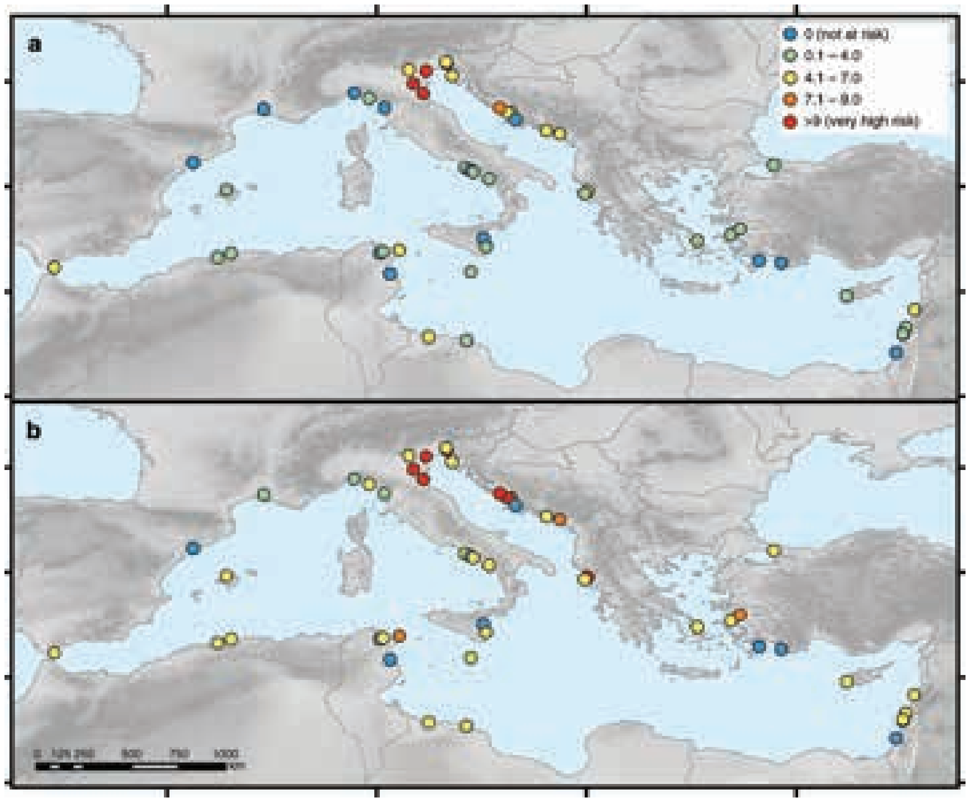

Figure 3 Flood risk index at each World Heritage site under current and future conditions. a In 2000 and b in 2100 under the high-end sea-level rise scenario

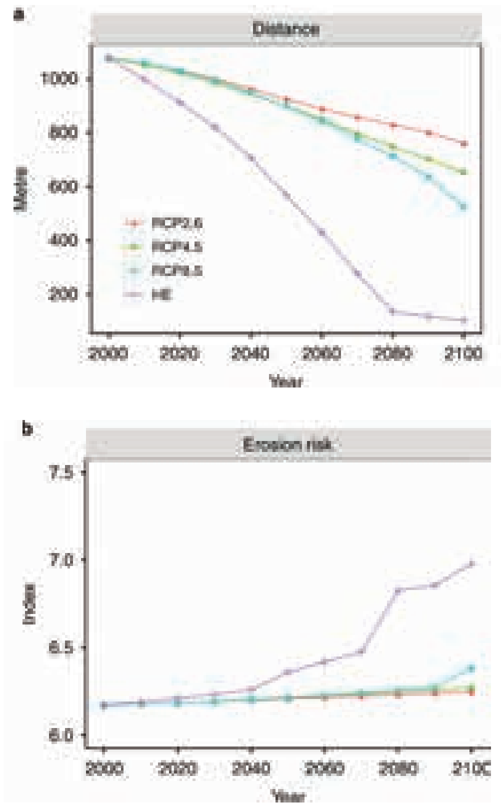

Figure 4 Temporal evolution of the dynamic erosion risk indicators at each World Heritage site, averaged across the Mediterranean region. Results are shown from 2000 to 2100 for RCP2.6, RCP4.5, RCP8.5 and the high-end (HE) scenario. a Mean distance from the coastline (in m) and b mean erosion risk index

Erosion risk

Under current conditions, 42 WHS are at risk from coastal erosion, which corresponds to 86% of all sites located in the LECZ. This number increases to 46 WHS under the HE scenario. Erosion risk is predominantly determined by the distance of a WHS from the coastline. Already in the base year, 31 WHS are at least partly located within 10 m of the coastline, which increases to 39 sites under the HE scenario (Supplementary Figure 4), based on the assumption that all areas below the amount of SLR are permanently inundated (see Methods). The average distance from the coast decreases from roughly 1.1 km in 2000 by 30% to 762 m under RCP2.6 and by more than 90% to slightly above 100 m under the HE scenario (Fig. 4a). As we assume the erosion risk indicators coastal material, mean wave height and sediment supply to remain constant in the course of the century, the erosion risk index increases only slightly from 2000 to 2100. The average erosion risk index increases from 6.2 in 2000 to 6.3 in 2100 under RCP2.6 and RCP4.5. Under RCP8.5 it increases to 6.4 and under the HE scenario it increases to 7, which corresponds to an increase of 13% compared to 2000 (Fig. 4b).

In the base year, the erosion risk index ranges from 0 for those sites not at risk to 9.8 (very high) at Tyre (299) (Fig. 5), which is located directly at the coastline (very high risk) and is characterised by sandy material (very high risk), a mean wave height of 0.7 m (high risk) and sediment supply of just below 1 mg l^{-1} (high risk). The second highest risk index can be found at Pythagoreion and Heraion of Samos (595). Under the HE scenario, erosion risk remains highest at Tyre, followed by Archaeological Ensemble of Tárraco (875), Pythagoreion and Heraion of Samos (595) and Ephesus (1018), all of which have a very high index of 9 and higher. Similar to flood risk, in 16 Mediterranean countries (including Gibraltar) at least one WHS is at risk from coastal erosion under at least one of the four scenarios. The highest number of WHS at risk can be found in Italy (14), which corresponds to 93% of the Italian WHS located in the LECZ, followed by Croatia (7; 100%) and Greece (4; 100%). Erosion risk varies moderately across the Mediterranean region and no regional pattern can be discerned as erosion risk indicators are mostly site-specific. (Please see Supplementary Figure 3 and Supplementary Figure 4 for the erosion risk indicators at each WHS and Supplementary Data 2 for the raw data of the indicators.)

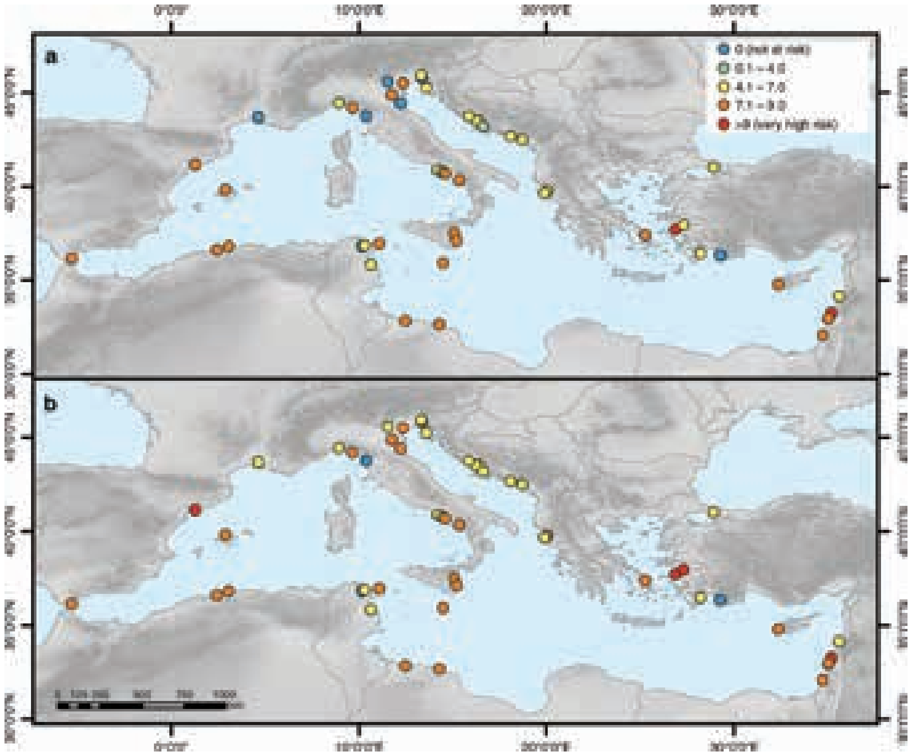

Figure 5 Erosion risk index at each World Heritage site under current and future conditions. a In 2000 and b in 2100 under the high-end sea-level rise scenario

DISCUSSION

In this study, we assess UNESCO WHS at risk from coastal flooding and erosion under four SLR scenarios until 2100, based on revised and extended spatially explicit WHS data. The use of an index-based approach enables a quick evaluation of both risks that can easily be applied to other locations[34,35,36.] With the help of the risk indices, we are able to rank and compare WHS, while at the same time we avoid attaching a monetary value to them[37]. The results of this study can therefore support adaptation planning at different spatial scales: at the national scale, especially in countries with a large number of WHS at risk such as Croatia, Greece, Italy and Tunisia; at the EU scale, as, for example, regulated under the EU Floods Directive[38]; and at the basin scale, as prescribed under the Barcelona Convention, which is the basis for the Mediterranean Action Plan and the Protocol on Integrated Coastal Zone Management (ICZM) in the Mediterranean[39]. Our results can be particularly useful in designating priority areas with urgent need for adaptation and can serve as a basis for further, more in-depth assessments[40]. Furthermore, the temporal evolution of the risk indices and their individual components can provide valuable information on the point in time when a WHS may be at risk or when a certain risk threshold may be exceeded23. This threshold can be referred to as an adaptation tipping point as its exceedance requires a (new) policy action[41,42]. An example of such potential tipping points for both risk indices is shown in Fig. 6. These insights can be used to ensure that the OUV of WHS at risk from either of the two hazards is preserved in the long term.

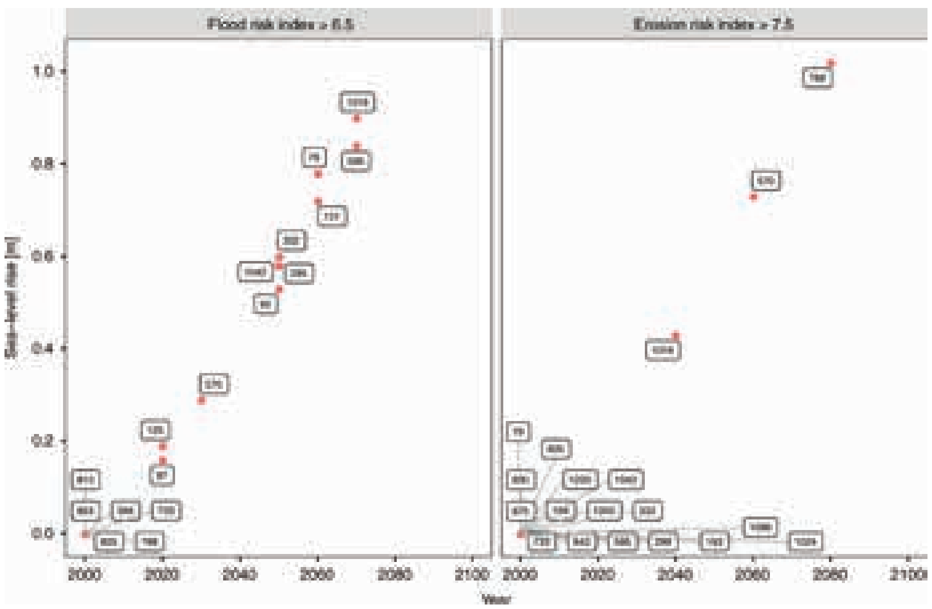

Figure 6 Examples of potential adaptation tipping points for the flood risk index and the erosion risk index. Both graphs show points in time when a World Heritage site may exceed a certain risk threshold with the respective amount of sea-level rise under the high-end scenario. Point labels show the official UNESCO ID of the sites affected. a Flood risk index threshold of 6.5 and b erosion risk index threshold of 7.5

In total, 47 WHS may be at risk from at least one of the two hazards by the end of the century, with Piazza del Duomo, Pisa (395) potentially at risk from flooding only and seven sites (UNESCO IDs 493, 498, 829, 975, 1024, 1096, 1240) from erosion only. Based on these results, only two sites, Medina of Tunis (36) and Xanthos-Letoon (484), are not at risk from any of the two hazards by 2100. Further, we find that 93% of the sites at risk from a 100-year flood and 91% of the sites at risk from coastal erosion under any of the four scenarios are already at risk under current conditions, which stresses the urgency of adaptation in these locations.

Risk will further increase by 2100, in particular in the second half of the century, when projections of SLR diverge considerably based on the respective scenario. Therefore, the magnitude of risk increase largely depends on global mitigation efforts in the next years, which should pursue the aim not to exceed RCP2.643 as planned under the Paris Agreement44 (projections based on RCP2.6 are closest to the 1.5 °C goal of the Paris Agreement). If the goal of the Paris Agreement is not met, the amount of SLR may exceed the height of a 100-year storm surge by a factor of 1.4 under RCP8.5 and a factor of 3 under the HE scenario in 2100. Therefore, SLR may become a larger threat to WHS than a present-day 100-year storm surge. A recent study of future ESL at the European scale has come to similar results, suggesting that present-day 100-year events in the Mediterranean may occur much more frequently, up to several times per year, by 210045. Our results illustrate the value of rigorous global-scale mitigation efforts which could be crucial in preventing WHS from losing their OUV, especially as protection measures only work effectively up to a certain water level. Recent research has shown that RCP2.6 may be exceeded by 210046,47,48, therefore adaptation planning should prepare for higher SLR scenarios.

As adaptation measures need to be integrated into the WHS without compromising its OUV, adaptation planning at WHS is particularly challenging[11,49]. Since a site's OUV is bound to its location, retreat seems to be the least favourable adaptation option11,19,24. While relocation of individual monuments such as the Early Christian Monuments of Ravenna (788) or The Cathedral of St. James in Šibenik (963) may be technically possible, it seems to be impossible to relocate WHS that extend over large areas such as urban centres, archaeological sites and cultural landscapes. Examples of non-UNESCO cultural heritage monuments that have been moved inland are Clavell Tower[50] and Belle Tout lighthouse[51] in the UK and Cape Hatteras Lighthouse in the USA[52]. However, we could not find any examples in the existing literature where a UNESCO WHS was relocated. Relocation should be assessed carefully on a case-by-case basis and may be a suitable adaptation strategy for those WHS where risk is very high.

Common accommodation strategies such as hazard insurance, emergency planning or land-use planning[53] cannot be applied to WHS, but strategies to raise awareness can be pursued. Terrill3 suggests to use the iconic nature of WHS to emphasise the severity of their loss in order to raise awareness of policymakers and heritage managers and to promote climate change mitigation3. Recent efforts at the national to local level that monitor cultural heritage and provide guidance for managing heritage in the light of climate change show that awareness is gradually increasing. Examples are the Irish Heritage Council, Historic England, the US National Park Service's Cultural Resources Climate Change Strategy and the Scottish Coastal Heritage at Risk project, which has developed a smartphone app for surveying cultural heritage at risk from coastal erosion. This project raises awareness of local communities and authorities who can help designate priority areas and can therefore support heritage management[54]. Further, Khakzad et al.[55] suggest to include coastal heritage into ICZM, which may help in increasing the efficiency of adaptation planning. Another accommodation strategy would be to remove the inventory of WHS, such as paintings or statues, during flood events.

Coastal protection seems to be a suitable adaptation strategy as it may be possible to integrate it into any type of cultural WHS (i.e. urban heritage, archaeological site, cultural landscape or monument) without compromising its OUV. One example is the MOSE (Modulo Sperimentale Elettromeccanico/Experimental Electromechanical Module) project currently under construction in Venice (www.mosevenezia.eu). The entire lagoon will be protected by submerged mobile barriers at the lagoon inlets that will be raised during high waters of at least 1.1 m. These barriers do not interfere with the appearance of Venice and the fragile ecosystem of the lagoon as long as they are not raised frequently18,49. This example illustrates that, in order to preserve the aesthetic value of a WHS, very expensive protection measures may have to be pursued. An alternative to hard protection measures may be the use of coastal ecosystems as soft, nature-based protection by attenuating water levels and stimulating sedimentation in certain locations[56,57].

A combination of awareness-raising strategies and protection measures seem to be the most suitable adaptation strategies, but relocation also needs to be considered, in particular where risk is very high. However, local-scale assessments are needed in order to devise adaptation measures that are tailored to the characteristics of individual WHS and the type of hazard they are at risk from[11,19]. With regard to flood risk, such local-scale assessments should additionally consider a potential low bias in return flood heights due to uncertainties regarding the rate of SLR to avoid an underestimation of risk in the adaptation process[58].

As a first-order risk assessment, using a simple methodology based on publicly available region-wide data, this study can easily be reproduced and applied to other regions where a high number of WHS is potentially at risk from coastal hazards due to SLR (e.g. South-East Asia). However, such assessments should bear in mind the limitations of this study. We have refrained from analysing the vulnerability of WHS to the two hazards as local-scale data concerning the internal characteristics of a WHS such as heritage material or heritage inventory are not readily available and including those in the analysis goes beyond the scope of this first-order assessment. Furthermore, we regard the use of depth-damage functions that are commonly applied in large-scale flood risk assessments to represent vulnerability[59,60,61,62,63,64] as problematic in the context of UNESCO World Heritage. Due to the high intangible value of WHS[3,11], it is very difficult and ethically questionable to quantify the damages at a WHS, which would imply that one WHS is more valuable than another12. However, if appropriate local-scale data are available, it may be possible to assess the tangible costs of coastal flooding and erosion by accounting for, for example, loss of revenue or cost of repairs[65].

The elevation-based (bathtub) approach used for modelling the floodplain tends to overestimate the flood extent, in particular in low-lying, mildly sloping terrain such as the Nile, Rhone and Po deltas6[6,67,] as hydrodynamic and hydraulic processes are not considered[36,68,69]. However, in steep terrain the flood extent is only slightly overestimated or even underestimated[66,67,68]. As large parts of the Mediterranean are characterised by steep topography[6], we expect this approach to provide a reasonable approximation of maximum potential flood extent at the majority of WHS. Furthermore, this modelling approach is extensively used in large-scale flood modelling6[0,61,62,70,71,72,73] and can be regarded as a standard in such assessments[35,74].

As we do not consider defence structures in place due to lack of data on coastal protection measures16, we may additionally overestimate risk in locations where protection measures exist. This appears to be the case at the Early Christian Monuments of Ravenna (788) and Archaeological Area and the Patriarchal Basilica of Aquileia (825), both located along the northern Adriatic Sea, where flood risk is modelled to be very high and erosion risk is modelled to increase rapidly at the end of the century, even though these WHS are currently located 6.7 and 3.5 km inland (Supplementary Data 2). A further example is Venice and its Lagoon (394), which is, according to our results, one of the WHS most at risk from coastal flooding (Fig. 3) and erosion (Fig. 5) until 2100. However, once construction of the MOSE project is completed (expected in 2018 as of the last official status[75]), risk will be reduced considerably as the flood barriers will protect the city and the lagoon from ESL of up to 3 m (www.mosevenezia.eu). According to our results, this protection level will be sufficient until 2100, with ESL projected to be 2.5 m under the HE scenario. As Venice has struggled with flood waters for centuries[49], it forms a special case; we did not find any other Mediterranean example where protection measures have been installed to protect an entire WHS.

We must also note that we may underestimate the floodplain in certain locations as it was not possible to account for human-induced subsidence even though it can be high in cities[76,77] such as Venice[78] and Istanbul[79] and in river deltas such as those of the Nile, Po and Rhone[80,81] due to ground water extraction. Currently, there is a lack of consistent data and of reliable scenarios projecting future development of human-induced subsidence60. Furthermore, the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) used is a surface model and as such it may overestimate elevation in forested and built-up areas[82,83]. We observe this effect in Venice and its Lagoon (394) where only small sections of the city's built-up areas are located at elevation increments of 1–3 m AMSL, although the City of Venice reports the island to be almost fully inundated (91%) during a flood of 2 m84. A second example is Ferrara, City of the Renaissance, and its Po Delta (733) where forest directly located at the coast[70] has elevation values of more than 10 m. Across the whole Mediterranean, built-up areas make up over 75% of the WHS located in the LECZ (see dataset), potentially leading to an underestimation of elevation, and therefore the risks of flooding and erosion in these locations. Despite its limitations, the SRTM DEM is currently the most consistent and commonly used global elevation model[85] and we did not have access to any other higher-resolution region-wide DEM as LiDAR (Light Detection And Ranging) data are only available for certain parts of the Mediterranean and the newly created CoastalDEM86 is not freely available. Please consult Kulp and Strauss[85] for an in-depth discussion of the SRTM limitations.

The limitations of this study can be addressed in local-scale assessments that should be conducted to develop specific adaptation strategies and to select suitable adaptation measures for individual WHS. We encourage other researchers to use the revised and extended WHS data as a starting point for such assessments that allow for applying hydrodynamic modelling approaches, including higher-resolution local-scale data, and accounting for vulnerability.

Our results can raise awareness of policymakers and heritage managers by pointing to the urgent need for adaptation as a large number of WHS are already at risk from coastal flooding and erosion under current conditions. Both risks will exacerbate in the course of the twenty-first century and possibly beyond, their magnitude depending on the global-scale mitigation effort in the coming years. However, adaptation can only be implemented to a limited degree, especially with regard to WHS, as their OUV may be compromised by adaptation measures. If no steps are taken, WHS may lose their OUV in the next centuries and may consequently be removed from the UNESCO World Heritage list. Therefore, mitigation efforts are as much needed as adaptation to protect our common heritage from being lost. As UNESCO WHS are monitored at least to a certain degree under the World Heritage Convention, they will more likely receive the necessary attention and funding for adaptation measures against the risks of SLR. This is particularly true for WHS in densely populated locations such as the cities of Venice, Dubrovnik, Tyre or Tel-Aviv due to the high potential impacts of coastal hazards[23,60]. Cultural heritage not inscribed in the World Heritage list will receive much less attention and many of these heritage sites will slowly disappear with SLR even though these sites are important parts of human history as well[23].

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ECONOMY – WIDE EFFECTS OF COASTAL FLOODING DUE TO SEA LEVEL RISE: A MULTI – MODEL SIMULTANEOUS TREATMENT OF MITIGATION, ADAPTATION AND RESIDUAL IMPACTS

Thomas Schinko[1], Laurent Drouet[2],
Zoi Vrontisi[3], Andries Hof[4,5],
Jochen Hinkel[6], Junko Mochizuki1,
Valentina Bosetti[2,7], Kostas Fragkiadakis[3],
Detlef van Vuuren[4,5] and Daniel Lincke[6]
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1. INTRODUCTION

This article presents a multi-model assessment of the macroeconomic impacts of coastal flooding due to sea level rise and the respective economy-wide implications of adaptation measures for two greenhouse gas (GHG) concentration targets, namely the Representative Concentration Pathways (RCP)2.6 and RCP4.5, and subsequent temperature increases. We combine our analysis, focusing on the global level, as well as on individual G20 countries, with the corresponding stylized RCP mitigation efforts in order to understand the implications of interactions across mitigation, adaptation and sea level rise on a macroeconomic level. Our global results indicate that until the middle of this century, differences in macroeconomic impacts between the two climatic scenarios are small, but increase substantially towards the end of the century. Moreover, direct economic impacts can be partially absorbed by substitution effects in production processes and via international trade effects until 2050. By 2100 however, we find that this dynamic no longer holds and economy-wide effects become even larger than direct impacts. The disturbances of mitigation efforts to the overall economy may in some regions and for some scenarios lead to a counterintuitive result, namely to GDP losses that are higher in RCP26 than in RCP45, despite higher direct coastal damages in the latter scenario. Within the G20, our results indicate that China, India and Canada will experience the highest macroeconomic impacts, in line with the respective direct climatic impacts, with the two first large economies undertaking the highest mitigation efforts in a cost-efficient global climate action. A sensitivity analysis of varying socioeconomic assumptions highlights the role of climate-resilient development as a crucial complement to mitigation and adaptation efforts.

ABSTRACT

The Paris Conference, officially known as the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), set out a long-term goal to limit ‘the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C’ (UNFCCC 2015). This ambitious global agreement is based on the notion that a 2 °C target may not adequately safeguard the planet from the dangerous effects of climate change, while keeping temperature increase well below 2 °C could substantially reduce the impact of climate change on the frequency and intensity of extreme events (Knutti et al 2016, Mitchell et al 2016, IPCC 2018). However, what may be considered as acceptable and unacceptable warming thresholds is open to societal value judgment. This requires an open and transparent debate about possible impacts as function of alternative temperature targets and the costs associated with reaching these targets (IPCC 2018).

Previous research has identified coastal impacts due to SLR as one of the key economic damages associated with climate change (e.g., Watkiss 2011), second after health impacts (i.e. pre-

mature mortality) and before agricultural impacts, energy sector impacts and riverine flooding (e.g., Ciscar et al 2014). A growing body of literature assesses the direct economic costs due to coastal flooding due to SLR, as well as the costs and benefits of adapting to these risks (e.g., Hinkel et al 2014, Diaz 2016). Many studies conclude that estimates of future damages are more sensitive to assumptions made on adaptation and risk reduction measures than to variations in climate- and socioeconomic scenarios (Hinkel et al 2014, Abadie 2018). Without adaptation, expected direct annual losses due to coastal floods could amount to 0.3%–9.3% of global GDP by 2100 (Hinkel et al 2014). The global costs for protection measures are estimated to be significant but much lower than the associated benefits through avoided damages (Hinkel et al 2014). Adaptation could potentially reduce sea level induced flood costs by a factor of 10, while failing to achieve global mean temperature targets of 1.5 °C or 2 °C will lead to higher levels of coastal flood risk worldwide (Jevrejeva et al 2018). In the long term, even under strong 1.5 °C and 2 °C scenarios, potential impacts due to SLR continue to grow for centuries (Nicholls et al 2018). These results indicate that strengthening adaptation and proactive disaster risk management efforts remains essential, and that in the long-run, soft and hard limits to adaptation may cause residual losses and damages even under stabilization of global temperature increase at 1.5 °C or 2.0 °C.

The above-mentioned studies do, however, not take the economy-wide effects into account. These indirect economic effects, which may arise due to feedback effects throughout the value chain and via international trade channels, are of crucial importance in climate change impact assessments since they can either add to or counterbalance the negative direct impacts.

CGE models have been heavily applied in the literature for the economy-wide assessment of climate-related impacts in several economic sectors (Bigano et al 2008, Aaheim et al 2012, Ciscar et al 2011, 2012, 2014, OECD 2015, Steininger et al 2016). The PESETA and PESETA II projects, for example, applied a comparative-static CGE analysis by introducing biophysical impacts as inputs to the General Equilibrium Model for Economy–Energy–Environment (GEM-E3) for Europe (Ciscar et al 2011, 2012, 2014). Other CGE studies have focused on SLR impacts explicitly (Bosello et al 2007, 2012, Carrera et al 2015, Pycroft et al 2016). Bosello and De Cian (2014) present a thorough literature review covering the different applications and methodologies followed by CGE models for the assessment of SLR impacts, indicating the strengths and caveats of the approaches.

CGE model-based impact assessments have the advantage that they provide large sectoral detail and regional detail as well as endogenous trade and substitution dynamics and hence are well suited to estimate cross-sectoral and cross-regional macroeconomic feedback effects (OECD 2015). This large detail also has a drawback: many assumptions have to be made, for instance regarding price elasticities, most of which can be uncertain, especially in the far future. CGE models are calibrated against current structures of the economy, and only some models take into consideration the changing structure of the economy in time. More simple economic growth models feature substantially less assumptions and are thus more flexible and easy to reproduce. However, as these models feature only an aggregate economy-wide representation with no sectoral detail, they utilize the 'damage function' approach translating temperature change to GDP loss at the aggregate level. Thus, these benefit-cost models are not able to provide insights on a sectoral level (Fisher-Vanden et al 2013).

A further limitation of the abovementioned impact and adaptation studies is that they ignore the changes in economic structure induced through mitigation efforts. Studies generally only evaluate the benefits of mitigation in terms of reducing impacts (e.g., Hinkel et al 2013 for the case of coastal floods), or the net benefits of adaptation in terms of reduced impacts (Ciscar et al 2011, 2012, OECD 2015, Diaz 2016) but without explicitly modeling underlying mitigation scenarios that may entail a complete reconfiguration of production processes and consumption patterns.

In this study we address the above mentioned limitations in assessing the macroeconomic impacts of coastal flooding due to SLR and related adaptation ambitions. The direct impacts are based on DIVA (Hinkel et al 2014), a coastal climate change impact model that assesses coastal flood risk based on local distributions of coastal extreme water levels (due to surges and tides), sea-level rise scenarios, socio-economic scenarios and adaptation strategies. The macroeconomic impacts are assessed by comparing between growth and CGE models, applying the relatively simple macroeconomic growth models FAIR (Den Elzen et al 2014) and WITCH (Emmerling et al 2016), and the more complex CGE model GEM-E3 (Capros et al 2014, E3MLAB 2017). In addition, our assessment of impacts is conducted in a framework that takes into consideration the evolution of economic structure induced through the transitions required to get to well-below 2 °C. We evaluate the direct and indirect economic effects of climate impacts and adaptation and assess how these effects would evolve under different adaptation and mitigation assumptions, thus providing insights on the mitigation-adaptation synergies and trade-offs. We also identify regional and sectoral hotspots due to SLR and coastal flooding. A sensitivity analysis further clarifies the effects of alternative socioeconomic development assumptions.

Taken together, this study moves beyond the current state of the literature in three ways: by applying different types of macroeconomic models for increased robustness of the results; evaluating climate impacts and adaptation on top of mitigation for acknowledging the feedback effects between climate change mitigation, remaining climate damages and adaptation policies; and conducting a dynamic analysis instead of a comparative static one for the investigation of different pathways related to different future climate and socioeconomic scenarios. It is important to note that for this study, we focus only on coastal flooding due to SLR and not on other climate-related impacts. Moreover, we concentrate on the assessment of indirect economic impacts from physical damages and associated direct impacts as provided by DIVA, but do not take into account further non-economic impacts, such as people at risk.

2. METHODS

2.1. Research approach, methods and data

We perform a multi-model macroeconomic assessment (figure 1) employing two different kinds of global macroeconomic assessment models: the inter-temporal optimal economic growth models FAIR and WITCH (Den Elzen et al 2014, Emmerling et al 2016), and the CGE model GEM-E3 (E3MLAB 2017). These state-of-the-art modeling tools are extensively used to evaluate the consequences of climate-related impacts and the effects of climate change adaptation in the medium-to-long term (Hof et al 2008, 2010, Ciscar et al 2012, 2014, Clarke et al 2014, Admiraal et al 2016, De Cian et al 2016). The DIVA model provides estimates of the direct impacts of coastal SLR in terms of expected annual damages by sea floods (the costs of migration or people actually flooded are not taken into account in our analysis), as well as annual costs for adaptation in terms of dike construction and dike maintenance. This exogenous input is introduced to the global macroeconomic models of WITCH, FAIR and GEM-E3 to quantify both the direct and indirect economic impacts of coastal flooding due to SLR. Further to the overall global aggregate picture of longer-term ripple effects, the GEM-E3 model provides a regional and sectoral disaggregation of costs.

While each of the models employed here has–to varying degrees–different theoretical backgrounds, structures and solution algorithms, the socioeconomic development and policy assumptions are harmonized in this study. To this end, we employ the widely used Shared Socioeconomic Pathways (SSPs) (Riahi et al 2017) with updated GDP projections from Labat et al (2015), which together reflect plausible global socioeconomic developments that together would lead to different challenges for climate change mitigation and adaptation. Each SSP can be projected under different radiative forcing pathways (RCPs), of which we include RCP2.6 and RCP4.5 (van Vuuren et al 2011). For our central scenarios, the socioeconomic and population assumptions are calibrated to the 'middle of the road' storyline of SSP2. This means that the three economic models are calibrated in a baseline run, which is not accounting for climate impacts, mitigation and adaptation measures, to match regional SSP2-based GDP projections.

In the following we present the main characteristics of each model employed in this study and a description of how the linkage between the coastal impact model DIVA and the macroeconomic models is established (see also table S1 in the supplementary material (SM, available online at stacks.iop.org/ERC/2/015002/mmedia) for a detailed summary of the macroeconomic models' characteristics and assumptions).

FAIR includes a simple economic growth model based on a Cobb-Douglas production function. This approach has been used for similar purposes in cost-benefit integrated assessment modeling (see e.g. Nordhaus 2007). We assumed that the regional trends in labor follow from regional population trends as given by the respective SSP. Historical capital stocks

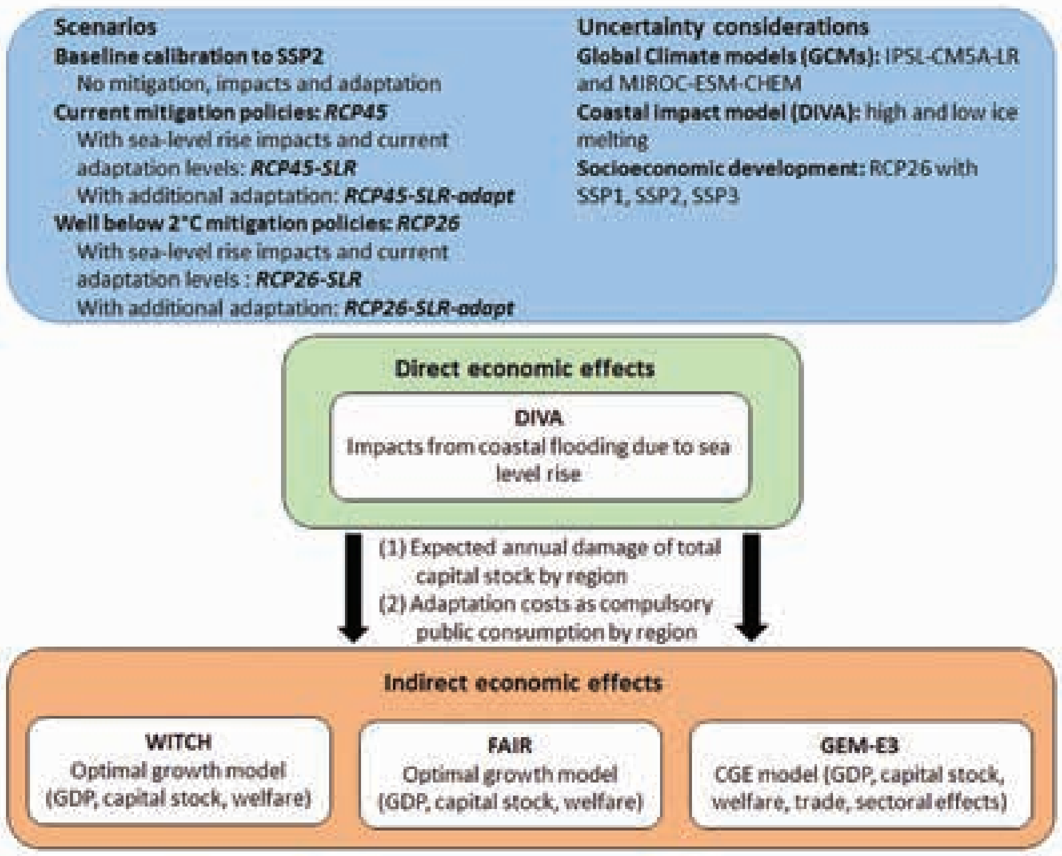

Figure 1: Multi-model framework adopted in this study.

and capital formation rates were based on the IMF Investment and Capital Stock Dataset 2015 (Gaspar et al 2015). Regional savings rates are assumed to converge linearly from 2013 historical levels to the same global level by 2100. In the baseline scenario, total factor productivity is calibrated so that GDP corresponds to the exogenous GDP path of the SSP2 scenario. In FAIR, the direct damages from SLR are deducted from productive investment to calculate the GDP effects. Hence, the direct damages have a long-term effect on GDP by lowering the productive capital stock. Technological progress is not assumed to be affected by direct damages. Adaptation costs are included by assuming that they replace productive investments, similarly as damages do.

WITCH is a global integrated assessment model, including a top-down inter-temporal Ramsey-type optimal growth model (i.e. intertemporal optimization of a regional welfare function, employing a Cobb-Douglas production function) linked with a bottom-up representation of the energy sector (Emmerling et al 2016). The non-cooperative nature of international relationships is explicitly accounted for, so that the simultaneous policy responses of a set of representative regions satisfy an open-loop Nash equilibrium (i.e. regions decide about own action without knowing what other regions are doing). For this study, similarly to FAIR, the DIVA SLR direct damages destroy regional capital stocks (excluding the energy-related assets) and the building and operating costs of dikes are withdrawn from regional consumption. This means that adaptation costs are implemented via increasing savings requirements and thus a reduction in regional final consumption.

GEM-E3 is a hybrid general equilibrium model with a detailed regional and sectoral representation (E3MLAB 2017). The model assesses the macroeconomic and sectoral impacts of the interactions of the environment, the economy and the energy system. The GEM-E3 model has been calibrated to the latest statistics (GTAP 9, IEA, UN, ILO) while for the EU Member States, Eurostat statistics have been included. CGE models like GEM-E3 simultaneously calculate the equilibrium in goods and services markets, as well as in the labor and capital markets, based on an optimization of welfare for households and cost for firms (Capros et al 2014). Production functions assume a constant elasticity of substitution across labor, capital, energy and intermediate goods. Consumer behavior is optimized, distinguishing between durable and disposable goods and services. A distinctive feature of the GEM-E3 model is the representation of an imperfect labor market through involuntary unemployment, both for skilled and unskilled labor supply. The model is recursive dynamic over time and driven by accumulation of capital and equipment. The GEM-E3 regions are linked through endogenous bilateral trade in accordance with the Armington assumption, meaning that products traded internationally are differentiated by country of origin via an elasticity of substitution parameter. This version of the GEM-E3 model includes 19 regions, explicitly representing the G-20 members except those that are Members of the European Union, and 39 categories of economic activities. In addition, the GEM-E3 environmental module covers all GHG emissions and a wide range of abatement options, as well as a thoroughly designed carbon market structure (e.g., grandfathering, auctioning, alternative recycling mechanisms). The integration of climate impacts in the GEM-E3 model follows the most up-to-date approach, in line with the applications of GEM-E3 in the PESETA and PESETA II projects (Ciscar et al 2012, 2014). SLR is assumed to directly affect the available capital stock of the economy, thus we deduct the monetary estimations of these damages, as provided by the DIVA model, from the total capital stock. Capital is mobile across all sectors, so the destruction of capital affects capital supply and demand in all economic activities. The effects of SLR are considered in this analysis as slow onset climate change events that lead to a resource limitation similar to what can be observed in overall economic activity once part of available capital is considered obsolete. In GEM-E3, the expenditure for the construction of dikes (i.e. the defensive capital) and the maintenance of dikes (defensive capital O&M) are introduced as additional expenditures by the government that do not add to the productive capacity of the entire economy, i.e. are not added to the capital stock of the economy that is available for the production of goods and services. We thus assume that this is a type of compulsory consumption and in particular assume that it is publicly funded through the increase of government demand of construction services. These increased public expenditures for adaptation to SLR in turn increase the public deficit (or reduce public surplus).

We rely on previously published (Hinkel et al 2014) DIVA model (Dynamic Interactive Vulnerability Assessment modeling framework, DIVA model 2.0.1, database 32) estimates of coastal impacts from sea-level rise and socio-economic change as exogenous input for the comprehensive macroeconomic assessment. DIVA's underlying DINAS-COAST database (Vafeidis et al 2008) represents the world's coast (excluding Antarctica) as 12,148 coastal segments with homogenous bio-physical and socio-ecological characteristics. For each segment area exposure is derived from the Shuttle Radar Topographic Mission (SRTM) high resolution digital elevation model (Jarvis et al 2008) and the GTOPO30 dataset (USGS 2015) for areas above 60 ° N and 60 ° S. SRTM has a vertical resolution of 1 m (which is the highest resolution available today on global scale) and spatial resolution of approximately 90 m at the equator (30 arc sec). For the calculation of population exposed to flooding the Global Rural Urban Mapping Project (GRUMPv1) elevation dataset with a spatial resolution of 30 arc sec was employed (CIESIN et al 2011). Exposed population is translated into exposed assets by applying sub-national GDP per capita rates (Vafeidis et al 2008) to the population data, followed by applying an assets-to-GDP ratio of 2.8 (Hallegatte et al 2013). Future exposure follows the population and GDP change projections from the SSP scenarios. Extreme water levels are also taken from the DINAS-COAST database (Vafeidis et al 2008) and are assumed to uniformly increase with SLR, following 20th century observations, which implies no change in storm characteristics (Menéndez and Woodworth 2010). Flood damages are calculated by combining elevation-based population and asset exposure with flood depths caused by extreme events. Following (Messner et al 2007) we assume a logistic depth-damage function (giving the fraction of assets damaged for a given flood depth) with a 1-m flood destroying 50% of the assets. Expected annual flood damages are computed as the mathematical expectation of damages based on extreme event distributions (Hinkel et al 2014). In this paper we consider only the damages to capital due to extreme sea-level events as the damages from land loss due to the gradual rise of sea-level are much smaller. It is a widely made assumption that submergence by gradual sea-level rise does not lead to damages to capital because this is a slow process and by the time gradual SLR arrives the capital stock will have fully depreciated (Tol et al, 2016). Protection is modeled by the means of dikes, following a demand function for safety based on local population density and GDP per capita, with a population density threshold of 30 people per km2 for protected land (Hinkel et al 2014). Adaptation costs are based on dike unit costs (1 km length, 1 m height) for protection infrastructure. Unit costs in earlier studies such as Hinkel et al (2014) are based on older studies (Dronkers et al 1990, Hoozemans et al 1993). For this study, these numbers have been updated with the newer estimates given by Jonkman et al (2013). Adaptation capacities are modelled by the demand-for-safety approach (Hinkel et al 2014) and depend mainly on local GDP per capita and local coastal population density, and thus vary between SSP scenarios. It is a widely accepted assumption that these two parameters are the main determinants of adaptation (Sadoff et al 2015, Hallegate et al 2013). Without further adaptation, dike heights are maintained, but not raised, so flood risk increases with time as relative sea level rises. With further adaptation, dikes are raised following the demand function for safety.

2.2. Scenarios

For socioeconomic development assumptions, we assume the SSP2 pathway in all scenarios. To assess the effects of different levels of mitigation ambition, we compare impacts from coastal flooding due to SLR in a 'current policies' climate change mitigation scenario ('RCP45-SLR') with a 'well below 2 °C' mitigation scenario ('RCP26-SLR') (see tables S8 and S9 for the two policy scenarios' sectorally resolved emission reduction pathways). These economic impact projections are compared with respective 'no SLR impacts' reference scenarios, either with RCP4.5 ('RCP45') for the former 'current policies' scenario, or with RCP2.6 ('RCP26') for the latter 'well below 2 °C' scenario. The costs of mitigation are accounted for in each model leading, all else being equal, to lower levels of GDP for the most ambitious mitigation scenarios. In terms of energy and climate policy assumptions, the 'current policies' scenario does not feature a specific carbon budget but is constructed in a bottom up manner by introducing current climate and energy policies and then allowing for a continuation of this climate policy ambition after 2020 (see section 5.2 of the SM for further information on how the 'current policies' mitigation scenario is linked to the RCP4.5 SLR impact scenario). The 'well below 2 °C' scenario is a cost-efficient global mitigation scenario that aims to limit the increase in global average temperatures below 2 °C above the pre-industrial level by 2100 with a > 66% likelihood (Luderer et al 2018). A global carbon price on all greenhouse gases is introduced after 2020 so as to limit global carbon dioxide (CO2) emissions to a carbon budget of approximately 1,000 GtCO2 over the 2011–2100 timeframe and limit other GHGs as well. No burden sharing regimes or carbon trading schemes are introduced, so emission reductions occur where and when it is most cost-effective. The FAIR and WITCH models optimize, while for these runs GEM-E3 has used the 2011–2050 budget as derived by IAMS (e.g. IMAGE) and has then optimized the pathway. See Luderer et al (2018) for a more detailed description of the 'current policies' and 'well below 2 °C' mitigation scenarios. When extending the analysis to the economic effects of adaptation to coastal flooding due to SLR, we consider two different adaptation ambition levels of each scenario. The first one ('RCP45-SLR' and 'RCP26-SLR') assumes that no additional adaptation measures are taken on top of current adaptation levels (i.e. dyke levels are maintained but not heightened above 2015 levels). The second one ('RCP45-SLR-adapt' and 'RCP26-SLR-adapt') assumes that adaptation ambitions follow an increasing demand for safety as described in Hinkel et al (2014).

To take into account biophysical modeling uncertainties, we employ both low and high ice melting scenario results from DIVA. Moreover, each of the scenarios is run for two different global climate models (GCMs) from the ISI-MIP archive (IPSL-CM5A-LR and MIROC-ESM-CHEM, which are spanning the whole SLR-range within the ISI-MIP data) to account for climate model uncertainties. With these models global mean sea-level rise values (in cm) range under RCP26 from 15–25 in 2050 and 25–56 in 2100, and under RCP45 from 18–29 in 2050 and 40–81 in 2100 (the exact values and their composition are given in tables S2 and S3 in the supplementary material). In a sensitivity analysis employing the optimal growth models FAIR and WITCH, we set out to asses yet another source of uncertainty by identifying the influence of changes in socioeconomic and population assumptions (the exposure component of climate-related risk) on the economy wide effects of coastal flooding due to SLR in a below 2 °C world. We contrast the 'current policies' scenarios with three different versions of the 'well below 2 °C' scenario that account for differences in socioeconomic development assumptions (i.e. reflecting population and economic growth assumptions for SSP1, SSP2 and SSP3, respectively)1 . See figure 1 for a summary of all scenarios and variations thereof considered in this analysis.

3. RESULTS

3.1. Global macroeconomic impacts

Figure 2 presents aggregate global economic impacts (measured in terms of global GDP losses) of coastal flooding due to SLR across climate scenarios (RCP45-SLR and RCP26-SLR) until 2050 and 2100. In addition, two different adaptation levels are compared: no further adaptation and full adaptation to SLR. The macroeconomic effects of impacts in each climate scenario are shown relative to global GDP levels of the respective mitigation scenario (i.e., RCP45-SLR is compared to RCP45, and RCP26-SLR is compared to RCP26). The portrayed uncertainty ranges account for three different dimensions of uncertainty, namely model ranges from FAIR, GEM-E3 and WITCH results, climate uncertainty due to high and low ice-melting and climate model uncertainty from two different GCM (IPSL and MIROC) projections. The differences between the three macroeconomic models' results are driven by the models' respective structures and their approaches to model climate change impacts as well as mitigation and adaptation policies (see Figure S1 in the SM, for an annotated version of figure 2 with additional labels for the macroeconomic models). For example, endogenous mitigation costs are highest for the WITCH model, which in turn also lead to higher overall macroeconomic impacts when adding impacts from coastal flooding due to SLR (see Luderer et al (2018) for a detailed assessment of mitigation costs).

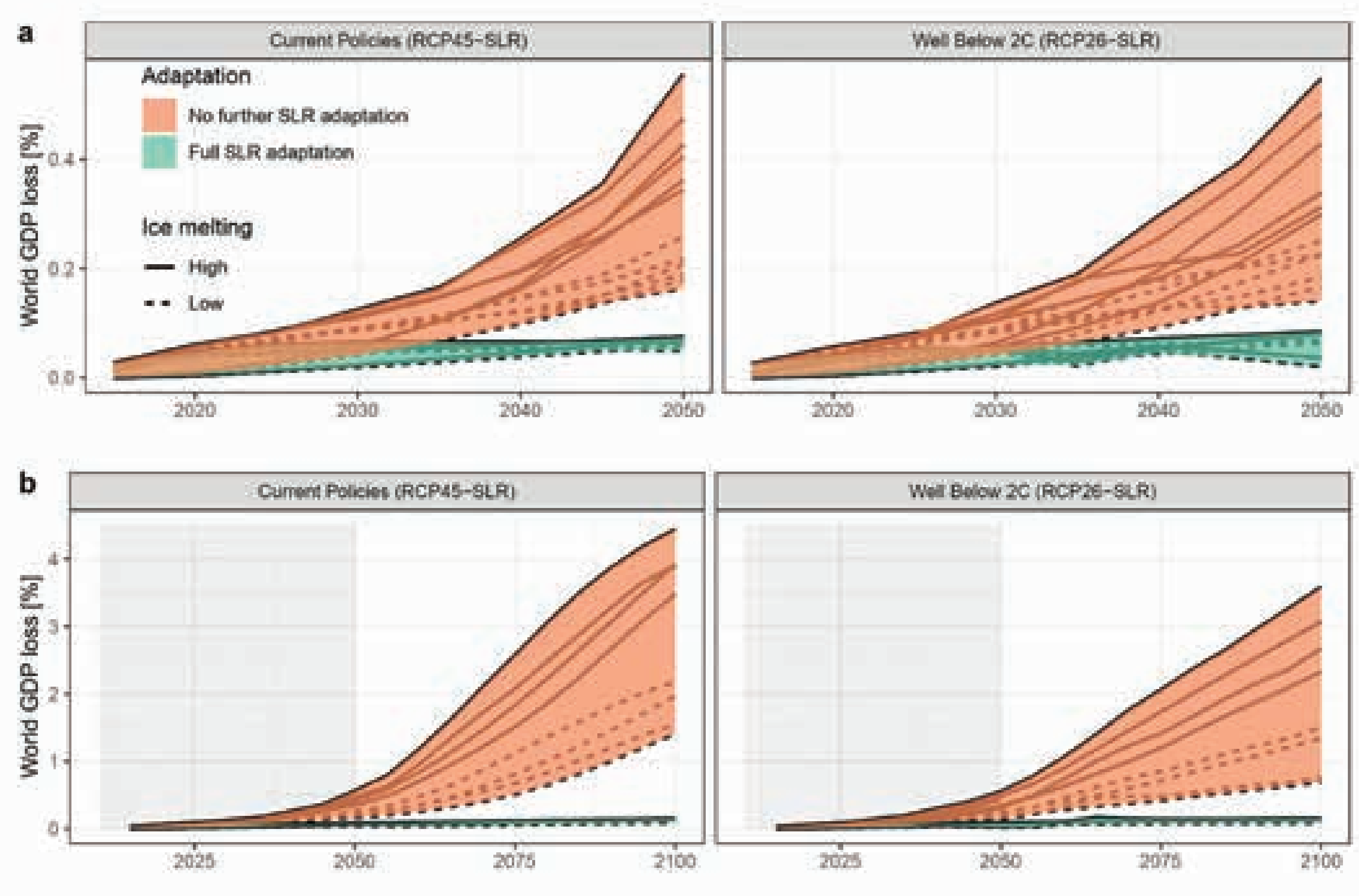

Figure 2:
World GDP loss from coastal flooding due to SLR across climate policy scenarios (RCP45-SLR and RCP26-SLR) and adaptation level until 2050 (top panels, a) and 2100 (bottom panels, b), relative to the respective reference climate policy implementation scenario without coastal flooding impacts (RCP45 and RCP26). The red and green uncertainty ranges account for FAIR, GEM-E3 and WITCH results, high and low ice-melting, and IPSL and MIROC climate projections. High ice-melting is highlighted by plain lines and low ice melting by dashed lines. Note: For the time horizon 2050, all three macroeconomic models have been used, while for 2100 only FAIR and WITCH were used.

Global GDP losses in all scenarios strongly depend on the level of adaptation and the assumed degree of ice melting. Without further adaptation measures, aggregate global GDP loss is about twice as high by 2050 with high ice melting (about 0.4%), than with low ice melting (about 0.2%). Full adaptation lowers the impact to less than 0.1% of global GDP in all cases, with much smaller differences between low and high ice melting. Hence, adaptation is found to be highly economically efficient, with adaptation costs being much lower than the corresponding benefits from avoided damages.

We find that up to 2050 the low- and high-end values of global GDP losses in the case of no further adaptation (RCP45-SLR and RCP26-SLR) are similar across the two policy scenarios. However, in the longer term, global GDP effects increase strongly by an order of magnitude, with higher impacts projected in the RCP45-SLR scenario compared to RCP26-SLR. Without further adaptation and assuming high ice melting, projected global economic losses can amount to more than 4% in RCP45-SLR and more than 3% in RCP26-SLR. With low ice melting, these numbers are more than halved. Again, further adaptation reduces the impacts significantly to less than 0.15% in all scenarios over the whole century. These effects include both the residual coastal flooding impacts and the costs of adaptation measures. This again confirms the importance and economic efficiency of adaptation in reducing global GDP loss from SLR, as costs of adaptation infrastructure affect the global economy much less than unabated climate impacts.

Projected global GDP losses are driven by the removal of available capital, a key productive resource of the economy, due to the expected annual damages by coastal flooding as a result of SLR. Figure 3 shows that, especially in the short term, all models project that global GDP losses are lower than direct economic costs. In the CGE model GEM-E3, this is because macro-effects are somewhat counterbalancing direct coastal flooding impacts through substitution effects in production processes and via international trade effects. In FAIR and WITCH, this is a direct consequence of the type of production function used. This is a common finding in the literature as described for example in Bosello and De Cian (2014). Towards 2100, and in particular for high ice melting scenarios (panels on the left-hand side), both WITCH and FAIR project larger macroeconomic effects relative to direct impacts. This indicates that large disruptions of capital due to climate change can have an increasing impact on the productive capacity of the economy.

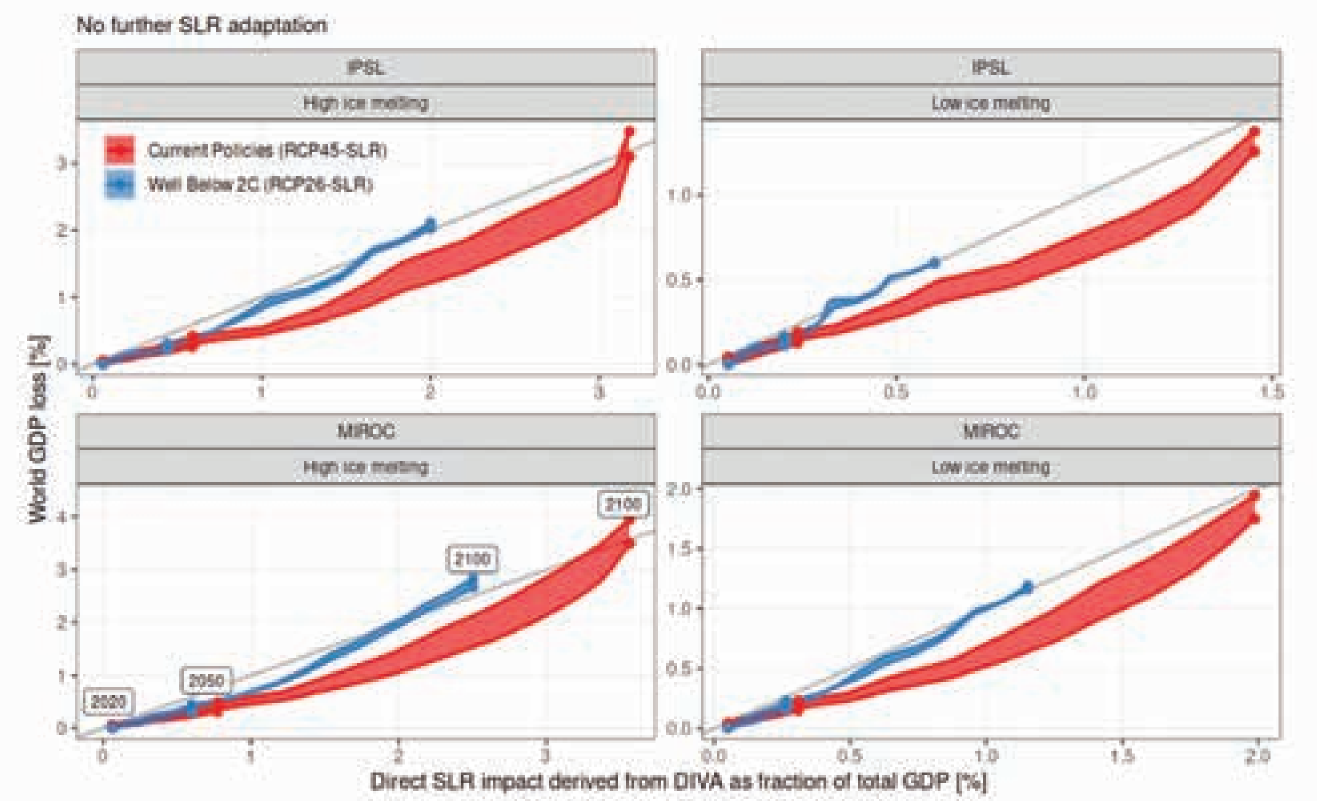

Figure 3:
Direct impacts from coastal flooding due to SLR (x-axis) versus economy-wide effects (y-axis) from 2020 until 2100 across climate scenarios (RCP45-SLR (red) and RCP26-SLR (blue)) in the case of no further adaptation. World GDP impacts are expressed in relation to the respective reference scenario (RCP45 and RCP26). The red and blue uncertainty ranges represent the bandwidth of the results of our economic models. Panels show the results using impacts computed from two climate models (IPSL: top panels; MIROC: bottom panels) each in combination with high (left panels) and low (right panels) ice-melting. Note: For the time horizon 2050, all three macroeconomic models have been used, while for 2100 only FAIR and WITCH were used. In 2100, 1% direct SLR impact in terms of DIVA GDP is equal to 6.7 trillion USD_{2014}.

