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XL CATLIN

Ocean Risk and the Insurance Industry

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In partnership with CLIMATE RISK INNOVATIONS

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Ocean Risk and the Insurance Industry

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Executive summary

A diverse array of ocean-related phenomena occur today and more 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.
- 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.
- 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.
- 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.

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

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 lesser-known 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 structure 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).

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[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

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, shellfish 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 sport-fishing guides. In summary, the ocean is a critical component for life on Earth and a key factor in the global economy.

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.

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

1.2 Today's ocean industries and the blue economy

Apart 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.

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[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.

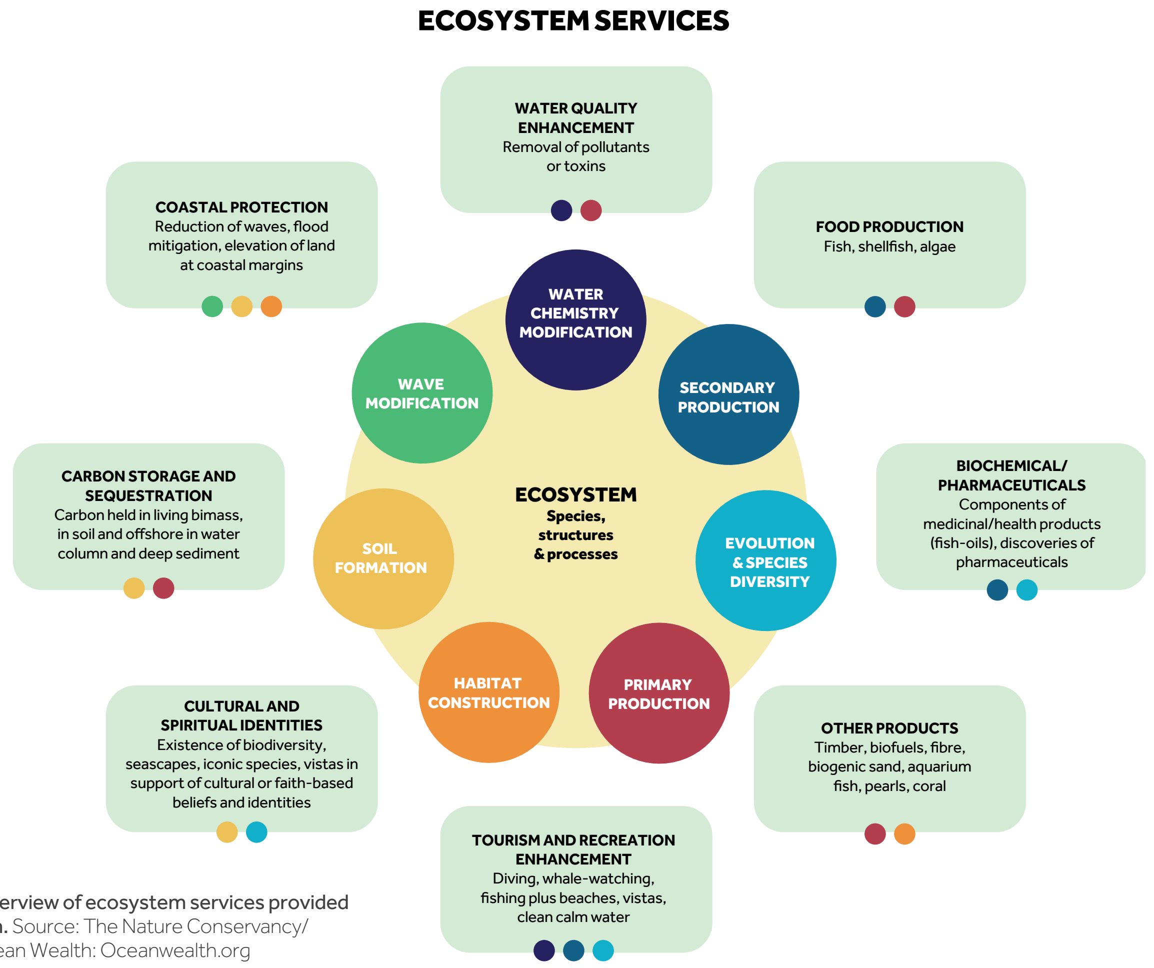

Figure 1: Overview of ecosystem services provided by the ocean. Source: The Nature Conservancy/ Mapping Ocean Wealth: Oceanwealth.org

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 Jersey and New York in October 2012 [Narayan et al., 2017].