In the well below 2 °C scenario RCP26-SLR, macroeconomic impacts relative to direct impacts are higher because capital markets are already affected by mitigation measures, as the low-carbon transformation of the economy is a capital-intensive process. Thus, removing one unit of capital in a capital-intensive economy (i.e. an economy with a high capital-to-GDP ratio) has more detrimental effects and the additional effect of coastal flooding therefore has a relatively stronger indirect impact. While this finding is robust across all participating models, the specific values of the results differ (see figure S2 in the SM). Moreover, we conducted a sensitivity analysis to clarify the robustness of this result for alternative socioeconomic development assumptions (i.e., running the two policy scenarios in combination with different SSPs). While we find that the pattern of how direct impacts relate to macroeconomic effects for the two policy scenarios (RCP45-SLR and RCP26-SLR) remains the same under alternative SSPs, the magnitude of the direct and the indirect impacts, expressed relative to the respective reference scenarios (RCP45 and RCP26), differs. This indicates the significance of socioeconomic assumptions in the assessment of climate costs (figure S3 in the SM).

3.2. Regional and sectoral effects

Turning to regional effects, figure 4 presents the breakdown of the global economy-wide impacts of coastal flooding due to SLR for G20 countries for the cases of high-ice melting without any further adaptation, relative to the respective reference scenarios (RCP45 and RCP26). By 2050 (upper panels in figure 4), the highest levels of GDP loss are projected for China (0.8%–0.9% under RCP26-SLR and 0.9%–1.0% under RCP45-SLR) and India (0.5%–0.6% under both scenarios), followed by Canada (0.3%–0.4% under both scenarios) and Indonesia (0.2%–0.3% under both scenarios). These are also the countries with the highest direct impacts according to DIVA model projections.

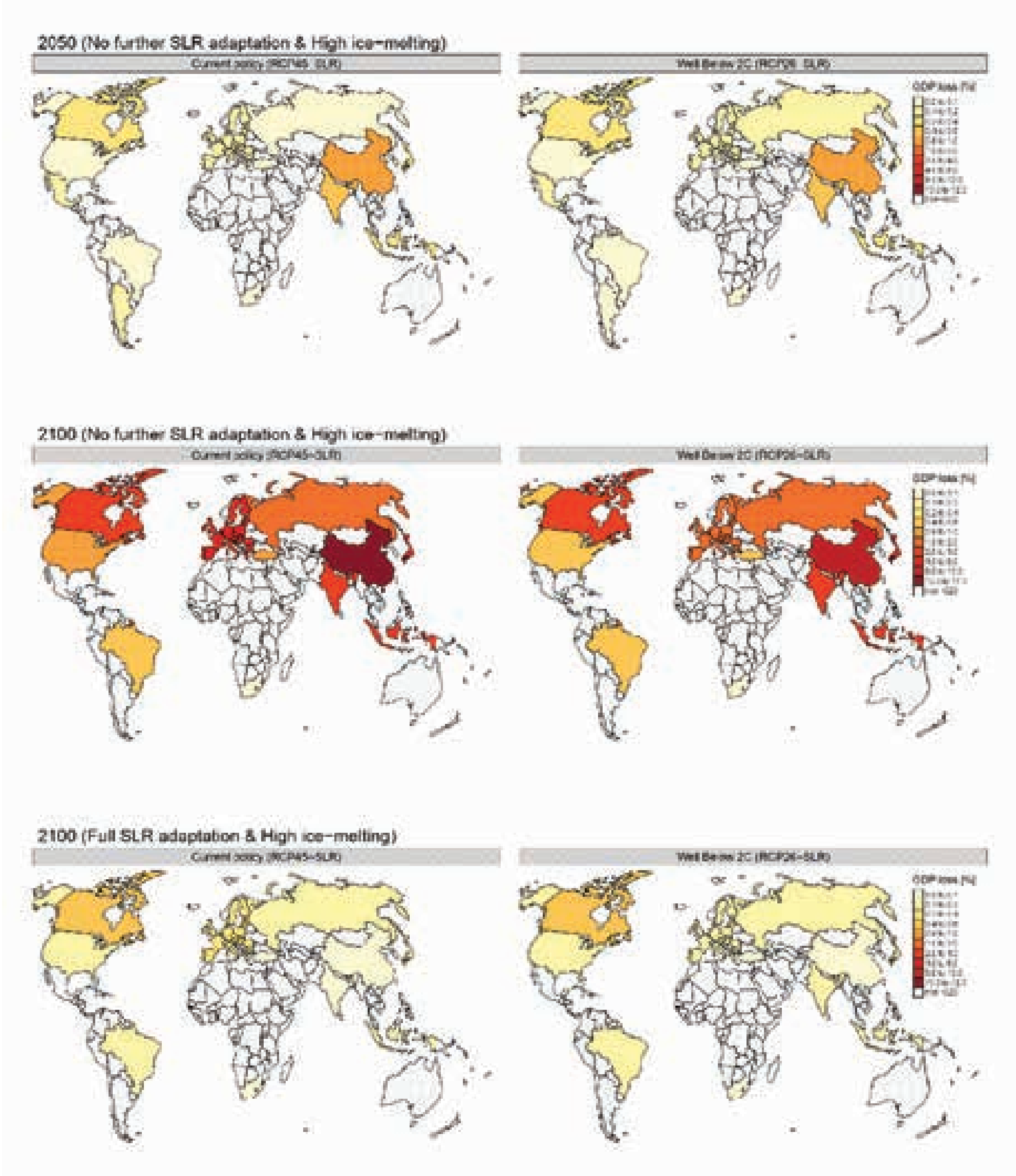

Figure 4:
GDP impacts due to coastal flooding in G20 countries for 2050 and 2100 across climate policy scenarios (RCP45-SLR and RCP26-SLR) in the cases of full and no further adaptation, and high ice-melting. GDP losses are expressed as an average of the different macroeconomic models, depending on regional detail, and are presented relative to the respective reference scenario (RCP45 and RCP26). Note: The number of macroeconomic models used for this visualization depends on the regional detail and time horizon of the respective model. For the time horizon 2050 all three macroeconomic models have been used, while for 2100 only FAIR and WITCH were used. Some G20 countries are missing from the map, since the regional aggregations in the models do not allow for a country-level assessment.

By 2100, the scale of economy-wide effects in G20 countries changes by an order of magnitude. China remains the G20 country with the highest projected GDP loss, which is now a factor of ten higher than it was in 2050 (9%–10% under RCP26-SLR and 11%–12% under RCP45-SLR). Other regions with high GDP losses by 2100 in the RCP45-SLR scenario are Japan (7%–8%) and Europe (4%–6%). However, this changes once stronger mitigation action is undertaken (RCP2.6-SLR), in which case Europe and Japan have relatively low GDP losses (see middle, right-hand panel in figure 4). Comparing the economic impacts between RCP45-SLR and RCP26-SLR indicates that strong decarbonization by the end of the century is highly effective in reducing potential future impacts, also at the level of individual G20 countries. Moreover, the lower panels in figure 4 indicate the effectiveness of comprehensive adaptation to coastal flooding due to SLR.

Overall, regional GDP impacts go in line with the regional distribution of direct impacts provided by DIVA. In particular, we find that GDP impacts are analogous to the share of direct damages to total capital stock of the economy, thus indicating that higher shares of destroyed capital stock result in more significant macroeconomic impacts.

A further key driver of the GDP effects is the regional allocation of mitigation efforts and SLR damages. We find that countries with high mitigation efforts (i.e. the biggest emitters, most notably China and India) coincide with the countries with the higher damages as a percentage of GDP. As these countries are also among the largest economies, this regional coincidence of mitigation efforts and SLR damages can have an important macroeconomic effect. In certain cases (i.e., specific regions, climatic or macroeconomic models), GDP changes due to coastal flooding impacts (RCP26-SLR and RCP45-SLR relative to RCP26 and RCP45, respectively), are higher in the RCP26-SLR scenario than in the RCP45-SLR one, despite that the level of direct damages is higher in the latter scenario (figure 5 and figure S5 and S6 in the Supplementary Material). This can be mainly attributed to the disturbances of mitigation efforts to the overall economy and in particular to the increased capital requirements for the low-carbon transition. As a result of the ambitious mitigation efforts, GDP levels in the RCP2.6 scenario are slightly lower than in the RCP4.5 scenario. In particular, in GEM-E3 model we find that the economy of the RCP2.6 scenario becomes more capital intensive and thus the destruction of one unit of capital due to unavoided damages has a stronger effect on GDP. In FAIR and WITCH, mitigation actually leads to less productive capital and a further loss of productive capital due to sea level rise impacts, and therefore has a stronger impact on GDP. The strength of this effect has been analyzed in a separate artificial well below 2 °C scenario run without mitigation costs using the FAIR model. This analysis showed that the same level of direct damages has an approximately 5% larger global GDP impact in 2050 and 2100 when interaction with mitigation costs are accounted for, with higher differences for countries with higher mitigation costs (see figure S4 in the supplementary material). In the longer term up to 2100, the difference between the two climatic scenarios is amplified and thus results are generally as expected: higher impact ranges for RCP45-SLR than for RCP26-SLR.

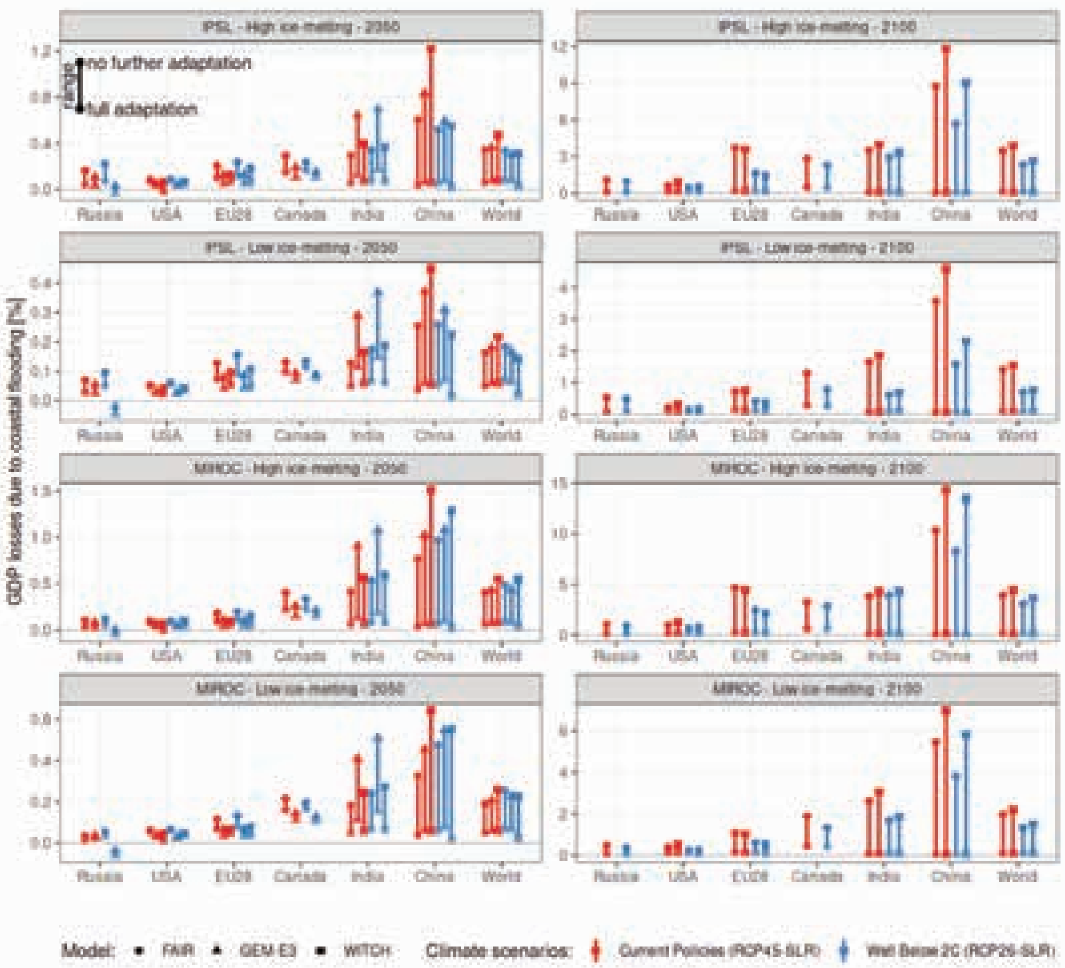

Figure 5:
Regional GDP impacts of coastal flooding due to SLR across climatic scenarios (RCP45-SLR and RCP26-SLR) for all macroeconomic and climate models, relative to the respective reference scenarios (RCP45 and RCP26). Lower values in the line range show the ‘full adaptation’ case, higher values show the ‘no further adaptation’ case. The shapes represent the economic models. Not all models are displayed in all panels, GEM-E3 provides information only for 2050 and WITCH does not provide information for Russia and Canada.

The GEM-E3 model further allows for a sectoral analysis of the impacts of coastal flooding and adaptation (figure 6). Although capital is assumed to be mobile across all sectors within a region in the GEM-E3 model, the impact of capital destruction from coastal flooding as a result of SLR differs by sector. This is mainly due to the different production structures of each sector, and in particular due to different levels of capital intensity and differences in the ability to substitute across production factors (see table S11 of the SM for respective details). Thus, the result of different production structures is that changes in capital availability, hence the price of capital, affect each sector with a different intensity. Furthermore, the destruction of capital stock due to climate impacts implies a lower overall capital stock and thus lower investment requirements for the maintenance of capital. This lower demand for investments is another driver of changes in sectoral production, as lower demand in sectors that deliver investment goods reduced their overall production levels (see table S11 of the SM for respective details).

Our results indicate that if no further adaptation measures are undertaken, 'construction', 'agriculture' and 'energy intensive industries' are the three hardest hit economic sectors on a global level, while the services sector is less affected due to the high elasticity of substitution and the respective demand for delivery to investments. The construction sector is also key in delivering investment goods and thus a lower investment demand for the maintenance of existing capital stock results in production losses. On the other hand, the agriculture sector is characterized by a capital intensive production process with low substitutability of capital and thus lower capital availability increases the cost of production and results in production losses. This holds for both climate policy scenarios, RCP26-SLR and RCP45-SLR, although certain differences may be noted across the two, depending on the relevant importance of a sector in each respective economy (e.g., bioenergy in RCP2.6 is more affected than in RCP4.5 as this sector becomes larger). On the contrary, the implementation of adaptation measures against coastal flooding (RCP45-SLR-adapt and RCP26-SLR-adapt) has positive effects on the 'construction' sector, which instead of being among those hit hardest, is now among the sectors with the lowest negative impacts. This is mainly driven by the fact that the 'construction' sector is key to delivering services for adaptation and substantially expands its output level due to the high physical protection investments in the full adaptation scenario. In connection to the sectoral analysis, GEM-E3 further allows for an assessment of employment effects. The increased public demand for labor-intensive construction services initially raises demand for labor. However, coastal flood damages to the capital stock are translating into negative effects to the overall economic activity, which in turn leads to a slight reduction in total employment levels, despite the increase in construction activities for adaptation measures.

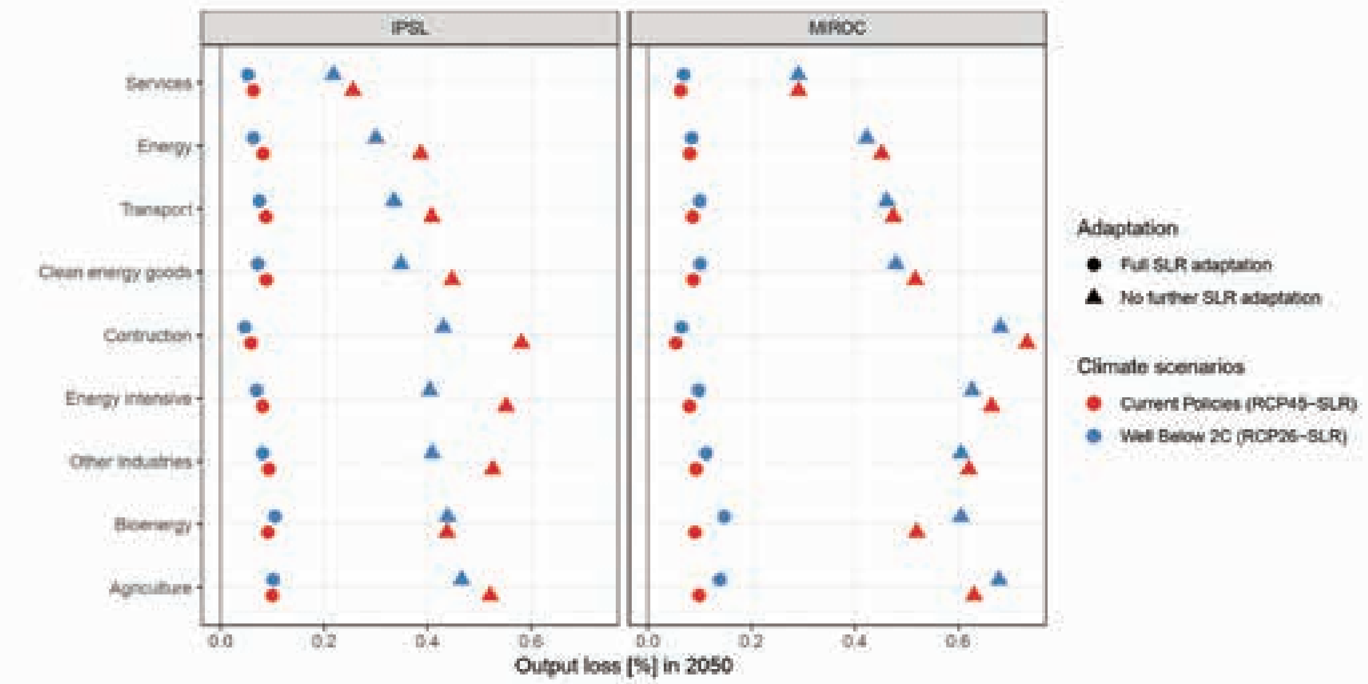

Figure 6:
Sectoral output effects triggered by coastal flooding impacts due to SLR across climate policy scenarios (RCP45-SLR and RCP26-SLR) with and without further adaptation, relative to the respective reference scenarios (RCP45 and RCP26).

4. DISCUSSION AND CONCLUSIONS

In this paper, we carried out a multi-model assessment of the macroeconomic impacts of coastal flooding due to SLR and the respective macroeconomic implications of adaptation measures for a RCP2.6 (equivalent to a 'well below 2 °C') world compared to a RCP4.5 (or 'current policies') scenario. We combined our analysis, focusing on the global level, as well as on individual G20 countries, with corresponding stylized RCP2.6 and RCP4.5 mitigation efforts in order to understand the implications of interactions across mitigation, adaptation and coastal flooding impacts due to SLR on a macroeconomic level. Overall, our multi-model analysis indicates that aggregate macroeconomic impacts are robust across the different model types, from simple optimal growth models (FAIR and WITCH) to more complex CGE models (GEM-E3).

Our results indicate that until the middle of this century, differences in macroeconomic impacts between the two climatic scenarios are small, but increase substantially towards the end of the century. Moreover, direct impacts can be partially absorbed by substitution effects in production processes and via international trade effects until 2050, resulting in GDP losses that are lower than direct damages. By 2100 however, we find that this effect is turned around and economy-wide effects become even larger than direct impacts. Within the G20, our results indicate that China, India and Canada will experience the highest macroeconomic impacts, with the two first large economies undertaking the highest mitigation efforts in a cost-efficient global climate action. In addition, we find that strengthening adaptation will be crucial for limiting direct as well as economy-wide impacts from coastal flooding already before 2050, but especially after mid-century. Particularly the construction sector and other energy and capital-intensive industries will benefit directly and indirectly from fostering adaptation activities. It is important to note that in this study we only evaluate the performance of adaptation measures in terms of direct and indirect economic effects on GDP. It would be a fruitful area for future research to also consider further reaching co-benefits (such as triggering entrepreneurial activities and productive investments by lowering the imminent threat of losses from disasters) and co-costs (e.g. in the agricultural sector due to waterlogging induced by flood embankments) of adaptation (Surminski and Tanner 2016).

In contrast to the majority of the existing literature (e.g., Ciscar et al 2011, 2012, Hinkel et al 2013, OECD 2015, Diaz and Moore 2017), we implement the impacts from coastal flooding due to SLR in a 'well below 2 °C' world, on top of the climate mitigation policies that lead to a reduction in GHG emissions and thus to the respective RCP2.6 scenarios. We find that the disturbances of mitigation efforts to the overall economy may in some regions lead to a counterintuitive result, namely to GDP losses that are higher in RCP26-SLR than in RCP45-SLR, despite that the direct coastal damages are higher in the latter scenario. This can be seen for certain model regions and only in the earlier period until 2050 when mitigation efforts are particularly high. As GDP is already reduced due to high mitigation efforts, the removal of further primary resources from the economy has a more noticeable effect in RCP26-SLR than in RCP45-SLR when measured in relative terms of GDP. In some cases, GDP losses in RCP26-SLR are bigger than in RCP45-SLR even in absolute terms. For the CGE model GEM-E3, the explanation is that decarbonization efforts lead to a more capital-intensive economy in the RCP26 scenario, and thus the destruction of capital in RCP26-SLR has a stronger effect on GDP than in RCP45-SLR. In addition, the rate of return of capital is higher in the RCP26 scenario, thus a reduction of one unit of capital corresponds to more loss of value and therefore bigger GDP losses. For the IAMs, FAIR and WITCH, mitigation leads to less productive capital and a further loss of productive capital due to SLR impacts, and therefore has a stronger impact on GDP. An important caveat to this result is that we do not take into account climate change impacts other than those resulting from coastal flooding due to SLR. If these other damages are higher in RCP45 than in RCP26, this would lead to more destruction of capital in RCP45, which in turn could dampen or reverse this effect. In the period after 2050 until the end of the century GDP losses are, as one would expect, for all regions higher in RCP45-SLR than in RCP26-SLR.

It is important to note that all three macroeconomic models employed in this study are based on neoclassical modeling techniques that assume optimality in the baseline. Any disturbance (e.g., a carbon tax) will therefore lead to negative macroeconomic effects, unless it counterbalances larger distortions that exist in the baseline (e.g., when recycling carbon taxes counterbalances the effects of other taxes). This is especially important for assessing the regional macroeconomic impacts and in particular for the interpretation of our result that in some regions the medium-term macroeconomic impacts can be higher with higher mitigation efforts. This effect is particularly visible in relatively poor and emission-intensive regions (i.e., emissions as share of GDP) such as India and Russia, respectively, which further highlights the implications of mitigation effort-sharing decisions. This also implies that for the RCP26 scenario, the macroeconomic impacts of SLR partly depend on the regional distribution of mitigation efforts: if instead of a global carbon tax, a more equitable effort sharing scheme was implemented, leading to more equal mitigation costs across regions, the additional GDP impacts of coastal flooding due to SLR could also be alleviated in certain regions. For further multi-model assessment exercises we therefore suggest involving alternative, heterodox macroeconomic models in the portfolio and applying different effort-sharing approaches. For example, post-Keynesian models that allow for initial capacity utilization rates lower than 1 or stock-flow consistent macroeconomic models that add the financial sector to 'real' economic activities, may both find different results, since they allow for relaxing the capital scarcity assumption via intensifying the utilization of existing capacities or increasing debt, respectively). Moreover, a risk-based assessment, capable of identifying and quantifying low-probability, high-impact events (see e.g., Hochrainer-Stigler et al 2014), as a complement to our modeling exercise, which is based on expected values, could be another worthwhile addition to the set of models used.

As explained above, our finding that macroeconomic impacts under RCP2.6 can be higher than under RCP4.5 due to distortion effects of mitigation may not be robust if other climate change impacts are taken into account. Hence, looking into further climate change impact sectors (e.g. health, agriculture, riverine flooding etc) is another important extension for future multi-model assessment research. Here, an additional challenge will be to identify approaches that allow the macroeconomic model integration of direct impact estimates and adaptation costs in other sectors than coastal impacts. While we shocked total regional capital stocks in the macroeconomic models with the direct impacts from coastal flooding due to SLR as estimated by DIVA, the integration of willingness to pay estimates for public health damages, for example, will require quite different modeling approaches. Moreover, it would be very interesting to move the analysis further on a lower geographic level, with more details in terms of vulnerable economic activities and infrastructure that are potentially affected differently by SLR.

Finally, a sensitivity analysis has shown that varying socioeconomic development assumptions (population and GDP growth rates according to different SSPs) has an impact on potential economic losses due to coastal flooding as indicated both by differences in direct and indirect impacts. Since the differences in direct biophysical model results, which in turn propagate into macroeconomic effects, are to a certain extent also driven by varying urbanization rates between levels assumed in the SSPs, we stress that uncontrolled urban development could substantially increase climate-related risk and hence jeopardize sustainable development. This finding is supported by earlier research (e.g. Merkens et al 2016), which finds that regions where high coastal population growth and development is expected will face an increased exposure to coastal flooding. Moreover, the world is already committed to long-term SLR in the range of 1.2 to 2.2 meter under present levels of global warming (Hinkel et al 2018) and even if global warming can be limited to well below 2 °C by the end of the century, natural climate variability continues playing a role. Consequently, risk sensitized and climate proof (adaptation) investment in urban infrastructure is a crucial complement to ambitious mitigation efforts, in order not to increase risks related to natural hazards, by for example, situating infrastructure in flood prone areas, as was experienced in the past (The Economist Intelligence Unit 2016, Hochrainer-Stigler et al 2017). This is particularly true for hot-spot countries, such as China, India and Japan, which we identified in this modeling exercise. Hence, regarding concrete policy suggestions, we put forward the idea of fostering climate-related-risk screening in investment appraisals, particularly in the identified hot-spot countries. While these results indicate that exposure as a driver of climate-related risks and related economic impacts has to be taken seriously to prevent jeopardizing the gains from ambitious climate change mitigation efforts, we do not want to give the impression that proper risk-sensitized investment efforts and adequate adaptation measures outweigh the role of climate change mitigation. This is due to the likely emergence of non-economic losses and damages that may arise after socioeconomic (soft) and physical (hard) limits to adaptation have been reached, and of potentially systemic risk that can only be prevented by substantial mitigation efforts. We therefore see our results as a strong signal to the international policy scene to strengthen the ambitions for climate change mitigation, but to do so by synergistically approaching climate change adaptation and risk-sensitizing socioeconomic development.

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1 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria **2** RFF–CMCCEuropean Institute onEconomics and the Environment (EIEE),CentroEuro-Mediterraneo suiCambiamenti Climatici,Milan, Italy **3** School of Electrical and Computer Engineering, E3MLab, National Technical University of Athens, Athens, Greece **4** PBL Netherlands Environmental Assessment Agency, the Hague, The Netherlands **5** Utrecht University (UU), Utrecht, The Netherlands **6** Global Climate Forum (GCF), Berlin, Germany **7** Bocconi University, Milan, Italy

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GLOBAL AND EUROPEAN SEA-LEVEL RISE

European Environment Agency
www.eea.europa.eu

KEY MESSAGE

- Global mean sea level in 2018 was higher than any year since measurements started in the late 19th century, about 20 cm higher than at the beginning of the 20th century.

- Global sea level rise has accelerated since the 1960s. The average rate of sea level rise over the period 1993-2018, when satellite measurements have been available, has been around 3.3 mm/year.

- Evidence for a predominant role of anthropogenic climate change in the observed global mean sea level rise and in the acceleration over recent decades has strengthened since the publication of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.

- All coastal regions in Europe have experienced an increase in absolute sea level, but with significant regional variation. Most coastal regions have also experienced an increase in sea level relative to land.

- The rate of global mean sea level rise during the 21st century will very likely be higher than during the period 1971-2015. Process-based models considered in the IPCC special report on the ocean and cryosphere in a changing climate project a rise in sea level over the 21st century in the range of 0.29-0.59 m for a low-emissions scenario and 0.61-1.10 m for a high-emissions scenario. However, substantially higher values cannot be ruled out. Several recent model-based studies, expert assessments and national assessments have suggested an upper bound for 21st century global mean sea level rise in the range of 1.5-2.5 m.

- Global mean sea level in 2300 will likely be 0.6-1.1 m above current levels for a low-emissions scenario and 2.3-5.4 m for a high-emissions scenario. These values will rise substantially if the largest estimates of sea level contributions from Antarctica over the coming centuries are included.

- The rise in sea level relative to land along most European coasts is projected to be similar to the global average, with the exception of the northern Baltic Sea and the northern Atlantic coast, which are experiencing considerable land rise as a consequence of post-glacial rebound.

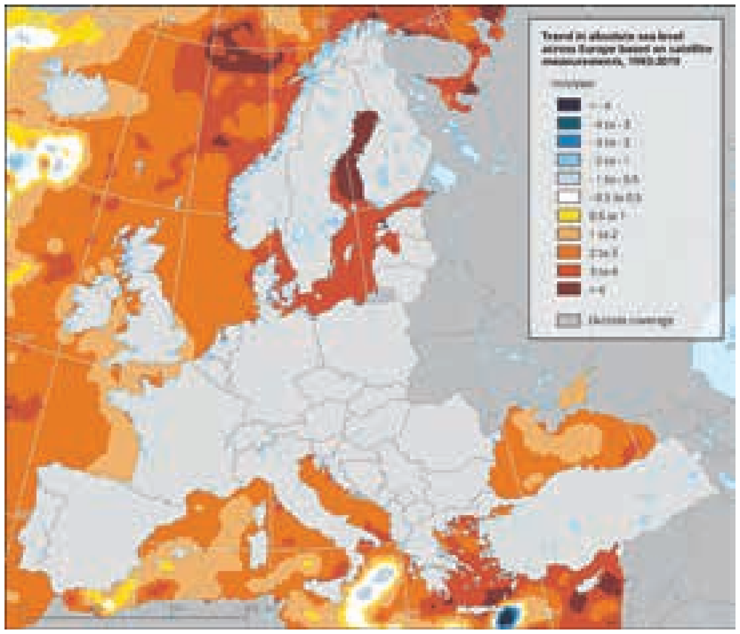
- Extreme high coastal water levels have increased at most locations along the European coastline. This increase appears to have been predominantly due to increases in mean local sea level rather than changes in storm activity.

- Projected increases in extreme high coastal water levels are likely to be primarily the result of increases in local relative mean sea levels in most locations. However, several recent studies suggest that increases in the meteorologically driven surge component could also play a substantial role, in particular along the northern European coastline.

- All available studies project that damages from coastal floods in Europe would increase many fold in the absence of adaptation, although the specific projections depend on the assumptions of the particular study.

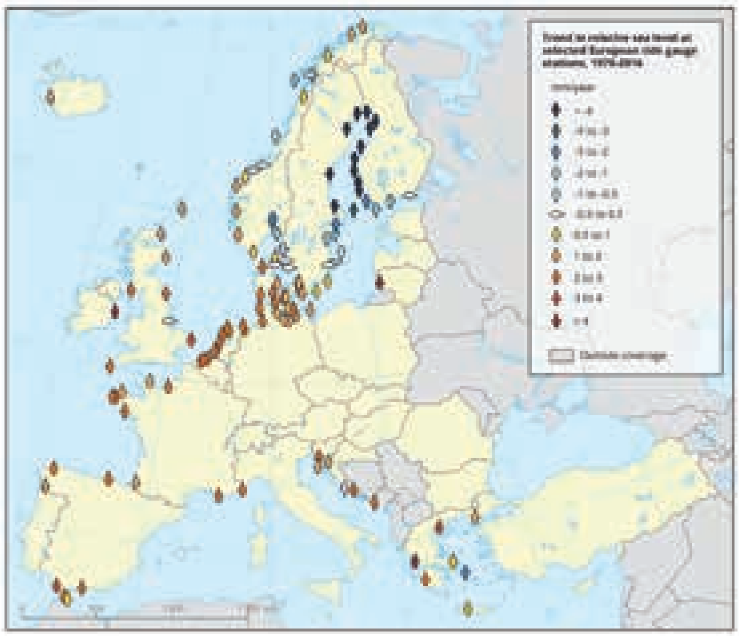
WHAT ARE THE TRENDS IN MEAN SEA LEVELS GLOBALLY AND ACROSS EUROPEAN SEAS?

Fig. 2: Trend in absolute sea level across Europe based on satellite measurements, 1993-2019



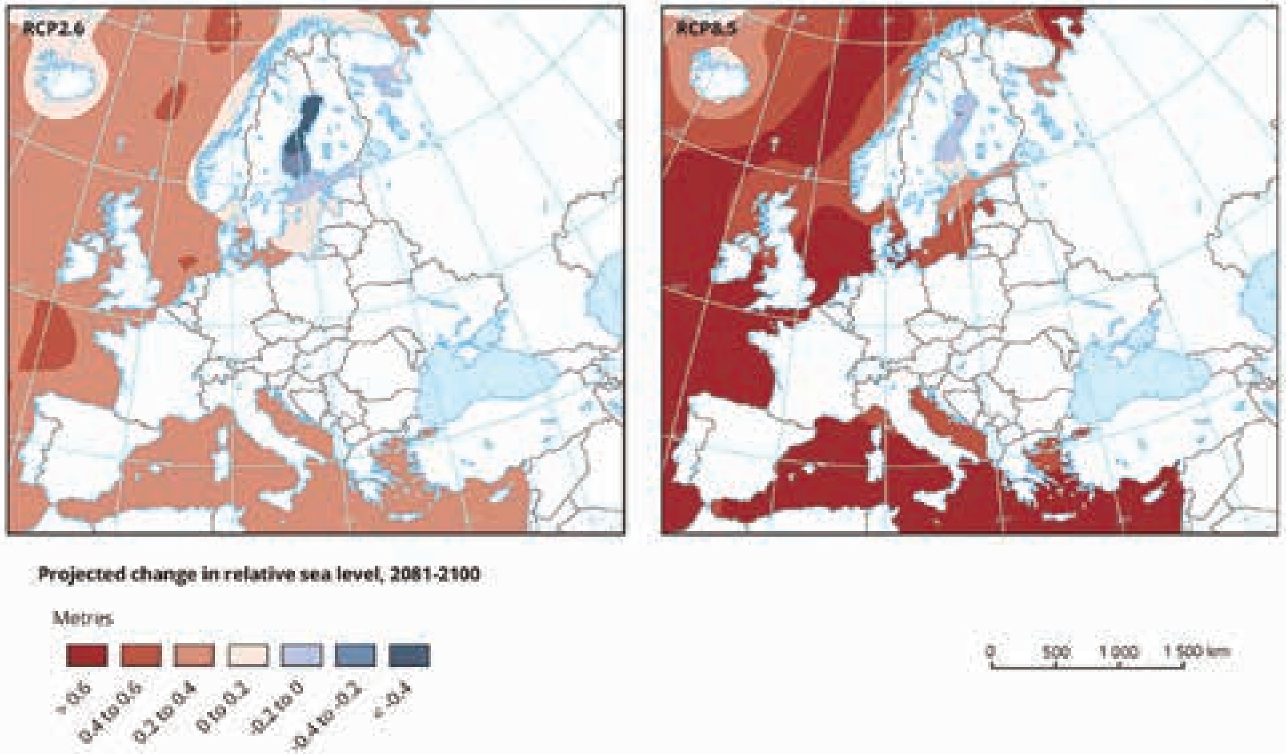
Data sources:
Time Series of Mean Sea Level Trends over Global Ocean
provided by Copernicus Marine Environment Monitoring Service

Fig. 3: Trend in relative sea level at selected European tide gauge stations, 1970-2016



Data sources:
Relative sea level trends (tide gauge data)
provided by Permanent service for mean sea level (PSMSL)

Fig. 5: Projected change in relative sea level, 2081-2100



Data sources:
IPCC SROCC data on sea level rise
provided by Intergovernmental Panel on Climate Change (IPCC)

Past trends: global mean sea level

Sea level changes can be measured using tide gauges and remotely from space using satellite altimeters. Many tide gauge measurements have long multi-decadal time series, with some exceeding more than 100 years. However, the results can be distorted by various regional and local effects, such as vertical land motion processes. Satellite altimeters enable absolute sea level to be measured from space and provide much better spatial coverage (except at high latitudes). However, the length of the altimeter record is limited to about 25 years.

Figure 1 shows the change in global mean sea level (GMSL) since the early 20th century, based on different tide gauge reconstructions (green and red curves) and satellite altimeters (dark blue curve). GMSL in 2018, assessed by satellite altimetry, was the highest level over the entire record. GMSL reconstructions based on tide gauge observations suggest a rise of 16 (±4) cm over the period between 1902 and 2010.

GMSL rise has accelerated since the 1960s. The rate of GMSL rise during the period 1993-2018, for which satellite-based measurements are available, has been around 3.3 mm/year; this is more than twice as fast as the mean trend for 1901-1990, which was1.4 (±0.6) mm/year [i]. A further acceleration of sea level rise has also been detected within the satellite altimeter period [ii]. Over the five-year period 2014-2019, the rate of GMSL rise has amounted to 5 mm/year [iii].

The causes of GMSL rise over recent decades are now well understood. Multiple lines of evidence support the conclusion that the dominant cause of global mean sea level rise since 1970 is anthropogenic forcing. Thermal expansion and melting of glaciers account for around 75 % of the measured sea level rise since 1971. However, the contribution from melting of the Greenland and Antarctic ice sheets has increased since the early 1990s. Over the period 2006–2015, the sum of ice sheet and glacier contributions was the dominant source of sea level rise (1.8±0.1 mm/year), exceeding the effect of thermal expansion of ocean water (1.4±0.3 mm/year) [iv]. Changes in land water storage and groundwater extraction have made only a small contribution [v].

Past trends: mean sea level along the European coastline

Most European coastal regions experience increases in both absolute sea level (as measured by satellites) and relative sea level (as measured by tide gauges), but there are sizeable differences in the rates of absolute and relative sea level change across Europe.

Figure 2 shows linear trends in absolute sea level from 1993 to 2019 as observed by satellites. The main differences between regional seas and basins are primarily the result of different physical processes being the dominant cause of sea level change at different locations. For instance, the Mediterranean Sea is a semi-closed, very deep basin, exchanging water with the Atlantic Ocean through only the narrow Gibraltar Strait. Salinity in the Mediterranean Sea may increase in the future and this will tend to offset rises in sea level due to thermal expansion from warming. The NAO, interannual wind variability, changes in ocean circulation patterns, and the location of large-scale gyres and small-scale eddies are further factors that can influence local sea level in the European seas. Obviously, sea level changes in coastal zones are most relevant for society.

Figure 3 shows linear trends in relative sea level from 1970 to 2016 as observed by tide gauge stations in Europe. These trends are more relevant for coastal protection than absolute sea level. They can differ from those measured by satellites because of the longer time period covered and because tide gauge measurements are influenced by vertical land movement whereas satellite measurements are not. In particular, since the last ice age, the lands around the northern Baltic Sea have been, and are still, rising owing to the post-glacial rebound.

Projections: global mean sea level

The main approach to projecting future sea level are simulations with process-based climate models. A significant recent step forwards in projecting future sea levels is the improved understanding of the contributing factors to recently observed sea level rise, which has increased confidence in the use of process-based models for projecting the future. These models estimate the rise in GMSL during the 21st century (i.e. in 2100, compared with 1986–2005) to be likely in the range of 0.29-0.59 m for RCP2.6, 0.39-0.72 m for RCP4.5, and 0.61-1.10 m for RCP8.5 (Figure

4). The rate of GMSL rise in 2100 is estimated at 4-9 mm/year for RCP2.6 and 10–20 mm/year for RCP8.5 [vi].

A collapse of marine-based sectors of the Antarctic Ice Sheet (i.e. those areas where the bed lies well below sea level and the edges flow into floating ice shelves) could cause GMSL to rise substantially above the likely range projected for the 21st century, but the evidence is currently insufficient for estimating the likelihood of such a collapse. A structured expert assessment suggests that a GMSL rise of 2 or more metres cannot be ruled out [vii]. Various national reports have used values in the range of 1.5–2.5 m as upper estimates for GMSL rise during the 21st century [viii]. Whilst high-end scenarios are somewhat speculative, their consideration is nevertheless important for long-term coastal risk management, in particular in densely populated coastal zones [ix].

Sea levels will continue to rise far beyond the year 2100 due to continued thermal expansion and further ice loss from the Greenland and Antarctic ice sheet. GMSL rise is projected to reach 0.6-1.1 m by 2300 under ambitious mitigation (RCP2.6 extended) and 2.3-5.4 m under high emissions (RCP8.5 extended). These GMSL projections would rise substantially if the largest estimates of sea level contributions from Antarctica over the coming centuries were included [x]. A recent study has suggested that each 5-year delay in peaking of global greenhouse gas emissions increases median sea-level rise estimates for 2300 by 0.2 m, and extreme sea-level rise estimates by up to 1 m [xi].

Projections: mean sea level along the European coastline

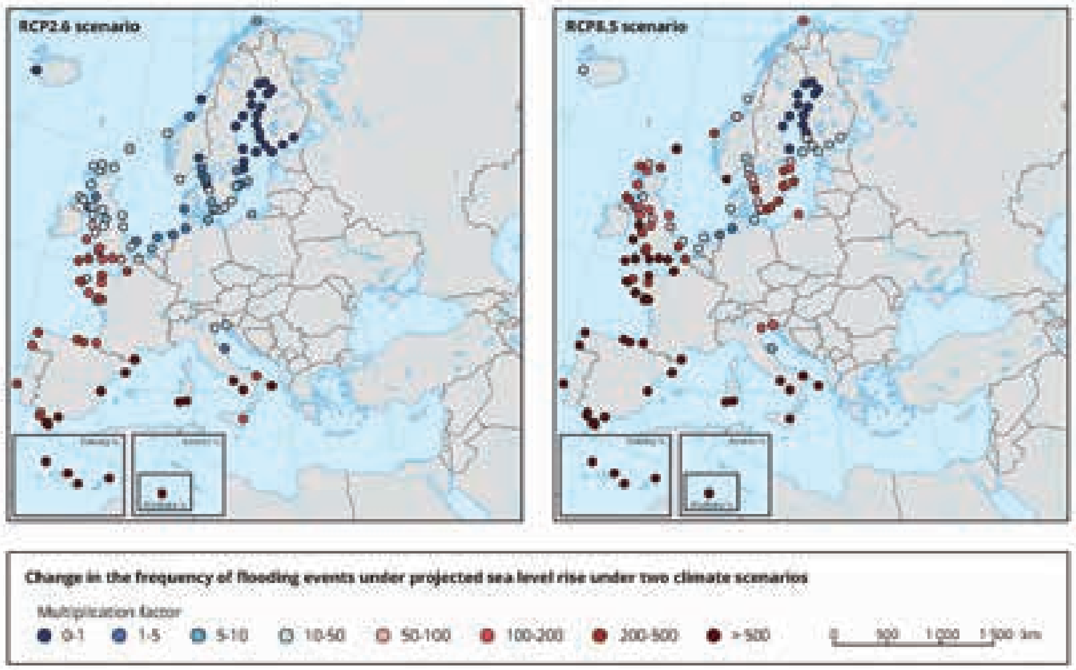
Regional and local sea levels differ from the global mean owing to large-scale factors such as non-uniform changes in ocean density and changes in ocean circulation, disintegrating land ice and post-glacial rebound, and local factors, such as vertical land movement [xii]. However, around 70 % of the world's coastlines are expected to experience a local mean sea level change within ±20 % of the projected GMSL change [xiii].

Relative sea level change along most of the European coastline is projected to be reasonably similar to the global average. The main exceptions are the northern Baltic Sea and the northern Atlantic coast, which are experiencing considerable land rise as a consequence of post-glacial rebound and changes in the gravity field of the Greenland ice sheet. As a result, sea level relative to land is rising slower than elsewhere in these regions or may even decrease (Figure 5) [xiv].

A probabilistic assessment of regional sea-level rise in northern and central Europe estimated relative sea level changes during the 21st century for the high RCP8.5 emissions scenario from –14 cm (in Luleå, northern Sweden) to 84 cm in Den Helder (Netherlands); high estimates (with a 5 % probability to be exceeded) range from 52 cm to 181 cm, respectively [xv].

WHAT IS THE TREND IN EXTREME SEA LEVELS ALONG EUROPEAN COASTS?

Fig. 6: Change in the frequency of flooding events in Europe under projected sea level rise under two climate scenarios



Note:
This maps show the estimated multiplication factor, by which the frequency of flooding events of a given height changes between 2010 and 2100 due to projected regional sea relative level rise under the RCP2.6 and RCP8.5 scenarios. Values larger than 1 indicate an increase in flooding frequency. Adapted from Figure 4.12 of the IPCC Special Report on the Ocean and Cryosphere (SROCC).

Data sources:
IPCC SROCC data on sea level rise
provided by Intergovernmental Panel on Climate Change (IPCC)

Past trends: extreme sea level along the European coastline

Producing a clear picture of either past changes or future projections of extreme high water levels for the entire European coastline is a challenging task because of the impact of local topographical features on surge events. While there are numerous studies for the North Sea coastline, fewer are available for the Mediterranean Sea and the Baltic Sea, although this situation is starting to improve.

Extreme sea levels show pronounced short- and long-term variability. A recent review of extreme sea level trends along European coasts concluded that long-term trends are mostly associated with the corresponding mean sea level changes. Changes in wave and storm surge characteristics mostly contribute to interannual and decadal variability, but do not show substantial long-term trends [i]. When the contribution from local mean sea level changes and variations in tide are removed from the recent trends, the remaining effects of changes in storm surges on extreme sea level are much smaller or even no longer detectable [ii]. Additional studies are available for some European coastal locations, but these typically focus on more limited spatial scales [iii]. The only region where significant increases in storm surge height were found during the 20th century is the Estonian coast of the Baltic Sea [iv].

In conclusion, while there have been detectable changes in extreme water levels around the European coastline, most of these are the result of changes in local mean sea level. The contribution from changes in storminess is currently small in most European locations and there is little evidence that any trends can be separated from long-term natural variability.

Projections: extreme sea level at the European coastline

The current research evidence suggests that projected increases in extreme sea level along the European coast during the upcoming decades will mostly be the result of mean sea level changes [v]. However, several recent studies suggest that changes in wave and storm surge climate may also play a substantial role in sea level changes during the 21st century in some regions. These studies project an increase in storm surge level for most scenarios and return periods along the northern European coastline, which can exceed 30 % of the relative sea level rise under the RCP8.5 scenario. Storm surge levels along most European coastal areas south of 50 °N showed small changes and in some regions may decline to partly offset the effect of mean sea level rise on projected extreme water levels [vi]. Sea level rise may also change extreme water levels by altering the tidal range and local wave climate. Tidal behaviour is particularly responsive in resonant areas of the Bristol Channel and the Gulf of Saint-Malo and in the south-eastern German Bight and Dutch Wadden Sea [vii].

The co-occurrence of high sea level and heavy precipitation resulting in large runoff may cause compound flooding in low-lying coastal areas. The Mediterranean coasts are at highest risk of compound flooding in the present. For example, compound flooding was the cause of the catastrophic floods in Venice in November 2019. A recent study found that climate change increases the risk of compound flooding along most parts of the European coast, including the eastern and southern coasts of the North Sea, the Norwegian coast, the west coast of Great Britain, the coast of northern France, and the eastern coast of the Black Sea [viii].

A 10 cm rise in sea level typically causes an increase by about a factor of three in the frequency of flooding to a given height. Figure 6 shows that the frequency of flooding events is estimated to increase by more than a factor of 10 in many European locations, and by a factor of more than 100 or even 1000 in some locations during the 21st century, depending on the emissions scenario [ix]. Large changes in flood frequency mean that what is an extreme event today may become the norm by the end of the century in some locations.

Coastal flooding affects people, communities and infrastructure. A recent study conducted within the ECONADAPT project has estimated the average annual losses from coastal flooding in the 17 main coastal cities in EEA member countries to increase from about EUR 1 billion in 2030 to EUR 31 billion in 2100 under the RCP8.5 scenario, in the absence of adaptation [x]. Much higher damages were identified in a recent study from the HELIX and PESETA III projects, which considers sea level rise in parallel with different scenarios of socio-economic development. In the absence of adaptation, this study projects an increase in the average annual damage from coastal flooding in Europe (EU28 and

Norway) from currently EUR 1.25 billion to a range between EUR 93 billion and EUR 961 billion by the end of the century, depending on the scenario. The annual number of people exposed is projected to rise from 102 000 to 1.52-3.65 million over the same time horizon [xi].

The potential impacts from coastal flooding can be substantially reduced by timely adaptation measures, but they are associated with significant costs [xii]. For any particular location, it is important to look in detail at the change in the height of flood defences that might be required. Where the flood frequency curve is very flat, modest increases in flood defences might be sufficient. Where the flood frequency curve is steeper, larger increases in protection height or alternative adaptation, including managed retreat, might be needed. Damage and protection cost curves for coastal floods within the 600 largest European cities are available from the RAMSES project [xiii].

www.eea.europa.eu/data-and-maps/indicators/sea-level-rise-6/assessment

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EARLY LAST INTERGLACIAL OCEAN WARMING DROVE SUBSTANTIAL ICE MASS LOSS FROM ANTARCTICA

Chris S. M. Turney et al.
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SIGNIFICANCE

Fifty years ago, it was speculated that the marine-based West Antarctic Ice Sheet is vulnerable to warming and may have melted in the past. Testing this hypothesis has proved challenging due to the difficulty of developing in situ records of ice sheet and environmental change spanning warm periods. We present a multiproxy record that implies loss of the West Antarctic Ice Sheet during the Last Interglacial (129,000 to 116,000 y ago), associated with ocean warming and the release of greenhouse gas methane from marine sediments. Our ice sheet modeling predicts that Antarctica may have contributed several meters to global sea level at this time, suggesting that this ice sheet lies close to a "tipping point" under projected warming.

ABSTRACT

The future response of the Antarctic ice sheet to rising temperatures remains highly uncertain. A useful period for assessing the sensitivity of Antarctica to warming is the Last Interglacial (LIG) (129 to 116 ky), which experienced warmer polar temperatures and higher global mean sea level (GMSL) (+6 to 9 m) relative to present day. LIG sea level cannot be fully explained by Greenland Ice Sheet melt (~2 m), ocean thermal expansion, and melting mountain glaciers (~1 m), suggesting substantial Antarctic mass loss was initiated by warming of Southern Ocean waters, resulting from a weakening Atlantic meridional overturning circulation in response to North Atlantic surface freshening. Here, we report a blue-ice record of ice sheet and environmental change from the Weddell Sea Embayment at the periphery of the marine-based West Antarctic Ice Sheet (WAIS), which is underlain by major methane hydrate reserves. Constrained by a widespread volcanic horizon and supported by ancient microbial DNA analyses, we provide evidence for substantial mass loss across the Weddell Sea Embayment during the LIG, most likely driven by ocean warming and associated with destabilization of subglacial hydrates. Ice sheet modeling supports this interpretation and suggests that millennial-scale warming of the Southern Ocean could have triggered a multimeter rise in global sea levels. Our data indicate that Antarctica is highly vulnerable to projected increases in ocean temperatures and may drive ice–climate feedbacks that further amplify warming.

The projected contribution of the Antarctic ice sheet to 21st-century global mean sea level (GMSL) ranges from negligible (1) to several meters (2, 3). Valuable insights into the response of ice sheets to warming may be gained from the Last Interglacial (LIG) (or Marine Isotope Stage [MIS] 5e in marine sediment records; 129,000 to 116,000 y before present or 129 to 116 ky) (4–9). This period experienced warmer polar temperatures and higher GMSL (+6 to 9 m, possibly up to 11 m) (4, 10–13) relative to present day, and was the most geographically widespread expression of high sea level during a previous warm period (4, 10). LIG sea level cannot be fully explained by Greenland Ice Sheet melt (~2 m) (8), ocean thermal expansion, and melting mountain glaciers (~1 m) (4), implying substantial Antarctic mass loss (3, 4, 14, 15). Half a century ago, John Mercer was the first to propose that the marine-based West Antarctic Ice Sheet (WAIS) is vulnerable to a warming atmosphere through loss of buttressing ice shelves and may have made a significant contribution to global sea level during the LIG (5–7). Recent work has further demonstrated that extensive deep, marine-based sectors of the East Antarctic Ice Sheet (EAIS) may have accelerated melting, thus contributing to higher LIG sea levels (14). While an isotopic signature of a relatively cool LIG climate preserved in the Mount Moulton blue ice field (16) may be explained by substantial WAIS mass loss (17), no direct physical evidence has yet been identified (4, 18). Temperature estimates derived from climate model simulations provide an indirect measure of change but typically suggest ~1 °C less warming than proxy-based reconstructions (4, 8, 19). When used to drive ice sheet models, these climate anomalies are not sufficient to remove the floating ice shelves that buttress ice flow from central Antarctica (20). In an attempt to bypass these problems, ice sheet models have been driven by a wide range of prescribed climate scenarios; however, these suggest widely different sensitivities dependent on model physics and parameterization (21, 22), with >2 °C (and in some instances >4 °C) ocean warming required for the loss of the WAIS, exceeding paleoclimate estimates (3, 9, 20, 23) and different sensitivities of Antarctic ice sheet sectors (18, 24, 25).

Here, we report a high-resolution record of environmental change and ice flow dynamics from the Patriot Hills Blue Ice Area (BIA), exposed in Horseshoe Valley (Ellsworth Mountains; Methods) (Fig. 1A). Horseshoe Valley is a locally sourced compound glacier system (i.e., with negligible inflow) that is buttressed by, but ultimately coalesces with, the Institute Ice Stream via the Horseshoe Valley Trough, making the area sensitive to dynamic ice sheet changes across the broader Weddell Sea Embayment (WSE) (26). Due to strong prevailing katabatic airflow, an extensive BIA (more than 1,150 m across) has formed to the leeward side of the Patriot Hills, where ancient ice is drawn up from depth within Horseshoe Valley (Fig. 1E). Regional airborne and detailed local ground-penetrating radar (GPR) surveys show a remarkably coherent series of dipping (24 to 45°) layers, broken by two discontinuities, which represent isochrons across the Patriot Hills BIA, extending thousands of meters into Horseshoe Valley. A "horizontal ice core" across the BIA spans the time intervals 0 to 80 ky and 130 to 134 ky (Methods and SI Appendix, Fig. S5) constrained by analysis of trace gases and geochemically identified volcanic layers exposed across the transect, which have been Bayesian age modeled against the recently compiled continuous 156-ky global greenhouse gas time series (CO_2, CH_4, and N_2O) (27) on the AICC2012 age scale (28) (Fig. 1B and Methods). The record is located 50 km inland from the modern grounding line of the Filchner–Ronne Ice Shelf in the WSE (29) and close to the Rutford Ice Stream, one of the largest methane hydrate reserves identified in Antarctica [total organic carbon estimated to be 21,000 Gt (30), equivalent to ~2,000 y of the current carbon emission rate of 10 GtC/year (https://www.co2.earth/global-co2-emissions)]. Today, precipitation at the site is delivered via storms originating from the South Atlantic or Weddell Sea (31). Crucially, the Ellsworth Mountains also lie in a sector of the continent that is highly responsive to isostatic rebound under a scenario of substantial WAIS mass loss, potentially preserving ice from around the time of the LIG in small valley glaciers and higher ground areas (32).

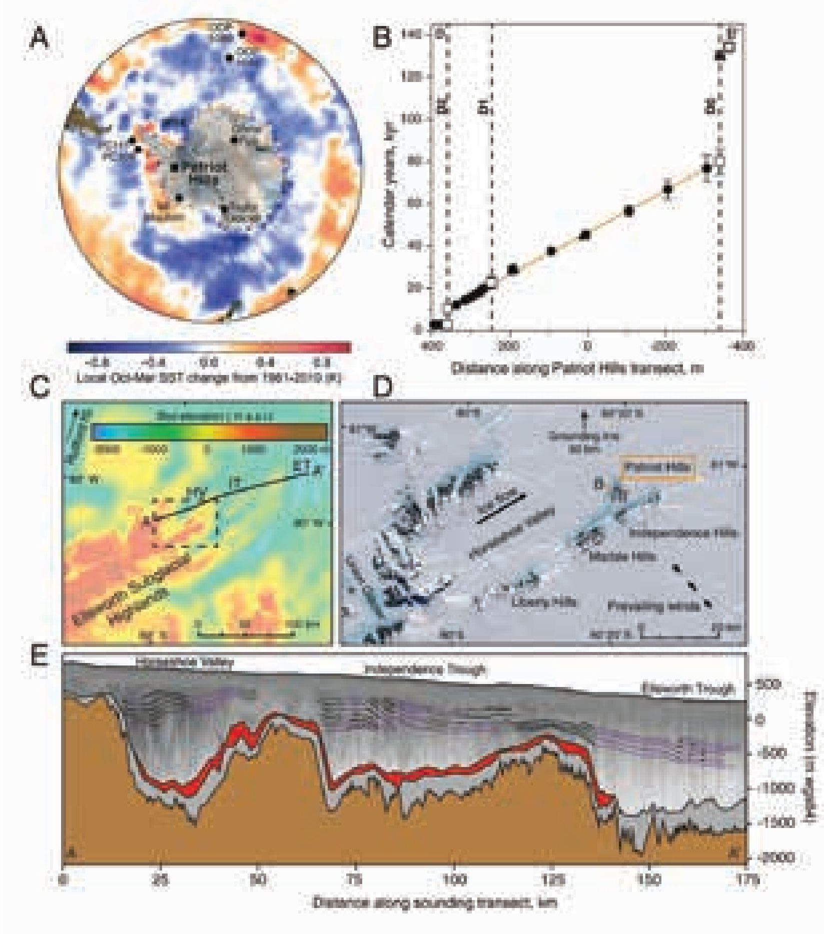

Fig. 1.
Location and age profile of the Patriot Hills BIA. (A) Location of Antarctic ice and marine records discussed in this study and austral spring–summer (October to March) SST trends (over the period 1981 to 2010; HadISST data). (B) Trace gas (circles), tephra (triangles), and boundary (square) age solutions for surface ice along transect B–B' relative to an arbitrary datum along the transect (displayed in D). The dashed lines denote unconformities D0–D2 at their surface expression. (C) Basal topography of the Ellsworth Subglacial Highlands (West Antarctica) with the locations of airborne radio-echo sounding transect A–A' (displayed in E) and Rutford Ice Stream (IS) (29). The Horseshoe Valley, Independence, and Ellsworth troughs are given by the initials HV, IT, and ET, respectively. (D) The location of Patriot Hills in Horseshoe Valley (LIMA background image) with the BIA climate line (marked by transect B–B'), dominant ice flow direction, and distance to grounding line. (E) Airborne radio-echo sounding cross-section of ice within Horseshoe Valley, Independence, and Ellsworth troughs (modified from ref. 29). Digitization highlights basal topography (brown), lower basal ice unit (gray), and upper basal ice unit (red) as well as internal stratigraphic features (black for observed, dashed for inferred, and purple for best estimate).

THE PATRIOT HILLS RECORD

The isotopic series of δD across the Patriot Hills BIA exhibits a coherent record of relatively low values between 18 and 80 ky, consistent with a glacial-age sequence (Fig. 2E). Below these layers and at the periphery of zones of higher ice flow (29), we find an older unit of ice exposed at the surface expressed by a step change to enriched (interglacial) isotopic values (Fig. 2E and SI Appendix, Fig. S7), implying proximal warmer conditions and reduced sea ice extent (33). Importantly, we identify a distinct tephra horizon near the boundary of this older unit of ice, which, based on major and trace element geochemical fingerprinting (Fig. 3 and SI Appendix, Fig. S11), is correlated to a volcanic ash from the penultimate deglaciation (Termination II) referred to as Tephra B in marine sediments on the West Antarctic continental margin (34) and identified at 1,785.14-m depth in the Dome Fuji ice core, where it is dated to 130.7 ± 1.8 ky (AICC2012 timescale) (28, 33, 34). The start of the oldest section of the sequence is dated here to 134.1 ± 2.2 ky, consistent with modeling studies, airborne radio-echo sounding lines, and GPR profiles, which imply older ice exists at depth in the Ellsworth Mountains (29, 32) (Fig. 1 B–E).

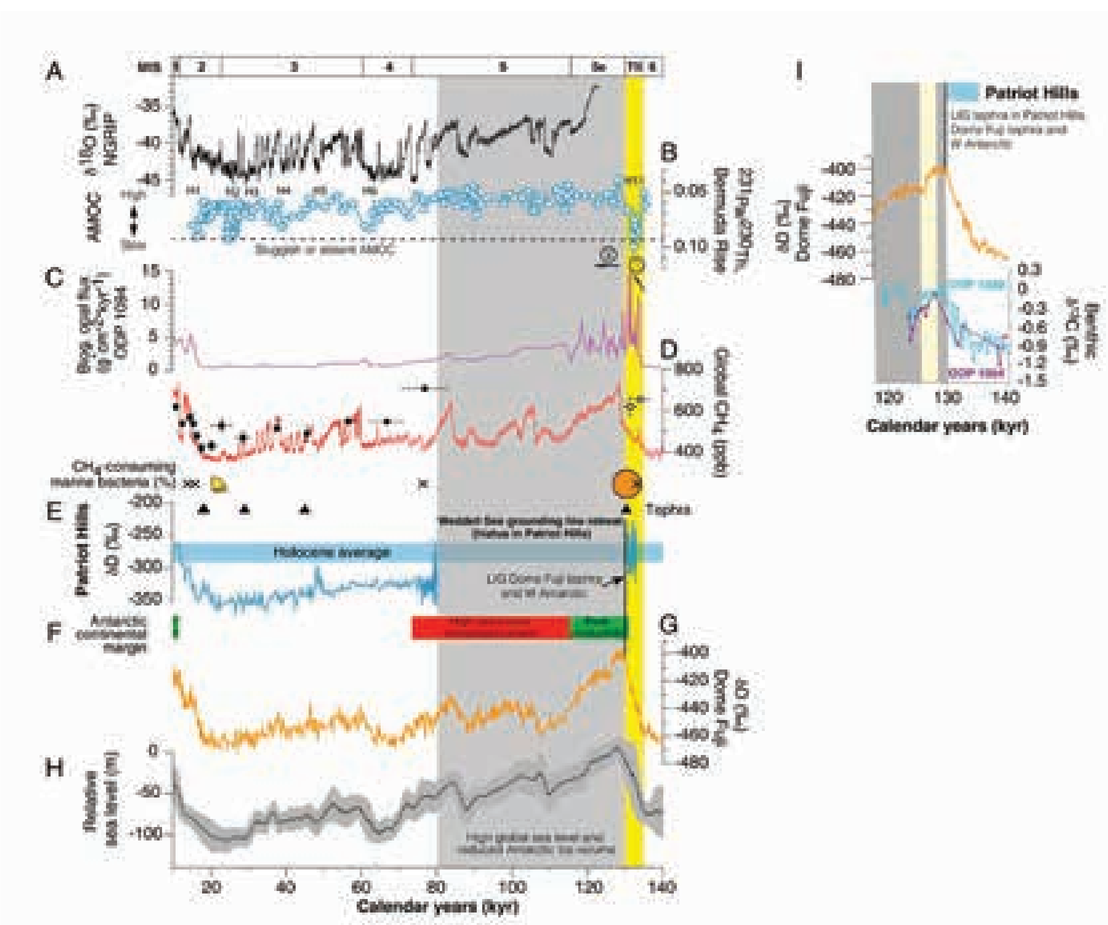

Fig. 2.
Climate, ocean circulation, and sea level changes over the past 140 ky. (A) $\delta^{18}O$ record from the North Greenland (NGRIP) ice core (106, 107). (B) Bermuda Rise $^{231}Pa/^{230}Th$ data (reversed axis; 1σ uncertainty) with dashed horizontal line denoting production ratio of 0.093 marking sluggish/absent AMOC (42). Selected North Atlantic Heinrich (H) events and reduced AMOC shown. (C) Biogenic opal flux from ODP Site 1094 (53.2°S) as a measure of wind-driven upwelling in the Southern Ocean (45). (D) Comparison between the recently compiled global atmospheric methane time series (red line; 2σ envelope) (27) with the methane record from the West Antarctic Patriot Hills (black circles with 1σ uncertainty; open circles mark anomalously high-concentration data excluded from age model; Methods). (E) The Patriot Hills record. Pie chart representation (circle and segments) of percentage methane-utilizing bacteria in 16S rRNA samples from Patriot Hills; crosses denote absence of these bacteria (Methods). Triangles denote the presence of geochemically identified tephra layers in the Patriot Hills transect, with δD (and mean Holocene; blue envelope 1σ) values. The gray shading denotes the timing of the surface elevation change across the WSE as indicated by the hiatus in the Patriot Hills sequence and inferred substantial Antarctic ice mass loss, consistent with the reported divergence of the isotopic signal observed between the horizontal Mount Moulton ice core record from the WAIS and East Antarctic ice cores (16, 17, 33), and peak global sea level (10). (F) Temporal changes in ocean productivity with peak productivity (PP) (green shading) during interglacials and subsequent enhanced content of calcareous microfossils in Antarctic continental margin sediments (red shading) (34). The dashed black line shows position of tephra identified in the Patriot Hills (−340 m), Dome Fuji (1,785.14 m), and Tephra B in marine sediments from the West Antarctic continental margin. (G) East Antarctic Dome Fuji $\delta^{18}O$ record (28, 33). (H) Reconstructed relative sea level curve with 2σ envelope (10). The yellow shading highlights the timing of iceberg-rafted Heinrich debris event 11 (H11), when large amounts of iceberg-rafted debris were deposited in the North Atlantic (43) and the $^{231}Pa/^{230}Th$ ratio on Bermuda Rise shifted toward the production ratio of 0.093, representative of sluggish or absent AMOC (42); the circled numbers 1 and 2 denote enhanced upwelling-induced warming in the Southern Ocean and Antarctic ice mass loss, respectively. (I) Close-up of Termination II and the onset of the LIG highlighting the high-precision correlation enabled by the Patriot Hills tephra (∼130 ky) and the carbon isotopic composition of benthic foraminifera from ODP Site 1089 and ODP Site 1094 (46) (Fig. 1A). The cream shading highlights the inferred collapse of the AABW reported from ODP 1094 (46). Dashed vertical line denotes LIG tephra in Patriot Hills, Dome Fuji, and West Antarctic continental margin.

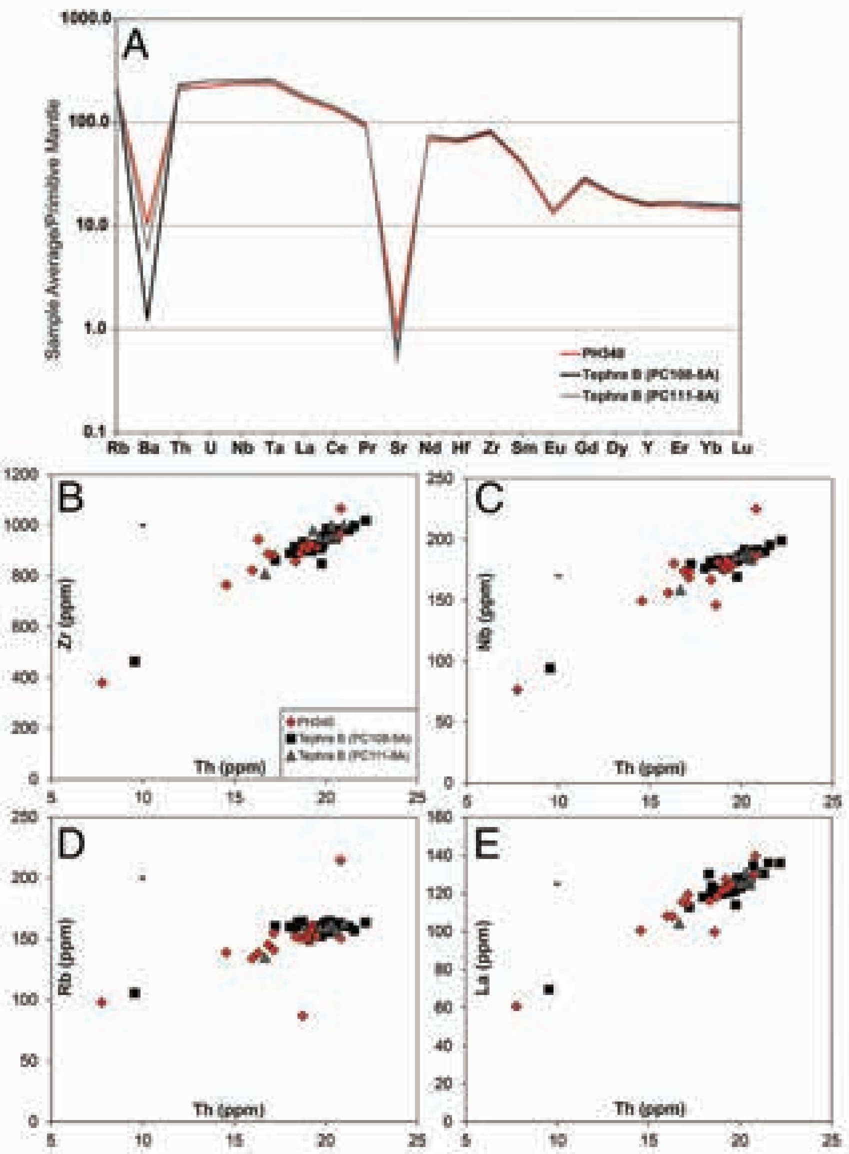

Fig. 3.

Average trace element concentrations of Patriot Hills tephra at −340 m and Tephra B from marine sediment cores PC108 (4.65-m depth) and PC111 (6.86-m depth) (34) normalized to Primitive Mantle (108). (A) Biplots show comparison between selected trace element concentrations of the tephra in the different sequences. Error bars on plots show 2σ of replicate analyses of MPI-DING StHs6/80-G (87), but errors are typically smaller than the data symbols (B–E).

The combined tephra and trace gas analyses suggest a ~50-ky hiatus after Termination II (130.1 ± 1.8 ky). Radio-echo sounding surveys across the WSE have identified a large subglacial basin comprising landforms reflecting restricted, dynamic, marine-proximal alpine glaciation, with hanging tributary valleys feeding an overdeepened Ellsworth Trough (35). The extensive nature of the subglacial features implies substantial and repeated mass loss of the marine sections of the WAIS (presumably through the Pleistocene), with the ice margin some 200 km inland of present day (35). However, the timing of most recent retreat is currently unknown. While previous surface exposure dating in the region has suggested that the WAIS contribution to global sea level rise during warmer periods was limited to 3.3 m above present (36), relatively short-duration interglacial periods may have resulted in near-complete deglaciation (35). Previous work has interpreted erosional features D1 and D2 in the Patriot Hills BIA to be a consequence of extensive ice surface lowering in Horseshoe Valley (up to ~500 m since the Last Glacial Maximum, 21 ky) and more exposure of katabatic-enhancing nunataks, resulting in increased wind scour (26, 37). While this scenario may explain unconformity D0, previous work has demonstrated Horseshoe Valley and the wider WSE to be highly sensitive to periods of ice stream advance or retreat in the last glacial cycle and Holocene, with dramatic reductions in surface elevation (26, 37–39), changes that may result in more than just increased wind scour. Importantly, the head of Horseshoe Valley is an overdeepened trough (down to ~2,000 m below sea level), while toward the mouth of the valley, a subglacial ridge is found at ~200 m below current sea level with an ice thickness of some 750 m (Methods and SI Appendix, Fig. S3), allowing the isolation and stagnation of ice in Horseshoe Valley over multiple millennia. Furthermore, glaciological investigations assessing the impact of ice shelf loss on glaciers along the Antarctic Peninsula provide important insights into the preservation of ice, albeit on a smaller scale. The 2002 Larsen B ice shelf collapse led to many of the tributary glaciers abruptly changing from a convex to a concave profile (cross-section) (40), with relict ice left isolated on the upper flanks of the valleys (41). These scenarios are consistent with extensive grounding line retreat across the inner shelf of the Weddell Sea and associated substantial ice loss across the wider WSE (29).

The ice at Patriot Hills therefore appears to preserve a record of glacier flow in Horseshoe Valley up to the moment when the Filcher–Ronne Ice Shelf collapsed, after which the sequence remained isolated due to regional ice flow reconfiguration for multiple millennia; a situation that persisted until the ice surface had risen sufficiently to enable the regional ice flow to recover sometime during late MIS 5. We cannot, however, discount the possibility that there were one or more cycles of ice mass gain and loss through MIS 5. The presence of a discrete older ice unit along the flanks of the Ellsworth Mountains (29) (Fig. 1 and SI Appendix, Fig. S2) and the subsequent inferred highly variable climate and/or sea ice extent across the wider WSE (SI Appendix, Figs. S7 and S13) imply the preservation of ice from MIS 6/5 (Termination II) and 5/4 transitions in Horseshoe Valley. Our data provide evidence for substantial mass loss across the WSE during the LIG.

OCEAN WARMING

What could be the cause of this ice loss in the South Atlantic sector of the Southern Ocean? Recent work has proposed that the iceberg-rafted Heinrich 11 event between 135 and 130 ky (during Termination II) may have significantly reduced North Atlantic Deep Water (NADW) formation and shut down the Atlantic meridional overturning circulation (AMOC) (42), resulting in net heat accumulation in the Southern Hemisphere (the bipolar seesaw pattern of northern cooling and southern warming) (43, 44) (Fig. 4A). Under this scenario, surface cooling during Heinrich 11 increased the northern latitudinal temperature gradient and caused a southward migration of the Intertropical Convergence Zone and midlatitude Southern Hemisphere westerly airflow (14, 45). Importantly, Heinrich 11 was probably one of the largest of the iceberg-rafting events over the last 140 ky (including H-1 and H-2) and during a time of likely weakened AMOC (42). In the Southern Ocean, the associated northward Ekman transport of cool surface waters (something akin to today; Fig. 1A) was likely compensated by increased delivery of relatively warm and nutrient-rich Circumpolar Deep Water (CDW) toward the Antarctic margin (14, 34, 43, 45, 46), potentially leading to enhanced thermal erosion of ice at exposed grounding lines (43, 47). This interpretation is supported by the enriched benthic foraminifera ^{13}C values into the LIG (46), a proxy for the influence of NADW on CDW in the south, implying northern (warmer) waters were reaching far south for much of this period (and a cause of persistent loss of ice volume) (Fig. 2I). The unambiguous precise correlation between the Patriot Hills ice and West Antarctic marine records (34) afforded by the Termination II tephra demonstrates that the warming recorded in the BIA is coincident with a major, well-documented peak in marine temperatures and productivity around the Antarctic continent and in the Southern Ocean (34, 45, 46) (Fig. 2). The subsequent delivery of large volumes of associated freshwater into the Southern Ocean during the LIG would have reduced Antarctic Bottom Water (AABW) production (46), resulting in increased deepwater formation in the North Atlantic (43, 48, 49) (Fig. 4C). Recent modeling results suggest that increased heat transport beneath the ice shelves can drive extensive grounding-line retreat, triggering substantial drawdown of the Antarctic ice sheet (2, 14, 20) (Fig. 4B). Of concern, warming of the ocean cavity in the WSE is projected to increase during the 21st century (50).

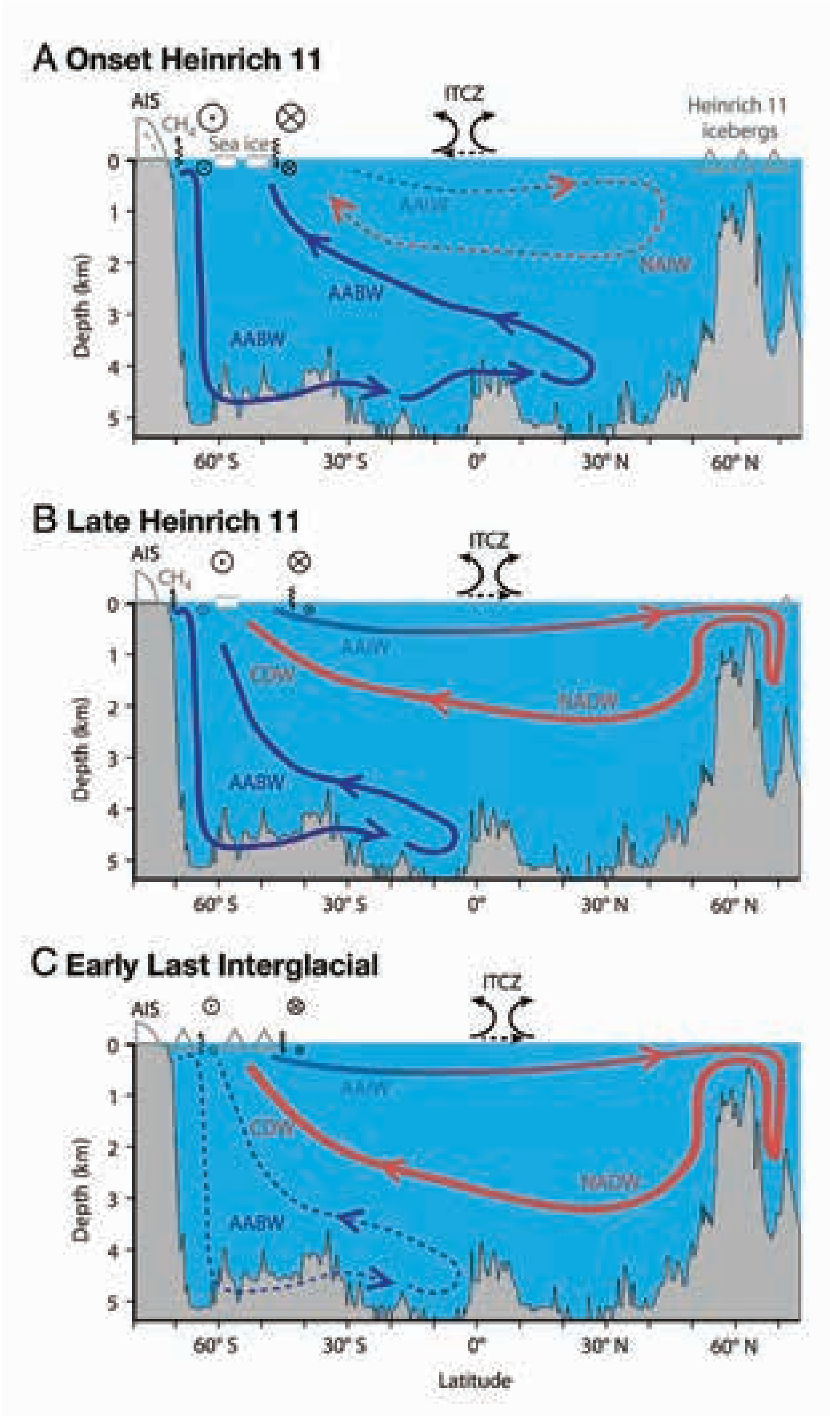

Fig. 4.
Ocean–atmospheric interactions during Termination II and the LIG. Panels show changing Atlantic meridional overturning circulation (AMOC) in response to iceberg discharge (A and B) in the North Atlantic (Heinrich event 11) during Termination II and (C) from the Antarctic Ice Sheet (AIS) during the LIG, with inferred shifts in atmospheric circulation including midlatitude Southern Hemisphere westerly (crossed circle) airflow and Intertropical Convergence Zone (ITCZ) (14, 43, 45, 46, 48). The vertical arrows denote CH4 and heat flux associated with Antarctic coastal easterly (dot in circle) and westerly (crossed circle) airflow (30, 47). AABW, AAIW, CDW, NAIW, and NADW define Antarctic Bottom Water, Antarctic Intermediate Water, Circumpolar Deep Water, North Atlantic Intermediate Water, and North Atlantic Deep Water, respectively.

With Southern Ocean warming and concurrent ice sheet retreat, the large methane reservoirs in Antarctic sedimentary basins (e.g., Rutford Ice Stream) could have become vulnerable to release (30) and may have contributed to elevated atmospheric levels through the LIG (8, 27) (Fig. 2D). High-latitude open water and sea ice are rich in microbial communities, components of which may be collected by passing storms and delivered onto the ice sheet (e.g., prokaryotes, DNA), offering insights into offshore environmental processes (51, 52). To investigate environmental changes prior to and after the ice sheet reconfiguration recorded in the Patriot Hills BIA, we applied an established ancient DNA methodology and sequencing to provide a description of ancient microbial species preserved within the ice (Methods). Methane-utilizing microorganisms were found in three samples along the Patriot Hills transect and were absent from other samples on the transect and laboratory controls. While such microbes are not obligate methylotrophs and can be present in nonmethane-dominated environments (53), they would be expected to be at very different abundances to what we find. The most striking feature of the Patriot Hills BIA genetic record was detected immediately prior to inferred ice loss, where Methyloversatilis microbes dominated the detectable microbial diversity (~130 ky) (Fig. 2E and SI Appendix, Fig. S15). Methyloversatilis was only found in high abundance in this sample (with trace amounts identified at ~22 ky). Crucially, Methyloversatilis are facultative methylotrophs and live on single and multicarbon sources (54), consistent with elevated levels of CH_4 and active methane oxidation by Methyloversatilis or other methanotrophic taxa in marine sediments or in the water column during the end of Termination II (SI Appendix). More work is needed to explore the potential for microbial methane utilization in this unique environment.

ANTARCTIC ICE SHEET MODELING

The inferred substantial mass loss across the WSE implies a major role for ocean warming during Termination II and the LIG. To provide a framework for interpreting ice sheet dynamics around the Patriot Hills and across Antarctica, we present a series of temperature sensitivity experiments using the Parallel Ice Sheet Model, version 0.6.3 (Fig. 5) (2). We report here nine different simulations that capture a range of ocean and atmospheric warming scenarios (0° to 3 °C). Importantly, the most comprehensive published high-latitude (≥40° S) network of quantified sea surface temperature (SST) estimates suggests an early LIG (~130 ky) warming of 1.6 ± 0.9 °C relative to present day (9, 23), providing an upper limit on the sensitivity of the Antarctic ice sheet to ocean temperatures. The pattern of circum-Antarctic ocean warming during this time period is not well established so we assume a spatially uniform warming pattern relative to present day temperatures. Our model time series illustrates that the majority of ice loss takes place within the first two millennia, depending on the magnitude of the forcing (Fig. 5 and Table 1). This corresponds to the time period of inferred loss of marine-based sectors of the ice sheet (Fig. 2), primarily in West Antarctica. In contrast to some whole-continent models, our simulations do not include mechanisms by which a grounded ice cliff may collapse (3), a process that produces considerably faster and greater ice margin retreat than reported here.

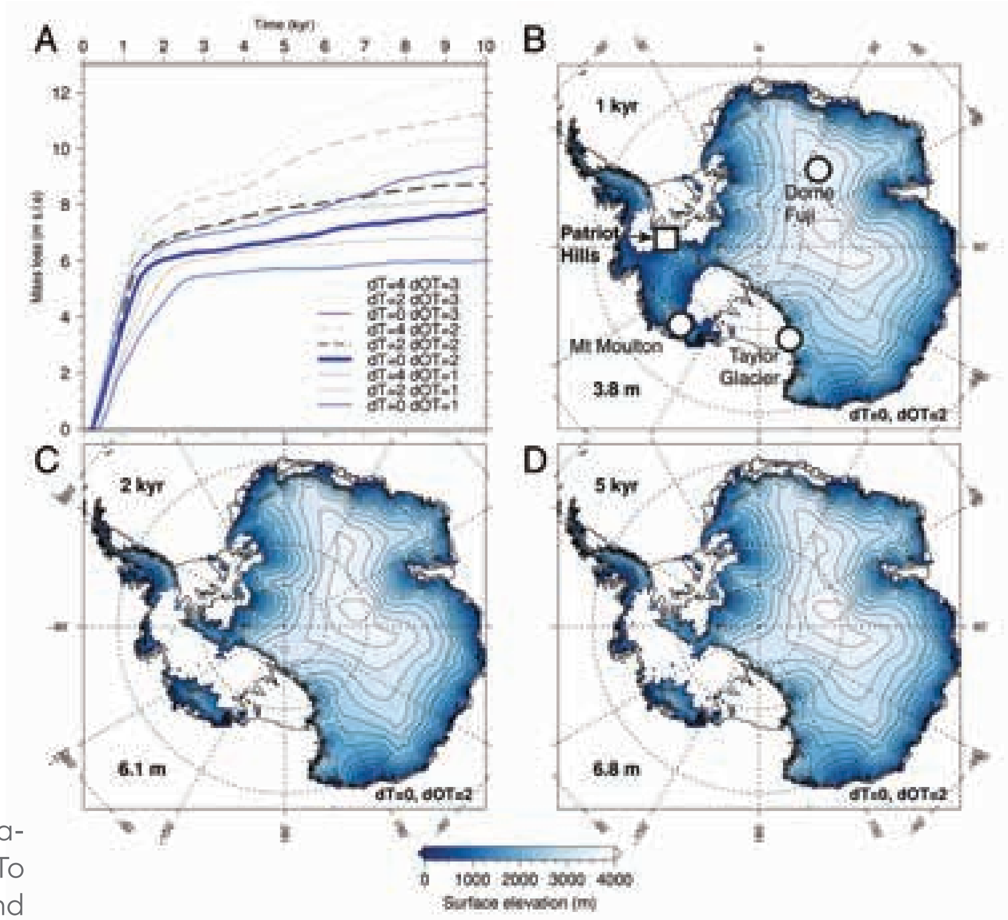

Fig. 5.
Modeled Antarctic ice sheet evolution under idealized forcing scenarios consistent with range of inferred LIG temperatures. (A) Sea level equivalent mass loss for ice sheet simulations forced by a range of air and ocean temperature anomalies relative to present day. “dT” and “dOT” describe atmospheric and ocean temperature anomalies, respectively. B–D show Antarctic Ice Sheet extent and elevation with 2 °C warmer ocean temperatures over time intervals of 1, 2, and 5 ky, respectively (with no atmospheric warming); equivalent sea level contribution is given in the Bottom Left corner of each panel. Locations of Patriot Hills (Ellsworth Mountains, WAIS) and ice core records discussed in this study are shown in B. Inset box in B outlines region shown in Fig. 6.

Table 1.

Sea level equivalent mass loss (meters) for Antarctic ice sheet simulations forced over 10,000 y by range of annual air and ocean temperature anomalies relative to present day

	1,000 y	2,000 y	5,000 y	10,000 y
1 °C SST warming				
0 °C air	2.2	4.5	5.7	6.0
2 °C air	2.5	5.5	6.5	6.8
4 °C air	2.9	6.5	7.7	8.2
2 °C SST warming				
0 °C air	3.8	6.1	6.8	7.8
2 °C air	4.2	6.7	7.9	8.8
4 °C air	4.8	7.6	9.4	11.2
3 °C SST warming				
0 °C air	4.7	6.6	7.6	9.4
2 °C air	5.4	7.1	8.5	10.4
4 °C air	5.9	8.1	10.3	12.5

Note: The temperatures applied were applied linearly over the first 1,000 y.

For the 2 °C warmer than present day ocean temperature scenario (comparable to reconstructed estimates) (9, 23), with no additional atmospheric warming, our model predicts a contribution to GMSL rise of 3.8 m in the first millennium of forcing (Fig. 5B). The loss of the Filchner–Ronne Ice Shelf within 200 y of warming triggers a nonlinear response by removing the buttressing force that stabilizes grounded ice across large parts of the WSE and the EAIS (most notably the Recovery Basin) (Fig. 6 and SI Appendix, Fig. S17). Ongoing slower ice loss subsequently occurs around the margins of East Antarctica, producing a sustained contribution to sea level rise. Even for relatively cool ocean-forced runs, we find the shelves collapse quickly between the 200-y intervals (SI Appendix, Fig. S18). Indeed, during the warmer ocean model runs, the shelves disappear too quickly to observe the relevant processes on the timescale covered by the snapshots. For instance, under the scenario of 2 °C linear warming, the ice shelves disappear within 600 y of forcing (when temperatures reached between +0.4 and +0.8 °C). Other modeling studies using a range of different setups have reported similar rapid losses of the ice shelves during the onset of the LIG (24, 25). Our results are therefore consistent with an increasing body of evidence that the stability of Antarctic ice shelves is vulnerable to a relatively low temperature threshold (2, 24, 25).

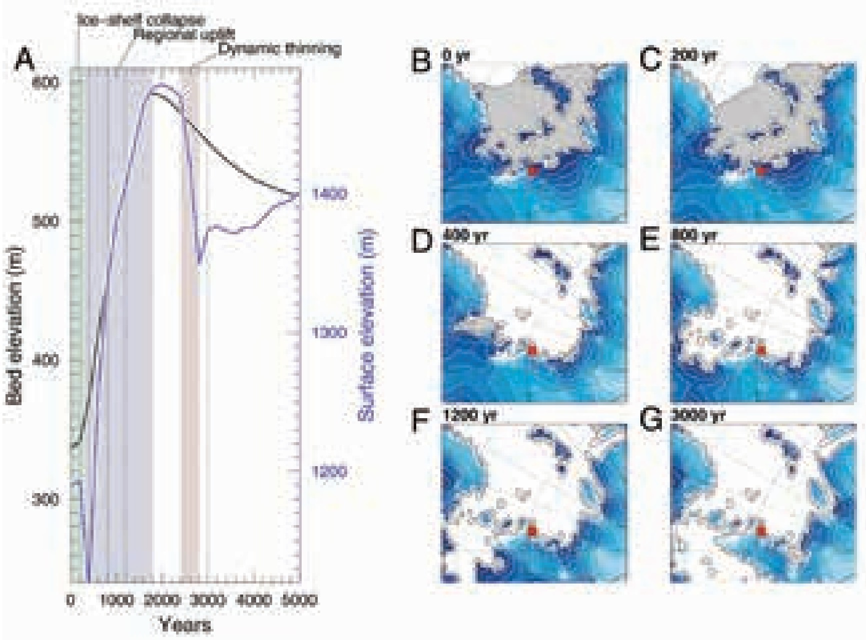

Fig. 6.
Bed (black line) and surface (blue) elevation changes at Patriot Hills (Ellsworth Mountains, WAIS) in response to 2 °C warmer ocean temperatures over a time interval of 5 ky (with no atmospheric warming) (A). Bed (black line) and surface (blue) elevation changes vs. time, with phases of the prevalence of particular processes, such as ice shelf collapse (mint shaded), regional uplift (gray shaded), and dynamic thinning (light-brown shaded), highlighted. (B–G) Selected time slices corresponding to dashed lines in A showing ice shelf extent and ice sheet elevation in the Weddell Sea Embayment (WSE) over the first 3 ky. Location of Patriot Hills is marked by the red square; the gray shaded areas are ice shelf covered, while the white areas are free of both grounded and floating glacial ice.

Recent work has suggested that the Ellsworth Mountains would have experienced a relatively large positive isostatic adjustment (>200 m) accompanying the loss of the WAIS (24, 25, 32), although the model outputs may be underestimated (25). To investigate how an evolving ice sheet geometry would manifest across the wider region, we extracted local ice surface and bed elevations for the WSE from the model simulation that uses a preindustrial ice sheet configuration with 2 °C ocean warming and no atmospheric warming. Fig. 6 A–G illustrates the sequence of events that take place as the ice sheet evolves. First, loss of the Filchner–Ronne Ice Shelf in the Weddell Sea triggers a nonlinear response, removing the buttressing force that stabilizes grounded ice across large parts of the WSE and the EAIS (most notably the Recovery Basin) (55). The loss of back-stress allows for an acceleration of grounded ice and a rapid but short-lived thinning episode (32). At the Patriot Hills, bedrock uplift of ~30 m over this 0.2-ky period is outpaced by a surface lowering of ~75 m, implying a net ice sheet thinning of around 105 m. Subsequently, regional-scale isostatic uplift elevates both the bed topography (~250 m) and ice sheet surface (~350 m) relative to the initial configuration. The difference between these two values reflects positive net mass balance of the ice sheet here (~0.055 m/y). After around 2.5 ky, renewed dynamic thinning of the ice sheet in the Patriot Hills leads to a rapid thinning and lowering of the ice sheet surface, at a rate exceeding regional-scale bedrock subsidence (120 m over 0.4 ky, or 0.3 m/y, compared to ~70 m over 3.2 ky, or 0.022 m/y, respectively) (Fig. 6). For the 1 and 3 °C warming scenarios, similar spatial losses are modeled, with GMSL rises of 2.2 and 4.7 m for the first millennium, respectively (Table 1). Atmospheric warming of the magnitude suggested by Antarctic cores (>4 °C) (16, 17, 56–58) adds an additional meter of equivalent global sea level within the first millennium (SI Appendix, Fig. S19).

Previous work has highlighted the sensitivities of the Ronne–Filchner and Ross ice shelves to warming under a range of model setups (3, 18). Recently published transient ice sheet model simulations covering the last glacial–interglacial cycle have investigated a range of scenarios encompassing different geothermal heat fluxes, ice shelf calving heights, mantle viscosity values, temperature and sea level forcing scenarios, etc. (24, 25). Importantly, these studies recognize the loss of the WAIS forced by warming across what is relatively narrow LIG temperature peak, with a maximum bedrock elevation of ~400 to 650 m, and surface elevation changes of >1,500 m, larger than that reported here. However, it is important to note that these relatively large estimates are likely influenced by the glacial loading that was experienced during MIS 6.

The Patriot Hills record is consistent with basin-scale mass loss early in the LIG (15, 32) as a consequence of regional ice dynamic changes and isostatically driven isolation of Horseshoe Valley from sustained ocean forcing. While some modeling studies have argued the loss of the Filchner–Ronne Ice Shelf does not display a strong marine ice sheet instability feedback (59) and that isostatically driven rebound may halt ice retreat (18), our results suggest otherwise. Indeed, recent work has proposed that if mass loss comparable to recent decades is maintained for as little as 60 y, the WAIS could be irrevocably destabilized over subsequent millennia through the collapse in the Amundsen Sea sector, overcoming any isostatically driven rebound (60). Future work will be required to undertake large ensembles of high-resolution ice sheet model simulations that capture the full range of ice dynamics, ice–ocean–atmosphere coupling, MIS 6 ice sheet configuration, and spatial and temporal temperature evolution across this period to fully capture the uncertainty associated with LIG mass loss. However, we consider our ice sheet modeling simulations to be comparable to previous studies (24, 25) in the magnitude of rate of change and mass loss, and support the interpretation of the Patriot Hill BIA record. Our results suggest substantial ice sheet mass loss and flow reconfiguration in response to ocean warming, outpacing any bedrock rebound that might have stabilized the ice sheet (Fig. 6). Furthermore, marine-based ice sheets are particularly vulnerable to hysteresis effects (61), which could explain the 50-ky hiatus in the Patriot Hills blue ice record, particularly given the relatively low modeled temperature threshold (0.5 to 0.7 °C ocean warming) for ice shelf loss (SI Appendix, Fig. S17).

The evidence for substantial mass loss from Antarctica in the early LIG has important implications for the future (4, 62). Our field-based reconstruction and modeling results support a growing body of evidence that the Antarctic ice sheet is highly sensitive to ocean temperatures. Driven by enhanced basal melt through increased heat transport into cavities beneath the ice shelves (2, 47), this process is projected to increase with a weakening AMOC during the 21st century (50, 63–65), which may lead to other positive feedbacks such as destabilization of methane hydrate reserves (30).

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Christopher J. Fogwill, Nicholas R. Golledge, Nicholas P. McKay, Erik van Sebille, Richard T. Jones, David Etheridge, Mauro Rubino, David P. Thornton, Siwan M. Davies, Christopher Bronk Ramsey, Zoë A. Thomas, Michael I. Bird, Niels C. Munksgaard, Mika Kohno, John Woodward, Kate Winter, Laura S. Weyrich, Camilla M. Rootes, Helen Millman, Paul G. Albert, Andres Rivera, Tas van Ommen, Mark Curran, Andrew Moy, Stefan Rahmstorf, Kenji Kawamura, Claus-Dieter Hillenbrand, Michael E. Weber, Christina J. Manning, Jennifer Young, and Alan Cooper

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OCEAN RISK AND THE INSURANCE INDUSTRY

Lead author: Falk Niehörster
Contributing author: Richard J. Murnane
Oceanrisksummit

EXECUTIVE SUMMARY

A diverse array of ocean-related phenomena occur today andmore are expected to emerge in the future as ocean risk evolves in response to the observed and accelerating warming, acidification, oxygen depletion and other man-made threats to the ocean. This report aims to raise awareness of potential insurance industry-related impacts of these interconnected threats and the important role the industry can play in managing emerging ocean risks, seizing new opportunities, and helping to make the industry, the global economy, and society more resilient and responsive to the consequences of a rapidly changing ocean.

The major findings of the report are:

The ocean and the many ecosystem services it provides are key natural resources for the 'blue economy'. The rise of the blue economy is being driven by rapid growth of marine transport and tourism, industrial use of coastal and seashore areas and extraction of resources from the ocean and marine environments. In the year 2010, the size of the worldwide blue economy hit USD1.5 trillion in value added, or approximately 2.5% of world gross value added ("GVA"). With a gross marine product of at least USD24 trillion, the blue economy today would rank as the world's seventh biggest economy. The blue economy's projected growth rate of around 5% per annum could double its GVA by 2030. Since insurance penetration covers only minor parts of today's blue economy this presents a significant business opportunity for the insurance industry.

The ocean and the marine ecosystems that support the blue economy are shifting. The ocean is showing a sustained and accelerating upward trend in sea-surface temperature, ocean heat content and sea levels in almost all ocean basins and, at the same time, ocean acidity is increasing and oxygen concentrations are decreasing. In response, there are first indications of shifts in large-scale ocean-atmosphere modes of variability (e.g. El Niño) and major currents of the ocean (e.g. Atlantic Meridional Overturning Circulation), as well as changes in almost all marine ecosystems. Marked biological manifestations of the impacts from ocean warming and other anthropogenic stressors have taken the form of ecological regime shifts.

The changes in the ocean have the potential to trigger catastrophic consequences, which can be termed 'ocean risk'. Ocean risk is a function of exposure and vulnerabilities to hazards arising from ocean change, which may or may not be avoided, reduced or adapted to through pre-emptive action. Ocean risk encompasses well-known phenomena, such as storm surge from tropical and extra-tropical cyclones, or other extreme weather events strongly influenced by oceanic modes of variability. But ocean risk also encompasses lesser-known and potentially surprising phenomena that are associated with the observed regime shifts in marine ecosystems such as outbreaks of marine-mediated diseases or economic shocks and/or food security crises due to sudden changes in marine ecosystems.

The impact of ocean risk on the insurance industry has three main components: 1) increasing loss potentials for many property and casualty (P&C) lines due to sea-level rise, increasing precipitation extremes and changing ocean-atmosphere modes (e.g. El Niño); 2) changing loss potential in various insurance lines such as health, aquafarming, political risk or product liability; and 3) an implied asset risk that could potentially strand entire regions and global industries, leading to direct and indirect impacts on investment strategies and liabilities.

Quantifying the financial impacts and managing emerging ocean risk requires new risk modelling solutions that go beyond better representation of the effects of ocean warming and climate change into traditional risk models of extreme weather events. In addition, there is a need for risk models that quantify the probability and economic impact of losing marine ecosystem services. Such ecosystem risk models would have the potential to unlock new insurance markets in the space spanned by ocean risk, international development programs and the blue economy.

Governments, supported by international organizations, could build public-private partnerships with stakeholders from the blue economy and establish independent ecosystem resilience funds designed to monitor and protect an ecosystem at risk and then to restore it after damaging events have occurred. For such restorations, insurance pay-outs would be used to activate post-event programs that guarantee the quickest possible restoration of the ecosystem itself, and hence its ecosystem services, to the economy and people of the country. This would effectively build resilience in countries most exposed to ocean risk and be an adaptation strategy using active management of marine ecosystems.

An eagle ray passes over a healthy reef system, Belize. © The Ocean Agency/XL Catlin Seaview Survey

Business opportunities for the insurance industry will arise in the form of new insurance solutions to transfer ocean risk. In addition to insurance products for loss of ecosystem services, there is an immediate demand for more standard products based on physical assets. The insurance industry could bundle the associated lines of business to allow for a strategic approach to growing business and coverages in the associated markets of ocean risk.

The insurance industry should acknowledge the changes in ocean risk associated with the warming of the ocean and the resulting changes in ecosystems, sea level, climate and extreme events. In response to these changes, companies should review and, if need be, revise their current business strategies. A prudent course of action could be to update a company's risk management practices. At the same time, however, changes in ocean risk will provide new business opportunities both for individual companies and the entire insurance industry. Novel insurance solutions and the existing capacity of the industry can be leveraged to manage ocean risks

INTRODUCTION: WHY IS OCEAN WARMING RELEVANT TO THE INSURANCE INDUSTRY?

The ocean is an important component of our increasingly connected global economy. It provides food and energy and enables efficient transport between markets that support complex global supply chains. Utilizing ocean resources, extracting energy and shipping goods across the ocean are not without risk. In fact, the insurance industry was founded on the need for relief from the risk associated with global marine transport[1]. Today, marine insurance covers a variety of risks, including cargo, hull and liability, and global marine underwriting premiums for 2016 amounted to almost USD30 billion[2]. As shipping volumes increase, larger vessels are being built, and with more ships at sea, the insurance industry is updating its risk management approaches for marine lines [Lloyds, 2018]. However, it is important to understand that ocean-related risk extends far beyond marine insurance.

An array of ocean-related factors are affecting insurers today and even more will emerge in the future as ocean risk evolves in response to the observed and accelerated warming of the ocean. Following the approach of Laffoley and Baxter (2018), 'ocean risk' in this report is defined as a function of exposure and vulnerabilities to hazards arising from ocean change, which may or may not be avoided, reduced or adapted to through preemptive action [Laffoley & Baxter, 2018]. Ocean risk encompasses well-known phenomena, such as storm surge from tropical and extra-tropical cyclones, or other extreme weather events strongly influenced by El Niño and other oceanic modes of variability. But ocean risk also encompasses lesserknown and potentially surprising phenomena that are associated with the observed regime shifts in marine ecosystems. For example, there is a growing potential for sudden economic shocks and/or food security crises due to changes in marine ecosystems – large blooms of toxic algae or sea-born viruses that disrupt marine food webs can affect human health and cause the loss of (farmed) fish populations on large scales.

The insurance industry's ability to continue 'business-as-usual' when it comes to ocean risk could become questionable as increases in atmospheric greenhouse gas concentrations continue to affect the ocean. Observed and future changes within the ocean and marine ecosystems have the potential to significantly affect the insurance industry in a number of ways, from the value of insurance companies' assets to the loss potential across various lines of insurance business. But the outlook is not necessarily bleak: change will create opportunities and give rise to new lines of business. The transfer of ocean risk has the potential to increase in size and relative importance for the insurance industry as the growing blue economy needs risk transfer for its investments. Furthermore, development strategies following the Paris Climate Agreement are beginning to support ocean risk transfer solutions for developing countries.

Ocean warming, ocean acidification and sea-level rise have already and undeniably occurred [IPCC, 2013]. Such changes by themselves do not have an immediate or direct impact on the insurance industry, rather they have cascading indirect effects. For example, with sea levels rising and the potential for more intense tropical cyclones, storm surges will extend further inland, which increases the likelihood of damage to agricultural land, critical infrastructure and coastal ports and enhances the potential for longer-term impacts on the global supply chain. In addition, ocean warming could increase the frequency and/or intensity of sudden outbreaks of harmful algal blooms or warm-water diseases in fish. These could in turn affect global food security, human health or product liability for the fishing industry. In less developed countries, losses of coastal fisheries due to changes in ocean currents and temperatures could induce or increase migration, or even encourage criminal actions such as piracy. Disputes over collapsing or spatially varying open ocean (pelagic) fisheries could trigger violent conflicts among nations. Marine-related shifts in trade, livelihoods and cultures could also produce regional political instability. Changes in trade routes, such as the opening of an Arctic seaway [Emmerson & Lahn, 2012], could have unfavorable geopolitical consequences for the global economy. Such cascading effects and potential scenarios, especially when combined with the growing interdependence of the global economy, would have significant consequences for the insurance industry.

With this report we hope to raise awareness of ocean warming and its potential impacts on the insurance industry and to initiate discussions and actions that will make society, and the insurance industry, more resilient to the consequences of ocean warming. But, as change begets opportunity, we also offer scenarios for new lines of insurance business and suggestions for how insurers might respond both as individual companies and as an industry to emerging ocean risks.

Introducing the struc:ture of this report

To explain how ocean risk affects the insurance industry, we first provide an overview of the significance of the ocean for the climate and the economy and how our dependency on ocean health and marine resources is going to deepen in the future (Chapter 1). This increasing dependency on resources and ecosystem services provided by the ocean coincides with growing evidence of substantial changes in the ocean such as ocean warming and acidification, sea-level rise, and even indications of changes to ocean circulation. These factors, in turn, are inducing significant changes to marine ecosystems. We provide an overview of the observed physical and biological changes in the ocean (Chapter 2). The impacts associated with these changes, which are affecting the loss potentials in different lines of business for insurers, include alterations to the distributions of extreme weather events and the loss of critical marine ecosystem services. Furthermore, the rise of the blue economy combined with emerging ocean risks is changing the value of assets of insurers in complex ways (Chapter 3). Modelling the impacts associated with ocean warming requires improved, or entirely new, risk models to enable a proper quantification of ocean risks (Chapter 4). Whilst there are challenges from ocean warming, there are also opportunities for the insurance industry. New risk transfer solutions for ocean risk can be provided that benefit society by supporting the development of the blue economy, sustainable growth and resilience in developing countries (Chapter 5). The report closes with a set of recommendations for individual insurers and an industry response to the emergence of ocean risk (Chapter 6).

1. THE OCEAN AND ITS ROLE IN CLIMATE, SOCIETY AND THE ECONOMY

The Earth is a blue planet. The ocean covers approximately 70% of its surface and is essential to the regulation of global climate, its variability and the distribution of extreme weather events. The ocean also hosts our planet's largest ecosystem – the marine flora and fauna that also play a vital role in the sequestration of greenhouse gases (GHGs). Humanity depends on and interacts with the ocean in multiple ways. Forty-four percent of the current global population lives near the coast and 8 out of 10 of the world's largest cities are coastal [Nganyi et al., 2010]. Seafood, shelfish and seaweed either supplement or are the main source of the diets of billions of people [Tacon & Metian, 2009; Beveridge et al., 2013]. Ocean products and coastal recreation promote health and wellbeing. Ocean resources generate income for companies that range in size from large international corporations to local sportfishing guides. In summary, the ocean is a critical component

Tropical Storm Noel, Fort Lauderdale, US, 2007.
© Dave/d_himself/Flickr

1.1 The ocean as a key component of the climate system

The ocean and its currents are of fundamental importance for the storage and distribution of the solar energy absorbed by the climate system. The change in Earth's total energy budget is defined as the difference between incoming solar and outgoing thermal radiation at the top of the atmosphere. Changes in the energy of the atmosphere and ocean together balance the resulting radiative mismatch. The ocean stores and, through its currents, distributes a major part of the solar energy absorbed by the climate system. Atmospheric winds and convection distribute the rest within the atmosphere, mainly through the transport of water vapor that, to a large extent, originates from evaporation at the ocean's surface.

There is spatial variability in the exchange of energy and water between the ocean and the atmosphere. Overall, the ocean is radiatively warmed in the tropics, transports heat poleward through ocean circulation, and is cooled by the radiative transfer of energy to the atmosphere and the transfer of latent and sensible heat to the atmosphere. The distribution of energy by the ocean influences a variety of key climate factors such as oceanic and atmospheric circulation, the extent of polar ice and sea level. The ocean also acts as a reservoir for GHGs, as it absorbs carbon and methane, two of the most important atmospheric GHGs. The exchange of energy and GHGs between the ocean and atmosphere essentially regulates Earth's climate [Reid et al., 2009; Rhein et al., 2013].

Beyond its influence on the overall state of global climate, the ocean also plays a key role in the occurrence of climate extremes. By transporting vast amounts of energy and being the main source of water to the atmosphere, the ocean determines atmospheric dynamics and weather patterns and provides the energy needed for the development of extreme events on both short (e.g., days, for tropical cyclones) and long (e.g., months to years, for droughts) timescales.

1.2 TODAY'S OCEAN INDUSTRIES AND THE BLUE ECONOMY

The ocean is an important component of our increasingly connecApart from its critical role in the climate system, the ocean offers a vast array of free resources, goods and services. By providing these ecosystem services, the ocean is a key natural resource for societies and economies [World Bank, 2017][3]. Placing a value on ocean assets and gross value added is difficult and has not been standardized. Nevertheless, it is clear that the industries that utilize the ecosystem services of the ocean [see Figure 1], collectively known as the 'ocean industry' or 'blue economy'[4], are a significant part of the global economy and can be classified as one of its fastest growing sectors.

A report by the Organisation for Economic Co-operation and Development (OECD) highlights the value of the blue economy [OECD, 2016]. According to the OECD, in the year 2010 the size of the worldwide blue economy hit USD1.5 trillion in value added, or approximately 2.5% of world gross value added (GVA)[5]. Breaking up the 2010 blue economy by sector [see Figure 2], offshore oil and gas accounted for 34% of total value added by ocean-based industries, followed by maritime and coastal tourism (26%), ports (13%) – measured as total value added of global port throughput – and maritime equipment (11%). Other industries accounted for shares of 5% or less. While the share of industrial capture fisheries is small (1%), it should be noted that inclusion of estimates of the value added generated by artisanal capture fisheries (mainly in Africa and Asia) would add further tens of billions of USD to the capture fisheries total [OECD, 2016].

The World Wide Fund for Nature (WWF) took a different approach to estimating the monetary value of the ocean and its ecosystem services. According to its 2015 report, the ocean's 'gross marine product', which it equates to a country's GDP, is at least USD2.5 trillion [WWF, 2015]. The report values the ocean assets that produce the gross marine product at USD24 trillion at least. The annual value contributed by offshore wind and oil and gas production, among the largest sectors in the OECD report, are not counted as part of the gross marine product. With these estimates, the ocean's economy would rank as the world's seventh largest.

Figure 1: Overview of **ecosystem services provided by the ocean.** Source: The Nature Conservancy/ Mapping Ocean Wealth: Oceanwealth.org

Cape May Peninsula showing rivers and tributaries flowing through saltmarsh, New Jersey. Coastal wetlands prevented USD625 million in flood damage to private property when Hurricane Sandy hit the eastern seaboard of the US in October 2012. © Ingo Arndt/ Minden Pictures/FLPA

At a national level, the contribution of the blue economy to GDP (or GVA) varies depending on the geography and economic development of individual countries. According to the OECD, in 2014 the ocean industry of the world's second largest economy, China, employed 9 million people and was worth USD962 billion, or 10% of China's GDP. The blue economy in the US was valued at USD258 billion in 2010, or 1.8% of GDP, whilst in Europe, the numbers equate to a GVA of almost USD550 billion a year, employing roughly 5.4 million people in 2016. While difficult to compare, these numbers highlight the important role of the blue economy for the biggest economies in the world. In developing countries with large coastal areas and/or marine territories, such as Indonesia, the blue economy comprises around 20% of GDP [Economist Intelligence Unit, 2015; OECD, 2016; World Bank, 2016]. Furthermore, and of relevance to insurers, in many countries where the blue economy is of significant size, there is also a large insurance protection gap. Insurance penetration is limited and covers only minor parts of the blue economy today.

One marine ecosystem service [see Figure 1] of direct relevance to the insurance industry is the protective effect of coastal ecosystems for shorelines and coastal infrastructure. Protection is provided by systems such as coral reefs, mangroves, oyster reefs or marshlands through their effect on: a) general wave attenuation (weakening of waves); b) storm surge attenuation; and c) maintaining shoreline elevation. As an illustration of the value of coastal ecosystem protection, a recent study found that existing coastal wetlands alone prevented USD625 million in flood damage to private property when Hurricane Sandy hit the eastern seaboard of the US near New New Jersey and New York in October 2012 [Narayan et al., 2017].

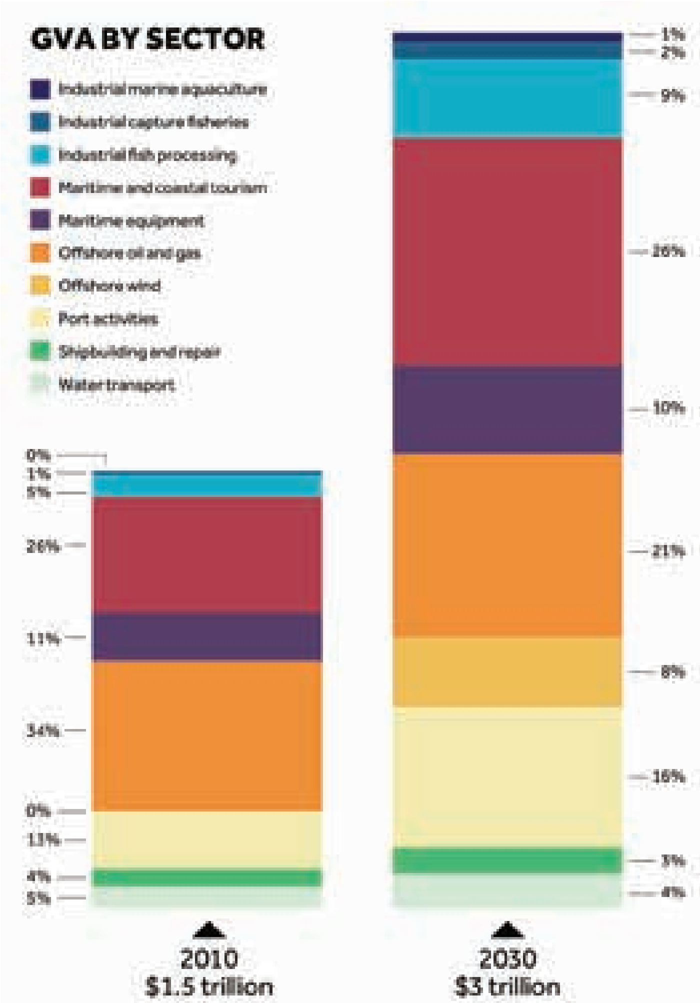

Figure 2: **Calculations from OECD, 2016, based on various industry reports.** Note: Artisanal fisheries are not included in this overview.