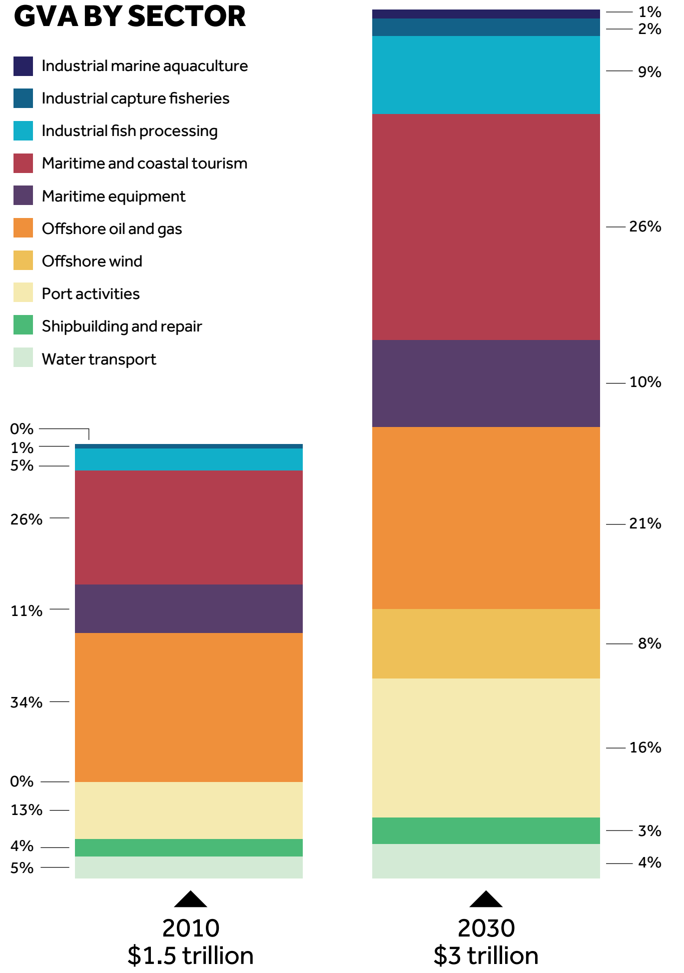

Figure 2: Calculations from OECD, 2016, based on various industry reports. Note: Artisanal fisheries are not included in this overview.

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 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].

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	

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

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 CO_2 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 sub-peak 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].

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[6] In this report, we present only an overview of ocean warming and acidification. Please check referenced literature for further information and regional details.

Nansen fracture 2016. © C. Yakiwchuck/ESA

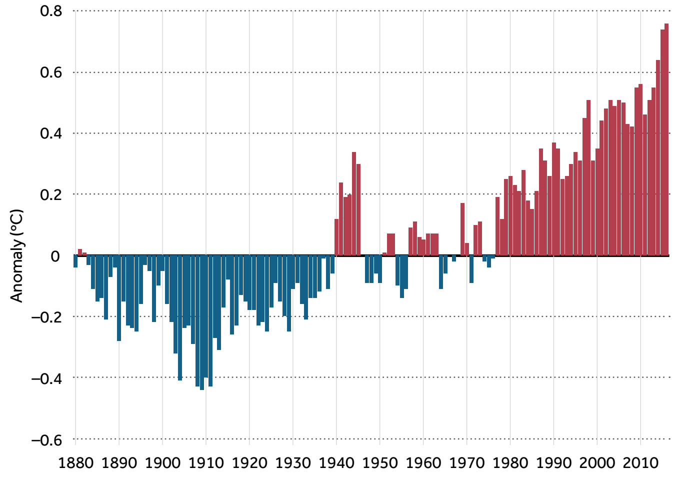


Figure 4: Annual global sea-surface temperature anomalies from 1880 to 2015 with superimposed linear trend (base period 1951–1980), red positive, blue negative. Source: National Centers for Environmental Information, http://www.ncdc.noaa.gov/cag/time-series/global/globe/ocean/ytd/12/1880-2016

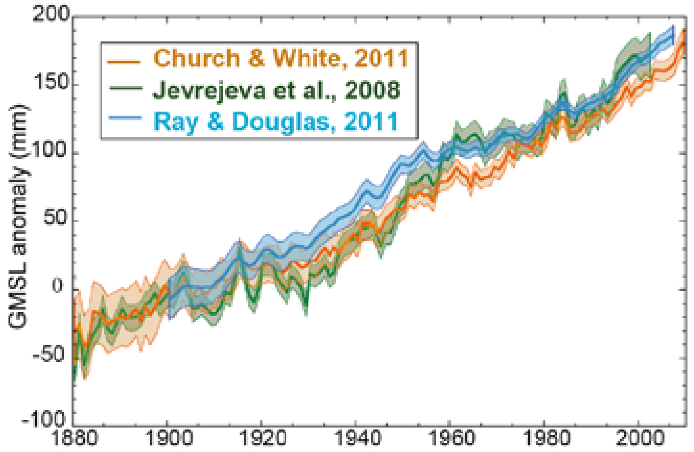


Figure 6: Yearly average of the Global Mean Sea Level (GMSL) reconstructed from tide gauges (1900–2010) by three different approaches [Jevrejeva et al., 2008; Church & White, 2011; Ray & Douglas, 2011] Source: IPCC, 2013

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 120x10^{21} 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].

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 pH-value, 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.

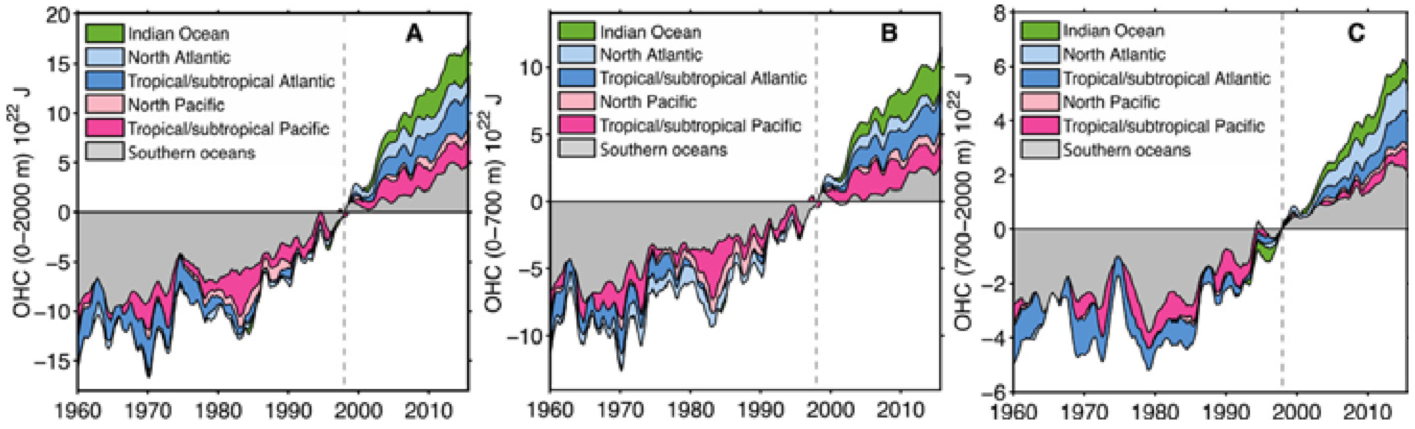


Figure 5: Ocean heat content for different vertical levels and ocean basins. Source: Cheng et al., 2017.