1.3. FUTURE GROWTH OF THE BLUE ECONOMY

While the blue economy is an important part of today's global economy, its volume and diversity are almost certain to increase and become an even greater economic force in the near future. The rise of the blue economy is being driven by the almost exponentially growing industrial use of coastal and seashore areas and extraction of resources from the ocean and marine environments. A conservative projection by the OECD suggests a doubling of GVA of the blue economy by 2030 [see Figure 2], or a growth rate of around 5% per annum, which gives the blue economy and in particular some of its sectors (e.g. marine aquaculture, offshore wind, fish processing, port activities) the potential to outperform the growth rate of the global economy as a whole [OECD, 2016]. New and emerging industries with enormous growth potential and an intensified use of marine resources include: industrial marine aquaculture; deep-water and ultra-deep-water oil and gas extraction; offshore renewable energy; seabed mining; marine biotechnology and pharma; high-tech marine products and services; maritime safety; and surveillance.

The drivers of growth for the blue economy are many and varied (see Figure 3) but have their origins in our growing capabilities in the ocean environment and the new technologies that make it both possible and economically viable to exploit ocean resources. Economic growth and demographic trends fuel the rising demand for resources such as fish protein, minerals, alternative energy and desalinated seawater. Other factors contributing to the growth of the blue economy include bioprospecting for the healthcare industry, seaborne trade, global tourism, ocean technology research and development, coastal and ocean protection, and rapid coastal urbanization [Economist Intelligence Unit, 2015]. This multitude of drivers of growth is what makes the OECD projection of a doubling of the blue economy by 2030 a conservative projection. In fact, apart from economic growth factors, there is an urgent political need to support the blue economy in order to solve problems resulting from growing coastal and global populations.

The global demand for food is on the rise, driven by growth in the world's population and widespread shifts in consumption patterns as countries develop. Despite overfishing and the exploitation of fisheries beyond their sustainable limits, more efficient capture techniques and increased efforts have kept the amount of fish being caught at sea by capture fisheries almost level for three decades. During this period, the rising demand for quality fish protein has been met by enormous growth in the production

Figure 3: Components of the ocean economy. Source: Data reused with the permission of the Economist Intelligence Unit [Economist Intelligence Unit, 2015].

Type of activity	Ocean service	Established industries	Emerging industries	New industries	Drivers of future growth
Harvesting of living resources	Seafood	Fisheries	Sustainable fisheries		Food security
			Aquaculture	Multi-species aquaculture	Demand for protein
	Marine bio-technology		Pharmaceuticals, chemicals		R & D in healthcare and industry
Extraction of non-living resources, generation of new resources	Minerals	Seabed mining			Demand for minerals
			Deep seabed mining		
	Energy	Oil and gas			Demand for alternative energy sources
			Renewables		
	Fresh water		Desalination		Freshwater shortages
Commerce and trade in and around the ocean	Transport and trade	Shipping			Growth in seaborne trade
		Port infrastructure and services			International regulations
	Tourism and recreation	Tourism			Growth of global tourism
		Coastal development			Coastal urbanisation
			Eco-tourism		Domestic regulations
Responses to ocean health challenges	Ocean monitoring and surveillance		Technology and R&D		R&D in ocean technologies
	Carbon sequestration		Blue carbon (i.e. coastal vegetated habitats)		Growth in coastal and ocean protection and conservation activities
	Coastal protection		Habitat protection, restoration		
	Waste disposal			Assimilation of nutrients, solid waste	

of farmed fish. The OECD projects that this trend will continue and that by 2030 two out of every three fish on our plates will have been farmed, much of it at sea. These trends highlight the critical importance of aquaculture in marine environments for closing the gap between production and demand for fish protein and food security in a world with a fast-growing population.

In summary, the outlook on the rise of the blue economy in the 21st Century includes a message for insurance: new opportunities will arise for the insurance industry as the importance of marine ecosystem services is recognized and the blue economy increases in size. Similar to establishing the blue economy as an individual asset class [Thiele & Gerber, 2017], the insurance industry could bundle the associated lines of business to allow for a strategic approach to growing business and exposure in the associated markets of ocean risk [see Chapter 5].

2. WARMING OF THE OCEAN AND ASSOCIATED CHANGES IN MARINE ECOSYSTEMS

While the blue economy is growing fast and its relative contribution to the global economy is increasing, the ocean and the marine ecosystems that support the blue economy are shifting. The ocean is showing a sustained and accelerating upward trend in sea-surface temperature (SST), ocean heat content (OHC) and sea levels in almost all ocean basins. At the same time, ocean acidity is rising and oxygen concentrations are decreasing. In response, there are changes in almost all marine ecosystems that support today's businesses and the future growth strategies for the blue economy.

2.1 OCEAN WARMING, PHYSICAL AND CHEMICAL CHANGES

Since the Industrial Revolution, the atmospheric concentrations of CO2 and other GHGs have increased significantly. The radiative properties of GHGs are well known and the increased CO_2 concentrations cause an enhanced greenhouse effect – GHGs absorb infrared radiation emitted from the surface of the Earth and thereby trap thermal energy in the Earth's atmosphere [IPCC, 2013].

As the atmosphere warms it also transfers heat to the ocean. In fact, over 90% of Earth's excess heat from GHG increases has been absorbed by the ocean [Johnson et al., 2015]. As a consequence, SSTs, vertically integrated OHC, sea levels and melting glaciers and ice sheets are all increasing at an accelerating rate [IPCC, 2013; Cheng et al., 2017; Nerem et al., 2018] and oxygen concentrations are being depleted in large areas [Schmidtko et al., 2017]. Furthermore, as the concentration of CO_2 in the atmosphere increases, more is absorbed by the ocean, causing ocean acidity to increase [IPCC, 2013]. In recent decades considerable efforts in developing observational systems and models of the ocean and atmosphere have greatly reduced the uncertainty in the corresponding observations and today there is no doubt about accelerated ocean warming and its significance for climate overall [Reid, 2016; Cheng et al., 2017][6].

2.1.1. Sea-surface temperature

The latest records of globally averaged SST show an increase relative to a base period from 1951–1980, with a warming trend of ~0.13°C per decade since the beginning of the 20th Century and a small subpeak around 1940 (see Figure 4) [IUCN, 2016]. The SSTs of the last three decades have been warmer than at any time since instrumental records were first obtained on a routine basis around 1880. As of 2016, 13 of the warmest SST years on record since 1880 have occurred since 2000 (except for 1997 and 1998).

Against this background, the increase in global surface temperature and SST appeared to stall around 1998, producing what has been called a 'hiatus' in temperature growth that did not fit the predictions of global climate models [Roberts et al., 2015]. Throughout this period, in contrast to SST, OHC increased (see Section 2.1.2). Today, it is clear that the warming hiatus was a short-term feature influenced by Pacific variability [Watanabe et al., 2015] and SST and its rate of change have continued an upward and accelerating trend [Smith et al., 2015].

Nansen fracture 2016. © C. Yakiwchuck/ESA

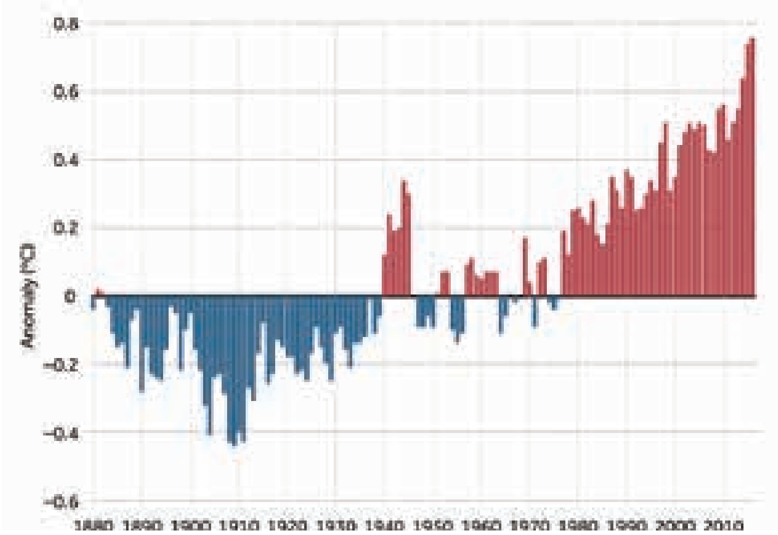

Figure 4: Annual global sea-surface temperature anomalies from 1880 to 2015 with superimposed linear trend (base period 1951–1980), red positive, blue negative. Source: National Centers for Environmental Information, http:// www.ncdc.noaa.gov/cag/time-series/global/globe/ocean/ytd/12/1880-2016

2.1.2. Ocean heat content

Ocean warming is ongoing and not limited to the surface. Analyses of OHC shows that approximately two-thirds of the heat trapped by GHGs that has been absorbed by the ocean since 1970 has been absorbed by the upper 700 meters with one-third absorbed into the deep ocean below 700m depth (see Figure 5). The increase in OHC is pronounced up to 2010 in the Northern Hemisphere and in the North Atlantic [Rhein et al., 2013]. The heat content of the upper 700m of the ocean is today roughly 120x1021 joule higher than in 1995, which is equivalent to around 240 times the global human energy consumption of 2013 [IUCN, 2016].

2.1.3. Sea-level rise

A direct consequence of increasing OHC is sea-level rise (SLR) due to the thermal expansion of seawater when heated. Additional contributions to SLR come from melting continental ice sheets and glaciers. Global average sea level has risen roughly 20cm over the last century (see Figure 6). Rates of SLR (1.7mm/year) computed using alternative approaches over the longest common interval (1900–2001) agree with this estimate within the range of uncertainty. Furthermore, the rate of SLR has accelerated since 1930 with yet another increase in the rate of change (to 3.2mm/year) since the 1990s [Church et al., 2013]. Newer studies using other data sources confirm the worrying acceleration of SLR [Clark et al., 2015; Nerem et al., 2018].

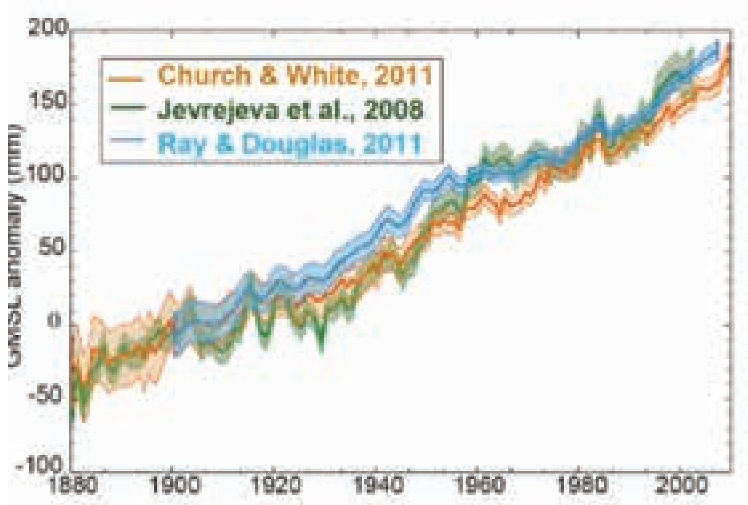

Figure 6: Yearly average of the Global Mean Sea Level (GMSL) reconstructed from tide gauges (1900–2010) by three different approaches [Jevrejeva et al., 2008; Church & White, 2011; Ray & Douglas, 2011] Source: IPCC, 2013

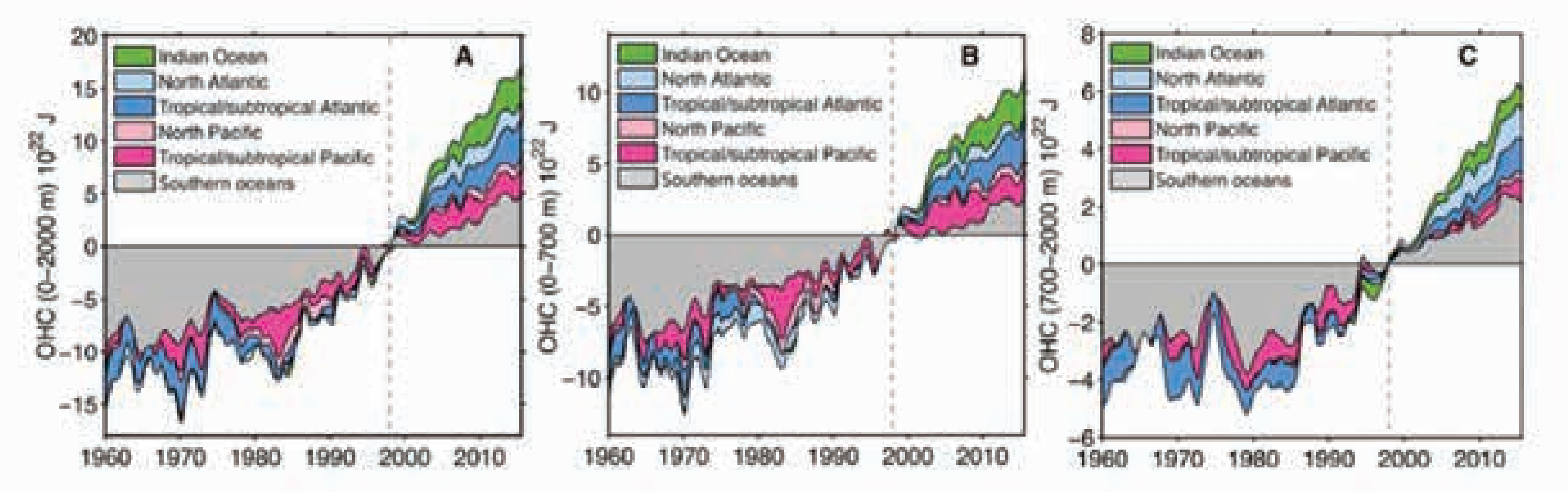

Figure 5: Ocean heat content for different vertical levels and ocean basins. Source: Cheng et al., 2017.

2.1.4. Ocean acidity

As the concentration of atmospheric CO_2 increases due to anthropogenic emissions, the ocean absorbs more CO_2 to maintain equilibrium with the atmosphere. Approximately 50% of the anthropogenic CO_2 produced each year is retained by the atmosphere, while ocean and land sinks each absorb about 25% of the remainder. Once CO_2 has been absorbed by the ocean, a series of chemical reactions result in an increase in the ocean's acidity. Time series observations of ocean acidity show a long-term increase due to the solution of CO_2 in the ocean (or decrease in pHvalue, see Figure 7). Since the Industrial Revolution began, surface ocean pH has decreased by more than 0.1 units on the logarithmic scale of pH, representing an increase in acidity of around 30%. This represents a significant increase for marine ecosystems as many calcifying marine organisms, such as corals and some plankton, become vulnerable if ocean acidity gets too high.

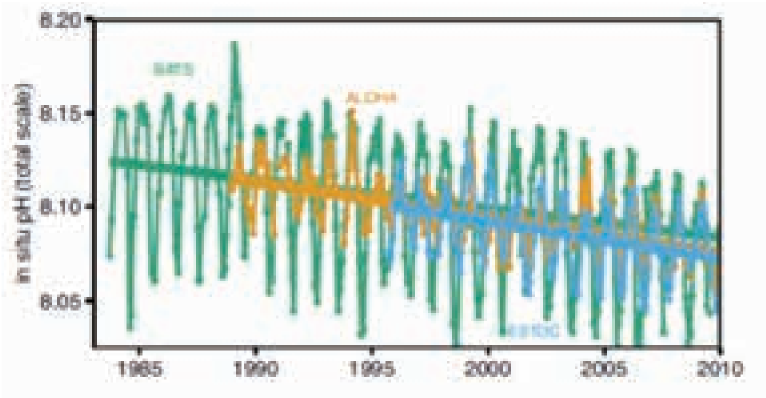

Figure 7: **Long-term trends of surface seawater pH (middle) at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009); and c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Lines show linear fits to the data.** Source: IPCC, 2013.

2.1.5. Ocean oxygen

Oxygen is important for the productivity of marine ecosystems and its solubility in seawater is temperature dependent: oxygen solubility decreases as temperature increases (less oxygen in warmer water). At the surface, a reduction in oxygen due to warming is not critical as there is a ready supply from the atmosphere. But, when water becomes isolated from the atmosphere, for example due to subduction associated with ocean circulation, a lower oxygen content set at the surface can eventually lead to anoxia at depth as oxygen is consumed by respiration of organic matter. Observational evidence for declines in ocean oxygen and the expansion of low oxygen zones was first presented by Keeling and Garcia in 2002 [Keeling & Garcia, 2002]. Possible causes for the decline include warming-related increased stratification, warming of the upper ocean leading to lower oxygen saturation levels, biological effects and ocean circulation changes.

More recently, Schmidtko et al. (2017) found that global ocean oxygen inventories have declined by more than 2% since 1960, with large regional variations including hot-spots with reductions of as much as 33% and the occurrence of so-called dead zones (see Figure 8).

2.1.6. Ocean currents and modes of variability

Variability in, and the distribution of, extremes in the atmosphere–ocean system are dominated by large-scale modes of climate variability. Phenomena like the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), or different monsoon systems have well-known, dominant, local and remote effects on the variability of extreme events. These modes are very likely to be affected by the warming of the ocean, as they are sensitive to variables such as temperature differences or ocean-atmosphere interactions.

The underlying dynamics of these modes of variability are highly complex, and scientific understanding of them is still far from complete. Furthermore, due to the long timescales of ocean dynamics, the relatively short length of observational data, and inherent natural variability, it is difficult to detect trends in these indices. However, quantifiable changes to these important modes are beginning to emerge as the recorded observations continue. For example, over the last 20 years there has been a distinct change in El Niño events, with a shift of the mean location of SST anomalies towards the central Pacific [Zhou et al., 2014; Cheng et al., 2017]. Furthermore, there is some evidence emerging that the Atlantic Meridional Overturning Circulation (AMOC) is weakening [Rahmstorf et al., 2015; Sévellec et al., 2017], which is important for the ocean dynamics in general as well as for the development of some climate and weather extremes in the North Atlantic basin [McCarthy et al., 2017]. Further research is required to increase confidence in a weakening AMOC, but the observed trend provides another indication of changes to large-scale dynamics within the ocean.

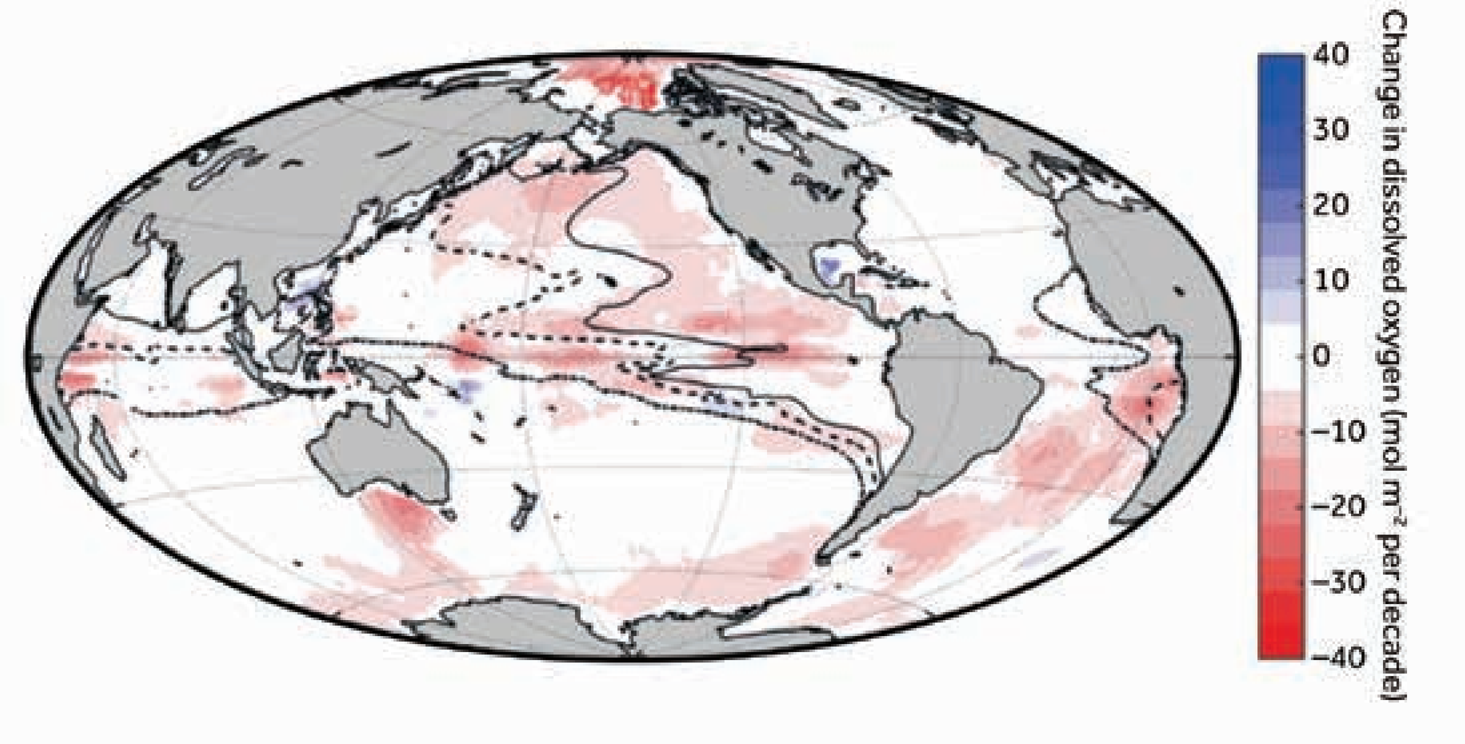

Figure 8: **Changes in dissolved oxygen in ocean water.** Source: Schmidtko et al., 2017.

2.2 CHANGES IN MARINE ECOSYSTEMS

While the development of observational systems and progress in climate science have increased our knowledge of physical changes in the ocean, the effects of these changes on marine ecosystems have not been explored, and are therefore not understood to a comparable level of detail. Nevertheless, recent years have seen considerable progress in quantifying changes to marine ecosystems.

In 2016, the International Union for Conservation of Nature (IUCN) published a comprehensive summary of the impact of ocean warming on marine ecosystems [IUCN, 2016]. As of today, the IUCN report is the most comprehensive assessment of ocean warming and its linkages to marine biology and ecosystem research, and it enables a rigorous assessment of emerging risks from changes in marine ecosystems. The report tells a complex story of regime shifts in the ocean and marine ecosystems, of change that is underway and locked in for decades, and which is already starting to have significant impacts today (see Figure 9)[7].

While ocean warming can have positive effects on the productivity of some marine ecosystems, the emerging evidence suggests a number of (sometimes coupled) negative effects that science is just starting to understand, but about which there is reason to be very concerned.

There is substantial observational evidence that many ecosystems are responding to changes to regional climate and nutrient regimes caused predominantly by the warming of SST and ocean current changes. While warm-water corals are at the frontline of ocean changes, there are other less well-known but already observable consequences: mid-latitude seagrass, high-latitude pteropods and krill, mid-latitude bivalves, and finfish, for example, have all changed in abundance and spatiotemporal distribution. In general, the speed of change in the ocean, such as the poleward range shifts in marine systems and (invasive) species, is happening between 1.5 and 5 times faster than on land. Such range shifts are potentially irreversible and have great impacts on marine ecosystems.

Furthermore, marine ecosystems are often linked to seasonality and/or other cycles within their environments. Such phenological events can affect the lifecycles of individual species that are a function of environmental conditions or synchronicity in predatorprey relationships. With likely but uncertain changes to oceanic modes of variability and currents (see Section 2.1.), there is also increasing uncertainty concerning the phenological dependence of marine food webs and ecosystems. Given the non-linear dynamics and coupling of a large number of species in marine ecosystems, the unknown impacts of changes in oceanic modes of variability creates the potential for sudden shocks within marine food webs and other marine ecosystems.

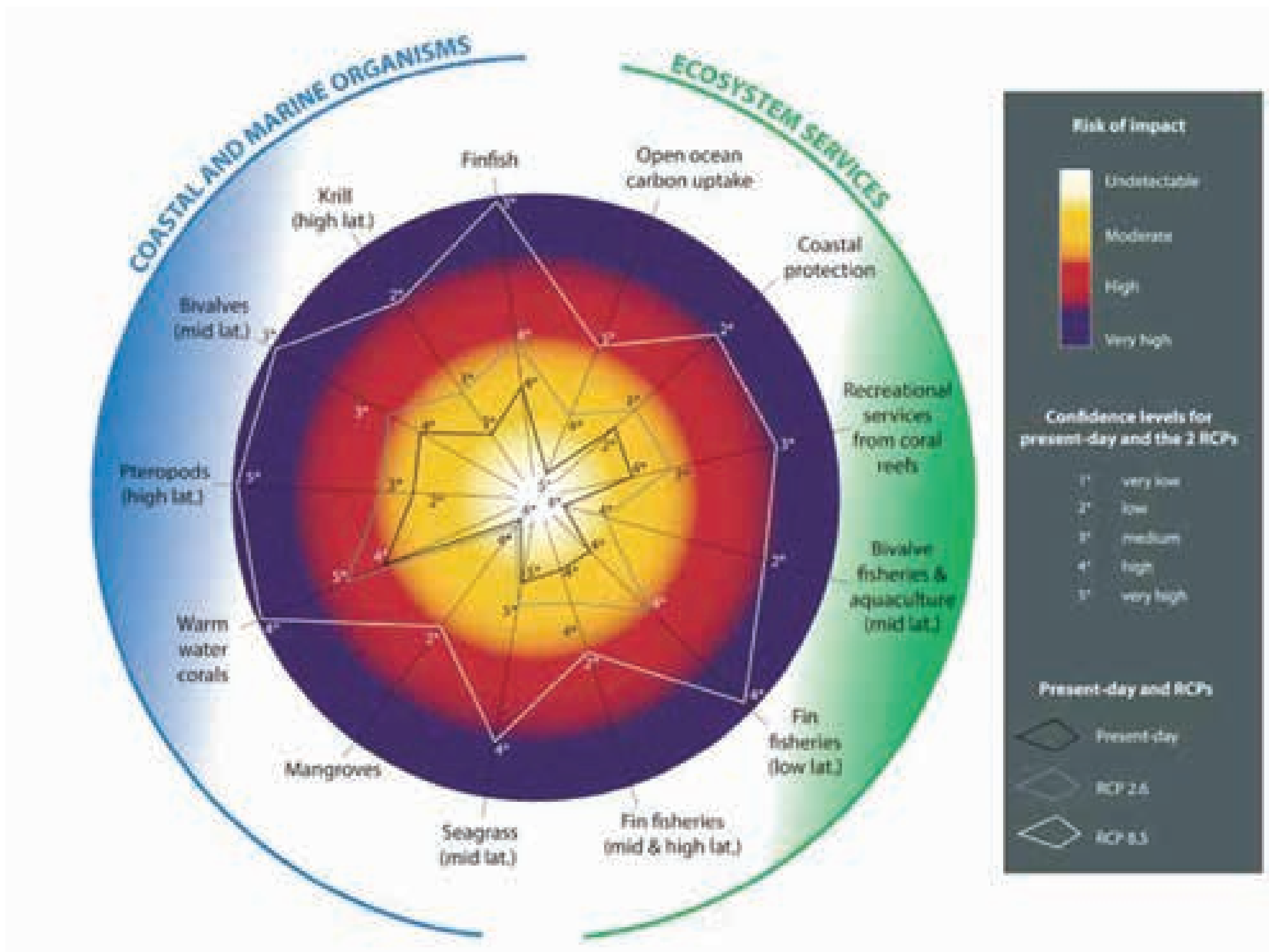

Figure 9:
Impacts on marine ecosystems of changes in the ocean today (black) and future projections from two contrasting anthropogenic CO_2-emission scenarios[8] (RCP2.6 (gray) and RCP 8.5 (white)) from IPCC, 2013.
Source: IUCN, 2016, adapted from Gattuso et al., 2015

In the following, we give a short summary of selected changes in marine ecosystems as reported by IUCN [for more details see IUCN, 2016].

2.2.1. Microbial response (including bacteria, viruses and others)

Ocean warming and associated reduced oxygen levels affect the biodiversity and functioning of marine microbes including bacteria and viruses. Different sensitivities to warming and reduced oxygen levels among different microbial populations are resulting in changes to biodiversity with implied changes in microbe-virus interactions. In addition, there are physical shifts in the geographic ranges of disease organisms and their vectors or reservoirs in the ocean. Given the complexity of these interactions, there remain large uncertainties regarding both the current state and future projections of marine microbial responses. However, ocean warming could be critical for increased pathogen survival, allowing the emergence of warm-water diseases in historically cooler seas. There is now first evidence of increases in diseases among many wild populations of plants and animals in marine systems linked to changes in SST and an increased rate of viral infections on a significant scale in oceanic food webs [IUCN, 2016].

2.2.2. Algae (for more details see Appendix 1)

Over the past three decades, unexpected new algal bloom phenomena were often attributed to eutrophication caused by nutrient pollution, but more recently, novel harmful algal bloom (HAB) episodes are being linked to ocean warming. The drivers for the rapid growth of algae that leads to HABs are light, water temperature, salinity, water column stability and nutrients. Due to ocean warming, on average SSTs are increasing and ocean stratification is enhanced; both are potential growth factors for marine algae. These factors can be coupled with shifts in ocean currents and modes of coupled ocean-atmosphere variability such as ENSO to promote the occurrence of HAB events. Emerging algae responses to ocean warming include: 1) range expansion of warm-water at the expense of cold-water species; 2) changes in abundance and the seasonal bloom window; and 3) increased cellular toxin content of HAB species. However, since ocean warming signals for HABs are hard to isolate due to a lack of observational data and coinciding signals from eutrophication, there remains a high degree of uncertainty in future projections.

2.2.3. Plankton

The IUCN report provides evidence of extensive changes in plankton ecosystems over the last 50 years including pheno ena such as production, biodiversity and species distributions. These changes appear to be driven mainly by climate variability and ocean warming. Consistent with many other observed changes, there is an increasing poleward shift of plankton species that is a geographical (spatial) adjustment to optimum conditions. Furthermore, there are phenological shifts of plankton and changes in seasonal appearance, with many planktonic organisms now appearing earlier in their seasonal cycles than in the past. This is leading to a loss of temporal synchrony and a potential mismatch between plankton, fish and other marine wildlife. As plankton is the base of an extensive food web, these changes have had effects on fisheries production and other marine life [IUCN, 2016].

2.2.4. Marine fish

There are approximately 15,000 species of marine fish in the ocean [Froese & Pauly, 2016]. They inhabit almost all parts of the ocean, from surface water to deep-sea trenches, coral reefs to hydrothermal vents on seamounts and mid-ocean ridges [Cheung et al., 2005]. Marine fish are sensitive to seawater temperature changes because their physiological performance is largely dependent on environmental temperature. Fish that are tropical or polar and fish in their early life stages are generally most sensitive to ocean warming because they have narrower ranges of temperature tolerance.

Observations to date suggest that many fish have shifted their ranges poleward by tens to hundreds of kilometers as the ocean has warmed. This is resulting in species invasions, local extinctions and shifts in community structure. With an increasing dominance of warmer-water species and disturbances of trophic interactions, distributions of target and non-target species for fishing industries increasingly overlap. Shifts in fishing grounds of target species may therefore increase bycatch and reduce the effectiveness of conservation measures such as Marine Protected Areas (MPAs). Where some species move to deeper water this will reduce catchability by surface fisheries and increase catchability by deepwater fisheries.

Ocean warming is modifying the seasonality of biological events such as spawning and migration. This affects fish because of mismatches in the availability of their prey and the potential introduction of new predators. Complex cascading effects in marine food webs, beginning with plankton, will likely cause the maximum body size of fish to decrease under ocean warming. In addition, non-climate human stressors such as fishing and pollution interact with climateinduced changes in fish populations, further increasing the sensitivity of marine fish to climatic stressors [IUCN, 2016].

2.2.5. Coastal ecosystems (corals, mangroves, marshes)

Coastal areas have warmed 35% faster than the open ocean since 1960 and are more susceptible to impacts from warming, SLR, changes in storms and increased land run-off than any other ocean realm. Given the high value of coastal ecosystem services, changes to these ecosystems come with high risk for coastal communities and the blue economy.

Fish in a brain coral in Belize. © The Ocean Agency/XL Catlin Seaview Survey

Bleached coral, Great Barrier Reef. © The Ocean Agency/XL Catlin Seaview Survey

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• Corals (for more details see Appendix 2)

The rate of warming in coral reef areas increased from ~0.04°C per decade over t he past century to 0.2°C per decade from 1985 to 2012. During the 20th Century, reefs experienced bleaching due to prolonged high temperatures approximately once every six years. However, within the last three decades the frequency of bleaching stress has increased. Together with other anthropogenic stressors (e.g., eutrophication), ocean warming and acidification have reduced the proportion of reefs in which ocean chemistry will allow coral reefs to grow from 98% (ca. 1780) to 38% (ca. 2006) and the number continues to drop [IUCN, 2016].

Consecutive large bleaching events in the Great Barrier Reef in 2016 and 2017 highlighted the increasing stress on coral reef systems and the economic vulnerabilities. Since 1982, just after mass bleaching events were observed for the first time, records show that the average percentage of the Great Barrier Reef exposed to temperatures where coral bleaching or death is likely has increased from about 11% a year to around 27% a year [Yates et al., 2017].

In addition to increased temperatures and acidity, coral reef systems are also impacted by the indirect effect of SLR. Furthermore, warmer upper ocean temperatures could potentially intensify tropical cyclones and lead to greater wave and surge damage to coral reefs. Enhancing reef resilience through targeted management actions will help reefs to resist and recover from disturbance, and local actions to mitigate climate change impacts may be necessary to preserve reef resources.

• Mangroves

Between 1980 and 2005, 19% of the global stock of mangroves was lost [Spalding et al., 2010], mainly as a consequence of logging and changes in land use. The direct effects of ocean warming on mangroves are highly uncertain but are likely to be mostly beneficial, with a poleward shift in their distribution and increasing mangrove productivity and biodiversity, particularly at higher latitudes. However, where the current rate of SLR exceeds the soil surface elevation gain, mangroves with low tidal range and low sediment supply could be submerged, resulting in further loss or fragmentation of mangrove habitats, and/or species composition changes.

• Marshes

Changes to the future community composition of saltmarshes due to ocean warming is uncertain because individual species respond differently. Complex feedback between plants, microbes, the built environment and physical processes will determine whether marshes can keep pace with SLR. Low-latitude marshland declines are expected due to conversion to mangrove, while high-latitude marshlands are likely to expand. Increased plant production is likely, which will generally improve ecosystem services. There is high uncertainty regarding other aspects, such as carbon sequestration capacity, which may increase, and a likely increase in methane emissions from marshland, both of which affect climate-motivated restoration activities-

2.3 Summary of changes in the ocean

In summary, the observed physical changes in the ocean and the resulting consequences for marine ecosystems are reason for great concern. Due to the long timescales of dynamics associated with the exchange of CO_2 and heat between the atmosphere and the ocean, warming would continue even if CO_2 emissions were reduced to zero tomorrow. Changes in temperature and heat content are of an order that is becoming relevant in terms of large-scale dynamics and there are indications that systemic features in the ocean, such as the AMOC, are indeed starting to react [Rahmstorff et al., 2015]. Today, the external forcing (energy gain per time) for the ocean is huge and is starting to disrupt the stability of the quasi-equilibrium of the physical ocean system. In the near future it is possible that we will start to see changes to regional oceanic modes or currents as a consequence of changes to gradients of temperature and/or salinity. Sensitive, coupled ocean-atmosphere modes (e.g., ENSO and monsoon circulations) could be altered, with consequences for regional and global weather patterns. In fact, ENSO, the most dominant oceanatmosphere mode, which has a strong influence on the distribution and intensity of a number of extreme weather and marine biological events, is already showing signs of change [Zhou et al., 2014; Cheng et al., 2017].

As a consequence of physical changes in temperature and currents, as well as acidification and oxygen depletion, a marine biological response is now starting to show. Although marine ecosystems are far from well-understood and historical data is sparse, it is becoming increasingly clear that regime shifts have started. Marked biological manifestations of the impacts from ocean warming and other stressors have taken the form of biogeographical, phenological, biodiversity, community-size and species-abundance changes that point towards ecological regime shifts. Such regime shifts often interfere, or are predicted to interfere, with the benefits we depend on from the ocean. Multiple stressors (warming, acidification and oxygen reduction) interact cumulatively, and exposure to one stressor (such as warming) can decrease the tolerance of a species to another stressor. There is a worrying lack of detailed experiments regarding the temperature dependence of the survival, reproduction and growth of pathogenic organisms and their carriers.

The problem is that while we know ocean warming is driving change in the ocean – this is well documented – the consequences of this change are far less clear [IUCN, 2016]. However, what is certain is that we will see a very different ocean in the future – maybe even in the near future.

What are the relevant impacts of ocean warming for the insurance industry given the changes in the ocean and marine environments described in this chapter? We begin to explore these impacts in Chapter 3.

3. THE IMPACTS OF OCEAN WARMING AND CHANGING MARINE ECOSYSTEMS

3.1. Impacts on extreme weather events and climate

As the ocean is one of the most important drivers for weather, the warming of the ocean affects several aspects of extreme weather events relevant to the insurance industry. A number of recent studies focused on the impact of climate change and ocean warming on the distributions of extreme events have found changes in the distribution and loss of relevant characteristics of some extremes and their impacts [SREX, 2012; Niehörster et al., 2013; IUCN, 2016; AIR, 2017].

It is important to note that detecting climate signals for extreme events (with very long return periods) remains controversial as there is not enough reliable, historical data to disentangle potential climate change signals from internal variability (or noise), especially when it comes to regional changes[9]. A lack of complete physical understanding of the links between climate forcing and some lossrelevant characteristics of extreme events further complicates the debate. However, by using physical reasoning and selected, wellestablished links between ocean dynamics and extreme events, some signals of ocean warming on insurance-relevant aspects of extreme events can be isolated. In general, many insurance-relevant hazards show increased loss potentials due to the warming of the ocean. The main drivers of this trend are: a) SLR, which increases the loss potential from storm surge and inundation; b) an intensified hydrological cycle, which increases the moisture content of the atmosphere and the loss potential from heavy precipitation of extreme events; and, c) changes in large-scale climatic phenomena and oceanic modes (e.g., ENSO, monsoons, AMOC), which affect spatiotemporal distribution and frequencies of weather extremes such as droughts, floods and storms, sometimes on global scales.

3.1.1. Tropical cyclones

Tropical cyclones acquire energy (in the form of latent heat) mainly from the evaporation of water from the surface of the ocean, which is positively dependent on SST [Emanuel, 1986]. Consequently, there is some evidence that increased SSTs have led to an increase in the intensity of the most severe tropical cyclones over the last decades [Emanuel, 2005; Kossin et al., 2007, 2013; Elsner et al., 2008]. On the other hand, tropical cyclone intensity is not only dependent on local SSTs, but also on other oceanic factors such as larger SST patterns throughout the tropics [Vecchi et al., 2008], upper-ocean heat content that controls feedback processes of intensification [Lin et al., 2013], ocean stratification [Emanuel, 2015] or salinity of the upper ocean [Balaguru et al., 2016]. In addition to the ongoing debate about the physical linkages between climate forcing and tropical cyclone activity, issues remain regarding the quality of historical data on tropical cyclone activity [Vecchi & Knutson, 2008] and whether the above-mentioned signals of intensification go beyond a deficiently quantified internal variability [Knutson et al., 2010].

Rescue operations in Port Arthur, Texas, 2017 © Staff Sgt. Daniel Martinez

The impacts on tropical cyclone activity of a warmer climate remain deeply uncertain [Ranger & Niehörster, 2012]. The current consensus however is that, globally, climate change is likely to lead to either reduced, or essentially unchanged, tropical cyclone frequency, but with an increase in average maximum wind speeds. This relationship might be caused by a trade-off between frequency and intensity [Kang & Elsner, 2016]. There is less consensus over projections for individual ocean basins. While the latest results do point to some definitive changes within individual basins, impacts and signals will be influenced by decadal and multi-decadal variability [AIR, 2017; LaRow et al., 2014; Villarini & Vecchi, 2012]. This lack of consensus also applies to the impact of ocean warming on other loss-relevant hurricane characteristics, such as storm size [Lin et al., 2013], genesis potential, and location of landfall, which are all currently under investigation [e.g., Sun et al., 2017] but remain uncertain for individual regions of highly concentrated exposure to tropical cyclone risk.

Other signals on the impact of ocean warming on tropical cyclones are also emerging such as a poleward migration in the latitude of the maximum intensity of tropical cyclones [Kossin et al., 2014]. The physical mechanism driving this result is hypothesized to be due to the expansion of the tropical circulation in response to rising SST. However, other mechanisms have been proposed based on inter-basin changes in tropical cyclone activity [Moon et al., 2015]. Regardless of the exact physical mechanism, changing modes of oceanic variability are playing an important role.

Furthermore, evidence has emerged for potentially longer tropical cyclone seasons. This can be observed for example in the North Atlantic, where the increase in SST is most pronounced [Kossin, 2008], or the South China Sea [Yan et al., 2012]. A longer hurricane season, starting earlier and ending later, would obviously increase the loss potential of a single season and, in addition, can change some storm characteristics that increase the damage potential of individual storms. This may have been the case for Hurricane Sandy, which hit the US East Coast at the end of October 2012. Sandy's interaction with an extra-tropical upper trough, a phenomenon that is more likely to occur later in the season, helped to increase its damage potential by maintaining the storm's intensity and influencing the cyclone towards making landfall.

There is strong consensus on the impact of warming on rainfall associated with tropical cyclones, which is expected to increase [Knutson et al., 2010] in part due to warmer air being able to hold more moisture. In support of this, Trenberth (2011) has shown that the moisture content of air over the ocean is closely correlated with SSTs [Trenberth, 2011]. Consistent with these findings, Emanuel (2017) estimates that today's probability of a hurricane with extreme precipitation hitting Texas is six-fold what it was in the late 20th Century and will be 18-fold by the end of the 21st Century [Emanuel, 2017].

An important loss component of tropical cyclones is the damage due to storm surge. Recent studies point towards a substantial increase in the potential for large storm surges induced by ocean warming and increased OHC. In case studies, Lin et al. (2012) find thatt here is an approximately 30% increase in surge and inundation along the coast from landfalling tropical cyclones that moved over areas with high OHC, as compared to those that do not encounter a region with high OHC along their storm track [Lin et al., 2012]. In addition to the impacts of rising OHC, SLR is also increasing the risk from storm surge of tropical cyclones. Using SLR scenarios for the Gulf of Mexico, Bilskie et al. (2016) found that the total area of developed and agricultural lands inundated by storms increases by large amounts with rising sea level. However, their results also indicate highly sensitive nonlinear responses from local alterations to the coastal floodplain elevations, including barrier island morphology and land use [Bilskie et al., 2016].

In summary, the damage potential of tropical cyclones has increased. This is not only due to the debatable increase in the maximum wind speed of the strongest storms, but is more clearly linked to SLR and the intensified hydrological cycle. Both effects add to the flood risk associated with tropical cyclones by increasing storm surge and precipitation extremes.

3.1.2. Extra-tropical winter storms

Due to the polar oceans warming at a greater rate than tropical oceans, the temperature gradient between the poles and the tropics has decreased in the lower atmosphere. On the other hand, warming of the upper tropical troposphere and cooling within the stratosphere at high latitudes can act to increase the latitudinal temperature gradient in the upper troposphere [Bengtsson et al., 2009; Harvey et al., 2014]. Changing meridional temperature gradients alter the position of the jet streams and consequently the main storm tracks of extra-tropical cyclones (ETCs) in both hemispheres. Observations suggest that these changes have led to a poleward shift in ETC tracks in some ocean basins [Fyfe, 2003; Ulbrich et al., 2009; Berry et al., 2011; Wang et al., 2012], which in turn might affect the spatial distribution of risk associated with ETCs in some regions. However, it is noteworthy that there are regional differences and remaining uncertainties to these findings due to issues with historical data and natural variability.

In addition to changing storm tracks, an analysis by Wang (2012) suggests that ETC activity over the period 1871–2010 increased slightly in the Northern Hemisphere, with more substantial increases being seen in the Southern Hemisphere [Wang et al., 2012; Wang et al., 2016]. However, notable regional variations in historical trends are evident, as are profound seasonal to decadal or longer-scale variabilities [e.g., Colle et al., 2015], combined with the uncertain clustering of storms [Karremann et al., 2014; Cusack, 2016], all of which hamper definitive conclusions for any given region and/or time period.

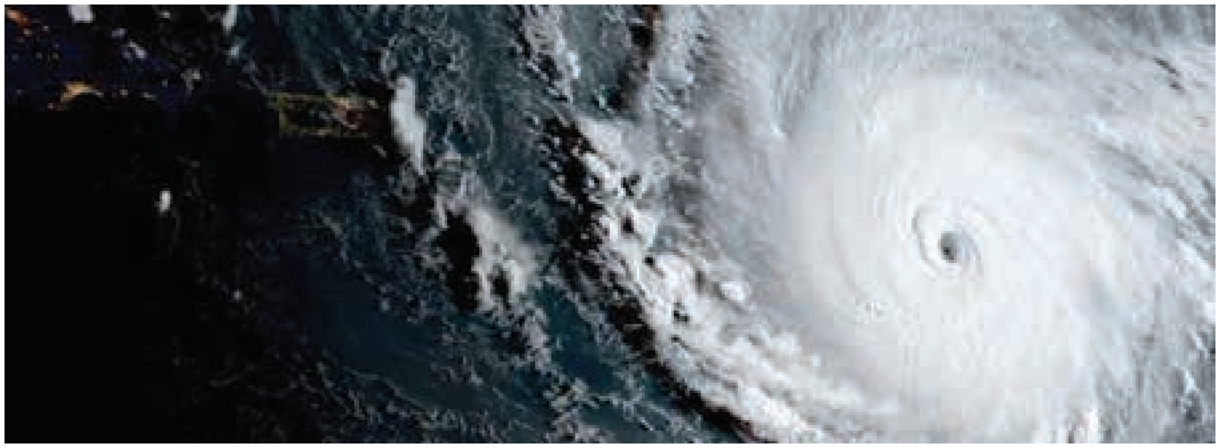
More recently, Vose et al. (2014) found a similar increase in storm frequency as well as an increase in intensity at mid- and high latitudes [Vose et al., 2014]. A possible mechanism that could promote storm intensity is larger amounts of latent heat in the atmosphere due to the increased moisture capacity of warmer air, which is confirmed by some modelling studies [e.g., Michaelis et al., 2017].

There is an ongoing debate regarding the observed changes as well as the general response of ETC activity to climate forcing. Some studies of historical ETC activity report increasing activity [Wang et al., 2012; Vose et al., 2014; Wang et al., 2016], whereas others report unchanged or even decreasing activity [Feser et al., 2015; Dawkins et al., 2016]. While some of these discrepancies in the analysis of trends are caused by low-frequency variability and substantial basin-wide and/or regional differences, other discrepancies arise from the classification of relevant ETC metrics [Ulbrich et al., 2009] or uncertainties in historical ETC data [e.g., Befort et al., 2016].

Climate projections of ETCs for the 21st Century [e.g., Mizuta, 2012] indicate that the global number of ETCs will likely decrease, primarily as a result of fewer weak cyclones. But, crucially, the number of strong cyclones is expected to increase. However, strong regional differences can be found in different ocean basins. There is some consensus that storm activity will increase over the North Pacific and more uniformly in the Southern Hemisphere [AIR, 2017]. For the North Atlantic and European regions, the results are more heterogeneous. A recent literature review by Mölter et al. (2016) finds consensus that the frequency and intensity of storms, cyclones, and high-impact wind speed will increase over Central and Western Europe. In contrast, future extra-tropical storminess over Southern Europe is very likely to decrease. For Northern and Eastern Europe, the results of the evaluation remain inconclusive [Mölter et al., 2016]. Some of the heterogeneity in regional changes is associated with the potential poleward shift of the storm track in climate projections for the 21st Century [Ulbrich et al., 2008; Bengtsson et al., 2009; Chang et al., 2012; Barnes & Polvani, 2015; Tamarin & Kaspi, 2017]. However, the link between regional variations and a poleward movement of storm tracks remains somewhat uncertain due to methodological biases and numerical modelling techniques [Harvey et al., 2014].

Although there is considerable uncertainty about some aspects of the impact of ETCs, the flood damage potential of ETCs is increasing due to various loss-relevant factors. For example, there is an increasing flood risk due to positive trends in precipitation, likely as a result of increased temperature and saturation vapor pressure [Trenberth, 2011], which will very likely continue in the future [Yetella & Kay, 2016; Nissen & Ulbrich, 2017]. Furthermore, studies show statistically significant positive trends in wave heights during the period 1950–2002 over most of the mid-latitudinal North Atlantic and North Pacific, which increase the destructive potential of ETCs and the associated storm surges [SREX, 2012; Vose et al., 2014]. It is important to note that the overall loss potential from ETC-induced flooding is also accentuated by SLR.

Even with an ongoing debate in the scientific community about climate impact on ETCs, it is clear that a number of oceanic components, such as the AMOC [McCarthy et al., 2017], the pattern of SST increase, the OHC [Nissen et al., 2014], or the observed loss of sea ice [Oudar et al., 2017; Screen et al., 2018], play an important direct and indirect role in ETC activity and its loss-relevant factors. Given the observed changes in all of those components (see Section 2.1.), a shift in the loss potential from ETCs is very likely. Furthermore, and similar to tropical cyclones, there is an upward trend in the loss potential from ETCs caused by SLR and the intensified hydrological cycle, which increases flood risk associated with ETCs from increasing storm surge and precipitation extremes.



Hurricane Irma, September 2017. © NOAA

3.1.3. Summary of the impact of ocean warming on tropical and extra-tropical cyclones

The frequency, intensity and spatio-temporal distributions, as well as other loss-relevant characteristics of tropical and extra-tropical cyclones, are dependent on a range of forcing factors that are directly or indirectly affected by ocean warming (see Sections 3.1.1 and 3.1.2). Many of these forcing factors have already changed and will continue to change with further ocean warming in the coming decade(s). Although there is a good physical understanding of the impact of some individual forcing factors on catastrophic storms, the combined impact of the full range of oceanic forcing factors is still deeply uncertain. However, given the critical dependence of loss-relevant characteristics of storms on oceanic forcing factors and the significant oceanic changes observed, a regime shift away from historical values might be deeply uncertain in its details, but, at the same time, quite likely to occur. The consensus for changes in tropical cyclones and ETCs is similar: overall numbers will decrease but the strongest cyclones will occur more frequently.

Whether this regime shift has already occurred, or has just started to occur, is a question science cannot answer today and will not be able to answer for quite some time due to the lack of high-quality data required for the detection of significant changes to (individual characteristics of) events with return periods of two hundred years and more. Significant or not, in most cases there is not enough data to estimate a linear trend, and inherent non-linear coupling and feedback effects in the climate system make any assumption of linearity very likely to fail. The result of this situation is an increasing uncertainty in the exceedance probability for the losses from tropical and extra-tropical cyclones. However, all else being equal, the impact of SLR and an intensified hydrological cycle are creating a positive trend in the loss potential from these events today and even more so in the coming decade(s).

3.2. Impacts from changing marine ecosystems

Given the critical importance of ecosystem services for the economy, in particular for developing countries, the impacts of ocean warming on marine ecosystems can have a variety of destabilizing effects that can trigger losses from various lines of insurance. For example, the potential for regime shifts in large parts of marine ecosystems could result in sudden shocks in a world with increasingly connected global supply chains and volatility in commodity markets. The acceleration of marine resource use globally over the past decades has led to a decline in fish stocks and overall marine ecosystem health [IUCN, 2016]. In fact, industrial fishing today covers more than half the surface area of the world's ocean, an area larger than four times the acreage of land-based agriculture [Kroodsma et al., 2018]. This has implications for developing countries in particular, as food security and coastal livelihoods are compromised. Ocean warming could lead to societal stress, food security crisis and market failure on a systemic, global level. The effects of potential shocks to marine ecosystems and the blue economy could affect various insurance lines including (but not limited to) terrorism and political violence, political risk, business interruption, marine and aviation, agriculture, environmental liability, and product liability.

While these indirect impacts on insured losses caused by systemic shifts should be taken seriously, there are many, more direct effects of changes in marine ecosystems that are increasing the loss potential in other lines of business. As science is just starting to understand the cascading effects, in the following sections, we present just some of the most relevant direct impacts of changing marine ecosystems that are affecting the insurance industry today.

3.2.1. Ecosystem impacts on flood risk

Every year coastal flooding causes a significant amount of economic damage and insured losses globally [Mohleji & Pielke, 2014]. The protective effects of various coastal habitats (marshes, mangroves, wetlands, etc.) help to reduce the damages from coastal erosion, inundation and storm surges via general wave attenuation, storm surge attenuation and maintaining shoreline elevation. The loss of substantial portions of these protective coastal ecosystems due to increases in sea level and water temperature, in combination with other stressors – such as land-use competition – is increasing the loss potential of flooding from extreme weather events in affected coastal areas.

As already mentioned, a recent publication [Narayan et al., 2017] suggests that the protection provided by coastal wetlands across the northeastern US was more than USD625 million in avoided flood damages from Hurricane Sandy alone. For census tracts with wetlands, there was on average a 10% reduction in property damage across the region. The damage reduction benefits varied by state, reaching as high as 29% for Maryland. In the same study, the benefits of wetlands beyond an individual hurricane were estimated for an event set of 2,000 storms. Annual flood losses to properties in Ocean County, New Jersey, located behind existing marshes, were predicted to be on average 20% less than for areas where marshes have been lost. The benefits of saltmarsh conservation for damage reduction are much higher for properties at lower elevations. Another recent study reveals highly sensitive non-linear responses of storm surge to local alterations to the coastal floodplain elevations, including barrier island morphology and land use [Bilskie et al., 2016]. The results of these studies highlight that the observed loss of huge tracts of coastal wetlands (see Section 2.2) is substantially increasing the loss potential from coastal flooding.

Scientist performing microbiological test on seawater samples. © Shutterstock

3.2.2. Ecosystem impacts on human health risks

Evidence suggests that the observed warming of the upper ocean could affect many vector-borne diseases through a range of mechanisms such as altering disease, vector, or reservoir distributions, or by increasing outbreak probability and risk of disease transmission [Kovats et al., 2003; WHO, 2004; Lloret et al., 2016]. As ocean temperatures rise, the risk of diseases currently associated with warm waters is increasing in historically cold-water regions.

There are early signs that human health is already being impacted by the enhanced survival and spread of tropical diseases due to increasing temperatures, particularly for pathogenic species of bacteria in the genus Vibrio (one of which causes cholera) and HAB species that cause a variety of neurological illnesses (such as ciguatera, which is caused by eating fish that contains ciguatera toxin produced by dinoflagellates).

From purely oceanic sources, human disease risk is most likely to be affected by changes in disease incidence for marine animals that are part of our diet, allowing for direct transmission of the pathogen to humans, or by the infections of wounds exposed during recreational activities (e.g., swimming). Increasing international tourism raises the possibility of exporting these diseases from tropical and sub-tropical destinations to other regions and increases the risk of 'tropical' illnesses in 'temperate' countries that may lack appropriate experience to recognize and treat them [IUCN, 2016].

The rise in toxic and harmful algae has adverse impacts on both living marine resources and public health, for example, fish and bird mortality and contaminated shellfish, as well as respiratory and gastrointestinal illnesses caused by brevetoxin exposures and neurotoxic shellfish poisoning [Ulloa et al., 2017]. Unfortunately, due to an insufficient understanding of how oceanic pathogens respond to the many environmental changes, the confidence in future projections of distribution of marine bacteria and viruses is low, creating substantial uncertainty around the impact of ocean warming on health insurance.

3.2.3. Ecosystem impacts on aquafarming insurance

(for further details see Appendix 1)

Aquafarming of fish is a fast-growing industry – today farmed fish contributes around 50% of the global fish consumption [FAO, 2016]. A growing human population and increasingly difficult fishing at sea will make aquafarming an even more important factor for food security in the future. At the same time, the loss potential from insured aquafarms is increasing due to growth of exposure and several environmental risks that increase with ocean warming, including increased rates of HABs (see Appendix 1) and the increased spreading of diseases in warmer waters at aquafarming locations. Covered causes of premature death of fish such as environmental factors, storm damage and marine-mediated diseases are all increasing in probability but with large regional variations. These factors are often coupled; for example, warmer water temperature promotes the growth factors for marine microbes while, at the same time, putting additional stress on the immunity of fish to disease.

A number of recent loss events have highlighted these increasing risks (e.g., the red tide event(s) in Chile in 2016) and indicate a trend towards more frequent events and larger losses. In order to

Fisherman on a beach blanketed with dead sardines in Tolten, Temuco, Chile, May 2016. © Felix Marquez/AP/Rex/Shutterstock control the risk, insurers need to introduce a careful approach to structured solutions, including limits for the maximum loss from a single event.