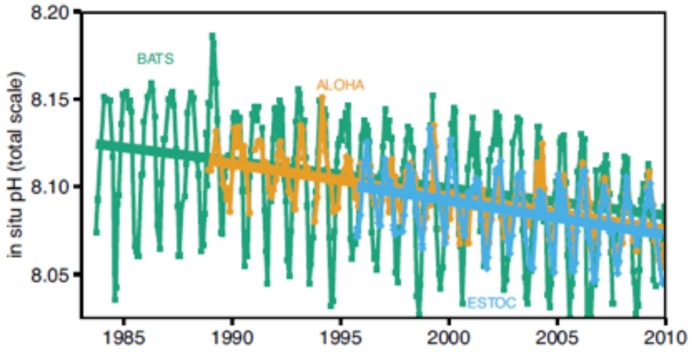


Figure 7: Long-term trends of surface seawater pH (middle) at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 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.

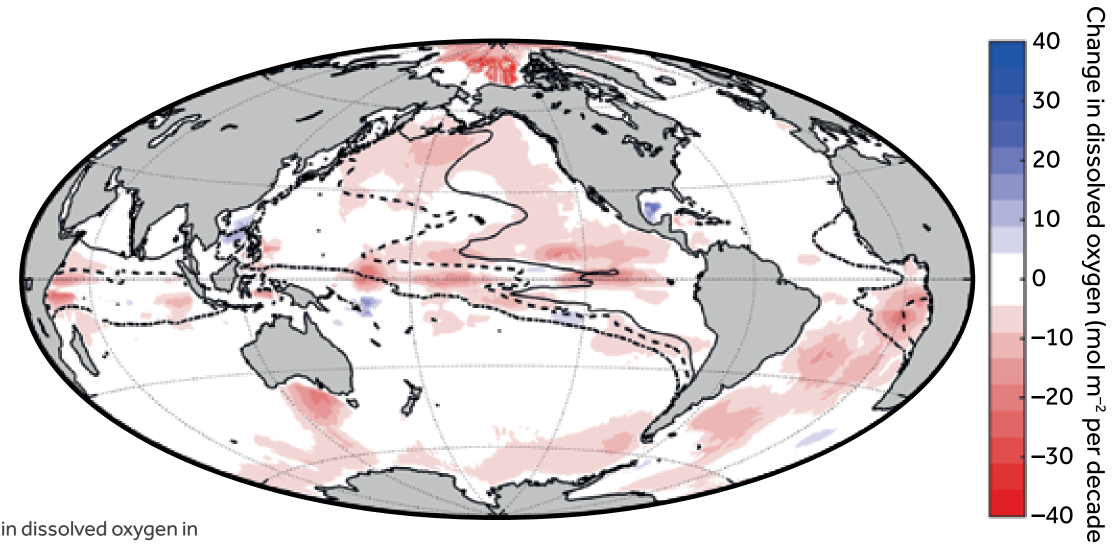


Figure 8: Changes in dissolved oxygen in ocean water. Source: Schmidtko et al., 2017.

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.