One way of mitigating the risk of increasing water temperatures is to move aquafarms to cooler waters. Ocean warming has already caused some aquafarmers to move poleward in order to follow the optimal temperature for fish farming in different regions. However, this exposes the fish to new types of environmental factors and diseases, and the regulated maximum number of fish farms per area limits the potential of this mitigation practice.

Other, more practical, ways to mitigate parts of the risks are currently being researched, for example bubble curtains that stop the transport of algae to aquafarming sites and oxygenation systems to prevent deoxygenation in warm coastal waters with no mixing. Furthermore, new observational systems can be used to assist in disaster management and decision-making to minimize potential losses. These practices should be monitored and potentially incentivized by risk-based pricing leading to premium reductions for good practice in aquafarming, as otherwise risks might become uninsurable.

As highlighted by a recent event, cargo insurance for the transport of live fish can also be impacted by HABs. In February 2017, an algal bloom killed some 170,000 salmon in Chile while they were being transported by boat. The algal outbreak was not located near any of the salmon farms that dot southern Chile's coastline but instead had infested sections of the shipping lanes used by producers. The boats, which recirculate ocean water into the tanks to keep the fish alive as they are transported, inadvertently passed through the infested waters and the salmon died in their tanks[10.]

Of concern to the business of shellfish farming, and also for some fish in tropical areas, consumption can transmit deadly toxins, such as ciguatera from harmful algae, and become an issue for product liability or product recall. Corresponding insurance products are likely to become more important to the aquaculture industry, especially to producers selling into the supermarket chains. Comprehensive traceability of the origin of aquaculture products is helping to drive demand for farmed fish in many countries, and there are also signs that consumers and their advocates are watching the industry closely. Again, the track record of aquaculture will determine future availability and cost of these classes of insurance [Secretan et al., 2007].

3.3. Changes in asset risk

The growing importance of the blue economy at global, regiona and national levels, combined with its dependencies on marine ecosystem services, is changing investment strategies and the value of assets in different parts of the economy such as the fossil fuel industry [McGlade & Ekins, 2015]. While there is a considerable investment opportunity in the blue economy, there are also considerable risks from ocean warming that need to be incorporated into investment strategies.

Stranded assets are defined as assets that have suffered from unanticipated or premature write-downs, devaluation or conversion to liabilities. While asset-stranding is a natura feature of any market economy, it is more significant when related to environmental factors because of the scale of stranding that can take place, and could constitute a substantia write-down in the fundamental value of financial assets [Dietz et al., 2016]. Changes to the physical environment driven by ocean warming – and society's response to these changes – could potentially strand entire regions and global industries within a short timeframe, leading to direct and indirect impacts on investment strategies and liabilities. In addition, the value of assets in other classes might be affected by the rise of the blue economy where they compete with and potentially replace traditional sectors, such as through new marine energy resources. This could lead to stranded assets in traditiona asset classes (e.g., fossil fuel) that might decrease in value. Over recent years the topic of stranded assets has become increasingly high profile [Lloyds, 2017; Carney, 2015] and also needs to be assessed in the context of ocean risk and the rise of the blue economy.

Aerial view of offshore windfarm, wind turbines at sea, UK.
© David Tipling/FLPA

Asset stranding due to changes in global economic processes can already be observed today. For example, the increase in renewable energy generation (including offshore wind), worsening air pollution, and decreasing fresh water availability caused by climate change, coupled with widespread socia pressure to reduce China's demand for thermal coal, have negatively impacted coal-mining assets in Australia [Caldecott et al., 2013; Lloyds, 2017].

While methodologies to manage the risk of stranded assets as a result of changing environmental factors have been laid out in detail [Lloyds, 2017], there is an urgent need to create additiona scenarios for potential shocks to marine ecosystem services as they are playing an increasingly important role.

A natural question related to the impacts of ocean warming presented in this chapter is: "How can we quantify the financia impacts and model ocean risk?" We begin to answer this question in the next section.

4. MODELLING OCEAN RISK

Emerging ocean risks require new risk modelling solutions. To properly account for trends in ocean risk there is a need to better incorporate the effects of ocean warming and climate change into traditional risk models of extreme weather events. In addition, there is a need for risk models that quantify the probability of losing ecosystem services. Such ecosystem risk models would have the potential to unlock new insurance markets in the space spanned by ocean risk, international development programs and the blue economy.

In general, risk models consist of four components: 1) an exposure or inventory database; 2) a vulnerability component that describes damage to the exposure as a function of hazard intensity; 3) a hazard event set or simulation of events; and 4) a financial component that accumulates damages and calculates resulting losses to the exposure.

Following the above-mentioned concept, one requirement for the development of risk models is a good inventory for the assets at risk by creating comprehensive maps of marine ecosystems. In addition, as with all risk models, there is a requirement for historical data of loss events. The hazard event sets and financial components can (partly) be adapted from existing risk models. For the vulnerability component it is necessary to develop an archive of observations of damaging events that can be used to develop empirical vulnerability functions and/or a series of laboratory experiments to increase scientific understanding and enable the development of experimentderived vulnerability functions. These requirements are a challenge, in particular when it comes to extreme events that damage or destroy marine ecosystems. However, there are positive and encouraging examples of how these challenges can be met [see Appendices].

4.1. Data requirements

Faced with the potential of losing critical marine ecosystems, it is increasingly urgent to collect ocean data and observe marine biological components in a more integrated fashion to provide the long-term baselines needed for risk transfer solutions. Many innovative risk products use relatively simple parametric triggers based on historical records. Long time series of physical and biological ocean data will be needed to realistically define triggers, characterize risk and properly price the risk. T

o support new risk products, historical datasets of marine ecosystems will need to be maintained and, where possible, expanded into new areas of the ocean where there are few or no sustained observations. Many new international research initiatives such as the Global Earth Observation System of Systems (GEOSS), with the Global Ocean Observing System (GOOS) as the ocean observation division of GEOSS, and the Group on Earth Observations Biodiversity Observation Network (GEO BON), are being set up to address these issues. Future biological monitoring of marine ecosystems, through an integrated and sustained observational approach, will be essential to improve our understanding of ocean risk and the development of ocean risk models [IUCN, 2016]. Alongside the need for data from historical events, there is a 'simple' need for high-quality and highresolution maps of the global distribution of ecosystems, habitats and species. Impressive first steps towards such an inventory have been set up in public-private partnerships, such as the Global Reef Record[11], the XL Catlin Seaview Survey[12], and the Global Atlas of Ocean Wealth from the work of The Nature Conservancy [Spalding et al., 2016].

SVII on Osprey Reef, Coral Sea, Australia.
©The Ocean Agency/XL Catlin Seaview Survey

4.2. Potential modelling solutions for ocean risk

4.2.1. Stationary risk models in a transient environment?

The inherent non-stationary climate induced by ocean warming and the associated implications for the probabilities of extreme weather events raise questions regarding the suitability of using risk-modelling approaches based on the expansion of historical data. As climate isn't stationary but transient, as highlighted by the observed accelerated ocean warming, there is a non-zero probability for a 'big surprise' or 'black swan' event – one or a sequence of events that fall outside of the event categories currently looked at by event sets derived from historical data and physical assumptions based on observed climatic conditions of the past.

Even if one assumes that the probability for a big surprise is negligibly small, there still remain important open questions regarding the use of risk models. The lack of historical and observational data and the existence of competing theories formalized in competing risk models, leads to a multitude of different answers for the return periods of extreme events, especially in today's transient environment. Unfortunately, it is difficult to assign confidence to, or the probability of, one answer being better than the other, a situation that can be described using the term 'ambiguity'[13]. It is characterized by a lack of precision in the knowledge of the probability distribution function (PDF) of losses rather than the lack of knowledge of where exactly in the PDF next year might fall. In the future, ambiguity created by accelerated ocean warming might be reason enough for rating agencies or insurance regulators to penalize companies that fail to address these issues in their enterprise risk management [Niehörster et al., 2013].

4.2.2. Incorporating the protective effects of coastal ecosystems into commercial risk models

Despite the issues associated with nonstationarity, there are relatively simple steps that can be taken to improve estimates from today's risk models. For example, risk models should be improved to capture the effects of nature-based solutions for flood risk and better incorporate the protective effects of coastal ecosystems on flood damage. While there are pilot studies that highlight the importance [Narayan et al., 2017], the technical approach for simulating the effects is not yet complete and far from being a standard. The ability to model the protective effect of coastal ecosystems would improve risk estimates in general. Furthermore, including the protective effects could help underwriters to identify profitable underwriting capacity where current premiums might be above the actual technical price assigned to the unmodelled protective effects. In addition, this ability would enable the quantification of long-term benefits of wetland presence for flood risk reduction. Such knowledge would aid decision-making and support urgently needed cost-benefit calculations for coastal planning. Risk models could then help to quantify, at least partially, the value of ecosystem services provided by coastal waters.

4.2.3. Risk models for marine ecosystems

There are various ways of modelling marine ecosystems on a local and regional scale. The most comprehensive – and computationally most expensive – method is a two-way coupling of dynamic ocean models with ecosystem models. Less computationally expensive, but in many cases still fit-for-purpose, would be models of marine ecosystems that can be nested into ocean models that provide the boundary conditions for local or regional ecosystem models that do not influence the physical dynamics of the ocean model [Van Hooidink, 2013, Van Hooidink et al., 2015]. As well as dynamical modelling, parametric approaches based on multivariate statistical relationships between ecosystem and external parameters can also be used for ecosystem modelling [Cooper et al., 2015].

As examples, models for coral bleaching [NOAA, 2009] or HABs exist (e.g., NOAA's HAB-OFS – harmful algal bloom operational forecast system – or the EU-funded HAB forecasting system ASIMUTH [Davidson et al., 2016]) that, when coupled to observational systems, are used as operational forecasting models. These types of models could be coupled to a long time series of numerically modelled oceanic boundary conditions to provide synthetic hazard event sets for coral bleaching or HAB risk models.

4.2.4. Ecosystem coupling in Earth System Models for simulating long time series and future projections

Improvements in ecosystem and coupled climate models are needed to provide a comprehensive overview of ecosystem change and directions of change in the future. A common problem in this respect is the inability to determine sufficient detail to make models more applicable at the regional scale. It remains to be seen if the required resolution can be achieved with global climate models or if statistical or dynamical downscaling techniques will be the only way to get to the required scales for the assessment of ecosystem impacts under climate change. However, the inclusion of feedback between marine biological processes (such as carbon and methane storage by coastal ecosystems) and climate in coupled climate models might help to reduce the uncertainty in future climate projections and, at the same time, allow an improved understanding of the complex and dynamic interactions between the biosphere and the climate system where scientific theories are incomplete [IUCN, 2016].

4.2.5. Integrated Assessment Models for evaluation of ecosystem services and climate change

In terms of quantifying the long-term effects of marine ecosystem services in different climate change scenarios, an improved representation of marine systems in Integrated Assessment Models (IAMs) would be beneficial for policy-making and discussions of costbenefit ratios for different emission scenarios and adaptation measures. Some relevant and encouraging approaches to using IAMs have been developed for this purpose [Dietz et al., 2016], but often lack a proper representation of ecosystem services in the modelling schemes.

Most of these approaches to modelling ocean risk are in the early stages of development and not yet suitable for non-research purposes. However, this does not mean that one should not already consider the implications of, and potential insurance solutions for, changes in ocean risk.

5. NEW INSURANCE SOLUTIONS FOR OCEAN RISK

Ocean warming not only changes the loss potential of extreme weather events, it also increases the chance of extreme events in critical marine ecosystems and the associated loss of ecosystem services for the blue economy. These events have the potential to affect the wellbeing of many people, communities and nations, and to create societal stress and economic failure on a local, regional and global scale. Recent socio-economic changes coupled with new and emerging ocean risks require novel risk management strategies and instruments that together could be considered part of the solution to ocean risk. Experimentation and time are needed to develop viable risk transfer solutions and for all parties to become comfortable with their use. But, ultimately, insurance solutions could support the global effort to enhance resilience to ocean risk.

5.1. Conceptual framework for insurance solutions to ocean risk

Many aspects of ocean risk will affect economies in the developing world and require novel forms of insurance. However, the developed world is also subject to ocean risk. In addition to insurance products for loss of ecosystem services, there is an immediate demand for more standard products based on physical assets.

To conceptualize a business development approach for insurers, a two-dimensional space is a convenient way to classify the range of potential insurance solutions associated with ocean risk and the innovation required (see Figure 10). One axis depicts the market continuum between developed and developing countries, the other the continuum between the more familiar physical impacts of ocean warming (such as SLR, ocean currents or weather events) and the impacts on ecosystem services, at the other end of the spectrum.

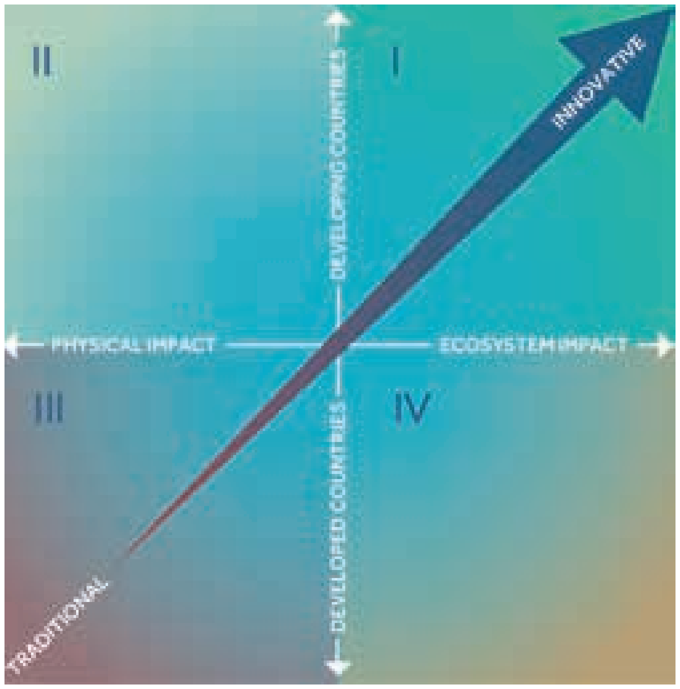


Figure 10: Conceptual diagram illustrating the continuum of ocean risk insurance products based on a country's development level and the type of insured asset. Each quadrant represents a different business segment with different risk transfer solutions. The diagonal provides a very general sense of the opportunity stage and innovation needed for products in each sector.

As depicted in Figure 10, ocean risk will provide insurers with opportunities for new products in the ocean risk 'space'. A variety of insurance products exist or could be designed for each quadrant, and the individual preferences of insurers will guide the choice of one or more quadrants as a focus for business development. For illustrative purposes, one example of insurance products for each quadrant will be provided (see Sections 5.2 and 5.3).

Hotel zone, Cancún, Quintana Roo, Mexico. © Kashfi Halford

However, as quadrant I requires the greatest amount of innovation for the development of insurance solutions (see diagonal in Figure 10), we provide more context for insurance solutions around the risk of losing marine ecosystem services in developing countries (see Section 5.2). Less context will be provided for examples of products in quadrants II-IV as these products are more similar to traditional insurance business (see Section 5.3).

5.2. Insurance solutions for marine ecosystem services in developing countries (Quadrant I)

5.2.1. International development goals and closing the protection gap (context for Quadrant I)

An emerging trend in international development policies is the inclusion of risk transfer mechanisms for extreme events in developing countries [OECD, 2014]. The insurance industry can support risk transfer in developing countries and play a critical role in increasing large-scale global resilience by offering innovative insurance solutions. Solutions could involve public-private partnerships (PPPs) at a sovereign level via multinational climate change agreements, or through other arrangements that increase resilience to cascading effects of ocean warming and climate change.

International organizations (e.g., United Nations, World Bank, etc.), which support development and climate change adaptation in developing countries, are increasingly highlighting the effectiveness of insurance for financial resilience and post-disaster recovery of economies [World Bank, 2013, 2014; OECD & World Bank, 2016]. While there is an important role for risk mitigation through emission reduction and climate adaptation, it is becoming increasingly clear that risk transfer solutions for unavoidable risks enhance the resilience to disasters in developing countries. If those risk transfer solutions are designed to protect and restore ecosystems at risk, they can themselves become a strategy for adaptation and mitigation.

Within the framework of the United Nations Framework Convention on Climate Change (UNFCCC), climate risk mitigation and adaptation for developing countries is funded by the Green Climate fund (GCF) [Green Climate Fund, 2015]. At the 15th meeting of the Conference of the Parties to the UNFCCC in 2009, developed countries committed to providing USD100 billion per year by 2020 as capitalization of the GCF [UNFCCC Conference of the Parties, 2009]. Funding will be provided by the GCF for proposals that support climate adaptation and risk mitigation, of which insurance instruments can be an effective part.

Another initiative that came out of international climate negotiations is the InsuResilience initiative[14] that aims to provide access to direct or indirect climate risk insurance by 2020 for up to 400 million additional people in the most vulnerable developing countries [Zwick et al., 2017]. To achieve this ambitious goal, the InsuResilience Solutions Fund was created in order to support PPPs that are in line with the goals of the initiative. Technical assistance and premium support facilities complete the fund. The long-term objective is to strengthen financial resilience in emerging markets and developing economies (EMDEs) by developing governmental capacity to create risk transfer solutions through insurance. It is noteworthy that the InsuResilience goal to provide indirect climate risk insurance can be provided on either a sovereign level or by protecting critical infrastructure such as marine ecosystems.

The attempt to close the insurance protection gap is an important global effort, and it needs to be recognized that for many developing countries a focus on protecting the blue economy is a critical component of this effort. While leveraging insurance to support resilience and post-disaster recovery from geophysical or meteorological extremes is currently the main goal of some of the above-mentioned PPPs, there is a lack of concepts for protecting critical marine ecosystem services.

Developing a risk transfer mechanism for marine ecosystem risk is particularly relevant for countries where the blue economy contributes a high percentage to the GDP. The lack of a corresponding risk transfer mechanism leaves a gap in the resilience-building strategies for countries with relatively large coastal areas, as marine ecosystem services often make significant contributions to their economies (e.g., ~20% in Indonesia). As the marine ecosystems that provide these critical services are changing, these economies are increasingly at risk of failure, with potentially severe consequences for hundreds of millions of people.

Apart from mitigation and adaptation, there are two insurance options to reduce the risk in affected countries that can be used in combination: a) increase the use of insurance by the population and the blue economy for extreme events in marine environments; and/or b) insure the restoration of ecosystems that provide critical ecosystem services. While the former would be a more traditional insurance approach, it doesn't protect the asset at risk, which is the marine ecosystem itself, as it provides the necessary resources for the economy. To protect the asset at risk, one needs to tackle the technical and legal obstacles to pursuing the latter option and start thinking about insuring the restoration of critical marine ecosystems after damaging events. This would increase the resilience of developing countries and thereby candidates for funding from organizations such as the GCF or InsuResilience that support resilience-building initiatives for developing countries.

5.2.2. Marine ecosystem services and insurance solutions: resilience funds (Quadrant IV)

The impacts of ocean warming and other stressors are stimulating the development of a new paradigm of active management and the restoration of ecosystems at risk. Developing human interventions using the ecologically sensitive design of artificial structures may become increasingly important as the effects of accelerated ocean warming put marine ecosystems under increasing stress [IUCN, 2016]. This could drive approaches away from merely 'protecting ecosystems' towards more active interventions to revive or restore ecosystems after extreme events that lead to disruption or loss of ecosystem services. Such post-disaster interventions should focus on sustaining resistance or increasing resilience in natural systems and their services, and increasing their adaptive capacity [IUCN, 2016]. Regular maintenance initiatives combined with restoration of ecosystems after extreme events, as recommended by the IUCN, is possible and could be financed by insurance instruments that provide capital for the necessary restoration after damaging events.

One very recent example of how insurance can be leveraged to create resilience is the Reef Resilience Fund in Mexico that was designed in partnership by The Nature Conservancy and Swiss Re[15,16]. As a pilot project, it provides a potentially scalable insurance mechanism for coastal resilience that leverages private capital structured in a fund format with underlying parametric insurance triggers. This pilot project is helping to build resilience in the Mexican resort towns of Cancún and Puerto Morelos, where the economy and community are heavily dependent on tourism related to the Mesoamerican Reef.

The general idea behind resilience funds is to leverage private and public capital to monitor, protect and maintain ecosystems and, using insurance pay-outs, to restore them after damage from extreme events (Figure 11). Ideally, countries and the blue economy will continue to benefit from the ecosystem services provided after the completion of the restoration programs. Pay-outs are scaled to cover restoration rather than the value of the ecosystems provided. Single ecosystems (e.g., a coral reef) could be covered by a parametric insurance product that is triggered by a pre-agreedupon event (e.g., bleaching of more than a certain percentage). The insurance pay-outs then quickly provide the necessary resources for the best possible restoration of the ecosystem insured.

When considering ocean risk and the efforts to protect and insure the restoration of critical marine ecosystems, there is significant potential for synergies between sovereign-level insurance and products aimed at stakeholders from the blue economy whose businesses are built on marine ecosystem services within the Exclusive Economic Zones (EEZs) of the particular country.

Governments, supported by international organizations, could build PPPs with stakeholders from the blue economy who operate in their EEZs, or with investors who are aiming to offset negative impacts of real estate elsewhere[17]. These PPPs could work with independent resilience funds that monitor and protect the ecosystem at risk and restore it after damaging events have occurred. For such restorations, insurance pay-outs would be used to activate postevent programs that guarantee the quickest possible restoration of the ecosystem itself, and hence its ecosystem services, to the economy and people of the country (see Figure 11).

In general, risk profiles and operational costs for ecosystem insurance in developing countries are unfavorable for insurers without sufficient business for it to scale. However, given the scale of worldwide ecosystem loss[18], there is an opportunity to develop insurance mechanisms that are scalable, as well as diversify and distribute individual risks. Risk pools created by multinational organizations and funds not only lower the operational costs for individual insurers but, at the same time, diversify the risks.

The concept of creating risk pools for insurance is not new [World Bank & BMZ, 2017]. Some examples of existing risk pools created to lower insurance costs and help provide the necessary scientific support are: African Risk Capacity (ARC), Caribbean Catastrophe Risk Insurance Facility Segregated Portfolio Company (CCRIF SPC), and the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI). These examples are all focused on catastrophe risk, but, unfortunately, as of today, none are focused on ocean risk.

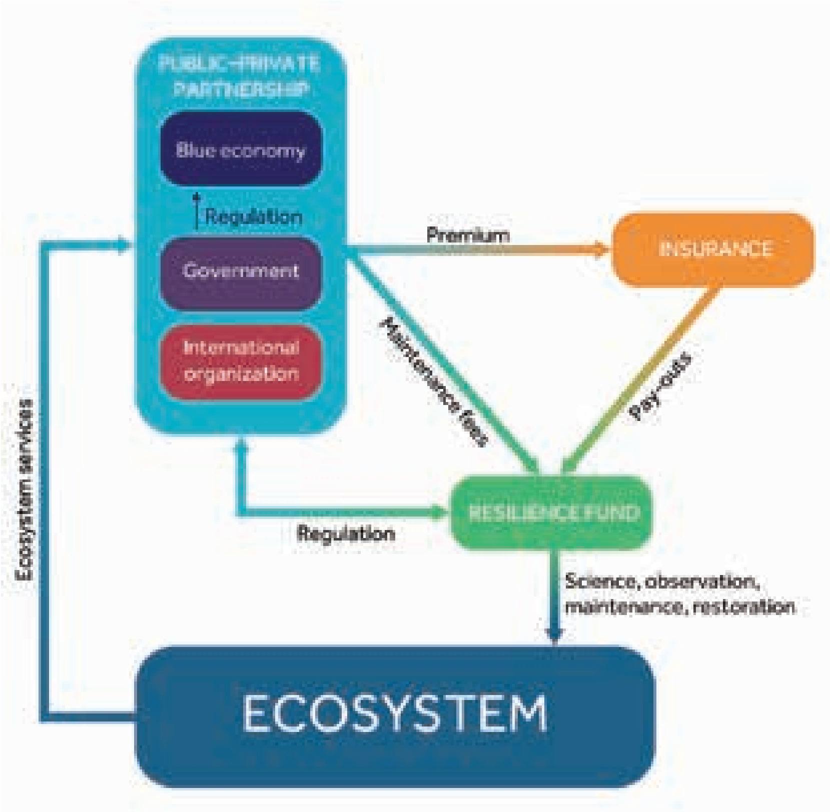


Figure 11: Possible structure of resilience funds in developing countries for sustainable ecosystem services and their insurance elements

5.3. Other insurance solutions for ocean risk (Quadrants II, III, IV)

5.3.1. Developing countries and physical impacts of ocean risk (Quadrant II)

Sea-level rise will pose an increasingly difficult threat for developed and developing countries [Dasgupta et al., 2007]. The initial impacts will likely be felt through an increasing frequency of nuisance flooding and/or during extreme events such as coastal flooding associated with storm surge. Repairs and rebuilding, either in place or further inland, and the recovery of contaminated agricultural land and infrastructure for tourism after a flood event will be costly. Developed countries are likely to have sufficient resources (e.g., government resources and/or private insurance) to recover from such events. Many developing countries on the other hand will be less resilient and require outside resources in order to have the best possible chance of recovery.

The impacts of nuisance flooding will likely be manageable as they are not catastrophic events. However, particularly for developing countries, the effects of storm surge can be catastrophic. For example, in 2008 Cyclone Nargis struck Myanmar and generated a tremendous storm surge along the Irrawaddy Delta that caused over 138,000 deaths and USD10 billion in damage [Enz et al., 2009]. Less extreme examples occur more frequently but can still cause significant problems for those affected and their national governments. Unfortunately, the risk of such events is growing in many developing countries as coastal populations and the infrastructure increase and sea levels rise.

A potential new risk transfer solution to help developing countries respond to growing flood risk is a sovereign-level, coastal flood insurance product that would cover the costs of rebuilding after a storm surge event. Some countries, such as Cuba, are already working on such schemes and are waiting to apply for premium support from donor organizations [Stone, 2018]. Such a product would require features that are common in existing sovereign-level insurance programs. First, in order to provide relief in a timely manner, a parametric trigger for the event would be needed. This could be based on objective observations, for example tide gauges, satellite observations of storm intensity, or the extent of inland flooding. If in situ observational platforms were used, they would have to be 'hardened' to withstand the extreme event. The choice of trigger would require a significant amount of upfront work. This work would entail determining the likelihood of flooding based on meteorological conditions and understanding local factors that could either offset or accentuate eustatic SLR.

A second common feature of sovereign-level insurance products is the involvement of multiple countries to take advantage of geographic diversification. Existing examples include CCRIF in the Caribbean, PCRAFI in the Pacific and ARC in Africa. In all of these regions, countries with coastlines will likely have a growing risk of coastal flooding as sea level rises. The geographic diversity associated with a network of countries distributed across the tropics could potentially form an attractive risk pool if they jointly participated in an insurance program for coastal flooding.

In most cases, developing countries have competing demands for a limited budget and it can be difficult to afford premium payments for insurance to cover low-probability, low-frequency events. However, a risk transfer product for flooding in developing countries would increase sovereign-level resilience and potentially include adaptation components for rebuilding and, therefore, qualify for premium support from international organizations such as the GCF or the InsuResilience initiative. In addition, other potential donors might find a planned premium support to be preferable to unplanned larger payments after an event.ì

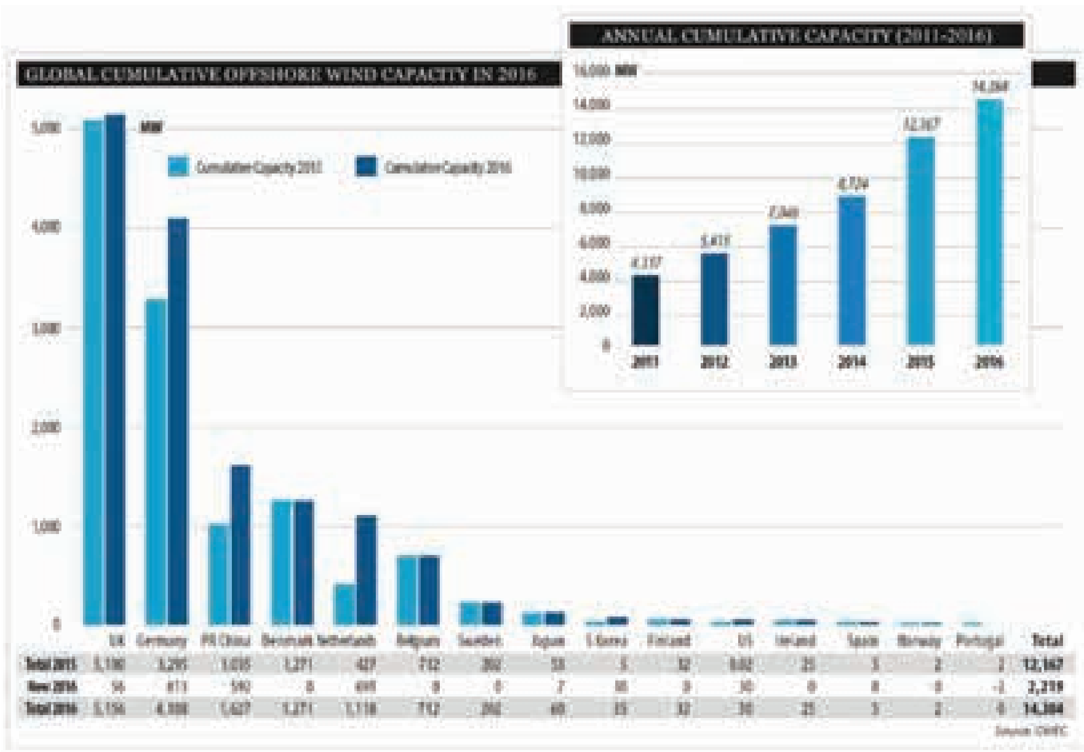


Figure 12: Global cumulative offshore wind capacity by country in 2016 and changes since 2015 (main figure). Annual global cumulative capacity from 2011 to 2016 (inset, top). Source: GWEC, 2017.

5.3.2. Developed countries and physical impacts of ocean risk (Quadrant III)

Here we give just one of many examples of an insurance product for a more traditional market of ocean risk in developed countries that aims to cover physical damage to economic assets: offshore wind insurance. Offshore windfarms can pose an investment challenge to a traditional insurance structure in a relatively new and rapidly growing segment of the blue economy.

Starting in 1991 with the first offshore wind park in Denmark, the number of offshore windfarms and the cumulative capacity for energy production has been growing rapidly and is now over 14 gigawatts globally, nearly 90% of which is produced in the North Sea (see Figure 12) [GWEC, 2017].

Offshore windfarms are likely to become more prevalent as the demand for renewable energy grows[19]. The price of an average windfarm with 80 turbines is around USD1.7 billion. Project pipelines for new offshore windfarms are strong in the US and Japan. And even in Europe, where offshore wind has already grown into a large industry, investments for new offshore windfarms until 2030 are projected to be at around USD160 billion [Corbetta et al., 2015].

Of the industries that have the potential to replace fossil fuel, the offshore wind industry is one of the most important for increasing sustainable energy contributions to global energy production. Financing the development of and offering insurance for offshore windfarms provides opportunities for investments and growing underwritten premiums. However, there are some important issues to be considered before entering this market.

Today, the insurance industry provides coverage for a wide range of situations, from the start of construction and cable laying, to disruption during both construction and operation, to losses due to equipment failure and catastrophic events. Insurance premiums for offshore windfarms in 2020 are projected to be at around USD800 million and will continue to grow [GWEC, 2017].

However, the technology for wind turbines and offshore windfarms is relatively new, having only started in 1991, and it is still evolving. Hence there is a significant learning curve for all parties in the transactions. The novelty of the wind product leads to pricing uncertainties due to the lack of experience with technology and loss events.

Insurers of offshore windfarms would do well to learn from the experience of insurance for offshore oil platforms, where premiums continued to increase in response to the occurrence of severe events that were outside past experience [Swiss Re, 2016]. Prior to the 1998 Piper Alpha disaster, premiums were set without engineering input and, for some companies, based on assets and adjusted for losses. In retrospect, this was a naive approach. After the Piper Alpha loss, insurers increased rates, started to demand more engineering information, and began monitoring exposure aggregation. But, even then, the rates were too low. In 2005 hurricanes Katrina and Rita damaged over 3,000 platforms and caused ~USD20 billion in losses; 113 platforms were destroyed, and 108 of those were built to pre-1988 standards. After 2005, rates more than doubled, deductibles were raised and limits were lowered. This history suggests that insurers should be cautious in their pricing strategies, by making adequate allowance for uncertainty in new products with limited loss histories such as offshore windfarms.

In the case of insuring offshore windfarms, a business approach that repeats the mistakes made in offshore oil insurance should be avoided. Given the long lifetime of offshore windfarms, significant uncertainties about conditions for the windfarms lie ahead. Through the non-linear and combined effects of SLR, potentially intensifying storms and changing wave dynamics, the risk for offshore windfarms is linked to the effects of ocean warming. Even the effects of future underwater landslides on the cables connecting the windfarms to the grid need to be considered. Given such concerns, a prudent approach for offshore wind insurance would be to add prudential margins to avoid negative surprises. In addition, a sensible approach to layering the risks and managing accumulations of associated risks should be followed before growing a company's exposure to offshore windfarms.

Similar to other climate-related risks (see Sections 3.1 and 4.2.), one could argue that in the case of offshore windfarms there really is a lack of precise knowledge about loss-occurrence probabilities, which could encourage a switch to a preference-driven ambiguity framework for risk management [Niehörster et al., 2013; Walker & Dietz, 2017].

5.3.3. Developed countries and ecosystem impacts (Quadrant IV)

The frequency of coastal HABs is likely to increase with ocean warming as some of the key environmental drivers for HAB events will be enhanced (see Section 2.2 and Appendix 1). HABs cause a broad range of economic losses and can be very disruptive to economic sectors such as commercial fisheries, tourism and hospitality. The economic damage in these sectors caused by blooms is analyzed in a recent study by Sanseverino et al. (2016) and comprises losses due to fishing closures applied to recreational fishers, reduction in amusement and recreational experiences of visitors near the beaches, and a drop in hotel bookings, restaurants and the number of rented holiday homes and boats [Sanseverino et al., 2016]. The economic effects on tourism and the recreational sector are influenced by the time period of the HAB and changes in the coastal water environment produced during a bloom. These changes include the discoloration of water, the accumulation of dead fish on beaches and the smell coming from algae decomposition [Hasselström, 2008; Sanseverino et al., 2016].

The impact of HABs in terms of economic losses was highlighted by recent HAB events such as those along the US West Coast, the Gulf of Mexico, the Baltic Sea and the Irish coast. Due to the growing importance of beach tourism and other industries sensitive to HAB events, local and regional economies can be severely disrupted especially by long-lasting HABs. Given the increasing probability of occurrence of HAB events, insurers could aim for a technical approach to estimate the associated risks and offer risk transfer to prevent local or regional economic disruption.

Public-private partnerships for regional or local economies could be created (similar to the structure of the resilience fund presented in Section 5.2.2) that would work together with the insurance industry towards a transfer of risk of HAB-induced losses to cover, for example, the risk of economic losses and clean-up costs for affected coastal areas and beaches. A key element of the PPP would be the maintenance of a healthy marine environment through monitoring and regulation, with a focus on avoiding eutrophication.

Although there are still serious challenges for the development of risk models to better estimate the risks from HABs, there have also been some encouraging first steps towards modelling HABs (see Appendix 1 and Chapter 4). However, the event definition is challenging as HABs can persist from weeks to months and, similar to modelling flood events, 'hours clauses' could complicate both the contract situation and an event-based risk modelling approach to HAB risk. In order to make this risk transfer a viable product for all parties involved, for each region one must define a meaningful definition of a trigger event that strikes a balance between economic impact, a limited spatial domain and a restricted time period. Given the changes in ocean risk and the potential for new business opportunities, how should individual companies and the insurance industry as a whole respond in order to maintain and grow sustainable business? We provide some insight in the next section.

6. HOW TO RESPOND TO CHANGING OCEAN RISK

The insurance industry should acknowledge the changes in ocean risk associated with the warming of the ocean and the resulting changes in ecosystems, sea level, climate and extreme events. In response to these changes, companies should review and, if need be, revise their current business strategies. A prudent course of action could be to update a company's risk management practices. At the same time, however, changes in ocean risk will provide new business opportunities both for individual companies and the entire insurance industry. Novel insurance solutions and the existing capacity of the industry can be leveraged to manage ocean risks and reduce the economic impacts of changes in the ocean. Insurance solutions can help to develop risk perception and incentivize behavioral change, both of which help protect important marine ecosystems and build resilience to ocean risks.

6.1. Individual company response: business opportunities and risk management

Changes in ocean risk could be assessed as part of a company's efforts to manage its overall exposure to loss. The scope of the assessment could include a consideration of the sensitivity of its assets and book of business to the impacts of ocean warming and, if deemed necessary, include adjustments to its book of business. The review could consider not only the current risk of the book, but sensitivity of its book to future changes in ocean risk due to ocean warming. As shown in this report, there are a variety of factors to consider, such as a change in flood risk due to sea-level rise and changes in extreme event intensity, rate of occurrence and location. The review effort could consider factors beyond the impacts to the natural catastrophe exposure and extend to other lines of business such as health, shipping, political risk or product liability that might be impacted in scenarios of systemic shocks to marine ecosystems.

Accounting for changes in ocean risk could require a company to make a concerted effort to improve its knowledge of and expertise in perils related to ocean risk. This could include training existing staff and hiring additional staff and/or consultants with the required expertise.

The goal of the review would be to consider expected changes and known unknowns, and the nature of this exercise would require significant effort and creativity. In some cases, the exercise could use past events as analogues for future events (i.e., defining deterministic/realistic disaster scenarios). For example, what is the business interruption risk of supply chain disruption in Rotterdam due to extensive port disruption from an intensified extra-tropical storm coupled with SLR, or the resilience of Long Beach port to a tsunami whose effects were enhanced by elevated sea levels? An analogue for this type of exercise would be the supply chain disruption from the 2011 flooding in Thailand. Defining realistic disaster scenarios (RDS) for such events could help to quantify the insured loss of the events and would be a good start to assess the overall exposure to ocean risk.

In other cases, the effort would be based on anticipated future events without a past analogue. For example, what would be the impact on a company's business if sea lanes across the Arctic were opened? There is no record of loss experience to guide model development or pricing from past events. For example, what would a company's liability be if a cruise ship were stranded in remaining pack ice and there was an outbreak of Legionnaires' disease? How would loss and liability be affected by the lack of infrastructure support, or the inability of other ships to access the cruise ship?

But, importantly, the review should strive to extend beyond relatively familiar scenarios to consider unexpected risk, in essence unknown unknowns. For example, what would be the impact on the book of insurance if due to a viral vector in a salmon fishery there were an outbreak of a paralytic disease that spread throughout a population before it was traced to the farmed salmon?

In addition to assessing risk, companies should consider building their capacity to develop new lines of business. As shown above, there are a variety of existing and evolving opportunities (Figure 10) that range from more traditional to more innovative. A company should consider how it might facilitate the penetration of traditional insurance products in developing countries as well as work to develop innovative products that would be of interest to developed and developing countries. For examples, see a recent World Bank publication on Sovereign Climate and Disaster Risk Pooling (World Bank & BMZ, 2017). The opportunities for de-

Large harbor cranes loading container ships in the port of Rotterdam. © VanderWolf Images/Shutterstock veloping ecosystem insurance are huge if the challenges in defining the product can be overcome. In many cases, developing these products will require developing new collaborations with NGOs (recall the reef ecosystem example involving The Nature Conservancy and SwissRe in Chapter 5) and/or international development agencies as exemplified by GCF or the InsuResilience initiative.

In addition to creating new business opportunities and changing ocean risk, future changes in ocean warmth and climate will challenge insurers to update risk management approaches, risk models and traditional methods of assessing risk. Currently, risk assessments are based on the premise that hazard and vulnerability are stationary. However, we are now clearly in a non-stationary environment, and the pace of change is increasing. This transient environment challenges the assumptions that are traditionally used to assess risk. Furthermore, the quantification of risk from losing critical marine ecosystems is still in its infancy and risk quantification is far from providing precise answers to what the exact risk might be. Thus, new approaches for assessing risk that account for increasing ambiguity are required (see Chapter 4).

One solution is to develop decision tools for handling the ambiguity, or uncertain probabilities, of risk induced by ocean risk [Niehörster et al., 2013]. This problem naturally extends from the ambiguity in some traditional insurance product around weather risks into ambiguous risks from extreme events in marine ecosystems. In essence, in order to capture the full range of possible effects, the development of such a framework will require both a suite of hypothetical but feasible scenarios or models that include an upper-limit worst case, and a set of best-practice models but with different modelling approaches. The scenarios should span hypothetical hazard events as well as vulnerability functions for the exposure of interest. The resulting distribution of exceedance probability (EP) curves and selected preferences of the insurer (such as capital requirements or the acceptable probability of ruin) can then be used as an input to an optimal business decision in the face of ambiguity [Niehörster et al., 2013; Walker & Dietz, 2017].

6.2. Industry response: creating resilience to ocean risk

It is becoming increasingly clear that the world will need to learn how to respond to emerging ocean risk in a variety of sectors and levels – from individuals to companies within the blue economy, and from national governments to regional economies actively protecting the global supply chain. The insurance industry could become an important partner in managing ocean risk and building socio-economic resilience. However, ocean risk is a novel concept and building innovative and viable ocean risk transfer solutions requires new partnerships, knowledge and tools from a concerted effort by the insurance industry.

Within the context of the Paris Climate Agreement, the concept of climate risk insurance has been proposed as a support mechanism for developing countries that are most vulnerable to climate risk and have a lack of adaptive capacity. Given the important contributions of the blue economy to the GDPs of coastal nations and small island developing states (SIDS), this often equates to managing ocean risks. Depending on the risk profile, insurance can be a cost-effective risk management solution, not just by contributing to a quick recovery after extreme events but also by changing risk perception and promoting behavioral change where protecting marine ecosystems is an effective method of adaptation to and mitigation of ocean risk.

The insurance industry must continue to proactively engage with multilateral organizations, governments and stakeholders in the blue economy to promote the value proposition of insurance for building socio-economic stability and resilience to emerging ocean risks. An excellent example of an industry response is the active involvement of the insurance industry in PPPs and networks such as the Insurance Development Forum (IDF), the InsuResilience Global Partnership or the Global Ecosystem Resilience Facility[20]. These growing networks bring together a large number of relevant parties including governments, multilateral organizations, investment firms, civil society organizations, academic think tanks and, last but not least, a growing number of insurance partners. These forums aim to be incubators for the development of novel insurance solutions for developing countries and to help close the global insurance protection gap.

However, there are currently only very few efforts directed towards the development of risk transfer solutions designed specifically for ocean risk. Given the critical importance of the ocean for stability and economic development, the insurance industry could take the initiative to form an ocean risk subgroup in one of the existing platforms or start a new international effort with a variety of governmental and non-governmental ocean agencies following the structure of the IDF or InsuResilience. This effort could leverage other initiatives such as Wealth Accounting and the Valuation of Ecosystem Services (WAVES), a World Bank-led global partnership, whose goal is to "...promote sustainable development by ensuring that natural resources are mainstreamed into development planning and national economic accounts" through the development of Natural Capital Accounts[21]. These accounts could help to connect sustainable development, ecosystem services and reduced sovereign risk and allow for risk transfer mechanisms that would lead to positive disaster recovery dynamics. Currently, the development of Natural Capital

A large bottom trawler in the midst of a storm in the North Atlantic. © Shutterstock

Accounts is focused on helping countries develop strategies to maximize economic growth while balancing trade-offs among ecotourism, agriculture and ecosystem services such as flood protection and groundwater recharge. Industry organizations could take the lead on extending this concept to marine resources to promote the value of marine and coastal ecosystems and the development of new business opportunities related to ocean risk. In order to be part of the solution, the insurance industry could encourage efforts to build effective regulatory frameworks for healthy marine environments consistent with United Nations Sustainable Development Goal 14 'Life Below Water'[22]. To support the development of those frameworks and build fit-for-purpose risk modelling tools, the insurance industry could drive awareness of the need to support the systematic collection of and open access to ocean and marine ecosystem data.

The development of ecosystem risk models is part of the solution to the emerging risk from loss or degradation of marine ecosystem services and there are encouraging examples of how such models could be built (see Section 4). The development of fit-for-purpose commercial ecosystem risk models should be proactively encouraged by the insurance industry, bringing together model vendors and the science community. At the same time, improvement of traditional catastrophe risk models by including the effects of coastal ecosystems should also be encouraged and risk quantification in a non-stationary climate with existing risk models should be discussed.

In developing countries, the growth of the blue economy is opening a new market for ocean risk solutions. In order to pave the way to sustainable solutions for all parties involved, a better understanding of the different sectors of the blue economy and their specific risks is required. This creates an opportunity for the insurance industry to establish a forum for dialogue with stakeholders from the blue economy.

We are only starting to manage ocean risk. Increasing our resilience to ocean risk requires that we better understand the contributing factors, develop appropriate risk models and create innovative products. Since its foundation, the insurance industry has demonstrated an admirable capacity to respond to emerging risks and evolving needs. By continuing the industry's tradition of innovation, insurers can contribute to a sustainable blue economy and the resilience of the global community.

www.oceanrisksummit.com/Content/press-releases/FALK-MAIN-REPORT-FINAL-LOW-RES.pdf

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HOW CITIES ARE USING ARCHITECTURE TO COMBAT FLOODING

Niall Patrick Walsh
Archdaily

Forty percent of the human population lives within 100 kilometers of a coastline, with one in ten living under ten meters above sea level. As climate change induces more volatile flooding events and long-term sea level rises, it is estimated that coastal flooding could cause as much as $1 trillion of damage per year by 2050. We cannot escape the reality that cities, and their populations, are more vulnerable to flooding than ever.

There is therefore a duty on architects, planners, and urbanists to plan and construct resilient responses that can slow, and even reverse, the effects of urban flooding. Around the world, cities are developing action plans that combine global thinking in resiliency with local geographic and urban conditions, all with a common goal of defending urban populations from floods. Below, we outline nine such examples, showcasing differences in scale and approach, as well as unique methods of using flood defenses as agents of social change, and urban regeneration.

BOSTON

Boston's coastline spans 47 miles of low-lying land. In response, the Mayor of Boston and SCAPE Landscape Architecture collaborated on a vision to "increase access and open space along the waterfront while better protecting the city during a major flooding event."

BROOKLYN

In the New York City borough of Brooklyn, Bjarke Ingels Group and Field Operations have developed a scheme that combines mixed-use development and a flood-resilient park. The master plan aims to reinstate natural habitats, elevate the standard for urban waterfront resiliency, and transform the way New Yorkers interact with the East River.

COPENHAGEN

While many urban visions for flood prevention adopt a macro scale, Copenhagen is testing a more pragmatic approach. The Climate Tile, created by THIRD NATURE, IBF, and ACO Nordic, redirects 30% of the projected increase in rainwater expected in the city in the coming years.

FAABORG

The coastal town of Faaborg, Denmark, is facing a high risk of flooding due to climate change. A development plan by Kjellander Sjöberg seeks to revive several closed-down industrial areas, and establish an open channel where water can be regulated and diverted away from the medieval city center.

HAMBURG

HafenCIty is a 385-acre new development in Hamburg, and one of the largest urban planning projects in Europe. From its planning stage in the early 1990s, civic leaders demanded that the entire area have the same level of flood security as areas of Hamburg adjacent to dikes. In response, the city is tiered with a 30-foot difference in elevation, from areas designed to flood, to buildings set 28 feet above mean sea level.

HOBOKEN

In the New Jersey city of Hoboken, in the aftermath of Hurricane Sandy, OMA put forward a comprehensive strategy to “resist, delay, store, discharge” storm surge. Along with hard infrastructure and soft landscaping, the strategy integrates policies for future development, a green circuit to trap water, and water pumps to support drainage.

NEW YORK CITY

In 2019, New York City announced a $10 billion coastal resilience project designed to protect Lower Manhattan. Half a billion dollars will be dedicated to fortifying most of Lower Manhattan with grassy berms in parks and barriers. On the eastern edge of Lower Manhattan, the coastline will be pushed out as much as 500 feet, generating a new public realm while raising the outboard edge to meet sea level rises and storm surge.

SEOUL

Rather than obstruct flooding, Seoul has invited water into the fabric of the city itself. The Cheonggyecheon River, once covered by roadways and highways, was renovated from 2003 to become a new central riverfront district. Set below street level, the project is designed to accommodate floodwater during rainy seasons, but also serve as a primary public space.

VENICE

The iconic Italian city has suffered from flooding for centuries, with climate change heightening concerns that the city's urban fabric is at risk. In response, MOSE began construction in 2003. A system of 78 storm gates anchored by four vast retractable gates, the scheme has been designed to seal the city's lagoon from high tides in fifteen minutes.

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www.archdaily.com/931720/how-cities-are-using-architecture-to-combat-flooding

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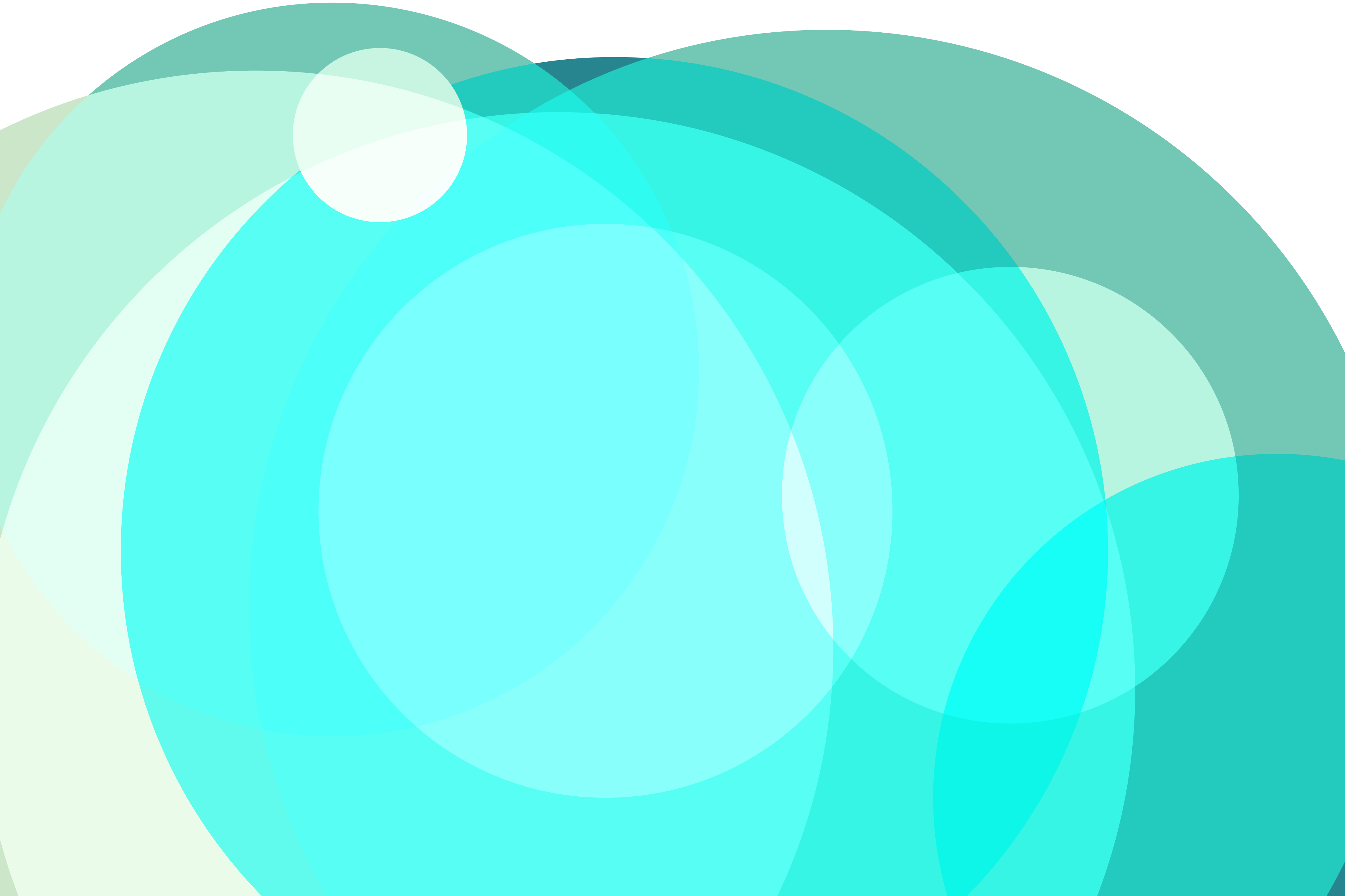

CHAPTER THREE

HALF OF THE WORLD'S BEACHES COULD DISAPPEAR BY THE END OF THE CENTURY, STUDY FINDS

Drew Kann
CNN

Climate change poses an existential threat to the world's sandy beaches, and that as many as half of them could disappear by the end of the century, a new study has found.

Even by 2050 some coastlines could be unrecognizable from what we see today, with 14% to 15% facing severe erosion.

While the amount of beach lost will vary by location, the study found that many densely populated areas -- including those along the US East Coast, South Asia and Central Europe -- could see some shorelines retreat inland by nearly 330 feet (100 meters) by 2100.

"We considered the threshold of 100 meters because if erosion exceeds 100 meters, then this means that most likely, the beach is going to disappear because most of the world's beaches are even narrower than 100 meters," said Michalis Vousdoukas, a coastal oceanographer and scientific officer at the European Commission who was a lead author of the study. "In a way, we consider this to be a conservative assessment."

The study was published Monday in the scientific Journal Nature Climate Change and was conducted by scientists from the European Commission's Joint Research Center, as well as universities in Spain, Portugal and the Netherlands.

Royal Palms Beach in the San Pedro area of Los Angeles is shown in 2017 studded with boulders placed to stop erosion.

Using updated sea level rise projections, the researchers analyzed how beaches around the world would fare in a future with higher seas and more damaging storms.

They also considered natural processes like wave erosion and a beach's underlying geology, as well as human factors -- like coastal building developments, dams and beach nourishment efforts -- all of which can affect a beach's health.

The study found that sea level rise is expected to outweigh these other variables, and that the more heat-trapping gases humans put into the atmosphere, the worse the impacts on the world's beaches are likely to be.

It's hard to overstate just how important the world's beaches are.

They cover more than one third of the world's coastlines, and serve as a critical buffer to protect coastal areas from storm surge.

Beaches are also important economic engines, supporting recreation, tourism and other activities.

And in some regions, the beach is more than just a vacation destination.

In places like Brazil and Australia, life near the coast revolves around the beach for much of the year.

"There are large parts of the world where sandy beaches have value that cannot be directly monetized," Vousdoukas said.

Some of the world's most popular stretches of sand are already waging a war against physics.

Normally, beaches are dynamic environments. Shorelines are supposed to naturally shift and change with the tide and respond to changes in sea level.

"The coast that we see today is just a snapshot in time," said Robert Young, the director of the Program for the Study of Developed Shorelines at Western Carolina University and a coastal geologist who was not involved in this study. "Our beaches, our wetlands and estuaries, they move back and forth in response to the changing sea level and they have since time began."

However, scientists say that when we develop near the water, we disrupt a beach's ability to move and halt the natural pro-

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Fig. 1 Ocean City, Maryland.
Ocean City's beach is an important economic driver for the local economy, city has had to spend millions of dollars in recent years to dredge up sand to keep up with the quickening pace of erosion.

Fig. 2 Barceloneta Beach, Barcelona.
This man-made beach in the heart of Barcelona, Spain, draws millions of visitors each year, but strong storms and rising seas have reduced the size of the beach significantly.

Fig. 3 Copacabana Beach, Rio de Janeiro.
This iconic Brazilian beach has been hit hard by a series of extreme storm surge events that have damaged the beach and sent sand spilling into surrounding streets.

Fig. 4 Surfers Paradise, Gold Coast, Queensland, Australia.
Surfers Paradise has dealt with erosion problems for years, but the cost of beach nourishment is expected to climb steeply as sea levels rise.

Fig. 5 Santa Monica Beach, Los Angeles.
Santa Monica Beach has already been drastically altered by humans over the years, and with a 66% chance that sea levels could rise more than three feet in the next 80 years, the beach's future remains uncertain.

Fig. 6 South Beach, Miami Beach, Florida.
Miami Beach's art-deco buildings and high-end real estate sit just feet above sea level, putting the city and its beach at serious risk from rising seas.

Fig. 7 Waikiki Beach, Honolulu, Hawaii.
The quintessential Hawaiian shoreline, Waikiki Beach could vanish in the next 15 to 20 years, according to a 2017 Hawaii Climate Commission report.

Fig. 8 Ocean Beach, San Francisco. .
After recent El Niño events consumed large chunks of this California beach, San Francisco has adopted a strategy of nourishing the beach by dredging sand and moving critical infrastructure further inland.

cesses that allow sand to replenish on its own.

Today, many of the beaches facing the worst erosion problems are located in urbanized areas, where high-rises and roads butt right up against the shoreline.

Places like Miami Beach are trucking in thousands of tons of sand to patch up badly eroded shorelines, while others have built massive sea walls and breakwaters in an attempt to hold precious sand in place.

But the financial and environmental costs of these projects are enormous, and scientists say rising seas and more powerful storms, supercharged by a warmer climate, will make this a losing battle.

Royal Palms Beach in the San Pedro area of Los Angeles is shown in 2017 studded with boulders placed to stop erosion.

"Right now, what we're trying to do everywhere is hold the shoreline in place. But over the next few decades, we are not going to be able to do that, even if we want to," Young said.

The new study found that as sea levels continue to rise, more and more beaches will face erosion problems.

The study found that Australia will likely see the most shoreline impacted, with at least 7,100 miles of coastline -- roughly 50% of the country's entire sandy coastline -- that could be threatened by 2100.

Other countries that could see huge lengths of shoreline eroded are Chile, China, the United States, Russia, Mexico and Argentina.

Vousdoukas said that small island states are also likely to suffer, especially those in the Caribbean because of their flat terrain.

The researchers did find that humans have some control over what happens to the world's beaches.

If the world's governments are able to stick to modest cuts to heat-trapping gas pollution, the researchers found that 17% of projected beach losses by 2050 could be prevented, a number that grows to 40% by 2100 if greenhouse gases are limited.

"By trying to accomplish the Paris agreement goals, we can reduce 40% of the impacts that we project in our study," Vousdoukas said.

Correction: The Nature Research press site originally distributed an incorrect version of this study, and two of those inaccurate findings were included in the original version of this story. The story has been updated with the correct percentage of beaches that could see severe erosion by 2050 and the correct percentage of projected beach losses that could be prevented through modest efforts to limit greenhouse gases.

https://edition.cnn.com/2020/03/02/world/beaches-disappearing-climate-change-sea-level-rise/index.html

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2 Mar 2020

2050 CLIMATE CHANGE CITY INDEX

Editorial staff
www.nestpick.com

At Nestpick, we understand that to help people moving to a new location, our team must keep a close eye on trends and developments in the most popular cities around the world. Currently, how climate change will shape our planet both in the coming years and the distant future is at the forefront of many of our minds. To help us understand this better, we decided to conduct a study aiming to determine how the climate might change for major metropolises around the globe. The results reveal those destinations which may face the biggest shifts by 2050, including potential temperature changes, water shortages and rising sea-levels. We hope that this study will serve as a call-to-action for those in charge to ensure that the correct legislation and safeguarding procedures are in place to ensure the longevity and liveability of these cities.

Before beginning the study, it was important to acknowledge the difficulty of climate change prediction science, and the added challenge of presenting climate data in a way that is easily understandable. To undertake this challenge, we consulted several existing research methodologies from established climate change experts and reports to build the framework for our research. These include Jean-Francois Bastin, an Ecologist at the University of Ghent, the Koppen-Geiger climate classification system, the World Resources Institute data on water shortages, and more. We then put together a list of 85 cities which were covered in these existing studies. Looking at climate categorisation, average temperature, sea-level changes and water stress, we then determined which cities are predicted to experience the highest and lowest climate change shift between now and 2050.

"These results are eye-opening to our team at Nestpick, as a number of the cities which will undergo the most drastic changes in climate over the next three decades such as Bangkok and Amsterdam are some of the most popular destinations with expats and contractors looking for opportunities abroad. Millennials, Gen Z-ers and those even younger will increasingly need to keep climate change in mind when searching for the city they would like to eventually settle in," Comments Omer Kucukdere, CEO at Nestpick. "Governments need to be aware of potential changes coming so that they can mitigate damage. Proper funding into infrastructure and safeguarding would help to ensure that these cities stay ahead of climate-related problems, and ensure the livelihood of these urban centres for future generations."

Below you can find the full table of results ranked by Total Climate Shift, highest to lowest. Each individual column is filterable. All 'Scores' including the 'Total' are out of 100, where the higher the number, the greater the predicted change in climate between now and 2050. Please note that this study does not take into account current spending on countermeasures or how this may impact predicted climate shifts.

				SEA LEVEL			
#	City	Country	Income Group	Potential Sea-level Rise Impact 2050 (Score)	Temperature Baseline: 1970 - 2000 (Degrees C)	Temperature 2050 (Degrees C)	Temperature Shift (Degrees C)
1	Bangkok	Thailand	Upper-middle-income	100.00	28.40	30.07	1.67
2	Ho Chi Minh City	Vietnam	Lower-middle-income	88.67	27.50	29.17	1.67
3	Amsterdam	Netherlands	High-income	89.56	10.04	11.30	1.26
4	Shenzhen	China	Upper-middle-income	28.06	22.85	24.70	1.85
5	Melbourne	Australia	High-income	2.24	15.36	16.73	1.37
6	Cardiff	UK	High-income	45.88	10.48	12.23	1.75
7	Seoul	South Korea	High-income	6.30	12.21	14.33	2.12
8	Boston	US	High-income	8.23	10.27	12.87	2.60
9	Nairobi	Kenya	Lower-middle-income	1.00	18.62	20.93	2.31
10	Marrakesh	Morocco	Lower-middle-income	1.00	19.33	22.20	2.87
11	Manila	Philippines	Lower-middle-income	37.01	27.40	28.90	1.50
12	Chicago	US	High-income	1.00	10.19	13.30	3.11
13	Hong Kong	Hong Kong	High-income	15.27	23.01	24.57	1.56
14	Toronto	Canada	High-income	1.00	8.41	11.43	3.02
15	Istanbul	Turkey	Upper-middle-income	2.39	14.04	16.13	2.09
16	Beijing	China	Upper-middle-income	1.00	12.42	14.50	2.08
17	Kiev	Ukraine	Lower-middle-income	1.00	7.94	10.93	2.99
18	Santiago	Chile	High-income	1.00	15.40	16.53	1.13
19	New Orleans	US	High-income	37.37	20.85	22.73	1.88

CLIMATE			WATER SHORTAGE				
Climate Type 2021	Climate Type 2051	Climate Shift (Score)	Water Shortage 2020 (demand vs. supply ratio)	Water Shortage 2040 (demand vs. supply ratio)	Water Shortage Relative Change (%)	Water Stress Increase (Score)	TOTAL
Tropical Savanna Wet Summer	Tropical Savanna Wet Summer	20.35	0.34	0.31	0	1.00	100.00
Tropical Savanna Wet Summer	Tropical Savanna Wet Summer	11.44	0.51	0.46	0	1.00	85.27
Temperate Humid Warm Summer	Temperate Humid Warm Summer	7.53	0.15	0.28	0	1.00	84.28
Temperate Dry Winter Hot Summer	Tropical Monsoon	83.21	0.48	0.41	0	1.00	62.21
Temperate Humid Warm Summer	Temperate Humid Warm Summer	8.67	1.20	2.01	410	100.00	49.53
Temperate Humid Warm Summer	Temperate Humid Warm Summer	15.02	0.11	0.10	0	1.00	47.03
Continental Dry Warm Summer	Temperate Dry Winter Warm Summer	91.43	0.16	0.16	0	1.00	45.75
Continental Humid Warm Summer	Temperate Humid Warm Summer	85.59	0.50	0.51	0	1.00	44.82
Temperate Humid Warm Summer	Tropical Savanna Wet Summer	100.00	0.09	0.11	0	1.00	44.80
Arid Steppe Hot	Arid Desert Hot	58.14	1.54	2.47	172	42.53	44.64
Tropical Savanna Wet Summer	Tropical Savanna Wet Summer	19.39	0.41	0.67	0	1.00	40.79
Continental Humid Warm Summer	Temperate Humid Warm Summer	91.25	0.81	0.94	0	1.00	40.71
Temperate Dry Winter Hot Summer	Tropical Monsoon	62.64	0.48	0.41	0	1.00	40.68
Continental Humid Warm Summer	Temperate Humid Warm Summer	88.29	0.07	0.08	0	1.00	39.33
Temperate Dry Hot Summer	Temperate Dry Hot Summer	29.55	1.54	2.78	232	56.92	39.31
Continental Dry Summer very Cold Winter	Temperate Dry Winter Hot Summer	88.22	4.91	4.23	0	1.00	39.30
Continental Humid Warm Summer	Temperate Humid Warm Summer	85.39	0.03	0.04	0	1.00	37.98
Temperate Dry Cold Summer	Temperate Dry Hot Summer	14.47	1.64	3.51	294	71.89	37.97
Temperate Humid Hot Summer	Temperate Humid Hot Summer	8.67	0.01	0.01	0	1.00	36.13

				SEA LEVEL			
#	City	Country	Income Group	Potential Sea-level Rise Impact 2050 (Score)	Temperature Baseline: 1970 - 2000 (Degrees C)	Temperature 2050 (Degrees C)	Temperature Shift (Degrees C)
20	Helsinki	Finland	High-income	1.00	5.40	8.23	2.83
21	St. Petersburg	Russia	Upper-middle-income	1.16	5.37	8.23	2.86
22	London	UK	High-income	28.49	11.13	13.20	2.07
23	Philadelphia	US	High-income	18.34	12.19	15.40	3.21
24	New York	US	High-income	16.09	12.02	14.97	2.95
25	Oslo	Norway	High-income	1.12	6.62	8.87	2.25
26	Ljubljana	Slovenia	High-income	1.00	9.77	13.30	3.53
27	Hamburg	Germany	High-income	24.48	9.60	10.97	1.37
28	Belfast	UK	High-income	20.39	9.53	10.63	1.10
29	Jerusalem	Israel	High-income	1.00	16.35	19.60	3.25
30	Baltimore	US	High-income	4.26	13.08	16.43	3.35
31	Dubai	United Arab Emirates	High-income	20.84	27.46	29.03	1.57
32	Seattle	US	High-income	8.63	11.04	13.60	2.56
33	Ottawa	Canada	High-income	1.00	6.48	9.53	3.05
34	Montreal	Canada	High-income	1.48	6.90	10.10	3.20
35	Dublin	Ireland	High-income	16.88	10.20	11.53	1.33
36	Budapest	Hungary	High-income	1.00	11.23	14.27	3.04
37	Jacksonville	US	High-income	15.94	20.90	22.87	1.97
38	Cincinnati	US	High-income	1.00	11.82	15.20	3.38

CLIMATE			WATER SHORTAGE				
Climate Type 2021	Climate Type 2051	Climate Shift (Score)	Water Shortage 2020 (demand vs. supply ratio)	Water Shortage 2040 (demand vs. supply ratio)	Water Shortage Relative Change (%)	Water Stress Increase (Score)	TOTAL
Continental Humid Warm Summer	Temperate Humid Cold Summer	78.00	0.27	0.35	0	1.00	34.53
Continental Humid Warm Summer	Temperate Humid Cold Summer	75.88	0.44	0.40	0	1.00	33.69
Temperate Humid Warm Summer	Temperate Humid Warm Summer	21.04	0.67	0.58	0	1.00	33.61
Temperate Humid Warm Summer	Temperate Humid Warm Summer	39.85	0.50	0.58	0	1.00	32.91
Temperate Humid Warm Summer	Temperate Humid Warm Summer	34.57	1.62	1.65	6	2.43	29.02
Continental Humid Warm Summer	Temperate Humid Cold Summer	65.08	0.22	0.27	0	1.00	28.62
Temperate Humid Cold Summer	Temperate Humid Warm Summer	62.04	0.07	0.09	0	1.00	27.09
Temperate Humid Warm Summer	Temperate Humid Warm Summer	11.96	0.08	0.07	0	1.00	25.64
Temperate Humid Warm Summer	Temperate Humid Warm Summer	14.74	0.08	0.08	0	1.00	23.11
Temperate Dry Hot Summer	Temperate Dry Hot Summer	35.86	3.52	5.27	70	17.80	22.71
Temperate Humid Warm Summer	Temperate Humid Warm Summer	43.14	1.38	1.43	11	3.69	22.56
Arid Desert Hot	Arid Desert Hot	8.54	7.08	8.01	15	4.68	22.35
Temperate Dry Cold Summer	Temperate Dry Hot Summer	36.32	0.35	0.34	0	1.00	22.21
Continental Humid Cold Summer	Continental Humid Hot Summer	47.45	0.02	0.03	0	1.00	20.28
Continental Humid Warm Summer	Continental Humid Hot Summer	46.00	0.05	0.07	0	1.00	20.06
Temperate Humid Warm Summer	Temperate Humid Warm Summer	11.80	0.89	0.90	0	1.00	18.47
Temperate Humid Cold Summer	Temperate Humid Warm Summer	41.45	0.05	0.07	0	1.00	17.49
Temperate Humid Warm Summer	Temperate Humid Warm Summer	9.39	0.23	0.24	0	1.00	16.47
Temperate Humid Warm Summer	Temperate Humid Warm Summer	39.01	0.05	0.06	0	1.00	16.35

				SEA LEVEL				
#	City	Country	Income Group	Potential Sea-level Rise Impact 2050 (Score)	Temperature Baseline: 1970 - 2000 (Degrees C)	Temperature 2050 (Degrees C)	Temperature Shift (Degrees C)	
39	Washington	US	High-income	1.00	13.37	16.37	3.00	
40	Osaka	Japan	High-income	8.60	16.26	18.20	1.94	
41	Copenhagen	Denmark	High-income	8.27	8.84	10.83	1.99	
42	Stockholm	Sweden	High-income	1.00	6.65	9.70	3.05	
43	Rome	Italy	High-income	1.00	15.59	18.13	2.54	
44	Nashville	US	High-income	1.00	14.59	17.70	3.11	
45	Zagreb	Croatia	High-income	1.00	11.55	13.87	2.32	
46	Delhi	India	Lower-middle-income	1.00	25.05	27.23	2.18	
47	San Francisco	US	High-income	4.65	13.92	15.33	1.41	
48	Vienna	Austria	High-income	1.00	10.54	12.87	2.33	
49	Auckland	New Zealand	High-income	4.56	15.29	17.20	1.91	
50	Prague	Czechia	High-income	1.00	10.07	11.83	1.76	
51	Milan	Italy	High-income	1.00	13.38	15.87	2.49	
52	Doha	Qatar	High-income	4.67	27.08	29.40	2.32	
53	Warsaw	Poland	High-income	1.00	8.32	10.73	2.41	
54	Taipei	Taiwan	High-income	1.00	22.05	23.67	1.62	
55	Athens	Greece	High-income	1.00	17.87	20.37	2.50	
56	Perth	Australia	High-income	3.91	18.48	20.30	1.82	
57	Atlanta	US	High-income	1.00	16.33	18.70	2.37	

CLIMATE			WATER SHORTAGE				
Climate Type 2021	Climate Type 2051	Climate Shift (Score)	Water Shortage 2020 (demand vs. supply ratio)	Water Shortage 2040 (demand vs. supply ratio)	Water Shortage Relative Change (%)	Water Stress Increase (Score)	TOTAL
Temperate Humid Warm Summer	Temperate Humid Warm Summer	36.05	0.01	0.01	0	1.00	14.97
Temperate Humid Hot Summer	Temperate Humid Hot Summer	19.73	0.34	0.31	0	1.00	14.44
Temperate Humid Warm Summer	Temperate Humid Warm Summer	20.02	0.13	0.14	0	1.00	14.28
Temperate Humid Cold Summer	Temperate Humid Cold Summer	33.98	0.10	0.10	0	1.00	14.00
Temperate Dry Hot Summer	Temperate Dry Hot Summer	31.69	0.93	1.06	0	1.00	12.93
Temperate Humid Warm Summer	Temperate Humid Warm Summer	31.39	0.09	0.09	0	1.00	12.79
Temperate Humid Warm Summer	Temperate Humid Warm Summer	30.72	0.07	0.09	0	1.00	12.48
Arid Steppe Hot	Tropical Savanna Wet Summer	29.60	4.53	3.97	0	1.00	11.96
Temperate Dry Cold Summer	Temperate Dry Warm Summer	22.25	0.99	1.05	0	1.00	11.93
Temperate Humid Warm Summer	Temperate Humid Warm Summer	29.32	0.04	0.06	0	1.00	11.83
Temperate Humid Cold Summer	Temperate Humid Warm Summer	21.62	0.12	0.13	0	1.00	11.55
Temperate Humid Warm Summer	Temperate Humid Hot Summer	28.46	0.03	0.04	0	1.00	11.42
Temperate Humid Warm Summer	Temperate Humid Warm Summer	27.95	0.33	0.36	0	1.00	11.19
Arid Desert Hot	Arid Desert Hot	20.05	51.77	51.21	0	1.00	10.92
Temperate Humid Warm Summer	Temperate Humid Warm Summer	26.62	0.03	0.04	0	1.00	10.57
Temperate Humid Warm Summer	Temperate Humid Warm Summer	25.50	0.29	0.05	0	1.00	10.04
Temperate Dry Hot Summer	Temperate Dry Hot Summer	25.07	0.64	0.94	0	1.00	9.84
Temperate Dry Hot Summer	Temperate Dry Hot Summer	19.09	0.21	0.40	0	1.00	9.77
Temperate Humid Warm Summer	Temperate Humid Warm Summer	24.85	0.21	0.21	0	1.00	9.74

				SEA LEVEL			
#	City	Country	Income Group	Potential Sea-level Rise Impact 2050 (Score)	Temperature Baseline: 1970 - 2000 (Degrees C)	Temperature 2050 (Degrees C)	Temperature Shift (Degrees C)
58	Phnom Penh	Cambodia	Lower-middle-income	11.10	28.30	29.60	1.30
59	Barcelona	Spain	High-income	1.43	16.27	18.77	2.50
60	Lyon	France	High-income	1.00	12.04	13.87	1.83
61	Edinburgh	UK	High-income	5.54	8.77	10.43	1.66
62	Miami	US	High-income	1.40	24.68	26.03	1.35
63	Denver	US	High-income	1.00	10.77	12.90	2.13
64	Madrid	Spain	High-income	1.00	14.70	16.77	2.07
65	San Diego	US	High-income	5.28	17.81	19.07	1.26
66	Sydney	Australia	High-income	1.00	18.00	19.57	1.57
67	Buenos Aires	Argentina	High-income	1.47	17.30	18.43	1.13
68	Calgary	Canada	High-income	1.00	4.13	6.27	2.14
69	Lisbon	Portugal	High-income	3.65	16.90	18.47	1.57
70	Berlin	Germany	High-income	1.00	9.86	11.63	1.77
71	Cape Town	South Africa	Upper-middle-income	1.24	17.39	18.50	1.11
72	Brussels	Belgium	High-income	1.00	10.77	12.60	1.83
73	Paris	France	High-income	1.00	12.19	13.63	1.44
74	Mexico City	Mexico	Upper-middle-income	1.00	17.02	18.20	1.18
75	Kuala Lumpur	Malaysia	Upper-middle-income	1.00	26.73	29.03	2.30
76	Los Angeles	US	High-income	2.57	19.00	20.40	1.40

CLIMATE			WATER SHORTAGE				
Climate Type 2021	Climate Type 2051	Climate Shift (Score)	Water Shortage 2020 (demand vs. supply ratio)	Water Shortage 2040 (demand vs. supply ratio)	Water Shortage Relative Change (%)	Water Stress Increase (Score)	TOTAL
Tropical Savanna Wet Summer	Tropical Savanna Wet Summer	4.05	0.06	0.05	0	1.00	9.46
Temperate Dry Hot Summer	Temperate Dry Hot Summer	19.68	31.82	35.98	13	4.26	9.26
Temperate Humid Warm Summer	Temperate Humid Warm Summer	23.38	0.03	0.04	0	1.00	9.06
Temperate Humid Warm Summer	Temperate Humid Warm Summer	13.83	0.28	0.27	0	1.00	8.84
Tropical Monsoon	Tropical Monsoon	21.38	0.19	0.21	0	1.00	8.50
Arid Steppe Cold	Arid Steppe Cold	15.55	14.88	18.28	25	6.92	8.17
Temperate Dry Winter Hot Summer	Temperate Dry Winter Hot Summer	20.97	0.51	0.67	0	1.00	7.93
Temperate Dry Winter Warm Summer	Temperate Dry Winter Hot Summer	11.52	5.77	5.42	0	1.00	7.52
Temperate Humid Hot Summer	Temperate Humid Hot Summer	1.53	1.56	1.95	70	17.85	6.72
Temperate Humid Hot Summer	Temperate Humid Hot Summer	16.65	0.00	0.00	0	1.00	6.35
Continental Humid Warm Summer	Continental Humid Warm Summer	17.46	0.71	0.85	0	1.00	6.30
Temperate Dry Hot Summer	Temperate Dry Hot Summer	12.16	0.68	0.87	0	1.00	6.30
Temperate Humid Cold Summer	Temperate Humid Cold Summer	16.71	0.41	0.29	0	1.00	5.95
Temperate Dry Warm Summer	Temperate Dry Warm Summer	10.06	1.96	2.19	25	7.01	5.87
Temperate Humid Warm Summer	Temperate Humid Warm Summer	15.82	0.67	0.78	0	1.00	5.53
Temperate Humid Warm Summer	Temperate Humid Warm Summer	15.50	0.34	0.46	0	1.00	5.38
Arid Steppe Hot	Arid Steppe Hot	15.30	0.47	0.70	0	1.00	5.29
Tropical Rainforest	Tropical Rainforest	14.88	0.43	0.75	0	1.00	5.09
Temperate Dry Warm Summer	Temperate Dry Hot Summer	11.64	3.63	3.34	0	1.00	5.04

				SEA LEVEL			
#	City	Country	Income Group	Potential Sea-level Rise Impact 2050 (Score)	Temperature Baseline: 1970 - 2000 (Degrees C)	Temperature 2050 (Degrees C)	Temperature Shift (Degrees C)
77	Houston	US	High-income	1.16	20.82	22.97	2.15
78	Reykjavik	Iceland	High-income	1.00	4.64	6.83	2.19
79	Tokyo	Japan	High-income	1.00	15.81	17.80	1.99
80	Las Vegas	US	High-income	1.00	19.25	21.07	1.82
81	Singapore	Singapore	High-income	3.05	27.00	28.33	1.33
82	Munich	Germany	High-income	1.00	9.60	10.83	1.23
83	Rio de Janeiro	Brazil	Upper-middle-income	2.03	23.58	24.53	0.95
84	Orlando	US	High-income	1.00	22.23	24.23	2.00
85	Marseille	France	High-income	1.00	15.15	16.40	1.25

CLIMATE			WATER SHORTAGE				
Climate Type 2021	Climate Type 2051	Climate Shift (Score)	Water Shortage 2020 (demand vs. supply ratio)	Water Shortage 2040 (demand vs. supply ratio)	Water Shortage Relative Change (%)	Water Stress Increase (Score)	TOTAL
Temperate Humid Warm Summer	Temperate Humid Warm Summer	14.42	0.56	0.58	0	1.00	5.02
Temperate Humid Cold Summer	Temperate Humid Cold Summer	14.99	0.04	0.04	0	1.00	4.21
Temperate Humid Hot Summer	Temperate Humid Hot Summer	12.72	1.14	1.03	0	1.00	4.09
Arid Desert Hot	Arid Desert Hot	10.94	0.23	0.25	0	1.00	3.25
Tropical Rainforest	Tropical Rainforest	1.00	3.24	3.57	15	4.62	2.22
Temperate Humid Warm Summer	Temperate Humid Warm Summer	8.63	0.27	0.25	0	1.00	2.18
Tropical Savanna Wet Summer	Tropical Savanna Wet Summer	5.32	0.68	0.70	0	1.00	1.59
Temperate Humid Hot Summer	Temperate Humid Hot Summer	6.85	0.36	0.36	0	1.00	1.35
Temperate Dry Hot Summer	Temperate Dry Hot Summer	6.11	0.29	0.34	0	1.00	1.00

* *www.nestpick.com/2050-climate-change-city-index-usa/*

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SEAS THREATEN 80 AIRPORTS AROUND THE WORLD

Tina Huang and *Noah Maghsadi*
World Resources Institute

Airports are a major part of a country's infrastructure. In addition to being travel hubs, they also enable economic activities and play a key role in national security. But many are vulnerable to sea level rise, especially those established in low-lying coastal areas.

Using sea level rise data from Climate Central and airport locations from OpenFlights, we found that 80 airports could be underwater with one meter of sea level rise, which researchers at the UN's expert climate panel predict is likely to occur by 2100 if emissions aren't reduced. Even if emissions are curtailed and warming is limited to 2 degrees Celsius, about half a meter of sea level rise is likely by the end of the century, which would flood 44 airports around the world.

The reason airports are threatened by sea level rise is simple: many of them capitalize on low, flat areas, which are required for long runways to facilitate takeoff and landing. Airplanes need room to gain altitude, which they can easily do over bodies of water, without worrying about tall buildings. This type of land is typically found near large bodies of water – wetlands, marshlands and floodplains – areas that are especially susceptible to sea level rise and storm surge. But while building airports near bodies of water started off as an advantage, it is now quickly becoming a liability due to climate change.

WHICH AIRPORTS ARE MOST AT RISK?

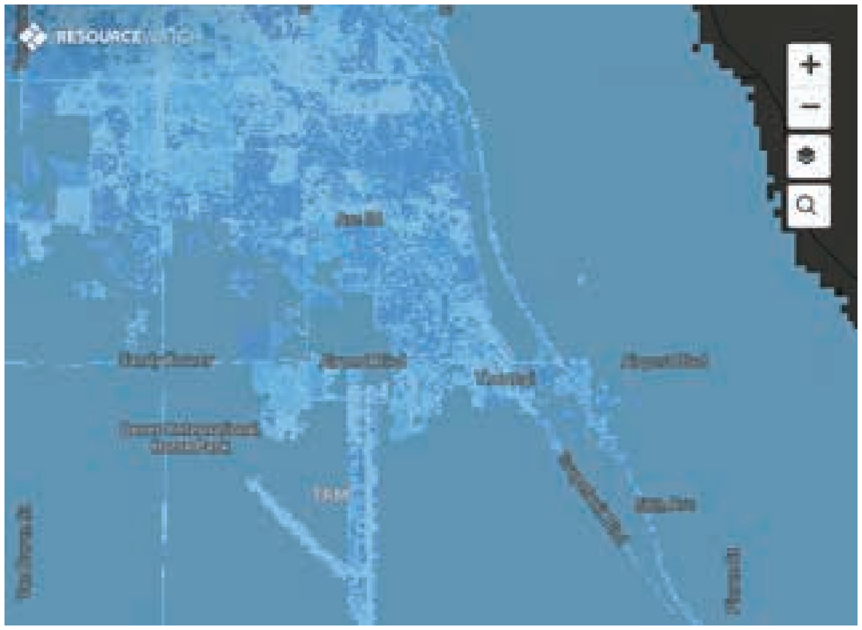
Airports are at risk all over the world, but the highest number of affected airports are in North America, Europe and Asia, because there are more airports on these continents. The images below show the impact that half a meter and one meter of sea level rise would have on select airports.

North America

Six airports in North America could be underwater with just half a meter of sea level rise. This figure increases to 12 at one meter of sea level rise and includes airports such as Key West International Airport and Jacqueline Cochran Regional Airport.

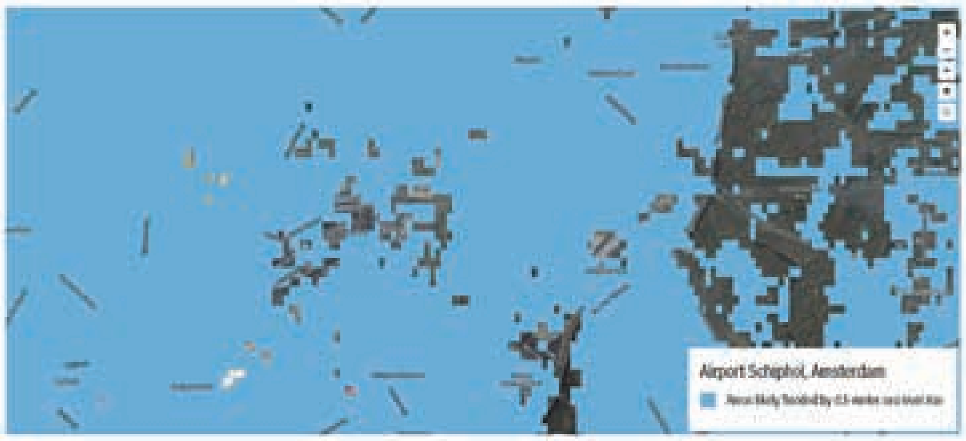
Key West International Airport, located in Florida, has between 50 and 60 commercial airline flights each day and registered 870,000 passengers in 2018, according to its website. The visual below shows the impact of expected flooding on this airport with both half a meter and one meter of sea level rise.

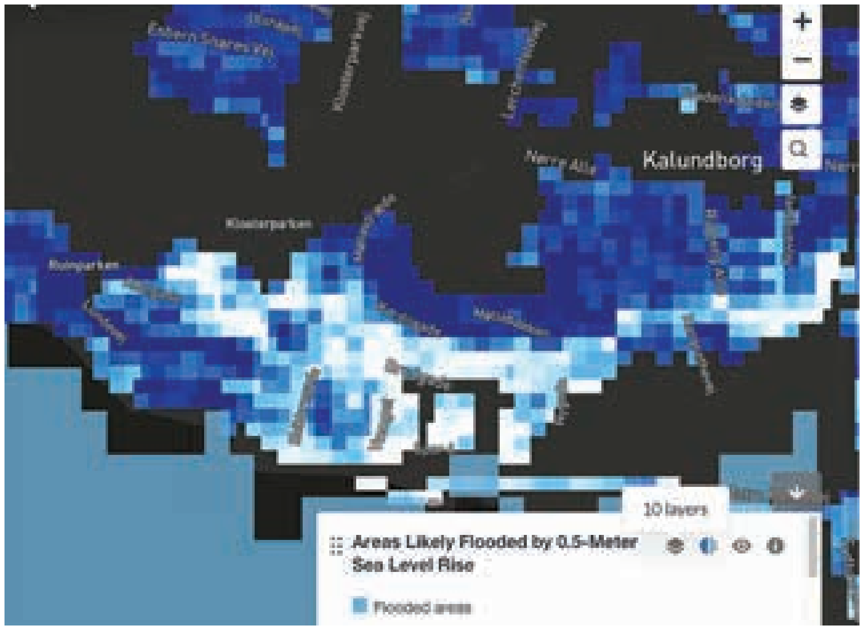
In California, the Jacqueline Cochran Regional Airport averages 209 aircraft operations a day and has 127 aircrafts based at the airport. Located near the Salton Sea, this airport would be completely flooded with only half a meter of sea level rise.



Europe

Within Europe, 11 airports are at risk of being underwater with half a meter of sea level rise, and 23 are at risk if sea level rise reaches one meter.





Amsterdam's Airport Schiphol is the 11th busiest airport in the world and is predicted to be underwater with only half a meter of sea level rise. However, it's important to note that while the Climate Central maps show areas below certain sea-levels, they do not take into account flood barriers and other water management technologies implemented in the Netherlands.

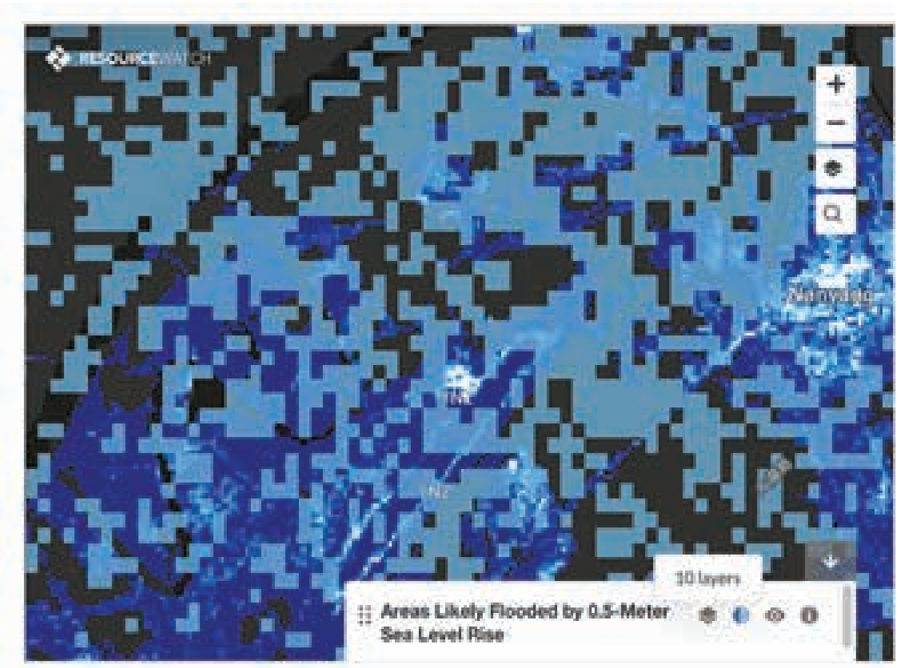
The Dutch have particularly strong water management strategies, such as building dikes, seawalls, and underground spaces where water can safely pool in the event of flooding. These measures, which are not reflected in the maps developed by Climate Central, are designed to mitigate flood impact on infrastructure and reflect a significant investment in water-management technologies.

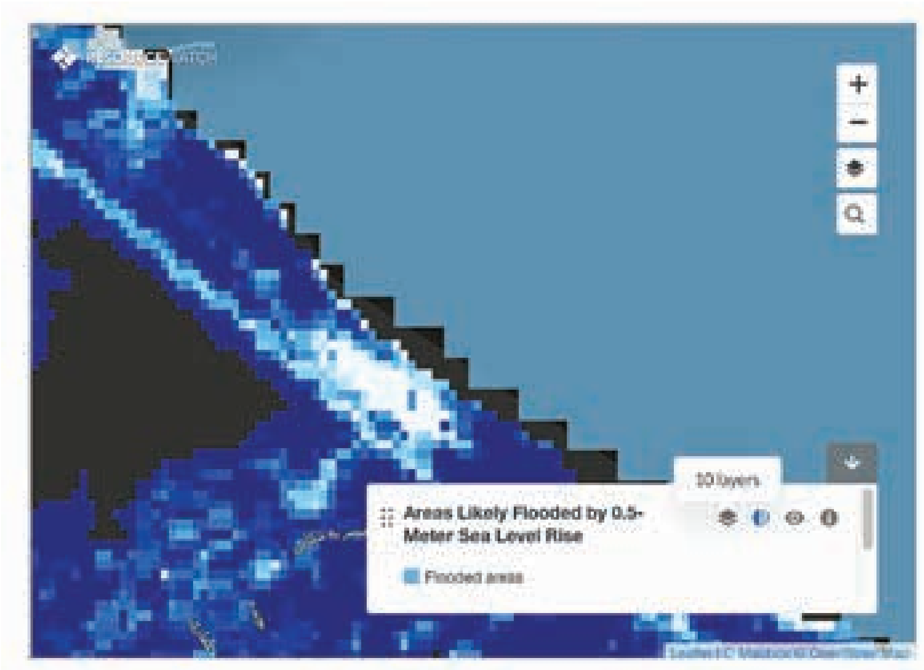
Another European airport at risk from just half a meter of sea level rise is Denmark's Kalundborg Airport. The map below shows the location of airport overlaid with half a meter of sea level rise.

Asia

Seven of Asia's airports are at risk from half a meter of sea level rise, and 14 are at risk from one meter of sea level rise, including China's Yancheng Airport and Iran's Ramsar International Airport.

Yancheng Airport, seen below, could be flooded by only half a meter of sea level rise. This airport, located in Jiangsu Province, China, is a hub for both commercial and international flights, and averages 44 flights a day.





Ramsar International Airport is situated on the coast of the Caspian Sea. Half a meter of sea level rise would flood part of Ramsar Airport's runways.

A TURBULENT FUTURE FOR AIR TRAVEL

While 80 airports would be inundated with one meter of sea level rise, they're hardly the only ones affected by climate change. Lots of airports will feel the effects of storm surge and extreme weather, even if they're not completely submerged by rising seas.

We are already getting a taste of what this will look like. LaGuardia, John F. Kennedy International Airport and Newark (N.J.) International Airport all experienced severe flooding from nearby water bodies during Hurricane Sandy in 2012. This flooding caused around 10,000 canceled flights and millions of dollars in lost revenue. And in September 2018, Kansai International Airport in Japan became surrounded by ocean in the aftermath of a typhoon. These events showcase what may be the new normal for airports once the rising waters of climate change become more permanent.

And it's not just the United States. Airports around the world are under threat from storm surges and rising seas. For example, in September 2018, Kansai International Airport in Japan became surrounded by ocean in the aftermath of a typhoon. When important transportation hubs like airports are flooded, it is safe to assume that everyday travel routes like roads and train tracks are also inundated. The complete shutdown of transportation services by natural disasters like these demonstrate what may be the new normal for airports once the rising waters of climate change become more permanent.

Other aspects of climate change threaten air travel. Extreme heat, which comes with thinner air, has the potential to ground planes by making them unable to generate lift, and also may make air travel more turbulent.

As the implications of sea level rise are becoming better understood, many airport managers are acting to protect airports in the near-term. Singapore's Changi airport has recently resurfaced its runways to allow for better drainage and is building expansions on higher elevations. In the United States, Boston Logan Airport and San Francisco International Airport have worked to install new flood barriers to stave off rising seas. Last October, officials at San Francisco International Airport decided to move ahead with a $587 million plan to build up the airport's seawall from three feet to eight feet tall.

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This piece originally appeared on the VRI's Resource platform *https://blog.resourcewatch.org/2020/02/05/runways-underwater-maps-show-where-rising-seas-threaten-80-airports-around-the-world/*

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SEA LEVEL RISE ACCELERATING ALONG US COASTLINE, SCIENTISTS WARN

★ *Oliver Milman*
www.theguardian.com

INUNDATION AND FLOODING ARE STEADILY BECOMING MORE LIKELY

The pace of sea level rise accelerated at nearly all measurement stations along the US coastline in 2019, with scientists warning some of the bleakest scenarios for inundation and flooding are steadily becoming more likely.

Of 32 tide-gauge stations in locations along the vast US coastline, 25 showed a clear acceleration in sea level rise last year, according to researchers at the Virginia Institute of Marine Science (Vims).

The selected measurements are from coastal locations spanning from Maine to Alaska. About 40% of the US population lives in or near coastal areas.

The gathering speed of sea level rise is evident even within the space of a year, with water levels at the 25 sites rising at a faster rate in 2019 than in 2018.

The highest rate of sea level rise was recorded along the Gulf of Mexico shoreline, with Grand Isle, Louisiana, experiencing a 7.93mm annual increase, more than double the global average. The Texas locations of Galveston and Rockport had the next largest sea level rise increases.

Generally speaking, the sea level is rising faster on the US east and Gulf coasts compared with the US west coast, partially because land on the eastern seaboard is gradually sinking.

Researchers at Vims said that the current speed-up in sea level rise started around 2013 or 2014 and is probably caused by ocean dynamics and ice sheet loss. Worldwide, sea level rise is being driven by the melting of large glaciers and the thermal expansion of ocean water due to human-induced global heating.

“Acceleration can be a game changer in terms of impacts and planning, so we really need to pay heed to these patterns,” said John Boon, Vims emeritus professor and founder of institute’s project to chart sea level rise.

About 61,000 tons of sand is being dumped on Miami Beach to counter rising sea levels as highest rate of rise was recorded along the Gulf of Mexico shoreline. Photograph: Joe Raedle/ Getty Images

WORLDWIDE RISE BEING DRIVEN BY MELTING OF LARGE GLACIERS

The US's National Oceanic and Atmospheric Administration (Noaa) has also reported an acceleration in sea level rise, warning that if greenhouse gas emissions are not constrained there may be a worst-case scenario of as much as a 8.2ft increase by 2100, compared with 2000 levels.

The current pace of change means "we may be moving towards the higher projections", according to Molly Mitchell, a Vims marine scientist.

"We have increasing evidence from the tide-gauge records that these higher sea-level curves need to be seriously considered in resilience-planning efforts," Mitchell said, adding that the US west coast will probably start seeing more rapid increases, akin to the east.

"Although sea level has been rising very slowly along the west coast, models have been predicting that it will start to rise faster. The report cards from the past three years support this idea."

Even at the lower end of Noaa projections, of about 12 inches of sea level rise by 2100, several US cities such as Miami and New York face considerable harm from flooding events.

The climate crisis will probably drive more powerful storms, such as the recent hurricanes Irma and Harvey, which would exacerbate flooding through storm surge.

www.theguardian.com/environment/2020/feb/03/sea-level-rise-accelerating-us-coastline-scientists-warn

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CLIMATE CHANGE: CAN THE INSURANCE INDUSTRY AFFORD THE RISING FLOOD RISK?

Robert Armstrong in New York
and *Oliver Ralph* in London
Financial Times

On November 8, Pam Webb worked a usual day at Truffle Lodge, her spa business in the Yorkshire village of Fishlake, near the River Don. Floods were expected nearby, but an email from the UK's Environment Agency told her that Fishlake was safe.

The agency was wrong. At 9.30pm the water started pouring into the business and Ms Webb's home next door. "It came in the front and back, it came up through the flooring in every single ground floor room," she says. "It's heartbreaking seeing your home and business going in such a small amount of time."

The flood caused tens of thousands of pounds in damage and forced the spa to close for nine weeks. Adding to the trauma, says Ms Webb, flooding had been excluded from her insurance policies about a year earlier, so she has had to pick up the entire cost.

It is a scenario that has played out again across parts of the UK over the past 10 days, with two severe storms hitting the country and adding to the cost associated with climate change. Economic damage worldwide from flooding last year was $82bn, the greatest of any natural peril, according to Aon. Just $13bn of that was insured.

Global warming means that flooding is likely to become more frequent, say natural catastrophe modelling specialists. Warmer air holds more moisture, leading to wetter and more frequent severe storms. Last year Nasa used temperature data gathered from space to reveal that every additional 1C of ocean surface temperature increases the probability of severe storms by 20 per cent. Meanwhile rising sea levels mean more coastal flooding, with some estimates suggesting that 230m people are at risk from storm surges, a risk amplified by steady migration towards conurbations near coasts and rivers.

Those numbers, combined with the lack of cover, should be an attractive target for a global insurance industry that has abundant capital after low interest rates drew fresh investors seeking better returns into the sector. The risk consultancy Milliman estimates that the US market alone could generate $48bn of annual premium revenue for insurers.

Floods were once considered too irregular to underwrite profitably, but sophisticated catastrophe models – which can more accurately predict where floods might occur – have changed that.

"Reinsurance companies want the risk," says Nancy Watkins, principal and actuary at Milliman. "They have been the leaders, and have been running around trying to sell [flood reinsurance] for four or five years."

Yet, managing the increased flooding is going to be very expensive. Insurance systems and government programmes have developed haphazardly, and are ill-suited to deal with the growing risks. This is prompting a rethink over which risks should be held publicly, and which privately.

"The world has got enough insurance capital to protect against flood risk," says Stephen Hester, chief executive of insurer RSA. "It's a question of whether society wants people who live on flood plains to pay the right price for the risk, or whether there should be some sort of subsidy."

In the US the National Flood Insurance Program, the federal scheme that provides the overwhelming majority of US residential coverage, has about 5m policies providing $1.3tn of cover. The numbers look large, but only 15 per cent of US households have any flood coverage at all. During 2017's Hurricane Harvey that hit Texas and Louisiana, 70 per cent of the estimated $125bn in damage was uninsured.

Flood insurance is mandatory for anyone in the US with a government-backed mortgage – that is, most US homeowners – if the home falls into a designated "special flood hazard area," defined as being at risk of inundation at least once every 100 years.

But the NFIP, established in 1968, was never designed or capitalised to operate like a private insurer. The idea "was to price the product so more people would have it and it would [then] reduce the disaster costs to the government", says David Maurstad, chief executive of the NFIP. By design, "the government would make up the difference" in above-average years for flooding.

This arrangement worked until about 20 years ago. Between 1978 and 2003, the NFIP paid out claims of under $500m a year. Since then, the claims have averaged $3.5bn a year. Premiums and fees have been inadequate to cover the payouts. In 2017, the federal government forgave $16bn in NFIP debt. Even so, the scheme owes $20bn to the US Treasury.

That the mandatory coverage areas are too small is only part of the problem, say critics. They also give the impression that flood risk stops at a line on a map. In fact, "flood risk varies continuously both within that 100-year floodplain and beyond", says Carolyn Kousky, executive director of the Wharton Risk Center. Flood risk is not included in US home insurance policies, creating the impression, say flood experts, that the risk is incidental or secondary.

These are not the only distortions. NFIP charges premiums that do not vary with the replacement cost of houses, so expensive houses pay below-market rates. It means taxpayers are effectively providing subsidies for luxury beach houses. "The more expensive your house, the better deal you are getting from the NFIP," Ms Watkins says.

The NFIP is not permitted to withdraw coverage once it is granted, so pays repeatedly to repair and rebuild thousands of homes in high-risk areas. According to the Pew Charitable Trust, such "severe repetitive loss" properties had cost the NFIP more than $12.5bn as of 2016.

Private insurers hesitate to compete against a subsidised product. A warren of state regulations makes matters worse. In Louisiana, for example, raising premiums because of an "act of God" – defined as a storm or other natural cause – is forbidden. Several US states ban or limit the use of catastrophe models in setting premiums.

Various attempts to reform the NFIP and bring premiums into line with the risks have met resistance from coastal residents, their representatives in Congress and the real estate industry. The latest effort, "Risk Rating 2.0," would have linked prices and risk more closely. Originally scheduled to take effect this year, it was recently pushed into 2021.

Rising flood risks

230M

People around the globe at risk from storm surges – about 3% of the population

70%

Of the estimated $125bn in damage caused by Hurricane Harvey was uninsured

$3.5BN

Average annual cost of claims paid by the US National Flood Insurance Program since 2003

The UK has tried a different model. Flood Re, the UK scheme, forces all home insurance buyers to chip in to subsidise the cost of cover in flood-prone areas. Homeowners pay about £10 per year over their existing premium and, in theory, insurance for people in risky areas becomes more affordable.

Flood Re was set up by the government in 2016. If it runs out of money, the industry has to top it up, but that has not happened yet. "The political desire at the time [it was set up] was for it to be an industry-owned solution," says Andy Bord, Flood Re's chief executive.

To discourage new development in flood prone areas, Flood Re does not apply to homes built after 2009.

Flood Re is only supposed to last for 25 years. The intention was that it should act as a catalyst for better flood planning by the government, local authorities and homeowners, so that by 2039 insurance would be more affordable for people in flood-prone areas, even without the subsidy.

There is scepticism in the industry about whether this is achievable. But Mr Bord says "four out of five people [in flood prone areas] have made a saving of 50 per cent or more on their home insurance".

China and Australia are among the countries that have asked Flood Re for details about the design of the scheme.

Flood Re has yet to be fully tested. The years since 2016 have been relatively quiet for UK floods, although recent events such as Fishlake may prove a more rigorous test. It has only dealt with 1,100 claims in total since it was set up, Mr Bord told the Financial Times in January, far short of initial expectations that it would deal with 2,000 per year.

But they have to avoid complacency, says Mr Bord. "People are taking action, but not fast enough," he says. "If you haven't been flooded, you think it can't happen to you. If you have, you think it won't happen again."

Flood experts agree that, in relatively wealthy countries, the price of living near the water must better reflect the risks, to both stop overbuilding and encourage infrastructure investment. Many also believe that private insurance – the free market – offers the best pricing mechanism.

Yet there is a reason that, as Wharton's Ms Kousky says, "there is almost nowhere in the world with a fully private disaster insurance market." Floods, she says, "are concentrated and correlated risks … you have lots of quiet years and then a really bad year." This requires insurers to hold lots of capital, and therefore charge high premiums.

In some areas high premiums would bring down the prices of prime real estate. In others, they would force out low-income residents. The political barriers to either are high.

Barry Gilway, chief executive of Citizens, a Florida-based property insurer, uses the example of Florida Keys. "Without subsidisation no homeowner could really afford to live or build in

Photo by Piyush Priyank on Unsplash

Monroe County due to the extremely high costs of funding the risk. After Hurricane Irma [in 2017] they had to rebuild to new building codes. While absolutely appropriate, that is very expensive. With no affordable housing and extremely high insurance costs, where do all the people in the service industry live?"

A few steps would make the public-private balance easier to achieve. Investment in detailed public flood maps would also help increase risk awareness and improve underwriting. The First Street Foundation, a non-profit group, has begun work on this in the US, but public investment is required. "We need an atlas of flooding," says Stijn Van Nieuwerburgh, a real estate economist at Columbia University.

Ms Kousky of Wharton recommends a system modelled on the way terrorism is insured in the US: a private market with insurers backstopped by the government. 'We want to have some amount of risk-based pricing [but] that's perfectly do-able even with a government backstop at a very high level."

Following the example of the UK, new buildings could be excluded from subsidy programmes. Alternatively, people could be given help to make their homes more resilient, so that future floods cause less damage and cost less to repair. Flood Re wants to be able to cover victims not just for the costs of repairing damage but also to "build back better".

"Flood risk management cannot be done by the insurance industry alone," says Konrad Schoeck, a flooding specialist at reinsurance group Swiss Re. "It needs to be the insurance industry, the government and private homeowners."

It may be that the suffering caused by flooding is not yet enough to force hard choices. But with waters continuing to rise that is unlikely to remain the case.

"As levels of risk rise, there will be more questions about uninsurability and what you do about it," says Arno Hilberts, vice-president at risk modelling company RMS. "You will reach a threshold where insurance systems don't really work."

Prevention key to cutting climate costs

While wealthy countries such as the US and UK struggle to decide which climate change risks the state should carry, the calculus for poor or middle-income countries is very different.

Avoiding the worst impact of floods will cost billions. In Indonesia, Jakarta is slowly sinking which last year led President Joko Widodo to announce plans for a new capital on the island of Borneo.

Even where the problems are not so eye-catching, there is often little private insurance in place to cover the growing flood risk as few people can afford it. But there is a role for insurers. One is to help countries finance the cost of dealing with floods via so-called parametric insurance policies sold to aid agencies or governments. These policies pay out as soon as a threshold, such as the depth of a flood, is breached.

The Centre for Disaster Protection funded by the UK government has just been set up in London to help countries understand how insurance or other forms of financing could help.

"There is a challenge in the way the world pays for disasters, waiting for them to happen and then paying for them, rather than preparing in advance," says Daniel Clarke, the centre's director. Insurance can help but it has to be tailored to cover the right risks. "The only thing worse than no insurance is bad insurance that people rely on and then it doesn't come through."

One of the challenges is to get three very disparate groups – insurance companies, governments and aid agencies – to work together.

"The consequences of the climate crisis such as repeated flooding is ultimately a humanitarian issue. But it's not one that the public sector and charities can solve on their own – we need to collaborate with commercial partners," says Simon Meldrum, a former banker who is now an investment specialist with the British Red Cross.

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CAN THE DUTCH SAVE THE WORLD FROM THE DANGER OF RISING SEA LEVELS?

Simon Kuper
Financial Times

On the afternoon of January 31 1953, the sea off the Dutch coast rose so high that it attracted sightseers. Just after 6pm, national radio warned of "dangerous high water". That was almost the only notice given.

A telegram from the Storm Flood Warning Service went out to the 30 officials and organisations who had bothered subscribing to it, but few read it on time, recounts Kees Slager in his history De ramp ("The Disaster").

That night, the north to north-westerly storm broke dykes in the south-western Netherlands. Piet van den Ouden, an 18-year-old in the village of Oude-Tonge, saw the water rushing through the letter box.

As the family fled upstairs, he managed to save his parents' false teeth. But looking out of the window, he recalled much later, "I got a terrible fright: the other side of our street was gone! The little houses had all crashed.

"The worst moment was when I saw my oldest brother's house further along the street collapse. Back in the attic, I told my father. And something happened that I'd never seen before: my father began to cry."

About a tenth of Oude-Tonge's population drowned in the flood: 305 people, including 65 on Van den Ouden's street, though his brother miraculously survived. The village's rickety working-class quarter collapsed almost entirely.

Van den Ouden spent the following days recovering neighbours' bodies, and the nights drinking himself senseless to cope, recounts Slager.

The disaster killed 1,835 people in the Netherlands, and 307 on the English east coast. Within 18 days, the Dutch government had created the "Delta Commission" to advise on preventing future floods.

Over the next 45 years, the country spent billions building the Delta Works: a network of dams, dykes, sluices and storm barriers that is unmatched worldwide. Though most of the Netherlands is either below sea level or prone to river floods, the number of people killed by flooding since 1953 is zero.

The Dutch had a preview of history. As sea levels rise ever faster this century, more places on earth will flood. Coastal cities, such as New York, Shanghai, Miami and Jakarta, and river deltas, in Bangladesh and Vietnam, face a battle to survive.

Can the Dutch – with their centuries of experience fighting the water – save the planet? Can they even save themselves? Or will our children have to abandon some of the world's most densely populated places?

The Roman author Pliny the Elder, who spent time in the Low Countries in the first century AD, described "a pitiful land flooded twice a day, so that the inhabitants are forced to live in huts on self-made heights, where they warm limbs stiffened by the northern winds on a fire of dried mud".

It took nearly two millennia, but the Dutch tamed the waters. Local water boards were set up from the 13th century to maintain the dykes. The Dutch learnt to reclaim land from the water: the so-called polders, typically flat lands, below sea level, were protected by dykes.

There were disasters – a flood in 1421 probably killed thousands of people – but gradually the Dutch worked out a system of pragmatic, unideological co-operation to protect themselves. After all, whether you were Catholic or Protestant, or a Protestant who despised rival Protestants, everyone needed dykes.

This co-operative system became known as the poldermodel. It's often seen as the basis for today's Dutch politics of eternal coalition. In modern Dutch, the verb polderen has come to mean "to bring all groups together to hammer out a compromise".

The most famous story of Dutch flood protection was probably taken from a French story, then popularised by an American. In 1865, Mary Mapes Dodge, an author who had never visited the Netherlands, published the children's novel Hans Brinker, or the Silver Skates. It includes a brief and wholly implausible story of an unnamed Dutch boy who saves his country by plugging a dyke with his finger.

The book became a bestseller, and the boy an international legend. However, the idea of an individual hero is quintessentially

American. For the Dutch, the hero is always the poldermodel.

Since 1953, the Dutch have taken a zero-tolerance attitude to flooding. "Safety first," says Peter Glas, the Delta commissioner, whose office in a Hague skyscraper (like many Dutch offices) has a sea view. "Other countries are better in disaster response – rebuild!"

The Dutch, who in 1953 had just one helicopter of their own, tend to be in awe of nations that are good at rescuing stranded people from rooftops or flying in soldiers to clear wreckage. Instead, the Netherlands does prevention: each inhabitant is meant to have a risk of just one in 100,000 of drowning in a flood in any given year.

Dutch prevention has long been a source of much pride among officialdom. In 1986, when the Eastern Scheldt storm-surge barrier was completed, my school class in Leiden was among many bussed out for a freezing, boring outing to witness the giant piece of infrastructure.

Most of the time, though, the Dutch public live in happy complacency about the potential risk of flooding. Their defences have worked so well, at a relatively modest annual price, that most citizens have almost forgotten about them.

The Netherlands has spread its spending on flood defences over seven centuries. About half the Delta Fund's budget of €1.1bn for this year goes on protection against the water. Though certain Dutch far-right politicians complain about "climate hysteria", Glas says: "I must say that all investments have been unanimously accepted by parliament."

Water boards can also raise local taxes to invest in flood defences, so altogether the Dutch spend about €1bn a year, or just over 0.1 per cent of gross domestic product, on what they call "dry-feet insurance". Much of that money, as they always tell visiting foreigners, goes on maintenance.

All this is cheaper than waiting for disaster and then rebuilding: the World Bank estimates that every dollar spent on flood defences yields returns of $7 to $10. But Bianca Nijhof, managing director of the Netherlands Water Partnership network, says: "The forward and integrated way of thinking that the Netherlands [has] is something that you don't see anywhere else worldwide, not on that scale."

One afternoon, Marc Walraven, an official at the ministry of infrastructure and water management, drove me out to see what he called "the Netherlands' front door": the Maeslantkering, a storm surge barrier at the mouth of the river flowing from Rotterdam to the sea.

I had grown up in a polder landscape 25 miles north, and it all looked familiar: canals, cows, wind, drizzle. The western Netherlands is Europe's most densely populated landscape, and within a couple of kilometres we passed wind turbines (reducing CO2 emissions), greenhouses that grow food under heat lamps (creating emissions) and, finally, the Maeslantkering (protecting against their effects).

1.835

People in the Netherlands killed in the flood of 1953

We turned on to a dyke, passed a wet jogger and reached a locked gate with a sign saying "No entrance". This overlooked outpost houses a majestic piece of infrastructure that is constantly visited by foreign delegations looking for a model. In the visitors' centre, two officials proudly showed each other videos of themselves dubbed for Italian TV, each opining about flood-threatened Venice.

Another recent visitor was George P Bush, the Texas Land Commissioner and nephew of George W, who is trying to find a way of protecting Houston without angering local climate deniers. He's on a very 21st-century mission: to safeguard his region's oil refineries against climate change.

0

People in the Netherlands killed by flooding since 1953

Though the Maeslantkering was completed in 1997, foreign visitors often find it futuristic. It consists of two metal arms, each the size of an Eiffel Tower. It's an open door: ships sail by every few minutes, into and out of Rotterdam.

The barrier stands ready to close when the waters rise by three metres. That level hasn't been reached since its construction, though Walraven is hoping it might be one day. "Not just a little bit," he admits. "That's what you do it all for."

His team spend their days doing maintenance, training and exercise, and carrying pagers ready for the big moment. The door needs to close just once in its lifetime to earn its money: any flood that shuts Europe's busiest harbour, Rotterdam, could cause hundreds of billions' worth of damage, one official told me.

But since the Maeslantkering was completed, the Netherlands has shifted tack: it has gone from battling the water to making a very Dutch compromise with it. Under the slogan "Room for the river", it has created lakes, parks and even parking garages designed to flood when necessary so as to divert the waters from inhabited places.

Whenever a city starts thinking of protecting itself against floods, someone will say: "Bring in the Dutch." Increasingly, the world needs their expertise.

The standard line is that if countries stick to the Paris accords, we can limit temperature rises to 1.5C or at most 2C, keeping the earth liveable. But the brutal reality is that there is no sign of that happening. To be on track to meet the accords, we would need to halve global carbon emissions by 2030. In fact, emissions have been setting new records every year.

Each country has a selfish incentive to keep emitting, because if it cuts and other countries don't join in, it would damage its own economy while barely slowing climate change. Petteri Taalas, secretary-general of the World Meteorological Organization, a UN agency, said in January: "On the current path of CO2 emissions, we are heading towards a temperature increase of 3C to 5C by the end of the century."

The only question is how high the seas will rise. The UN's Intergovernmental Panel on Climate Change predicts a rise of 84cm by 2100 if emissions continue on current trends, and adds that more than one metre isn't unlikely. But the IPCC's predictions have tended to prove over-optimistic; the phrase "faster than expected" punctuates recent climate science.

The Dutch meteorological agency, the KNMI, calculates that sea levels might rise two metres by 2100 even if the Paris targets are met, and three metres if not. This would mean a new world, especially as many coastal cities are subsiding – Jakarta, spectacularly, by 10cm a year in places.

"That's an order of magnitude bigger than today's sea-level rise," notes Stefan Aarninkhof of the Delft University of Technology, whose world-class hydraulics engineering department trained much of the Dutch water sector. The tight links between experts in government, the private sector and universities often go back to Delft undergraduate days.

The Netherlands is the best-protected delta in the world. If the sea level rises, this will be the last delta to be evacuated

Harold van Waveren

Henk Ovink, the Netherlands' international water envoy, studies a map of the world's biggest cities, and remarks: "We really have a problem." The blue dots on the map, signifying cities, are overwhelmingly on the coasts.

Most of the 1.1 billion people now living in flood-prone areas are threatened by rivers rather than seas, according to the Netherlands Environmental Assessment Agency.

More are migrating towards the danger, largely because river deltas and coasts are fertile, well-connected and attractive places to live.

By 2050, the agency predicts, 70 per cent of the global population will live on 0.5 per cent of the world's land area, much of it beside the water. Usually, as in Oude-Tonge in 1953, poor neighbourhoods face the highest risk. India, China and Bangladesh have the largest populations under threat, but the US, too, has several endangered cities.

Along with the incentive to keep emitting, each country has an apparently contradictory yet existential incentive to protect itself from flooding. How will they do it?

Glas drops two thick volumes on his table: Bangladesh Delta Plan 2100. Like Vietnam's Delta Plan, it was drawn up with Dutch advice. Bangladesh resembles a Netherlands with neither wealth, strong governance, nor the 40 years of time that the Dutch took to implement their Delta Plan. Even with forward planning, it will struggle to save itself.

The US does have the resources to protect itself – incomparably more, in fact, than the Netherlands did in 1953. It also has the need. Since 2005, hurricanes, storms and floods in New Orleans, Houston, Puerto Rico and the New York area alone are estimated to have killed over 4,000 people – more than died in the attacks of 9/11, and nearly double the US death toll in Afghanistan since 2001.

Given climate change and the rising coastal population, the problem will worsen. But so far, the US appears structurally ill-equipped to handle it. Whereas the Dutch poldermodel evolved to fight the water, the American system emphatically didn't.

Ovink witnessed this first-hand. In October 2012, he tracked Hurricane Sandy on his iPad as it killed 233 people in eight countries, and caused nearly $70bn in damage, culminating in New York.

Soon afterwards, Shaun Donovan, the US secretary of housing and urban development, made a study tour of the Dutch water defences. Ovink took him around and, after saying goodbye, wrote him an email: "Dear Shaun, I think Hurricane Sandy can be a game changer for the United States. If you agree, I'd love to work with you. I hope I'm not being too forward." Donovan replied as his plane landed in Washington, DC: "You're being just forward enough."

Ovink went to the US, where he became known in President Barack Obama's White House as "Henk the water guy". He describes his book about the experience, Too Big, as "Tintin in America": a visiting foreigner marvels politely at American ways. Whereas the Dutch treat water as a national affair, in the US, each town or state is expected to manage its own defences. Obama tried to break through silos and put $60bn of federal money to work, but it went against the grain. The project hit trouble even before the climate-denying Trump administration took over.

Cynthia Rosenzweig, who heads the climate impacts group at the US National Aeronautics and Space Administration's Goddard Institute for Space Studies, says: "If you look at the approximately $15bn earmarked for New York City rebuilding and resiliency after Sandy, just over half of those funds had been spent as of last May."

2030

Year by which the world would need to halve global carbon emissions to be on track to meet the Paris accords

And whereas the Dutch aim for prevention, the US devotes awesome energy to response: rebuilding after disasters. The way the Federal Emergency Management Agency compensates victims, Ovink discovered, is: "You may build back, but not better. Even if you know what to change, to improve, you cannot spend that money to safeguard against future disasters."

US government regulations aim to ensure that nobody can

Photo by Tim Roosjen on Unsplash

use this compensation to improve their home. Fema wants to focus more on prevention but this would require an overhaul of the US system.

When Ovink met victims of Sandy at a soup kitchen in New Jersey, he discovered that they preferred their system as it is. "The people in this soup kitchen couldn't care less about a blue-eyed bald guy from the Netherlands talking about working together, about building back innovatively, about climate change and the future." They didn't trust the government to do anything more than replace what they had lost. "Just give me back what I had, they say." And so the US spends billions rebuilding structures that will be destroyed by the next storm.

Ovink says: "Stupid infrastructure still has a business case, making us more vulnerable with every dollar we invest." The National Flood Insurance Program has repeatedly bailed out more than 30,000 "severe repetitive loss properties", each flooded an average of five times.

In 2018, the NFIP was $20.5bn in debt, even after Congress had cancelled debts of $16bn the previous year. Many endangered American homes are "waterfront properties", a category almost unknown in the Netherlands, where nobody is allowed to build on the beach.

Dutch water experts who have visited the US tend to marvel at American "Hans Brinkerism": the notion that protection against the water is an individual duty. In Miami, there are buildings that have their own private sea walls – no matter that these will divert floods on to the neighbours.

In Houston and other cities, says Bas Jonkman, professor of hydraulic engineering at Delft, some companies have built dykes to protect themselves. Marjolijn Haasnoot, of Delft-based research institute Deltares, saw a street in Louisiana where almost every house sat on what she recognised as a terp: a small man-made mound that the medieval Dutch used to keep their homes dry. The only house without a terp, she foresaw, "will get all the water. This would be unthinkable in the Netherlands."

In fact, when it comes to flood defences, the contemporary US sounds remarkably like Slager's description of the medieval Netherlands. The basic principle then was elc sinen dike: each polder took care of its own dyke, without reference to the neighbours. The richer people didn't help out the poor. The "dyke counts" in charge of flood defences were wealthy men appointed not for their expertise but because they had made donations to the monarch.

The disaster of 1421 was due partly to money being spent on wars instead of dykes. There was also denial of the problem: in October of that year, a month before the floods, two rival potentates agreed, probably wrongly, that the practice of salt mining was not weakening the dykes.

For all the US's dysfunction, many American cities have now realised that they need to start thinking collectively and, possibly, even nationally. "It's more than a local problem," notes Jonkman. "It's New York and Boston and Norfolk and Charlotte and New Orleans and other cities." Several of them are considering large-scale flood defences.

New Orleans's total spending on flood defences after Hurricane Katrina is about $15bn, says Jonkman. That includes the rapidly built "Great Wall of Louisiana", the $1.1bn Lake Borgne Storm Surge Barrier – but it isn't fully adapted to future projected sea-level rises, says Rosenzweig.

Now New York is debating spending $119bn on a storm barrier. This would take 25 years to build, and critics say it underestimates future sea levels. Inevitably, Donald Trump has tweeted: "A massive 200 Billion Dollar Sea Wall, built around New York to protect it from rare storms, is a costly, foolish & environmentally unfriendly idea that, when needed, probably won't work anyway. It will also look terrible. Sorry, you'll just have to get your mops & buckets ready!"

Eric Klinenberg, director of the Institute for Public Knowledge at New York University, who studies cities and climate change, says: "The federal government is an inconsistent partner. It has become an oppositional partner under President Trump."

Moreover, he adds, neighbourhood groups have stalled some post-Sandy projects: "We have become so hostile and divisive that we even pick fights with our own allies." Because of these issues, even wealthy New York, with its vast resources of brainpower, and leaders who believe in climate change, isn't protected from the next Sandy.

If New York cannot save itself, many lesser resourced cities won't. That raises a chilling question: should some of them be abandoned? Ovink says: "Retaining all places in the world is impossible in the long run."

Here and there, abandonment has already begun. Indonesia plans to move its capital from Jakarta – hit again by flooding this January – to the Indonesian part of the island of Borneo. Bangladeshis are migrating every day from the country's perennially flooded delta to the slums of the capital Dhaka. Even in England, where coasts are eroding (by an average of two metres a year in Yorkshire), certain places are becoming uninhabitable.

2050

The year by which the Netherlands Environmental Assessment Agency predicts that 70 per cent of the world's population will live on 0.5 per cent of the world's land area, much of it beside the water

Small island development states such as Kiribati and the Maldives will probably reach that point this century, their drinking water supplies salinated by the rising seas even before the land goes under.

Klaus Jacob, geophysicist at Columbia University, questioned whether New Orleans should be rebuilt after Katrina, given the city's growing long-term threats. Sanjay Khanna, futurist at the law firm Baker McKenzie, sketches a scenario in which Americans threatened by either floods or droughts (in cities such as Las Vegas or Los Angeles) retreat to the safe, ample freshwater supplies of the Great Lakes region.

Miami's outlook is particularly gloomy. Much of its waterfront is protected by what looks like a waist-high garden wall. Building Dutch-style defences is an improbable outcome in low-tax Florida, and might not help anyway: the city is built on porous limestone, so it also floods from below.

Jonkman says it's still unknown what kind of protection might work here. Miami, officially incorporated as a city in 1896, may already be past midlife. It could thrive for a few more decades as a disposable playground for rich people with a short-term property market. When the city winds down, the main victims will be the usual victims of water disasters: the poor, who lack the resources to start again.

In New York too, says Rosenzweig, "There is beginning to be a conversation about strategic relocation." Downtown Manhattan and Staten Island are particularly flood-prone but parts of every borough are at risk.

Jacob has proposed moving people to "higher-lying neighbourhoods in Brooklyn and Queens, to some degree in northern Manhattan".

You would think that if anyone can withstand the future, the Dutch can. Harold van Waveren, of the ministry of infrastructure and water management, says: "The Netherlands is the best-protected delta in the world. If the sea level rises, this will be the last delta to be evacuated."

Yet that moment may be coming. I began my research thinking that the Dutch could save the world, but finished it doubting whether they could even save the Netherlands. In 2017, the research institute Deltares sent an informal message to government officials: studies by the KNMI and others indicate that, beyond 2050, sea-level rise might happen faster than you expect. Haasnoot of Deltares summarises the response: "Jeez, that's intense." The state asked her to write a report.

Deltares convened a hackathon together with the government, think-tanks and universities. They came up with four possible responses to a sea-level rise of more than two metres: 1. Protect the coast by building dykes, and closing off the rivers from the sea. 2. Protect the coast but keep the rivers open. 3. Build a new coastline in the sea, to protect the existing coast. 4. "Accommodate the water".

Broadly, the conundrum facing the Dutch can be distilled to a binary choice: should we stay or should we go? Staying would require large adjustments to the country's land and water management. The sea will almost certainly rise by two metres and more, if not by 2100 then surely by 2300. Sealing off the rivers could put an end to Rotterdam's status as a major harbour.

Eventually, huge amounts of sand would be required to build high enough dunes, the dykes would become so big that they'd eat up living space, pressure from seawater would salinate farmland and thinly populated areas such as the south-west (site of the 1953 floods) would probably have to be sacrificed as holding pens for flood water. Giant pumps would be needed to push the rivers upwards into the sea.

The Netherlands would be constantly upgrading its defences to cope with rising waters. It could build floating homes, even a floating airport, and bring back terps, but it would have to write off some of its current housing stock.

$119BN

The amount New York is debating spending on a storm barrier. It would take 25 years to build

One day, much of the country may be abandoned. People might be allowed to remain in certain areas at their own risk. Dutch water experts speak, half-jokingly, of "moving to Germany and learning German".

In Delft, 10 miles from the sea, I wandered through streets that still looked almost as they did when Johannes Vermeer painted here 400 years ago. It's questionable whether they'll be here in 400 years, or perhaps even in 100.

Alternatively, the Netherlands may have to choose between protecting either Delft or equally venerable Leiden, my hometown up the road. If it all sounds extraordinarily brutal, that may be because the Netherlands is the only country that is planning for the waters of 2100.

Haasnoot cautions: "There is still a large uncertainty about future sea-level rise. We have time to prepare, but no time to lose. We must keep our options open to adapt if necessary."

I ask her how she feels about her own scenarios. "Personally," she says, "I find it keeps getting closer. When I began working, in the late 1990s, climate change was the future. Now that I have small children, 2100 isn't that far away. I hope our children will still be here then. Walking around here, you think, 'If sea levels rise faster, it will be quite a change.'"

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CLIMATE CHANGE TO RAISE COSTS FOR US MUNI BOND ISSUERS

Billy Nauman in New York
Financial Times

Municipal bond investors across America are waking up to the financial risks of climate change, as increasingly frequent extreme weather threatens cities' ability to pay back their debts.

Within a decade, according to research from BlackRock, issuers equivalent to 15 per cent of today's "muni" market are likely to see increasing impacts of weather-related events that could knock as much as 1 per cent off their economic output.

Now, concerns over climate-change exposures have begun to spread in the $4.1tn market, about one-quarter of the size of the US Treasury market, where American cities, states, counties or other local governments go to raise money. About $11bn of munis change hands every day, according to the Securities Industry and Financial Markets Association.

It is only a "matter of time" before gaps in funding costs begin to emerge between cities with robust climate adaptation plans and those without, said Dan Rabasco, Boston-based head of municipal bonds at Mellon Investments.

"The risk has been identified by market participants," he said. "Looking at the severity of storms picking up…it will start to be factored in."

To help put investors' mind at ease, Mr Rabasco added, borrowers need to start spelling out their resilience plans explicitly. "What plans are they making? Are they hardening their infrastructure…are they trying to insulate central services? If they're just stating the obvious, that's not sufficient."

Although Mr Rabasco declined to comment on any specific bond issuers, East Baton Rouge, which was hit by flooding four years ago, is perhaps a case in point. In its prospectus for a $130m bond issued in August, the parish – the most heavily populated in the state of Louisiana – mentioned climate change only in general terms and did not put forward a detailed plan of actions it would take to buffer its effects.

"The occurrence of such extreme weather events has previously caused and could in the future cause negative economic impacts in the issuer that could result in a reduction of sales tax revenue," the bond documents read.

The risk has been identified by market participants. Looking

Photo by Jonathan Ford on Unsplash

at the severity of storms picking up…it will start to be factored in
Dan Rabasco, Mellon Investments

Credit rating agencies have begun to factor such risks into their evaluations, and reward those cities that appear well prepared.

Miami Beach, for example, issued "general obligation" bonds – backed by the Florida city's taxing authority, rather than any particular stream of revenue – in March last year. They were rated AA+ by Moody's partially because of Miami Beach's climate resilience work.

"In our view, the city maintains among the most robust plans attempting to address [climate change] risks that we've reviewed for US local governments," Moody's wrote in its analysis.

Where climate risk is most relevant to munis is where it can create an "acute revenue pressure", said Michael Rinaldi, senior director in Fitch Ratings' public finance group. This is especially the case for bonds backed by sales tax income – such as the one issued by East Baton Rouge – where a specific event can upend the economy even for a short period of time. That happened in 2016 and 2017, he noted, when public fears over the Zika virus ate into hotel tax collections across the state of Florida.

Fitch uses historical data to gauge the chances of extreme weather hitting a city, but with global warming causing these events to occur more frequently, the models are far from perfect.

As part of an ongoing environmental, social and governance arms race among rating agencies, Standard & Poor's recently rolled out a new tool that uses its data on companies' assets to better predict physical climate risk for corporate issuers – but has yet to apply the system to munis.

For now, investors are not punishing borrowers over these issues. BlackRock analysts recently compared two bonds with similar characteristics but vastly different climate risk profiles and found no difference in their yields. The first came from Jupiter, a Florida city near West Palm Beach, in an area beset by hurricanes. The second was from Neptune, New Jersey: an area near the Jersey Shore that is much more insulated from storms.

"If climate-related risks were being considered as a key factor, we would have expected the Neptune bond to carry a lower yield (higher price) than the Jupiter bond. We found similar results for other spot checks of bonds in areas of high and low climate risk," BlackRock's report states.

Mr Rabasco chalks this up to strong demand for municipal bonds, evident in dozens of consecutive weeks of inflows into specialist muni funds last year. "In an environment like that, investors aren't as discerning…They don't make analytical choices because they need to put cash to work," he said.

Still, he expects borrowing costs to diverge before long. "There's a bit of a learning curve, but it's happening."

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FLOODS AND COAL CLASHES SPOTLIGHT CLIMATE THREAT TO FINANCIAL SECTOR

Billy Nauman
Financial Times

Banks, insurers and asset managers face a growing threat from climate change, as the physical effects of global warming and the transition to a low-carbon economy pose unprecedented risks to the status quo.

Banks have been quick to capitalise on rising demand for sustainable financial products such as green bonds, but slower to account for the danger of stranded assets and mispriced risk on their balance sheets.

The real estate and mortgage markets are an area of particular concern, the McKinsey Global Institute has found. In the US state of Florida alone, McKinsey estimates that increased flood exposure could knock $30bn to $80bn off residential property valuations by 2050.

With increased flood risk and property devaluations comes the danger of mortgage defaults. Many homeowners have no flood insurance and will be exposed. Extreme weather and flooding can also affect people's livelihoods and ability to get to work and pay their debts.

"You could have a community breakdown and an infrastructure breakdown [where] roads are flooding more," says Hans Helbekkmo, partner at McKinsey. This also creates a higher chance of "strategic default", where homeowners walk away from a property once there is a significant fall in the price, he adds.

"The mortgage lending business would want to take a close look at this," says Mr Helbekkmo. Given that many mortgages are sold to government-sponsored enterprises such as Fannie Mae in the US, "governments could end up holding the bag".

Banks' commercial lending arms also face problems because of exposure to coal. The fuel is becoming economically unviable as natural gas and renewable energy prices drop. Yet many banks still lend to coal companies and are in danger of mispricing the risk, says Chris Hohn, the billionaire hedge fund manager.

Sir Chris has launched a campaign to compel lenders to disclose their exposure to coal. "The risk of a coal loan is accounted for by banks and regulators as investment grade, when in fact they are high-risk in nature," he says. The campaign has threatened legal action if they do not accurately weigh coal risk. "If you falsely mark a loan or risk weighting you can have breach of fiduciary duty."

Banks including JPMorgan Chase have recently been targeted by environmental activists, which want companies to stop financing fossil fuel and have used tactics from filing shareholder resolutions to protests at bank offices.

Companies face pressure from their customers to curb money going into fossil fuels

Insurers are also exposed, as they may be liable to cover legal penalties against coal companies held responsible for environmental damage, according to a research note by rating agency Moody's. "Insurers could…benefit from reduced exposure to potential environmental liability risks associated with thermal coal industries," the 2019 note said. More than 1,300 such lawsuits have been brought against companies and governments, according to activist group Unfriend Coal, which aims to make the sector uninsurable. In one instance, American Electric Power said last July that it would retire a 1,300MW unit at its power plant in Rockport, Indiana, to settle a lawsuit over air pollution.

So far a number of insurers have walked away from coal, especially in Europe, including Axa, Zurich and Swiss Re. Beyond fear of lawsuits, they have an incentive to try to mitigate harm of climate change however they can – including making it harder to operate coal-fired power plants.

"As a global insurer we are impacted by climate change, in everything from increasing fire risk to flooding," Joseph Wayland, general counsel of Chubb, said in July when it became the first large US insurer to stop covering coal companies.

As the climate changes, the data and models used by insurers to set rates "may well prove insufficient over time for the rising levels of risk", warned McKinsey. The position of participants "from insured to insurer to reinsurer to governments as insurers of last resort", needed examination, it added.

Insurers also risk losing money on investments if they own shares in fossil fuel companies holding stranded assets. Pension funds, sovereign wealth funds and asset managers are also likely to be affected. As much as $900bn worth of fossil fuel reserves will

Photo by Chris Gallagher on Unsplash

be written off if governments take action to keep global warming under 1.5C, according to FT estimates in a Lex In Depth report.

Yet stranded asset risk may be the tip of the iceberg for investors. New research from BlackRock, the investment management group, suggests that shifting investor preferences are likely to drive up prices for "sustainable" companies and punish those that perform poorly on environmental, social and governance (ESG) criteria.

They also face mounting pressure from customers and activists to curb money going into fossil fuels, but many investors are hesitant to fully divest. Instead, many large investors are trying to engage with companies to push them to green their operations.

A number of investor groups are banding together to put pressure on boards and chief executives, such as Climate Action 100+, which recently added BlackRock to its roster. The group focuses on big emitters, and has signed up 450 investors with more than $40tn in assets under management. However, the results have not lived up to some activists' expectations.

"We would celebrate the day the Climate Action 100+ rises to the challenge ahead of us. The initiative has involved a lot of self-congratulation and paper agreements, and it is untied to real-world outcomes," says Brynn O'Brien, executive director of the Australasian Centre for Corporate Responsibility.

"If it were to rapidly become more ambitious, transparent and consistent, it could be an extremely important initiative."

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LEAVING IS NO LONGER OPTIONAL

Christopher Flavelle
New York Times

WASHINGTON – The federal government is giving local officials nationwide a painful choice: Agree to use eminent domain to force people out of flood-prone homes, or forfeit a shot at federal money they need to combat climate change.

That choice, part of an effort by the Army Corps of Engineers to protect people from disasters, is facing officials from the Florida Keys to the New Jersey coast, including Miami, Charleston, S.C., and Selma, Ala. Local governments seeking federal money to help people leave flood zones must first commit to push out people who refuse to move.

In one city in the heartland, the letters have already started going out.

Last year, Giovanni Rodriguez, whose white midcentury house backs onto a creek in the southern suburbs of Nashville, got a letter saying his home "is eligible for participation in a floodplain home buyout program." The surprise came a few lines lower: If necessary, the city "would acquire properties through the use of eminent domain."

Mr. Rodriguez, a 39-year-old freelance musician and composer of funk, R&B and Latin jazz, said he had no interest in selling – at least not for what the city is offering, which he said wasn't much more than the $188,500 he paid for the home in 2013. "I would lose this house that I love," he said.

Eminent domain – the government's authority to take private property, with compensation, for public use – has long been viewed as too blunt a tool for getting people out of disaster-prone areas. It has a controversial history: Local governments have used it to tear down African-American neighborhoods, as well as to build freeways and other projects over residents' objections. Even when the purpose of eminent domain is seen as legitimate, elected officials are generally loath to evict people.

Still, in a sign of how serious the threat of climate change has become, some local governments have told the Corps they will do so if necessary, according to documents obtained through public records requests and interviews with officials. Other cities have yet to decide, saying they feel torn between two bad options.

The willingness to use eminent domain shows how quickly the discussion around climate has shifted. Even as President Trump publicly dismisses the scientific consensus of climate change, his administration is wrestling with how to move people out of the way of rising seas and increasingly intense rainfall.

Still, threatening to push people out of their houses is an extreme step, experts said.

"It's going to create a really big political backlash," said A.R. Siders, a professor at the University of Delaware who studies buyouts. Still, she praised the Corps for "recognizing that the degree of action we're taking needs to match the degree of the crisis."

The Corps' mission includes protecting Americans from flooding and coastal storms. It does that in different ways, including building sea walls, levees and other protections, and elevating homes. The Corps generally pays two-thirds of the cost, which can stretch into billions of dollars. The local government usually pays the rest.

As that risk grows because of climate change, the Corps has shifted toward paying local governments to buy and demolish homes at risk of flooding. The logic is that the only surefire way to guarantee the homes won't flood again is if they no longer exist. But it also uproots people and can destroy communities.

As a result, federally funded buyouts have usually been voluntary; residents could decline. But at the end of 2015, the Corps said that voluntary programs were "not acceptable" and that all future buyout programs "must include the option to use eminent domain, where warranted."

The consequences are now coming into view. In 2018, following a string of devastating hurricanes, Congress gave the Corps money to plan flood-control projects in more than three dozen cities and counties. Many of them now face a difficult decision – a dilemma the Corps saw coming.

"I know what we're saying" when asking cities to evict people, Jeremy LaDart, an economist with the Corps, said in a 2016 webinar explaining the approach. "In order to do this project with us, you're going to have to commit to buying out your constituencies and constituents, and doing something that may not be popular."

Some officials within the Corps were surprised by how far the policy went.

Photo by Casey Horner on Unsplash

Randall Behm was head of the committee within the Corps that studies buyouts. He said that voluntary programs are imperfect, often leaving vulnerable homes in place. Even so, Mr. Behm said the Corps should require eminent domain only for homes whose flood risk was so severe that their inhabitants were in physical danger.

"That's where we really need to clear out the structures," said Mr. Behm, who retired in 2018. By contrast, he said the Corps' current approach "scares a lot of community officials."

The Corps defended its policy. Without using eminent domain, officials said, the Corps can't guarantee to Congress that the buyouts lawmakers have funded will actually happen.

And that would leave residents still at risk. Imagine the Corps identifies 10 homes for buyouts, but only three people say yes, said Susan Layton, chief of planning and policy for the Corps' Norfolk District office, which is working on buyout plans in Florida. With a voluntary program, that leaves seven homes still exposed. "You're probably not doing your best job," she said.

The Corps applies a relatively simple formula to decide which houses should be condemned, officials said: It estimates how much damage a house is likely to suffer in the next 50 years, then compares that to what it would cost to buy and tear down the house, plus moving expenses for the owner. If the buyout costs less, the homeowner is asked to sell for the assessed value of the home. That price is not negotiable, and neither is the offer.

Many officials have balked, at least for now. Miami-Dade has yet to agree to evict residents, and New Jersey has refused. In the Florida Keys, Roman Gastesi, the county administrator, said he doubted the county commission would approve it.

"Eminent domain is not something that's going to be palatable," Mr. Gastesi said, adding that the Corps should fund the buyout program it's currently looking at in the Keys, but make it voluntary. "We don't want to kick people out of their houses."

But local officials in other communities have been willing to accept the Corps' terms.

Brookhaven, a town on Long Island in New York, agreed in 2018 to use eminent domain if necessary as part of a Corps plan to protect against flooding, according to James D'Ambrosio, a Corps spokesman. A spokesman for Brookhaven, Jack Krieger, referred questions to the Suffolk County government, which didn't respond.

In Okaloosa County, Fla., the Corps asked officials to say in writing that they had the authority and the expertise needed to evict homeowners. The county said yes last June, but added that it might need the Corps' help "justifying the necessity of the taking of private property," according to documents obtained through a public records request.

Asked for comment, a spokesman for Okaloosa County, Christopher Saul, responded: "We are prepared to work with the Corps of Engineers to the best of our abilities in order to preserve the safety of Okaloosans."

Other places appear to have had second thoughts. Last summer, Atlanta told the Corps that the city was able to use eminent domain, according to documents obtained through a public records request. The city informed the Corps in January that it was pulling out of the project.

Michael Smith, a spokesman for Mayor Keisha Lance Bottoms, didn't respond to requests for comment.

Another city looking at buyouts is Charleston. At a planning meeting in January, city staff told the Corps that they expected to acquire the land in phases, according to notes obtained through a records request.

Mark Wilbert, Charleston's chief resilience officer, said the city had told the Corps it would acquire the property required for the project. Asked if Charleston would use eminent domain for those who refuse, Mr. Wilbert said that "yeah, we'd look at it real close."

"It would not be the first place we would go," he added.

One of the first locales to invoke the threat of eminent domain is Nashville, where the Corps identified 44 homes it wanted the city to buy. Some homeowners have nonetheless said no.

Down the road from Mr. Rodriguez, Homer Adams, who is 98, said the city had approached him about buying his house. But he said that he and his wife, Wilma, who is 97, want to stay, and were under the impression that the program left them free to do so. "It was completely voluntary," Mr. Adams said.

The city, however, said every resident selected for the buyout got the same letter, saying eminent domain would be used if the city thought it was necessary.

Lonnie Smith, who lives in a house by another creek in the outskirts of Nashville, likewise said he didn't want to sell. So did David Woods, who said he thought his house was at less risk than some of the homes around it.

It now falls to the city to decide whether, and how, to enforce its pledge to the Corps to get these people out of their homes.

"Our preference is always, 'willing seller,'" said Tom Palko, assistant director of Nashville's storm water division. He said the city's approach was buying homes from people who want to participate, while giving those who don't time to change their minds.

Craig Carrington, chief of project planning for the Corps' Nashville district, said his office wasn't giving the city a deadline for evicting people. "We knew that this would take several years," Mr. Carrington said. "We're trying to eat the elephant one bite at a time."

Annie Daniel contributed reporting from Washington..

Christopher Flavelle focuses on how people, governments and industries try to cope with the effects of global warming. He received a 2018 National Press Foundation award for coverage of the federal government's struggles to deal with flooding. @ cflav

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THE SEA, LAPPING AT THE FRONT DOOR

Somini Sengupta
New York Times

What do you do when the sea comes for your home, your school, your church?

You could try to hold back the water. Or you could raise your house. Or you could just leave.

An estimated 600 million people live directly on the world's coastlines, among the most hazardous places to be in the era of climate change. According to scientific projections, the oceans stand to rise by one to four feet by the end of the century, with projections of more ferocious storms and higher tides that could upend the lives of entire communities.

Many people face the risks right now. Two sprawling metropolitan areas offer a glimpse of the future. One rich, one poor, they sit on opposite sides of the Pacific Ocean: the San Francisco Bay Area (population 7 million) and metropolitan Manila (almost 14 million).

Their history, their wealth, and the political and personal choices they make today will shape how they fare as the water inevitably comes to their doorsteps.

In both places, it turns out, how you face the rising sea depends mostly on the accident of your birth: Whether you were born rich or poor, in a wealthy country or a struggling one, whether you have insurance or not, whether your property is worth millions or is little more than a tin roof.

And, in both places, climate change has magnified years of short-sighted decisions. Manila allowed groundwater to be pumped out so fast that the land sagged and turned into a bowl just as the sea was rising. The Bay Area allowed people to build right at the water's edge, putting homes, highways, even airports at risk of catastrophic flooding.

But people tend to hold on, often ingeniously, as the water rises around them. In some cases that's because their properties are worth a lot, for now, at least, or because they have so little that they have nowhere else to go.

Now, Manila and the Bay Area face tough choices. They could adapt to the rising tide, which could mean moving people out of harm's way. Or, they could try to force the water to adapt to their needs by raising their defenses. For leaders, politically tough decisions lie ahead. What do they save on the water's edge, what do they forsake and how do they reimagine their coastal cities in an age of climate disruptions?

The Bay Area and Metropolitan Manila are both big and growing, with a lot of people and things to protect on the coast. How they deal with their circumstances today may offer lessons, for better or worse, for coastal cities elsewhere.

"Are we going to decide by not deciding, and wait for the water to reach our doorsteps?" asked Aaron Peskin, a member of the San Francisco board of supervisors.

"The biggest challenge is getting society to understand it, grapple with it, address it, plan for it, discuss the trade-offs."

METROPOLITAN MANILA

Rising water, sinking city

Desiree Alay-ay is in the thick of trade-offs.

Ms. Alay-ay, 30, grew up in a low-lying, flood-prone neighborhood on the northern fringe of Manila. It is not what she wants for her newborn baby. She wants to move, and take her parents with her.

Climate change has exacerbated a longtime problem in Manila. Because of a proliferation of fish ponds and the rapid extraction of groundwater, the ground has been subsiding. As a result, since the early 1990s, sea levels have risen much faster than the global average.

Storms repeatedly sweep away spindly-legged bamboo and tin houses on the water. People flee for a while, only to come back because they have nowhere better to go. In low-lying neighborhoods, like Ms. Alay-ay's, roads have been raised multiple times. Pariahan, a village just north of the city line, is now permanently underwater.

"Climate change doesn't create its own impacts. It magnifies wrong policies," said Renato Redentor Constantino, executive director of the Manila-based Institute for Climate and Sustainable Cities. "This is the case with sea level rise. A large part of Metropolitan Manila is facing more water-related impacts because of decades of myopic, cross-eyed land use planning."

More than 30 years ago, before Ms. Alay-ay was born, her parents, migrants from the countryside, built a small house in Malabon, the only neighborhood they could afford in Manila.

The water pooled up in the streets every rainy season. When they were kids, Desiree and her brother sneaked out and swam in the streets sometimes. Leaky sewers meant human waste sometimes floated by, which they referred to as "bazookas." Only tricycle cabs could ply through floods; when the water rose, her parents took her to school in a rented boat.

The city fought back by raising the road. So, Desiree's parents raised their house to stay above the road. They poured cement and sand on the floor, four times in 30 years, as though adding layers to a wedding cake.

Everyone lived like this. One neighbor raised the floor so high that the original kitchen sink is now ankle-high. Another abandoned the house altogether; its roof is barely above street level now, and water hyacinths have taken over the rooms.

It was only after Ms. Alay-ay had a baby that she set her mind to getting out of Malabon.

"I want my baby to have a good future," Ms. Alay-ay said. "I don't want him to experience what I've experienced."

She wanted her parents to come, too, so they could watch the baby while she and her husband went to work. But they had other plans. Leave the baby with us, her mother, Zucema Rebaldo, offered. But we're not moving. This is our home.

"This was a happy place for us," Mrs. Rebaldo said on a Sunday afternoon when I went to visit. "Even if people say one day it will be wiped out from the map. No question, I am staying."

Images of Christ looked down from the walls. Roosters crowed. Everyone knows her here, she said. They call her Lola Cema – Lola means grandmother, Cema is short for Zucema. They help one another out.

"I will die in this place," she said.

Her daughter listened quietly. She had heard this before, and, this afternoon, her face washed over with pain.

"It's hard," she said. "As their child I want them to move out of here to a place that's not flooded." Months of negotiations had ended in a deadlock.

Ms. Alay-ay's dilemma is magnified manyfold in a megacity like Manila.

Millions of the city's poorest live in hazardous, low-lying areas that are already lashed by tropical storms. Climate change is projected to make those storms even more intense and more frequent.

But, leaving those areas can mean being even farther from where you make a living. Or losing the neighborhood health clinic you've been going to for years. Or being marooned in a neighborhood where there are no tricycle cabs, let alone public transportation.

Forcing people to move away from the coast is not enough, said Antonia Yulo-Loyzaga, a member of the board of directors of the Manila Observatory, a research organization. They need to be able to find work nearby, or an efficient public transportation system to get there. That doesn't exist now; average commutes are two hours or more each way.

"You need some sort of rational, organized retreat from the coast," she said. "There's no option unless you want people to live in constant fear."

SAN FRANCISCO BAY AREA

A political lightning rod

A rising sea underscores the missteps of the past in the Bay Area, too.

The Pacific has risen 4 to 8 inches along the Northern California shore over the last century – and so, too, the San Francisco Bay, the ocean's largest estuary in the Americas. Depending on the growth of greenhouse gas emissions, the Pacific could rise 2.4 to 3.4 feet by 2100, which is why the California Coastal Commission has encouraged city governments to start planning for the future, either by fortifying their flood defenses, restoring wetlands, or, in some instances, making people move.

That is as difficult in the Bay Area as it is in Manila. "People's properties and investments are at risk," Jack Ainsworth, head of the commission, said in an interview. "It becomes very political and very emotional."

Unlike Manila, Bay Area municipalities are wealthy. And many of them are already paying handsomely to fortify high-value coastal infrastructure at risk.

Voters in San Francisco have approved a $425 million bond measure to start fortifying a sea wall along the bayfront road, the Embarcadero. Along the road sits some of the city's most expensive real estate; below it sits a subway line, a light rail tunnel, and part of the city's sewage infrastructure.

Meanwhile, the builders of a new real estate development in a former industrial area called Mission Creek are raising the old roads and warehouses by as much as 10 feet. And the San Francisco airport, which sits on tidal marshlands, is getting a $587 million makeover to raise its sea wall.

Farther south, a suburban community called Foster City, built on steadily subsiding landfill, has raised property taxes to increase the height of a levee that protects the area from storm surges. Nearby, county officials have rebuilt another levee to protect a golf course, along with a low-income community called East Palo Alto.

And on San Francisco's rugged Pacific shore, on Ocean Beach, a caravan of dump trucks is shifting sand to control erosion, while a portion of the adjacent coastal road known as the Great Highway is being moved inland.

"We basically built everything just about at the high tide line," said Laura Tam, a policy director at SPUR, a Bay Area urban planning and research group. "Nothing was built thinking of future changes in tides. We didn't think about sea level rise."

Nowhere is the danger more starkly on display as it is in Pacifica, a suburb south of the city, where coastal bluffs are so swiftly eroding that city officials have already demolished some properties before they could fall into the water.

And this is where John Raymond's dilemma is like a mirror image of what Desiree Alay-ay faces across the ocean. Around the time her parents built their house in Malabon, Mr. Raymond, a bankruptcy lawyer, bought his house on a bluff on the edge of the sea. The sound of the waves is a daily soundtrack.

One look from his window, and he can tell if it's a good day to surf. He loves it here. He wants to stay for as long as possible. But Mr. Raymond, 60, is also keenly aware of the risks.

The force of the waves has broken his garage doors a few times. His neighbor's windows have been broken by the pebbles tossed up by the beach. The only thing that protects his property from a rising sea, he knows, is a publicly funded sea wall right out front, erected to safeguard a sewer line and a coastal road. In a bad storm, when the waves pound that wall, his house shakes. His fear is that one day, the wall collapses – and his house gets red-tagged for demolition.

"If my house gets condemned because the sea wall fails and the ocean comes to the front door, I have to leave, and that's that," he said. "I'm taking the risk my house goes to zero."

The soft, sandy bluffs have been eroding for thousands of years. Climate change is accelerating that process, though, said Charles Lester, a former Coastal Commission official who now directs the Ocean and Coastal Policy Center at the University of California, Santa Barbara. The tides are higher and the waves are more frequently coming up to the foot of the bluffs.

On a gray Monday morning, Mr. Lester stood at the edge of the bluff on the north end of town, on a walking path that ribbons around an apartment complex called OceanAire. He pulled up on his phone a picture taken in the 1970s, when the complex was built: A wide grassy lawn lay in front. That's gone. Even when he first came here 10 years ago, the bluff was 90 feet wider. The bluff has stepped back since then. Today, at its narrowest point, a few steps separate an apartment balcony from the cliff's edge.

A sea wall had to be built – and then rebuilt, after it failed. A pile of boulders sits at the bottom of the wall to stave off damage from the waves.

"I see the challenge that the entire state and many states are facing: how to manage development along an inherently hazardous shoreline that is going to be increasingly hazardous under sea level rise and climate change," Mr. Lester said.

All that armoring, as it's known, has saved the apartment complex. But it has come with a public cost: The beach has narrowed. In some parts, there is no beach left.

That is the problem facing many Bay Area communities: How much do you armor the coast, what do you choose to save, and who will have to move? Managed retreat, as it's called, has become a political lightning rod.

Money complicates matters in other ways: Property taxes are a key source of revenue. Forcing people to move away would punch holes in city budgets. And anyway, who would pay to buy out homeowners?

Pacifica, for instance, can't. Some single-family houses on the bluff are worth upward of $1 million.

Already, there's been unmanaged retreat in Pacifica. Some sea walls crumbled, at one point endangering a row of apartments. The 52 tenants were entitled to zero compensation. They just had to move – in one of the most expensive counties in the state. The city spent $620,000 on demolition.

Other apartments, built years ago when the bluffs were wider, are now precariously close to the edge.

In an interview in December, Sue Vaterlaus, who was the Pacifica mayor at the time, said she was unsure about their future. "It's a hard thing," she said. "I'm not in favor of managed retreat, but at some point some of them may have to go."

Pariahan, the Philippines

The water 'just came and never left'

To visit the village of Pariahan, just north of the Manila city limits, is like visiting the last residents of the mythical city of Atlantis.

Pariahan, an island once connected to the mainland by a strip of land, at one point had about 100 houses. You could pick oysters from the sea and Java plums from the trees. Children went to school here. On Sundays, there was Mass at the local church, its door facing Manila Bay.

I hired a boatman to ferry me and a photographer to Pariahan from the mainland. First came a crowded little island, then a few solitary houses standing on berms, then many more abandoned houses with window frames staring out like vacant eyes. Then, finally, a cluster of houses, standing on stilts, and boats parked out front.

There were salt flats around Pariahan long ago, then fish ponds, which drew the water from under the ground. The land began to slowly sink, and by the time a powerful storm came along 10 years ago the island had become like a bowl. The water rose up and poured in. "It just came and never left," Benedicta Espiritu, 53, a lifelong resident, recalled.

Pariahan was submerged.

Ms. Espiritu, one of the few who remain here, raised the floor of the old house three times, and then built a new house on bamboo stilts.

The school roof has blown off. So Pariahan children now must pay for a 30-minute boat ride to attend class, which means they miss more often than not. Once a month, worshipers wade into

Photo by Michael Buillerey on Unsplash

Photo by Tim Foste on Unsplash

church; a priest is ferried in from a nearby village.

Ms. Espiritu doesn't plan to leave. She's grown accustomed to fleeing the storms and cleaning up afterward. She fears moving anywhere else will be prohibitively expensive. Never mind that Pariahan is drowning.

"We don't want to leave," she said. "When you have coffee, sugar and rice, life is good. The air is free. There's a solar panel for electricity."

"We can live here."

But Ms. Espiritu's family has been told that the holdouts of Pariahan will have to leave soon. There's a proposal to build a private airport nearby, on the edge of the slowly rising Manila Bay.

Jason Gutierrez contributed reporting from Manila.

Ms. Sengupta has received a George Polk Award for her work in Congo, Liberia and other conflict zones. Mr. Lee has been a member of two teams that received Pulitzer Prizes; one for coverage of the Sept. 11 terrorist attack on New York City and the other for photographs chronicling the conflict in Afghanistan and Pakistan

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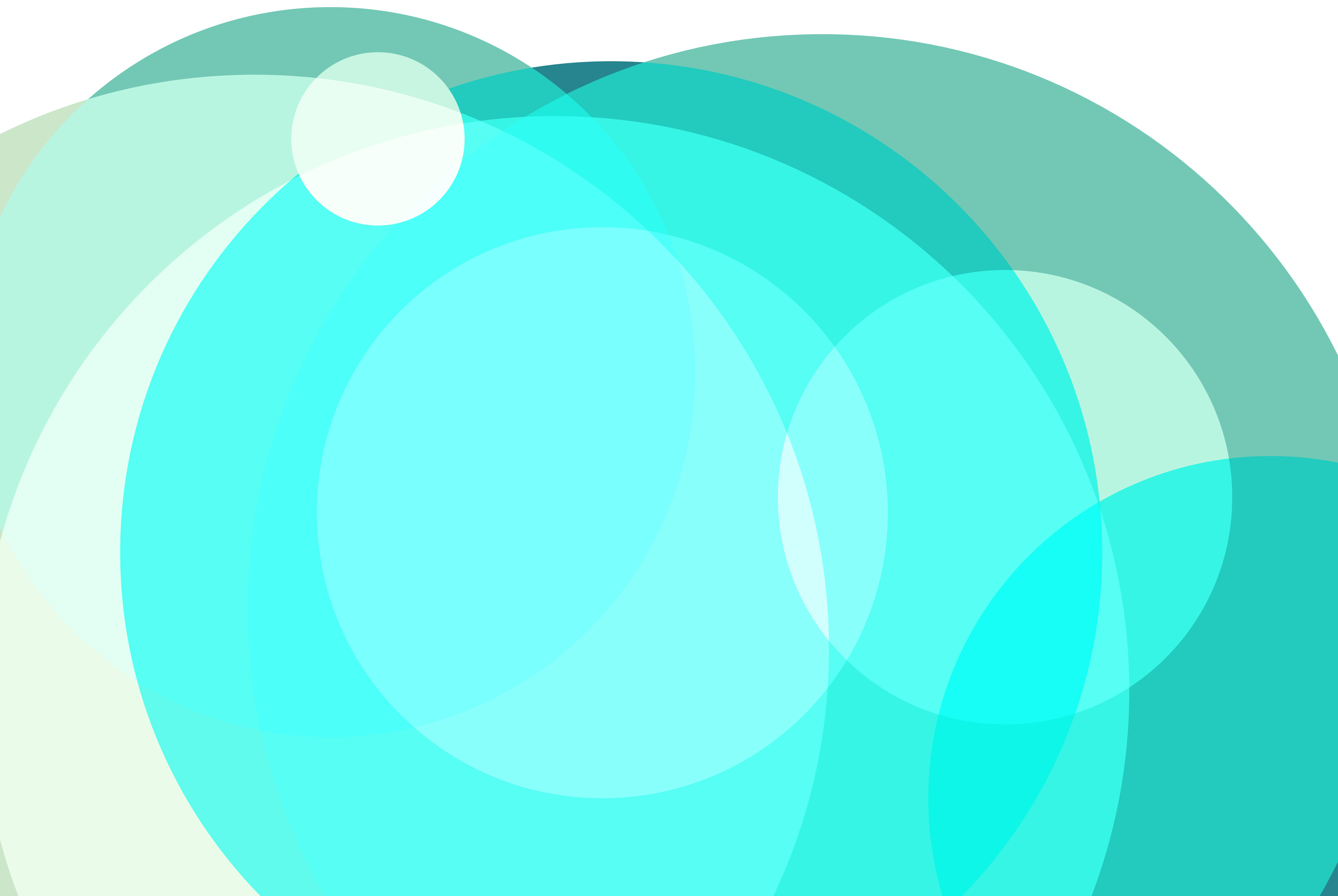

APPENDIX

CHAPTER ONE

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CHAPTER TWO

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Lead Authors:
Jochen Hinkel (Germany), Roderik van de Wal (Netherlands), Alexandre K. Magnan (France), Amro Abd-Elgawad (Egypt), Rongshuo Cai (China), Miguel Cifuentes-Jara (Costa Rica), Robert M. DeConto (USA), Tuhin Ghosh (India), John Hay (Cook Islands), Federico Isla (Argentina), Ben Marzeion (Germany), Benoit Meyssignac (France), Zita Sebesvari (Hungary/Germany)

Contributing Authors:
Robbert Biesbroek (Netherlands), Maya K. Buchanan (USA), Ricardo Safra de Campos (UK), Gonéri Le Cozannet (France), Catia Domingues (Australia), Sönke Dangendorf (Germany), Petra Döll (Germany), Virginie K.E. Duvat (France), Tamsin Edwards (UK), Alexey Ekaykin (Russian Federation), Donald Forbes (Canada), James Ford (UK), Miguel D. Fortes (Philippines), Thomas Frederikse (Netherlands), Jean-Pierre Gattuso (France), Robert Kopp (USA), Erwin Lambert (Netherlands), Judy Lawrence (New Zealand), Andrew Mackintosh (New Zealand), Angélique Melet (France), Elizabeth McLeod (USA), Mark Merrifield (USA), Siddharth Narayan (US), Robert J. Nicholls (UK), Fabrice Renaud (UK), Jonathan Simm (UK), AJ Smit (South Africa), Catherine Sutherland (South Africa), Nguyen Minh Tu (Vietnam), Jon Woodruff (USA), Poh Poh Wong (Singapore), Siyuan Xian (USA)

Review Editors:
Ayako Abe-Ouchi (Japan), Kapil Gupta (India), Joy Pereira (Malaysia)

Chapter Scientist:
Maya K. Buchanan (USA)

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38 MEDITERRANEAN UNESCO WORLD HERITAGE AT RISK FROM COASTAL FLOODING AND EROSION DUE TO SEA-LEVEL RISE

METHODS

General framework

We employ the conceptual risk framework of the Intergovernmental Panel on Climate Change (IPCC) widely used in the current literature[61,62,87,88,89], in which risk results from the interaction of hazard, exposure and vulnerability[90,91]. To assess coastal flood risk, we define hazard as the intensity (i.e. surge height) and frequency (i.e. return period) of a storm surge and exposure as the area of a WHS flooded, along with the flood depth. To assess the risk of coastal erosion, we define the amount of SLR as the hazard and determine exposure of a WHS to coastal erosion by the distance of a WHS from the coast, combined with the characteristics of the coastal zone that determine its sensitivity to coastal erosion. We do not assess a site's vulnerability to either coastal flooding or erosion as analysis of the internal characteristics of a WHS, such as heritage material and inventory, are needed. Such data are not readily available, and therefore this work is beyond the scope of this regional assessment.

In order to quantify flood risk and erosion risk we use an index-based approach, which is a well-established method in the literature[34,92,93,94,95,96,97,98,99] and particularly suitable for first-order assessments on regional scale to support adaptation planning[40,93,99]. With the help of the risk indices we are able to assess potential impacts on WHS with rising sea levels and compare WHS with each other without attaching monetary value to them[37]. For transparency reasons and to ease application of our methodology to other regions, we select risk indicators that are based on publicly available data. An overview of the data used can be found in Supplementary Table 2.

UNESCO World Heritage data processing

We use the UNESCO World Heritage List data of 2018 provided on the UNESCO website[2], in which each WHS is represented as a point, with longitude and latitude coordinates. We extract all cultural WHS located along the Mediterranean Sea. To account for WHS consisting of more than one site, so-called serial nominations31, we manually check each WHS and add further point data entries for serial sites based on maps and descriptions provided on the UNESCO website[2]. To reflect each WHS location as accurately as possible, we follow the methodology used in Chang et al.100 and Dassanayake et al.101. Therefore, we correct the location of misplaced WHS by using Google Earth™ satellite imagery. Where in doubt, we additionally compare photos and site descriptions provided on the UNESCO website with photos of the Panoramio web service embedded in Google Earth™ (as of January 2018 replaced by photos from Google Maps). Next, we examine WHS maps downloaded from the UNESCO website and digitise the outline of each site with the help of Google Earth™, resulting in one polygon for each serial WHS. We validate our WHS polygons by comparing them to those produced as part of the European PROTHEGO project, available in a map viewer[102].

Subsequently, we extract the WHS located in the LECZ based on the lowest elevation value of each WHS polygon in the SRTM DEM version 4.1[103,104]. The LECZ represents all land with an elevation of up to 10 m in hydrological connection to the sea[33]. This way we ensure that all sites potentially exposed to coastal flooding and erosion are included in the analysis.

Flood risk

To assess WHS at risk from ESL, we calculate the floodplain of a storm surge with a 100-year return period under four SLR scenarios from 2000 to 2100. We use a 100-year storm surge as it is a standard measure for coastal protection and has been widely used in previous assessments[60,61,62,72,73,76,77,105,106,107]. To account for spatial differences in the floodplain across the Mediterranean basin, we use storm surge data from the Mediterranean Coastal Database (MCD)[108,109], where surge heights are available for each of the approximately 12,000 coastal segments. We select surge heights that are derived from the Global Tide and Surge Reanalysis (GTSR) dataset which accounts for ESL due to storm surges and tides. A detailed description of the methods used for developing the dataset can be found in Muis et al.72. In the MCD, a downscaled version of the GTSR data is available. To ensure that all data used for the analysis are referenced to the same vertical datum, we convert the vertical datum of the surge data, referenced to the mean sea level, to the EGM96 geoid, the vertical datum of the SRTM data[68,73,85,86]. To do so, we use the mean dynamic ocean topography110, which is the difference between mean sea level and the geoid.

To account for plausible increases in ESL due to SLR, we combine the adjusted surge heights with four SLR scenarios based on the Representative Concentration Pathways (RCPs)111. We use the regionalised SLR projections by Kopp et al.112 that account for three ice-sheet components, glacier and ice cap surface mass balance, thermal expansion and other oceanographic processes, land water storage and non-climatic factors such as Glacial Isostatic Adjustment[112,113]. These projections are available as grid points with a spatial resolution of 2° by 2°. We select the median projections (50th percentile) of RCP2.6, RCP4.5 and RCP8.5 for 2010–2100 to cover the likely range of uncertainty regarding SLR, as well as the 95th percentile of RCP8.5 (5% probability) to account for a HE scenario. We spatially join the grid points of the SLR projections to the coastal segments of the MCD closest to each point and calculate the ESL of a 100-year storm surge for each coastal segment, scenario and 10-year time step. We do not account for potential changes in storminess as confidence in these projections is low[114].

We model the 100-year coastal floodplain for each SLR scenario with the help of a planar elevation-based (bathtub) approach using the SRTM DEM, which is extensively used in large-scale flood modelling[60,61,62,70,72,73]. The SRTM data used have a spatial resolution of 3 arc seconds (approximately 90 m at the equator) and a vertical resolution of 1 m104. Based on these data, we determine the area of each WHS located at elevation increments from 0 m up to 4 m in hydrological connection to the sea in a first step. Next, we attribute the calculated ESL to the nearest WHS. If more than one ESL can be attributed to one WHS, we calculate a weighted mean based on the number of raster cells with a specific ESL height assigned to each WHS. To determine the area of each WHS flooded (in %), we linearly interpolate between respective elevation increments based on the ESL assigned, following the method of Hinkel et al.60. We further calculate the maximum flood depth per WHS (in m) based on the difference between the ESL and the elevation value in the SRTM DEM. For WHS located below 0 m according to the SRTM data, we assume the minimum elevation value of each WHS to be 0 m. We apply this assumption to correct for artefacts present in the SRTM data, such as individual pixels with very low-elevation values (e.g. −20 m at Venice and its Lagoon (394))[115]. Using these values would result in unrealistically high maximum flood depths. Further, we do not account for existing flood protection measures in our analysis due to a lack of consistent region-wide data. Data of existing flood defences may be available for specific locations across the region, but integrating those into our analysis would compromise the consistency of our results.

For the flood risk index, we scale flood area and flood depth linearly to values ranging from 0 (not at risk) to a maximum value of 5 (very high risk), assuming that a WHS is at very high risk when at least 50% of the site are flooded with a flood depth of at least 1 m[60,116] (Table 1). We must note that we could not find any studies assessing flood risk based on the area of an object flooded; therefore, we assume that the OUV of a WHS is seriously threatened if at least half of the site is flooded. In a last step, we calculate the sum of the scaled flood risk indicators, which results in an index ranging from 0 to 10.

INDEX / INDICATOR	0 NOT AT RISK	1 VERY LOW	2 LOW	3 MODERATE	4 HIGH	5 VERY HIGH
FLOOD RISK						
Flood area (%)	0	> 0				≥ 50
Flood depth (m)	0	> 0				≥ 1
EROSION RISK						
Distance (m)	> 500	500				< 10
Coastal material		rocky	–	muddy; rocky with pocket beaches	–	sandy
Mean wave height (m)		0.1				> 0.8
Sediment supply (mg l⁻¹)		11.5				< 0.5

Table 1 Scale values used for the components of the flood risk index and the erosion risk index

Erosion risk

To analyse WHS at risk from coastal erosion due to SLR, we calculate an erosion risk index for each WHS from 2000 to 2100 under the four SLR scenarios (RCP2.6, RCP4.5, RCP8.5, HE). We adopt the indicators used in previous index-based approaches on coastal erosion[40,92,93,94,96,117,118] and cultural heritage at risk from coastal erosion[5,34,95] and select those that play a key role in the Mediterranean[119] and for which data are publicly available. Accordingly, we assume that erosion risk is determined by a WHS's distance from the coast, the coastal material, mean wave height and sediment supply.

We use the coastline of the MCD[108] to calculate the shortest distance of each WHS from the coast. In several instances the coastline of the MCD considerably deviates from the actual coastline as detected with the help of Google Earth™, for example, around the cities of Trogir and Šibenik in Croatia or the city of Catania in Italy. In these instances, we use the distance from the coastline of the global self-consistent, hierarchical, shoreline database version 2.3.7[120] (see dataset). We calculate the change in coastline due to SLR with the help of the SRTM data under the assumption that all areas below the amount of SLR in hydrological connection to the sea are inundated121. Again we interpolate linearly between elevation increments[60] and calculate the decrease in a WHS's distance from the coastline for each scenario and 10-year time step. Further, we use the MCD to assign the coastal material and mean wave height to each WHS based on the coastal segments attributed to the site. If more than one coastal material type or wave height is attributed to a WHS, we adopt the dominant one. To account for sediment supply, we use a newly created dataset of mean monthly total suspended matter (TSM) concentration. TSM is a measure of water turbidity in coastal locations that can be used as an indicator for sediment supply[122]. The original data were produced in the context of the GlobColour project and were calculated based on satellite imagery[123]. We spatially join the grid point data of the TSM to the coastal segments of the MCD closest to each grid point. If more than one grid point can be attributed to a segment, we calculate the mean of the points that extend along that segment. Subsequently, we attribute TSM values to each WHS, following the same procedure. We must point out that TSM represents sediment supply only to a limited degree as it does not include river bedload supplied at river mouths, which plays an important role in counteracting coastal erosion in the Mediterranean[124,125]. A dataset of bedload sediment transport is currently not available for the entire Mediterranean region. For the erosion risk index, we scale the four indicators linearly to values ranging from 0 (not at risk) to a maximum value of 5 (very high risk) based on scale values used in the literature that we adapt to the environmental conditions in the Mediterranean basin (Table 1). Accordingly, we assume a WHS to be at risk from coastal erosion if it is located at least within 500 m from the coast with the highest risk at or below 10 m distance[95], accounting for a twofold increase in observed erosion rates in the Mediterranean due to SLR5,[126]. For coastal material we use the scale values of refs.5,96 and for mean wave height we adapt the values of ref[96]. For sediment supply we assume risk to be very high when the TSM concentration is below 0.5 mg l−1. We calculate one erosion risk index (ERI) for each WHS based on Eq. (1), where D stands for distance under the respective scenario and time step, M for coastal material, mWH for mean wave height and TSM for total suspended matter. We follow the weighting used in Reeder-Myers[34], which is largely based on previous assessments[5,92,118] and we adjust it to the indicators included in this analysis, ensuring that the relative importance of each indicator remains unchanged. As sediment supply primarily plays a role in calm waters (i.e. beaches, wetlands, inlets) where it can get deposited119, we exclude TSM from the risk index at WHS in rocky locations. In a last step, we scale the erosion risk index to a possible maximum value of 10:

$$\left.\begin{array}{l} ERI_{rocky} = (3D + 2M + mWH) \times [illegible] \\ ERI_{other} = (3D + 2M + mWH + TSM) \times [illegible] \end{array}\right\} \text{if } D > 500, ERI = 0 \quad (1)$$

Code availability

Spatial data processing was conducted in the Geographic Information System (GIS) software ArcGIS. The results of the spatial analysis were further processed in the software environment R to calculate the flood risk and erosion risk indices. The computer code of these calculations is available upon request.

Data availability

The WHS datasets produced for this study are available in text format (CSV) and polygon vector format at https://doi.org/10.6084/m9.figshare.5759538 (ref.[32]).

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46 ECONOMY – WIDE EFFECTS OF COASTAL FLOODING DUE TO SEA LEVEL RISE: A MULTI – MODEL SIMULTANEOUS TREATMENT OF MITIGATION, ADAPTATION, AND RESIDUAL IMPACTS

Author contributions

The study was designed by T S with major contributions by L D, Z V, A H and J M. T S, L D, Z V and A H took the lead in interpreting the results and authoring the paper. J H, V B, K F, D v V, D L and J M assisted the writing of the paper. L D, Z V, A H, J H, V B, K F, D v V and D L developed and ran the models. L D, assisted by T S, Z V and A H, developed the visualizations for the manuscript. T S edited the paper.

Footnotes

1 Even though the existing IAM modeling literature (Riahi et al. 2017) finds that, when starting from an SSP3 baseline, achieving a 2.6 W m−2 forcing level is unlikely, we run the three different SSPs with RCP2.6 as an important exercise to identify the role of exposure as driver of climate-related impacts. Moreover, there is still a chance that climate sensitivity is on the lower end of the uncertainty range (Cox et al. 2018), which means that the socio-economic developments of SSP3 could still be consistent with achieving 2 °C.

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58 GLOBAL AND EUROPEAN SEA-LEVEL RISE

INDICATOR SPECIFICATION AND METADATA

Indicator definition

This indicator comprises several metrics to describe past and future sea level rises globally and in European seas. Global sea level rise is reported because it is the second-most important metric of global climate change (after global mean surface temperature), and because it is a proxy of sea level rise in Europe. Past sea level trends across Europe are reported in two different ways: first, absolute sea level change based on satellite altimeter measurements that reflect primarily the contribution of global climate change to sea level rise in Europe; second, relative sea level change based on tide gauges that also include local land movement, which is more relevant for the development of regional adaptation strategies. The indicator also addresses changes in extreme sea level along the European coast.

The following aspects of sea level rise are included:

- observed change in GMSL, based on two reconstructions from tide gauge measurements (since 1880) and on satellite altimeter data (since 1993);
- spatial trends in absolute sea level across European seas, based on satellite measurements (since 1993);
- spatial trends in relative sea level across European seas,
  based on European tide gauge stations with long time series (since 1970);
- projected change in global sea level for three different forcing scenarios;
- projected change in relative sea level across European seas;
- projected change in the frequency of flooding events along European coasts.

Unit

- Change in sea level (mm).
- Rate of sea level change (mm/year).
- Increase in flooding events (unitless).

Rationale *Justification for indicator selection*

Sea level is an important indicator of climate change because it can have significant impacts on settlements, infrastructure, people and natural systems. It acts on time scales much longer than those of indicators that are closely related to near-surface temperature change. Even if greenhouse gas concentrations were stabilised immediately, sea level would continue to rise for many centuries.

Changes in GMSL result from a combination of several physical processes. The thermal expansion of the oceans occurs as a result of warming ocean water. Additional water is added to the ocean from the net melting of glaciers and small ice caps, and from the disintegration of the large Greenland and Antarctic ice sheets. Further contributions may come from changes in the storage of liquid water on land, in either natural reservoirs such as groundwater or man-made reservoirs.

Changes in sea level experienced locally differ from global average changes for various reasons. First, changes in water density are not expected to be spatially uniform, and the spatial pattern also depends on changes in large-scale ocean circulation. Second, changes in the gravity field, for instance as water moves from melting ice on land to the ocean, also vary across regions. Finally, at any particular location, there may be a vertical movement of the land in either direction, due, for example, to the ongoing effects of post-glacial rebound (also known as glacial isostatic adjustment), which is particularly strong in northern Europe, to local groundwater extraction or to other processes, including tectonic activity.

In Europe, the potential impacts of sea level rise include flooding, coastal erosion and the submergence of flat regions along continental coastlines and on islands. Rising sea levels can also cause salt-water intrusion into low-lying aquifers, thus threatening water supplies and endangering coastal ecosystems and wetlands. Higher flood levels increase the risk to life and property, including to sea dikes and other infrastructure, with potential impacts on tourism, recreation and transportation functions. Low-lying coastlines with high population densities and small tidal ranges are most vulnerable to sea level rise, in particular where adaptation is hindered by a lack of economic resources or by other constraints.

Damage associated with sea level rise is mostly caused by extreme events, such as storm surges. Of most concern are events during which the surge coincides with high tidal levels and increases the risk of coastal flooding owing to extreme water levels. Changes in the climatology of extreme water levels (i.e. the frequency and height of maximum water levels) may be caused by changes in local mean sea level (i.e. the local sea level relative to land averaged over a year or so), changes in tidal range, changes in the local wave climate or changes in storm surge characteristics. Climate change can both increase and decrease average wave height along the European coastline, depending on the location and season.

Changes in storm surge characteristics are linked to changes in the characteristics of atmospheric storms, including the frequency, track and intensity of the storms. The intensity of storm surges can also be strongly affected by regional and local geographical features, such as the shape of the coastline. Typically, the highest water levels are found on the rising limb of the tide. The most intense surge events typically occur during the winter months in Europe.

The most obvious impact of extreme sea levels is flooding. The best known coastal flooding event in Europe in living memory occurred in 1953 when a combination of a severe storm surge and a high spring tide caused in excess of 2 000 deaths in Belgium, the Netherlands and the United Kingdom, and damaged or destroyed more than 40 000 buildings. Currently, around 200 million people live in the coastal zone in Europe, as defined by Eurostat. Coastal storms and storm surges can also have considerable ecological impacts, such as seabird wrecks, disruption to seal mating and pupping, and increases in large mammal and turtle strandings.

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Policy context and targets

Context description

In April 2013, the European Commission presented the EU adaptation strategy package. This package consists of the EU strategy on adaptation to climate change (COM/2013/216 final) and a number of supporting documents. The overall aim of the EU adaptation strategy is to contribute to a more climate-resilient Europe. One of the objectives of the EU adaptation strategy is 'Better informed decision-making'. This will be achieved by bridging knowledge gaps and further developing the European climate adaptation platform (Climate-ADAPT) as the 'one-stop shop' for adaptation information in Europe. Climate-ADAPT was developed jointly by the European Commission and the EEA to share knowledge on (1) observed and projected climate change and its impacts on environmental and social systems and on human health, (2) relevant research, (3) EU, transnational, national and subnational adaptation strategies and plans, and (4) adaptation case studies. It was relaunched in early 2019 with a new design and updated content. Further objectives include 'Promoting adaptation in key vulnerable sectors through climate-proofing EU sector policies' and 'Promoting action by Member States'.

In November 2018, the Commission published its evaluation of the 2013 EU adaptation strategy. The evaluation package includes a report from the Commission, a Commission staff working document, adaptation preparedness scoreboard country fiches and reports from the JRC Peseta III project. This evaluation includes recommendations for the further development and implementation of adaptation policies at all levels.

In November 2013, the European Parliament and the Council of the European Union adopted the EU's Seventh Environment Action Programme (7th EAP) to 2020, 'Living well, within the limits of our planet'. The 7th EAP is intended to help guide EU action on environment and climate change up to and beyond 2020. It highlights that 'Action to mitigate and adapt to climate change will increase the resilience of the Union's economy and society, while stimulating innovation and protecting the Union's natural resources'. Consequently, several priority objectives of the 7th EAP refer to climate change adaptation.

Target *No targets have been specified.*

Related policy documents

7th Environment Action Programme
DECISION No 1386/2013/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet'. In November 2013, the European Parliament and the European Council adopted the 7 th EU Environment Action Programme to 2020 'Living well, within the limits of our planet'. This programme is intended to help guide EU action on the environment and climate change up to and beyond 2020 based on the following vision: 'In 2050, we live well, within the planet's ecological limits. Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience. Our low-carbon growth has long been decoupled from resource use, setting the pace for a safe and sustainable global society.'

Climate-ADAPT: Adaptation in EU policy sectors
Overview of EU sector policies in which mainstreaming of adaptation to climate change is ongoing or explored

DG CLIMA: Adaptation to climate change
Adaptation means anticipating the adverse effects of climate change and taking appropriate action to prevent or minimise the damage they can cause, or taking advantage of opportunities that may arise. It has been shown that well planned, early adaptation action saves money and lives in the future. This web portal provides information on all adaptation activities of the European Commission.

EU Adaptation Strategy Package
In April 2013, the European Commission adopted an EU strategy on adaptation to climate change, which has been welcomed by the EU Member States. The strategy aims to make Europe more climate-resilient. By taking a coherent approach and providing for improved coordination, it enhances the preparedness and capacity of all governance levels to respond to the impacts of climate change.

Evaluation of the EU Adaptation Strategy Package
In November 2018, the EC published an evaluation of the EU Adaptation Strategy. The evaluation package comprises a Report on the implementation of the EU Strategy on adaptation to climate change (COM(2018)738), the Evaluation of the EU Strategy on adaptation to climate change (SWD(2018)461),

and the Adaptation preparedness scoreboard Country fiches (SWD(2018)460). The evaluation found that the EU Adaptation Strategy has been a reference point to prepare Europe for the climate impacts to come, at all levels. It emphasized that EU policy must seek to create synergies between climate change adaptation, disaster risk reduction efforts and sustainable development to avoid future damage and provide for long-term economic and social welfare in Europe and in partner countries. The evaluation also suggests areas where more work needs to be done to prepare vulnerable regions and sectors.

METHODOLOGY

Methodology for indicator calculation

Sea level changes are measured using tide gauges and remotely from space using altimeters. Tide gauges provide direct measurements, but they are influenced by local processes such as land subsidence. Furthermore, there are significant gaps in the spatial coverage of tide gauges with long time series, including in Europe.

As far as the indicator derived from satellite altimetry is concerned, the global and European sea level trends are calculated from a combination of nine partly overlapping satellite missions. The data are corrected for seasonal variations, inverse barometer effects and post-glacial rebound.

Sea level projections are based on process-based models, which are rooted in state-of-the-art climate model simulations. Projections for relative mean sea level in Europe consider the gravitational and solid Earth response and land movement due to glacial isostatic adjustment, but not land subsidence as a result of human activities.

Projections of extreme sea level can be made using either process-based (dynamic) or empirical statistical modelling of storm surge behaviour driven by the output of global climate models.

Methodology for gap filling

Model-based projections for changes in regional sea level rise included only grid cells that are covered at least half by sea. Data for other grid cells partly covered by land and by sea were extrapolated using the nearest-neighbour method.

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UNCERTAINTIES

Methodology uncertainty

See 'Methodology' section.

Data sets uncertainty

Changes in global average sea levels result from a combination of several physical processes. The thermal expansion of the oceans occurs as a result of warming ocean water. Additional water is added to the ocean from a net mass loss of glaciers and small ice caps, and from the large Greenland and West Antarctic ice sheets. Further contributions may come from changes in the storage of liquid water on land, in either natural reservoirs such as groundwater or man-made reservoirs.

The changes in sea level experienced locally differ from global average changes for various reasons. Changes in water density are not expected to be spatially uniform, and changes in ocean circulation also have regionally different impacts. At any particular location there may also be a vertical movement of the land in either direction, due for example to the post-glacial rebound (in northern Europe) or to local groundwater extraction.

Projections from process-based models with likely ranges and median values for GMSL rise up to 2100 (relative to 1986-2005) have been made for three RCP scenarios. The contributions from ice sheets include contributions from ice-sheet rapid dynamical change. The value of the Antarctic contribution is the individual component with the largest uncertainty.

The level of uncertainty in future projections of extreme sea level for Europe remains high and is ultimately linked to uncertainties related to future mid-latitude storminess changes. This is an area in which current scientific understanding is advancing quickly, as climate model representations of aspects of northern hemisphere storm track behaviour are improving, because of, for instance, greater ocean and atmosphere resolution. However, the newest global climate models have not yet, typically, been downscaled to suitably fine scales and used in studies of future storm surges.

Rationale uncertainty *No uncertainty has been specified*

Data sources

Time Series of Mean Sea Level Trends over Global Ocean
provided by Copernicus Marine Environment Monitoring Service
IPCC SROCC data on sea level rise
provided by Intergovernmental Panel on Climate Change (IPCC)
Global mean sea level reconstruction (Uni Siegen)
provided by Universität Siegen
Global mean sea level reconstruction (satellite and altimetre, CSIRO)
provided by Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Relative sea level trends (tide gauge data)
provided by Permanent service for mean sea level (PSMSL)

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64 EARLY LAST INTERGLACIAL OCEAN WARMING DROVE SUBSTANTIAL ICE MASS LOSS FROM ANTARCTICA

Chris S. M. Turney, Christopher J. Fogwill, Nicholas R. Golledge, Nicholas P. McKay, Erik van Sebille, Richard T. Jones, David Etheridge, Mauro Rubino, David P. Thornton, Siwan M. Davies, Christopher Bronk Ramsey, Zoë A. Thomas, Michael I. Bird, Niels C. Munksgaard, Mika Kohno, John Woodward, Kate Winter, Laura S. Weyrich, Camilla M. Rootes, Helen Millman, Paul G. Albert, Andres Rivera, Tas van Ommen, Mark Curran, Andrew Moy, Stefan Rahmstorf, Kenji Kawamura, Claus-Dieter Hillenbrand, Michael E. Weber, Christina J. Manning, Jennifer Young, and Alan Cooper

METHODS

Patriot Hills.

Site description and geomorphological context.

The Patriot Hills BIA (Horseshoe Valley, Ellsworth Mountains; 80°18′S, 81°21′W) is a slow flowing (<12 m•y–1) compound glacier system situated within an overdeepened catchment that coalesces with the Institute Ice Stream at the periphery of the WSE (29, 37, 66–68) (Fig. 1 and SI Appendix, Figs. S1–S4). Airborne radio-echo sounding surveys across the Ellsworth Mountains have revealed several wide (up to 34 km across) and long (260 km) subglacial troughs containing ice up to 2,620 m thick (Fig. 1) (29), along the side of which, two radar zones have been interpreted to indicate layers of ice with contrasting physical properties, consistent with snow deposited during previous glacial/interglacial transitions. In contrast to the other troughs across the Ellsworth Mountains, contemporary ice within the Horseshoe Valley Trough maintains the slowest average flow speeds of all, at 12 $m•a^{-1}$ (cf. the main trunk of the Institute Ice Stream reaches speeds up to 415 $m•a^{-1}$). This is in large part due to the configuration of the Horseshoe Valley Trough where the ice thickness measures in excess of 2,000 m at the head of the valley and reduces to ~1,400 m downstream; toward the mouth of the valley, a subglacial ridge is found at ~200 m below sea level with the ice thickness some 750 m thick (SI Appendix, Fig. S3) (69). The new Digital Elevation Model data for the WSE is available at https://data.bas.ac.uk/full-record.php?id=GB/NERC/BAS/PDC/00937. The configuration of the bed and resulting slow flow in Horseshoe Valley has two major benefits for our study. It allows 1) a long record of ice to accumulate, and 2) the isolation and preservation of ice during periods of regional and Antarctic-wide mass loss.

In the lee of a small mountain chain at the end of Horseshoe Valley called Patriot Hills, strong local katabatic winds descend into the valley from the polar plateau, ablating the ice sheet surface by up to 170 $kg•m^{-2}•y^{-1}$ (68). As a result, ancient ice is drawn up from depth in the Horseshoe Valley Trough to form an extensive BIA (more than 1,150 m across; SI Appendix, Fig. S4) (31, 37, 38). High-resolution analysis using GPR (37) and isotopes identifies three distinct unconformities [surface distances relative to an arbitrary transect datum (31) set at zero]: 247 m (D1), 360 m (D2), and −339 m (D0). Based on the trace gas, tephra, and isotopic values of the surface ice beyond D0 (closest to Patriot Hills), we interpret this section of the record to be Termination II in age (see below). No glaciomarine sediments have been identified at any of the boundaries.

Previous work has interpreted erosional features D1 and D2 in the Patriot Hills BIA to be a consequence of extensive ice surface lowering in Horseshoe Valley (up to ~500 m since the Last Glacial Maximum, 21 ky) and more exposure of katabatic-enhancing nunataks, resulting in increased wind scour (26, 37). While this scenario may explain unconformity D0, other studies have demonstrated Horseshoe Valley and the wider WSE to be highly sensitive to periods of rapid ice stream advance or retreat in the last glacial cycle and Holocene with dramatic reductions in surface elevation (26, 37–39). Recent work investigating the impact of ice shelf loss on glaciers along the Antarctic Peninsula provides important insights, albeit on a smaller scale. The 2002 Larsen B ice shelf collapse led to many of the tributary glaciers abruptly changing from a convex to a concave profile (40), with relict ice left isolated on the upper flanks of the valleys (41). Under a scenario of extreme ice surface lowering arising from ocean warming during the early LIG, the ice at Patriot Hills preserves a record of glacier flow in the overdeepened Horseshoe Valley up to the moment when the Filcher–Ronne Ice Shelf collapsed, after which the sequence likely remained isolated for multiple millennia until the ice surface had risen sufficiently to reincorporate the isolated ice into the glacier sometime during late MIS 5. The relatively enriched deuterium and 18O stable isotope values, ancient DNA (notably the detection of Methyloversatilis microbes in the sample form −340 m in the Patriot Hills record), and ice sheet modeling are consistent with early offshore warming in the south Atlantic and substantial ice mass loss in the early LIG (34, 46, 62), preserving most (if not all) of the Termination II ice record during the period represented by the D0 unconformity (see below). We therefore consider D0 reflects a significant fall in surface elevation and change in flow direction due to isostatically driven isolation of the valley during a period of rapid drawdown of the ice streams across the WSE.

Chronology.

Chronological control across the transect is provided by a comprehensive suite of trace gas samples–carbon dioxide (CO2), methane (CH4) and nitrous oxides (N2O)–and volcanic tephra horizons. The trace gas measurements provide a range of possible age solutions against the recently published 156-ky smoothed global time series for these gas species (27), which together with the absolute constraints provided by the tephra horizons, allows the development of a robust chronological framework that can be tied directly to the isotopic series through high-resolution GPR (31, 37) (SI Appendix, Figs. S6 and S7). A Kovacs 9-cm-diameter ice corer was used to collect ice for gas and taken from >3-m depth to minimize modern air contamination and/or alteration (31). The samples were double bagged and sealed in the field, and transported frozen to the Commonwealth Scientific and Industrial Research Organisation (CSIRO) ICELAB facility in Melbourne for the extraction and measurement of trace gases using a modified dry extraction "cheese grater" and cryogenic trapping technique (70, 71). The trapped air samples were analyzed by gas chromatography, and the trace gas concentrations are reported against the calibration scales maintained by CSIRO GASLAB (72). Where sufficient material was available, duplicates were analyzed.

The presence of visible tephra layers (volcanic ash horizons) provides additional chronological control for the Patriot Hills BIA. Here, we report two new tephras from Patriot Hills at 10 and −340 m, both observed as ~4-cm units of dispersed shards (SI Appendix, Fig. S9). Shards were extracted by centrifugation of the melted ice samples and put onto a glass slide for electron microprobe analysis. The slides were ground and polished using silica carbide paper and decreasing grades of diamond suspension to expose fresh sections of glass. Single-grain analyses of 10 oxides were performed on a Cameca SX-100 electron microprobe at the Tephrochronology Analytical Unit, University of Edinburgh. See SI Appendix for operating conditions (73); geochemical results are provided in SI Appendix, Table S1. The shards from 10 m are bimodal, with a basanitic and trachytic composition (SI Appendix, Fig. S10). The shards from −340 m are trachytic in composition and exhibit a tightly clustered population (SI Appendix, Fig. S11). Both were compared to published tephras from across Antarctica (34, 74–84). The 10-m tephra has the closest match to be the basanite Tephra C from the WAIS Divide at 3,149.12 m (Similarity Coefficient or SC = 0.98), equivalent to 44.9 ± 0.3 ky (84). The −340-m tephra revealed the closest match to a tephra layer in the Dome Fuji ice core at 1,785.14-m depth [SC = 0.966; equivalent to 130.7 ± 1.8 ky on the AICC2012 timescale (28, 77, 85); data previously unpublished].

A widespread tephra found in marine sedimentary records on the West Antarctic continental margin (Tephra B) has been proposed to correlate to the tephra at Dome Fuji 1,785.14 m, but the correlation has until now remained only tentative in the absence of any reported geochemistry from the latter (34). Here, we find the major oxides from Tephra B have a close match to Patriot Hills −340 m (SC = 0.948), consistent with this interpretation. To test this correlation, we undertook trace element analysis of the glass shards from Patriot Hills at −340 m. Unfortunately, the Dome Fuji shards were too thin for analysis. However, we were able to undertake trace element analyses on Tephra B samples from two marine sediment cores from the West Antarctic continental margin: PC108 (4.65-m depth) and PC111 (6.86-m depth) (34). Trace element analysis of volcanic glass shards were performed using an Agilent 8900 triple-quadrupole inductively coupled plasma mass spectrometry (ICP-

MS) (ICP-QQQ) coupled to a Resonetics 193-nm ArF excimer laser ablation in the Department of Earth Sciences, Royal Holloway, University of London. See SI Appendix for operating conditions (86). Accuracies of laser ablation ICP-MS analyses of ATHO-G and reference StHs6/80-G MPI-DING (87) glass were typically ≤5%. Identical trace element glass chemistries (Fig. 2 and SI Appendix, Table S2) strongly support the correlation of Patriot Hills −340-m tephra horizon and the marine West Antarctic Tephra B (34), which is in turn correlated to Dome Fuji 1,785.14 m (33, 34, 77, 85), and probably originates from the Marie Byrd Land volcanic province (West Antarctica) (34). The recognition of a widespread tephra horizon across a large sector of the Antarctic at the very onset of the LIG provides a time-parallel marker horizon crucial for future studies investigating Antarctic ice sheet mass loss.

To develop an age model, we undertook Bayesian age modeling using a Poisson process deposition model (P_sequence) in the software package OxCal, version 4.2.4 (https://c14.arch.ox.ac.uk/) (SI Appendix, Tables S3 and S4) (88, 89). Using Bayes theorem, the algorithms employed sample possible solutions with a probability that is the product of the prior and likelihood probabilities (90, 91). "Calibration curves" with 20-y resolution were developed for the three trace gas species using the 156-ky time series (27). Taking into account the deposition model, the reported ages of the tephra layers, and the common age solutions offered by the trace gas measurements, the posterior probability densities quantify the most probable age distributions. The available constraints suggest the 1,156-m-long Patriot Hills BIA transect spans time intervals from ~134.2 to ~1.3 ky comprising four key zones: 4 (−362 to −339 m, equivalent to 134.2 ± 2.2 to 130.1 ± 1.8 ky), 3 (−326 to 240 m, equivalent to 80 ± 6.1 to 22.7 ± 2.8 ky), 2 (240 to 360 m, equivalent to 22.7 ± 2.8 to 10.3± 0.4 ky), and 1 (360 to 800 m, 10.3 ± 0.4 to 1.3 ± 0.6 ky). The Agreement Index (a measure of the agreement between the model–prior–and the observational data–likelihood) for the Patriot Hills age model was 101.6% ($A_{overall}$ = 71.2%), exceeding the recommended rejection Agreement Index threshold of 60% (89) (Methods). Regardless of the relatively large uncertainty associated with the oldest section of ice (zone 4), the identification of the 130.7 ± 1.8 ky (AICC2012 timescale) Tephra B/Dome Fuji 1,785.14 m (28, 33, 34) within Patriot Hills at −340 m unambiguously demonstrates the presence of Termination II-age ice. Future age constraints will inevitably help improve the accuracy and precision of the age model.

Isotopes.

δD and $\delta^{18}O$ isotopic measurements were performed between 1- and 3-m resolution at James Cook University using diffusion sampling–cavity ring-down spectrometry (International Atomic Energy WICO Laboratory ID 16139) (92). This system continuously converts liquid water into water vapor for real-time stable isotope analysis by laser spectroscopy (Picarro L2120-i). See SI Appendix for operating conditions. To ensure reproducibility, a subset of samples was rerun at University of New South Wales ICELAB for δD and $\delta^{18}O$ using a Los Gatos Research Liquid Water Isotope Analyzer 24 d (International Atomic Energy WICO Laboratory ID 16117). Reported overall analytical precision on long-term ice core standards is <0.32‰ for δD and <0.13 for $\delta^{18}O$ values. All isotopic values are expressed relative to the Vienna Standard Mean Ocean Water 2 (VSMOW2). The isotopic datasets generated in this study are available at the publicly accessible National Oceanic and Atmospheric Administration (NOAA) Paleoclimatology Database (93) and are available upon request.

Ancient DNA analysis.

BIAs offer the opportunity to process large-volume samples of continental Antarctic ice in the field (~7 kg per temporal sample), creating the prospect of generating sufficient microbial concentrations to permit detailed genetic biodiversity surveys (51, 52) (Fig. 2). To obtain the samples, a Kovac corer was thoroughly cleaned with 1 to 3% bleach and wiped with 95% ethanol between core extractions to minimize cross-contamination. After coring, the top 1 m of ice was removed and discarded, before 1- to 2-m-long cores were collected in 50-cm sections and immediately placed into clean PFTE flexible plastic tubing. A heat sealer was used to close the tubing at the top and bottom of the core. The sealed core was then cut from the remaining tubing with a sterile blade, and the process was repeated to encase the core in a second layer of the plastic tubing for protection during transport. Within 1 to 6 h of extraction, the tubing-encased BIA cores were hung inside a large dome tent to melt via solar radiation over 12 to 24 h, using black plastic bin liners around the plastic tubing to speed up the process where necessary. The melted BIA sample was transferred from the inside layer of tubing directly into a hand-powered vacuum filtration system cleaned with 1 to 3% bleach and ethanol wipes between samples. For each sample, disposable, sterile, 0.45-μm nitrocellulose filters were used to filter and collect whole bacterial organisms trapped in the ice during its formation, and reduce noise caused by environmental DNA. Filters were stored in sterile plastic bags, frozen at −20 °C, and returned to the Australian Centre for Ancient DNA in Adelaide for ultraclean genetic analysis.

Strict ancient DNA methodologies designed to assess low-biomass microbial samples were applied (94) (see SI Appendix for detailed methodology and analysis). DNA from all ice samples as well as extensive sampling and laboratory controls were extracted using two methods to maximize species recovery, and 16S ribosomal RNA libraries were amplified in triplicate using published, universal bacterial and archaeal 16S ribosomal RNA (rRNA) primers. After DNA sequencing, all individually indexed 16S rRNA libraries were de-multiplexed, quality filtered, and imported into QIIME, version 1.8.0. Microbial taxa were identified by comparing sequences to the Geengenes, version 13, reference database and binning sequences with 97% similar to known species into operational taxonomic units using closed reference clustering in UCLUST. Sampling and laboratory contaminants were then filtered from ice samples, and an average of 30.8% of the reads for each sample were retained (SI Appendix, Table S5). Retained sequences were then pooled, and the resulting taxa present in each sample were explored as a proportion of the total filtered DNA sequencing reads. Alpha and beta diversity was explored in QIIME, and importantly, no statistically significant differences in diversity were detected across the samples. Ancient DNA sample data are available upon request. While the current sample numbers limit resolution, our study highlights the untapped potential of BIA genetic data to exploit cryosphere microbial communities to investigate glaciological and environmental change (52).

Ice Sheet Modeling.

To investigate former ice sheet dynamics around the Patriot Hills and across Antarctica, we take a range of values for polar ocean warming (1 to 3 °C) (9, 11, 23) and employ the Parallel Ice Sheet Model (PISM), version 0.6.3 (2), an open source 3D, thermomechanical coupled ice sheet/ice shelf model. PISM employs a stress balance that superposes solutions of the shallow-ice and shallow-shelf equations, and incorporates a pseudoplastic basal substrate rheology to allow for realistic sliding over meltwater saturated sediments, a bed deformation model that simulates mantle dissipation and rebound arising from spatial changes in ice loading through time (95), and a subgrid basal traction and driving stress interpolation scheme to allow realistic grounding-line motion (96, 97). We prescribe a mantle viscosity of 1×10^{20} Pa•s, which is lower than the PISM default (1×10^{21}) and intended to capture more accurately the weaker mantle of West Antarctica, where the majority of mass loss takes place. In the experiments presented here, we chose not to implement the subgrid scale interpolated ice shelf basal melt component of this scheme (2, 98). Calving is parameterized using horizontal strain rates and a minimum thickness criterion (220 m) (99, 100). Our experimental methodology is identical to that described in detail elsewhere (101, 102). Climate and ocean temperature perturbations are applied as spatially uniform linear increments added to boundary distributions representing present-day conditions. Linear increases take place between 2,000 and 3,000 model years. The first 2,000 y (no forcing) allow any transient behavior associated with model initialization to take place in the absence of environmental perturbations, whereas the subsequent 1,000 y force the ice sheet to evolve slowly to changes in air and ocean temperature and precipitation. All experiments are run at a spatial resolution of 20 km.

Reconstructed summer SST anomalies relative to present day (the 1998 World Ocean Atlas) (9) were used to inform on a range of warmer air and ocean LIG conditions and applied to a stable modern configuration of the Antarctic Ice Sheet to help interpret the Patriot Hills record (Table 1). A limitation of this approach is that the transient history from the preceding glacial state is not simulated. However, for the response of the ice shelves, this colder prehistory should not be critical, and the experiments as performed are directly relevant for the future of the ice sheets. From these simulations, we extract data from the first 10 ky. The ice sheet modeling outputs support the view that ocean (rather than atmosphere) warming was the primary driver of ice shelf collapse and substantial early LIG mass loss in Patriot Hills and across large parts of Antarctica (SI Appendix, Fig. S18). With a surface ocean warming of 2 °C, our simulations suggest isolation and stagnation of ice in Horseshoe Valley and the loss of the Bungenstock Ice Rise within 400 y of warming (equivalent to 0.8 °C of warming as a result of the linear temperature increase over 2,000 to 3,000 model years) (Figs. 5 and 6) and ultimately restricted ice across the wider WSE (SI Appendix, Fig. S20).

We caution that, for the LIG, subsurface ocean warming is poorly constrained. While recent work has suggested that sea surface warming may propagate to depths important for ice shelves (including embayments) within a few decades (103, 104), proxy SSTs could instead record "bottom-up" warming (i.e., as a consequence of circulatory change) and may underestimate the magnitude of the warming. We however, consider, that warming of +2 °C is likely to be at the upper end of potential LIG warming scenarios (14) and the forcing used here in our simulations to be conservative. Recent work using PISM showed that substantial collapse of WAIS is possible within only a few centuries even under modest warming (105). Those simulations used a much stiffer bed parameterization and were run at 5-km resolution. Other studies have suggested with 5-km resolved PISM simulations that, if mass loss comparable to recent decades is maintained for as little as 60 y, the WAIS could be irrevocably destabilized over subsequent millennia through the collapse in the Amundsen Sea sector (60), overcoming any isostatically driven rebound. On the basis of these comparisons, we can be confident that our inference of substantial mass loss from WAIS under modest ocean/atmosphere warming is not especially dependent on the model used, the way that the bed is parameterized, or the resolution of the simulations. Modeled Antarctic ice sheet contributions to global sea level are provided in Table 1. The ice sheet model data are available upon request.

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Footnotes

1 To whom correspondence may be addressed. Email: c.turney@unsw.edu.au.
2 Deceased February 6, 2018.

Author contributions:
C.S.M.T., C.J.F., and N.R.G. designed research; C.S.M.T., C.J.F., N.R.G., N.P.M., E.v.S., R.T.J., D.E., M.R., D.P.T., S.M.D., C.B.R., Z.A.T., M.I.B., N.C.M., M.K., J.W., K.W., L.S.W., C.M.R., H.M., P.G.A., A.R., A.M., C.-D.H., M.E.W., C.J.M., J.Y., and A.C. performed research; L.S.W. and A.C. contributed new reagents/analytic tools; C.S.M.T., C.J.F., N.R.G., N.P.M., E.v.S., R.T.J., D.E., M.R., S.M.D., C.B.R., Z.A.T., M.I.B., N.C.M., M.K., J.W., K.W., L.S.W., P.G.A., T.v.O., M.C., A.M., S.R., K.K., C.-D.H., M.E.W., and A.C. analyzed data; and C.S.M.T. wrote the paper with input from all authors.

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72 OCEAN RISK AND THE INSURANCE INDUSTRY

APPENDIX 1: HARMFUL ALGAL BLOOMS

A very short introduction to harmful algal blooms

Microalgal blooms are a natural part of the seasonal cycle of the marine ecosystems around the world. However, some microalgal blooms can be harmful if the algae produce neurotoxins that destroy nerve tissue, affect the nervous system, brain and liver, and which can lead to the death of fish and humans. About 100 algae species have been identified that cause disease through neurotoxins such as domoic acid. In marine environments, these algae are mainly species of the families of diatoms (especially Pseudo-nitzschia) and dinoflagellates. Harmful algal blooms (HABs) are caused by a mass proliferation of these algae, with their growth depending on a complex interplay of different factors. Under favorable environmental conditions of light, temperature, salinity, water column stability and nutrients, algal populations of only a few cells can quickly multiply into dense blooms containing millions of cells per liter [Berdalet et al., 2016; IUCN, 2016]. Although eutrophication has played an important role in the proliferation of HABs, many of their growth factors are linked to ocean warming, especially to SSTs, ocean stratification, oceanic modes (such as El Niño) and ocean currents responsible for local nutrient upwelling. Observed changes in the occurrence of HABs started a debate on how the distribution, frequency and intensity of HABs will be impacted by climate change and ocean warming. Many harmful species of algae are expected to respond rapidly to current climate change. However, as nutrient over-enrichment (or eutrophication) from coastal run-off has contributed to changes in abundance and intensity of HABs, it is difficult to disentangle the different signals in the event data available for HABs. Furthermore, knowledge of marine microalgae's ability to adapt to new conditions is very limited. As of today, these complexities are leading to an uncertain future for the risk caused by HABs [IUCN, 2016]. The biological impacts of HABs can be quite severe and include fish die-offs, seafood contamination and illness in humans from the consumption of poisoned shellfish or fish. Economic losses accumulate from costs for treatment of acute and chronic health effects in humans, financial losses for fisheries and fish farming, and losses due to reduced coastal tourism and recreational activities as well as for administration and monitoring [Sanseverino et al., 2016]. Additional costs include lost revenue in the marine business caused by shellfish closure, product recall of contaminated seafood, lost revenue for the tourism industry in affected coastal areas, expenses to remove algae from the water or dead fish from the beaches and investment costs in preventing and monitoring HABs.

Recent HAB events

A HAB of the raphidophyta alga Pseudochattonella cf. verruculosa occurred during February and March 2016 on the coast of Chile. It killed nearly 12% of the Chilean salmon production, causing the worst mass mortality of fish and shellfish ever recorded in the coastal waters of western Patagonia. The HAB coincided with a strong El Niño event and the positive phase of the Southern Annular Mode that altered the atmospheric circulation in southern South America and the adjacent Pacific Ocean. This led to very dry conditions and higher than normal solar radiation reaching the surface.

The coastal waters of southern Chile, including the northern region of the Chilean Inland Sea, and both coasts of Chiloe Island and environs, were subjected to a series of massive HABs [Global Aquaculture Alliance, 2017]. The blooms resulted in extreme losses of wild and cultured fish, as well as widespread paralytic shellfish poisoning (PSP). Fish and shellfish farmers, artisanal fishers and the tourism industry suffered serious financial damage and the social upheaval that resulted was pronounced. Losses just from salmon fisheries were at about USD800 million[23].

Another ecologically and economically disruptive HAB affected much of the US West Coast in 2015 during a prolonged oceanic warm anomaly. Caused by diatoms of the genus Pseudonitzschia, this HAB stretched from Santa Barbara, California to southeastern Alaska and produced the highest particulate concentrations of the biotoxin domoic acid ever recorded in Monterey Bay, California. Bloom inception followed strong upwelling during the spring transition of the oceanic currents, which introduced nutrients and eliminated a local warm anomaly [Ramanujam & Carter, 2016; Ryan et al., 2017]. The bloom impacted major commercial and recreational fisheries in California in 2015 and 2016, including Dungeness crab and rock crab, and led to multiple and prolonged fishery closures and health advisories. Given the extensive geographic range and longevity of the bloom, the socio-economic impacts to California's fishing industry were significant. Losses to the Dungeness and rock crab fisheries were estimated at USD30 million, with additional substantial losses to other fisheries [Ramanujam & Carter, 2016].

Modelling of HABs

In response to the increasing event rates and economic impacts worldwide, several initiatives for collecting data, real-time observation systems and predictive modelling have been started. A searchable database of global HAB events has been created by the International Society for the Study of Harmful Algae (ISSHA)[24].

Encouraging examples of HAB modelling systems are NOAA's HAB-OFS, which operates in Florida and Texas in the US [Stumpf et al., 2009], the C-Harm model [Anderson et al., 2016] or the ASIMUTH project in Europe [Davidson et al., 2016]. These projects are aiming to produce national or regional HAB forecasts with lead times from days to seasonal, combining national monitoring program and satellite remote sensing data streams with regional-scale HAB transport models. However, none of these modelling systems has been used to estimate the background risk of HABs occurring.

A very short introduction to corals

Corals are marine invertebrates (the class of Anthozoa of phylum Cnidaria) living in symbiosis with microalgae called zooxanthella. The corals provide shelter and emit waste products that the algae consume as a nutrient. The algae in turn use photosynthesis to produce nutrients, many of which they pass on to the corals' cells. Corals typically live in compact colonies of large numbers of genetically identical polyps. Individual groups can grow by asexual reproduction of polyps. However, corals also breed sexually by spawning: polyps of the same species release gametes simultaneously over a period of several nights around full moon. Each polyp is a sac-like animal typically only a few millimeters in diameter and a few centimeters in length. A set of tentacles surround a central mouth opening, and an exoskeleton is created near the base through the excretion of calcium carbonate. Over many generations, the colony thus creates a large skeleton characteristic of the species – a coral reef.

Coral reefs occur to depths of about 50m with the majority of coral growth often found at 10 to 20m. Shallow-water coral reefs cover approximately 285,000km² and occur most abundantly in clear, shallow, tropical waters on the windward sides of continents and islands. The Pacific Ocean and Southeast Asia each contain about one-quarter of the world's coral reefs, followed by Australia (17%), the Indian Ocean (13%), the Atlantic (10%), and the Middle East (6%) [Beck & Lange, 2016].

Coral reefs are one of the most important components of the marine environment as they provide critical habitat for tropical fish and other reef fauna. As a result, they contain about 25% of the ocean's biodiversity. Coral reefs provide a large number of ecosystem services that billions of people rely upon [Gattuso et al., 2015]. Despite covering less than 0.1% of the seafloor area, coral reefs provide nearly USD9.8 trillion globally of social, economic and cultural services each year [Heron et al., 2016]. They are important as a source of food, medicine, and cultural and aesthetic value to coastal communities. In addition, coral reefs afford vital protection to coastlines by reducing wave energy during storm surge (associated with tropical storms) and other high-water events [Spalding et al., 2014; Narayan et al., 2017].

Coral bleaching, corals and ocean acidification, corals and sea-level rise

Ocean warming and acidification as well as sea-level rise are among the most important threats to the health of corals and can cause degradation or loss of coral reefs in various ways: coral bleaching can occur with high water temperatures; the calcification process is disturbed in an ocean environment that is more acidic; and sea-level rise causes erosion of coral reefs. In combination, these processes have the potential to seriously affect the health of coral reefs worldwide.

A sustained high water temperature of even 1 to 2°C above a coral's tolerance level, occurring for example during El Niño events, can cause coral bleaching [IUCN, 2016]. Coral bleaching is the process by which the corals expel their symbiotic algae, leaving the white skeleton visible through the transparent coral tissue. Bleached corals are susceptible to injury and starvation. If stressful temperature conditions abate within days to weeks, corals can regain their algae and survive the bleaching. However, if stress persists for several weeks or longer, corals can starve to death [Glynn, 1993]. Other stressors such as high nutrient levels from eutrophication or ocean acidification can make corals more susceptible to temperature stress [Anthony et al., 2008; Wooldridge et al., 2017]. In addition, ocean acidification will likely reduce the strength of coral reef structures, as oceanic acidity impacts the Appendix 2: Coral reef bleaching capacity of corals to form their limestone skeleton in the reefbuilding process. With reduced strength of reef structures, loss of reefs during disturbance events (e.g., bleaching, tropical cyclones) becomes more likely. Loss of reef structure is a natural process. However, it is important for the reefs to build more reef structure than is lost during those events. SLR plays a critical role for the erosion of coral reefs as it exacerbates impacts of coastal erosion, storm surge, waves, and tsunami hazards. Thus, with rising sea levels, it becomes more difficult for corals to rebuild the reef more quickly than it is eroding [Yates et al., 2017].

Coral bleaching events

There have recently been several mass bleaching events that highlight the risk of losing coral reefs as a consequence of ocean warming [Hughes et al., 2017]. Of particular note are the consecutive bleaching events on the Great Barrier Reef in Australia in 2016 and 2017, where the scale of bleaching was unprecedented in recent history with reported bleaching of over 90% of the surveyed reefs on the Great Barrier Reef. Given the enormous economic value and importance of the Great Barrier Reef for the economy [Deloitte, 2017], these bleaching events have caused huge economic losses with an estimated loss of around AUD1 billion in tourism alone [Swan & Campbell, 2016].

Coral bleaching: warning systems and modelling techniques

In response to recent coral bleaching events, high-resolution coral bleaching warning systems have become available such as the Coral Reef Watch from

NOAA [NOAA, 2009]. The NOAA warning product offers a modelled outlook that predicts the likelihood of coral bleaching heat stress on a week-by-week basis, up to four months into the future (the typical length of a bleaching season). Continuous satellite monitoring of SST at global scales and modelled predictions of approaching bleaching-level heat stress provide the chance to trigger bleaching response plans and support appropriate reef management decisions. The Global Reef Record incorporates these warnings and combines data layers of surveyed reefs with ocean data[25].

Other modelling techniques for long-term, climatological studies or the estimation of background risk for coral bleaching use multivariate statistics on (observed or modelled) ocean data to estimate coral reef health or bleaching onset [Cooper et al., 2015; Van Hooidonk et al., 2015; Lewis & Mallela, 2018]

Coral restoration techniques

Given the high, and often critical, value of coral reefs to coastal communities, coral reef restoration has been researched as a possible risk mitigation strategy for an increasing risk of coral bleaching [Meesters et al., 2015]. Coral reef restoration science continues to improve and can already provide effective solutions to coral reef restoration on small spatial scales [Beck & Lange, 2016; Lirman & Schopmeyer, 2016]. With combined coral enhancement and nature-based artificial structures there is a potential for quick recovery that even increases the resilience of the reef systems. New techniques such as 3D-printing of reef structures [Pardo, 2013], coral spawning and coral gardening [Rinkevich, 2015], as well as similar, sometimes combined, techniques, are providing a chance to increase the resilience of coral reefs and for quick recovery of coral reefs after bleaching events.

Several coral reef restoration projects[26], coral restoration startups[27, 28, 29] or larger engineering firms working in the field of coral restoration[30] are raising the hopes that larger-scale coral reef restoration might become feasible very soon.

1 https://www.lloyds.com/lloyds/about-us/history/corporate-history

2 https://iumi.com/news/press-releases/global-marine-underwriting-premiums-continue-to-fall-reports-iumi

3 The underlying concept of ecosystem services emphasizes the value of natural assets as critical components of economies and how they generate wealth and promote wellbeing and sustainability [Constanza et al., 2014]. In 2005, the concept of ecosystem services gained attention when the United Nations published its Millennium Ecosystem Assessment (MEA), a four-year, 1,300-scientist study aimed at policy-makers. Between 2007 and 2010, a second international initiative was undertaken by the UN Environment Program, called “The Economics of Ecosystems and Biodiversity” (TEEB) [TEEB Foundations, 2010]. The concept of ecosystem services has now entered the consciousness of mainstream media and business. The World Business Council for Sustainable Development actively developed and supports the concept [WBCSD, 2011, 2012]. However, there is ongoing debate about appropriate methods to quantify the value of ecosystem services and estimates vary considerably depending on the approach taken.

4 The ‘blue economy’ concept was first coined during the 2012 UN Conference on Sustainable Development [Silver et al., 2015]. It is an evolving concept that recognizes the need to maximize the enormous economic potential presented by the ocean, while preserving it.

5 To compare an industry’s contribution to the economy across countries, the share of total GVA is preferred to the share of gross domestic product (GDP) by the System of National Accounts. The difference between total industry GVA and total GDP is taxes less subsidies on products, which varies across countries.

6 In this report, we present only an overview of ocean warming and acidification. Please check referenced literature for further information and regional details.

7 Given the large number of marine ecosystems affected and the complexity of the underlying science, we can only give an overview of the main findings here. We strongly recommend the IUCN report for a more detailed assessment of specific risk assessments.

8 The future climate projections of the IPCC Fifth Assessment Report [IPCC, 2013] are based on future emission scenarios called Representative Concentration Pathways (RCP), including one mitigation scenario (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6.0) and one high-emission scenario (RCP8.5). RCP 8.5 has been developed as a business-as-usual scenario that can be avoided if fast and strong emission reductions could be achieved.

9 A comprehensive analysis of all loss-relevant aspects of classes of extreme events and specific regional changes with concentrated risks goes beyond the scope of this study. Instead we focus on a general understanding of what the observed warming of the upper ocean and increased SST implies for the most relevant extreme events.

10 https://www.reuters.com/article/us-chile-salmon/chile-algal-bloom-kills-170000-salmon-raising-concern-idUSKBN15O2LS

11 http://www.globalreefrecord.org

12 http://catlinseaviewsurvey.com

13 Ambiguity in this paper describes the inability to assign probabilities to future events with a satisfactory precision. Walker and Dietz provide a formal, mathematical definition of ambiguity [Walker & Dietz, 2017]. Note that the concept of ambiguity applies whenever there is Knightian uncertainty [Knight, 1921], but Knightian uncertainty doesn’t necessarily imply ambiguity since decision-makers might still treat Knightian uncertainty as if it were risk.

14 http://www.insuresilience.org/

15 https://global.nature.org/content/insuring-nature-to-ensure-a-resilient-future

16 http://www.swissre.com/global_partnerships/Designing_a_new_type_of_insurance_to_protect_the_coral_reefs_economies_and_the_planet.html

17 The restoration of wetlands, water and wildlife habitat is a USD3 billion industry. Wetlands ‘mitigation banks’ broker credits to offset negative environmental impacts of real estate, transportation and energy projects through the creation of more-than-equivalent positive impacts nearby. Funds such as Ecosystem Investment Partners have raised more than USD300 million to finance the restoration of thousands of acres of wetlands [Thiele & Gerber, 2017].

18 Globally there are 240,000km2 of coral reef, 130,000km2 of mangroves, and 37,000km2 ofsaltmarshes.

19 Whether a massive increase in offshore windfarms in coastal water will affect marine ecosystems is an important but complex question that is outside the scope of this report.

20 https://www.willistowerswatson.com/en/press/2018/03/willis-towers-watson-launches-the-global-ecosystem-resilience-facility

21 http://www.wavespartnership.org/en/natural-capital-accounting

22 http://www.un.org/sustainabledevelopment/oceans/

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CHAPTER THREE

115 2050 CLIMATE CHANGE CITY INDEX

This study was designed to show how climate change may affect some of the world’s most popular cities in the next twenty to thirty years. The final index includes 85 cities, based on top city destination lists, and those with comparable data included in the existing climate change reports utilised for this study. Some key travel destinations which will notably be affected by climate change in the coming years, such as Venice in Italy, have not been included in the final index due to a lack of data in the research framework.

The index is categorised into three key areas: Sea-Level, Climate and Water Shortage. The index is then ranked by the Total Score based on these three sections, where rank #1 indicates the city which is likely to encounter the most extreme changes in climate over the next three decades, and where rank #85 indicates the city which is least likely to encounter a dramatic shift in climate by 2050.

The Total Score = Potential Sea Level Rise Impact Score + Climate Shift Score + Water Stress Increase Score; All scores are out of 100.

Climate projections are usually provided for several scenarios. The “Business as usual” scenario was chosen for all factors. This scenario is described by the World Resources Institute as:

The “Business as usual” scenario (SSP2 RCP4.5) represents a world with stable economic development and steadily rising global carbon emissions, with CO2 concentrations reaching ~1370 ppm by 2100 and global mean temperatures increasing by 2.6–4.8°C relative to 1986–2005 levels.’

The full breakdown and methodology for each category can be found below.

Income Group

The income groups are defined as per the UN report ‘World Economic Situation and Prospects 2019’ under table ‘2019 capita GNI in June 2018’ p. 172.

Source: UN (2019), World Economic Situation and Prospects 2019, UN, New York, https://doi.org/10.18356/a97d12e3-en.

Sea Level

Potential Sea-Level Rise Impact: The higher the score, the higher the potential flooding/sea level impact in that city by 2050.

The Potential Sea-Level Rise Impact under the “Business as usual” scenario is based on sea-level rise projections (Kopp et al., 2014) and CoastalDEM® v1.1 map data (Kulp et al. 2018). The resulting projected impact was accessed through the COASTAL RISK SCREENING TOOL provided by Climate Analytics where maps show the areas affected by rising sea levels and coastal flooding. This factor does not take existing anti-flooding and control infrastructure of the city into account, where cities have already put anti-flooding measures to mitigate future risk into place. This factor also does not take into account extreme weather occurrences such as hurricanes, heavy downpours etc. Cities that are unaffected by coastal flooding or not geographically by the coast are automatically given a score of 1. The higher the score, the higher the potential flooding/sea level impact.

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Climate

The Climate category includes t he following data points:

- Temperature Baseline: 1970 - 2000 (Degrees °C)
- Temperature 2050 (Degrees °C)
- Temperature Shift (Degrees °C)
- Climate Type 2021
- Climate Type 2051
- Climate Shift (Score)
- Temperature

Temperature Baseline: 1970 - 2000 and Temperature 2050 show the average annual temperature based on Bastin's city analogue study.

Temperature Shift is calculated based on the change of annual temperature between 1970-2000, and includes projections for 2050.

Using the research article "Understanding climate change from a global analysis of city analogues" by Jean-Francois Bastin et al. (2019), this index created projections of temperature changes in roughly thirty years time based on the "Business as usual" scenario. The paper which describes how the climate of current-day cities will match those with different climates by 2050. For instance, the report predicts that in 2050, Amsterdam's climate will be analogous to the climate of Paris, London and Rotterdam today. Thus, for the purpose of this study, Amsterdam's 2050 temperature projection is based on the mean annual temperature in Paris, London and Rotterdam from 1970-2000. By matching each city in the index to its predicted equivalent climates for 2050, the predictions for 2050 annual temperature change were then able to be calculated.

Note that the temperature columns in the index are provided for reference, and do not contribute directly to the total score, as temperature is part of a wider set of climate parameters that make up the Climate Shift Score.

Source

Bastin JF, Clark E, Elliott T, Hart S, van den Hoogen J, et al. (2019) Correction: Understanding climate change from a global analysis of city analogues. PLOS ONE 14(10): e0224120. https://doi.org/10.1371/journal.pone.0224120

Climate Type 2021 and 2051

Climate Type 2021 and Climate Type 2051 use the official climate categories based on the "Koppen-Geiger Observed and Predicted Climate Shifts" projections via ArcGIS. Each climate type was matched with the official Koppen climate type classification.

Explanations of Koppen climate classification can be found here: (https://en.wikipedia.org/wiki/K%C3%B6ppen_climate_classification)

Source ArcGIS

Climate Shift Score

The Climate Shift Score is based on Bastin's climate change city analogues study and the climate type score. The score is an amalgamation of the change in climate type between 2021 and 2051 including the change in annual precipitation, change in annual temperature, change in temperature of the warmest month, change in temperature of the coldest month and change of precipitation in the wettest month.

Source

Bastin JF, Clark E, Elliott T, Hart S, van den Hoogen J, et al. (2019) Correction: Understanding climate change from a global analysis of city analogues. PLOS ONE 14(10): e0224120. https://doi.org/10.1371/journal.pone.0224120

Water Shortage

The Water Shortage category includes the following data points:

- Water Shortage 2020 (demand vs. supply ratio)
- Water Shortage 2040 (demand vs. supply ratio)
- Water Shortage Relative Change (%)
- Water Stress Increase (Score)

Water Shortage 2020 and Water Shortage 2040 data originates from the Aqueduct Water Risk Atlas which evaluates the current and future water stress levels for metropolitan areas in the world. Water Stress is defined as "the ratio of demand for water by human society divided by available water." The parameters which were taken into account for this index were the future value of water stress in 2020 and 2040 under the "business as usual scenario" for the central location of every city.

Due to lack of data in central areas of some cities, the data for the following cities was taken from the central metropolitan areas named below:

- Copenhagen: Tycho Brahe Planetarium, Copenhagen Municipality, Denmark,
- Miami: HistoryMiami Museum,
- New York: Brooklyn Museum,
- Reykjavik: Reykjavík Art Museum Ásmundarsafn
- Stockholm: Nobel Museum, Stortorget, Stockholm, Sweden.

Water Shortage 2020 and Water Shortage 2040 show the raw demand versus supply ratio where 1.00 indicates that water supply matches demand. A ratio of below 1.00 indicates that there is a greater supply of water than demand, where a ratio of above 1.00 indicates that demand outweighs supply.

Water Shortage Relative Change (%) is calculated using to the following formula: (max((ratio_2040 - 1),0) - max(ratio_2020 - 1),0)) / ratio_2020

The equation calculates the % increase in water stress, relative to the water stress in 2020. Water stress is defined as the difference between the demand vs. supply ratio and a ratio of one; as a ratio of one or less means the city is not under stress.

Water Stress Increase Score shows how some cities will experience an increase in water shortages over the next twenty years. The higher the score, the greater the increase in water stress. For example, Santiago's water demand vs. supply ratio shifts from 1.64 to 3.51 between 2020 and 2040, resulting in a Water Stress Increase Score of 71.89 due to the significant increase in water stress.

Most cities in this dataset, however, will not experience an increase in water stress, and were therefore given the lowest possible score of 1.00. A score of 1.00 was given in two cases:

When the water stress level predicted for 2040 is expected to be 1.00 or lower–meaning that there will be enough supply to meet demand. For instance, the water stress indicator for Vienna is expected to increase from 0.04 in 2020 to 0.06 in 2040. However, 0.06 is far below 1.00 and so despite the increase in

126 SEAS THREATEN 80 AIRPORTS AROUND THE WORLD

METHODOLOGY NOTES:

OpenFlights provides the latitude, longitude, and altitude (or elevation above sea level) of airports, but OpenFlights does not provide information on the total area or footprint of airports. Stantec, a large engineering company, estimates that the typical commercial airline runway is between 2,440 and 3,960 meters in length. Our analysis estimates a conservative footprint for each airport, having a radius of 1,000 meters. Airports with footprints that overlap with pixels from Climate Central's sea level rise dataset were highlighted in this analysis. But we excluded airports with elevations higher than expected sea levels and airports designed for seaplanes.

Our decision to focus on sea level rise of half a meter and one meter is based on end-of-the-century predictions made by the UN's Intergovernmental Panel on Climate Change. However, sea level rise estimates differ substantially. These estimates may be conservative because an assessment published in Nature, found that we may see two meters of sea level rise by 2100.

Read the full methodology on GitHub.