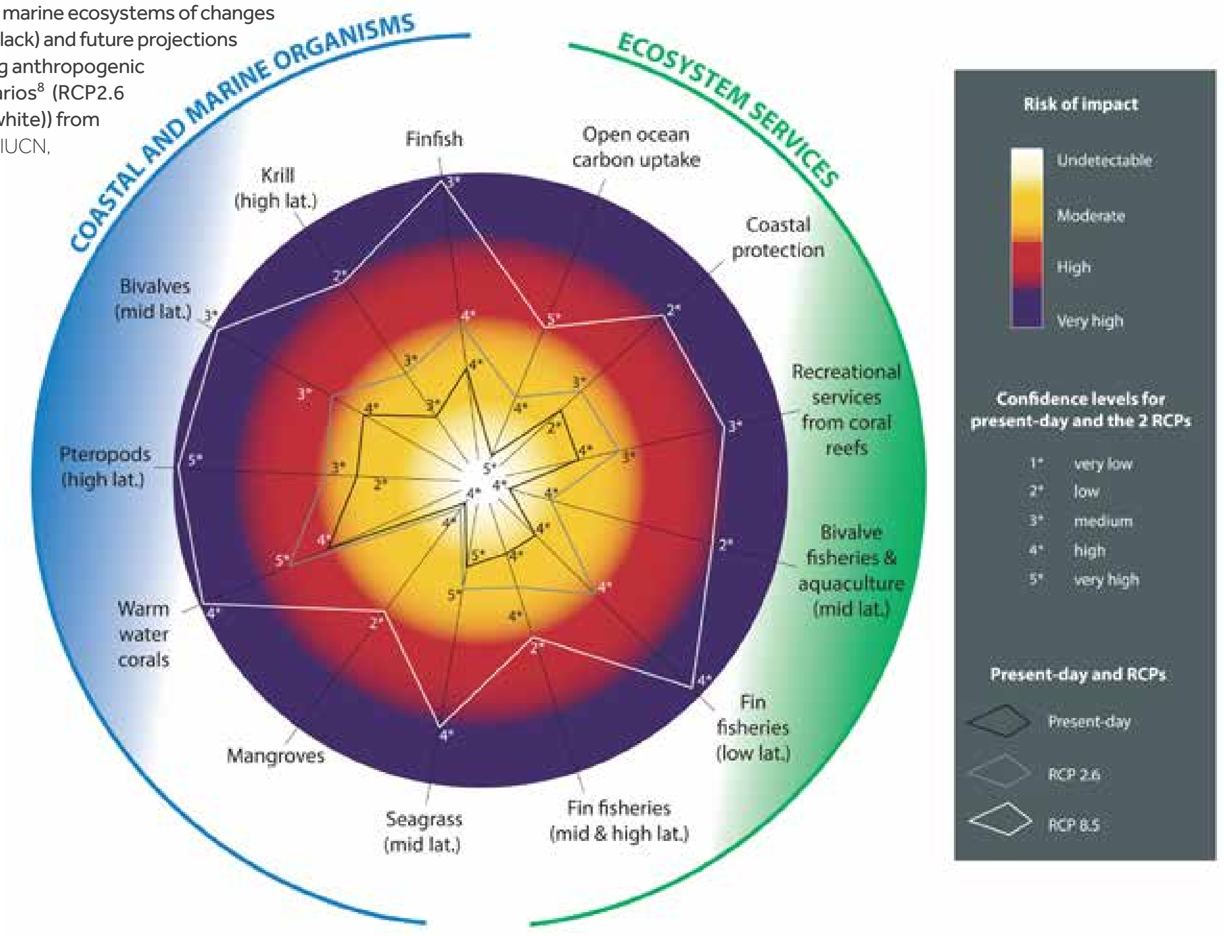
In 2016, the International Union for Conservation of Nature (IUCN) published a comprehensive summary of the impact of ocean warming on marine ecosystems [IUCN, 2016]. As of today, the IUCN report is the most comprehensive assessment of ocean warming and its linkages to marine biology and ecosystem research, 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 predator-prey 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 phenomena 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.

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

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 deep-water 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 climate-induced 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.

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[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.

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

- **Corals (for more details see Appendix 2)**

The rate of warming in coral reef areas increased from ~0.04°C per decade over the 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 ocean-atmosphere 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 loss-relevant characteristics of extreme events further complicates the debate. However, by using physical reasoning and selected, well-established 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

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[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.

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 that there 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].

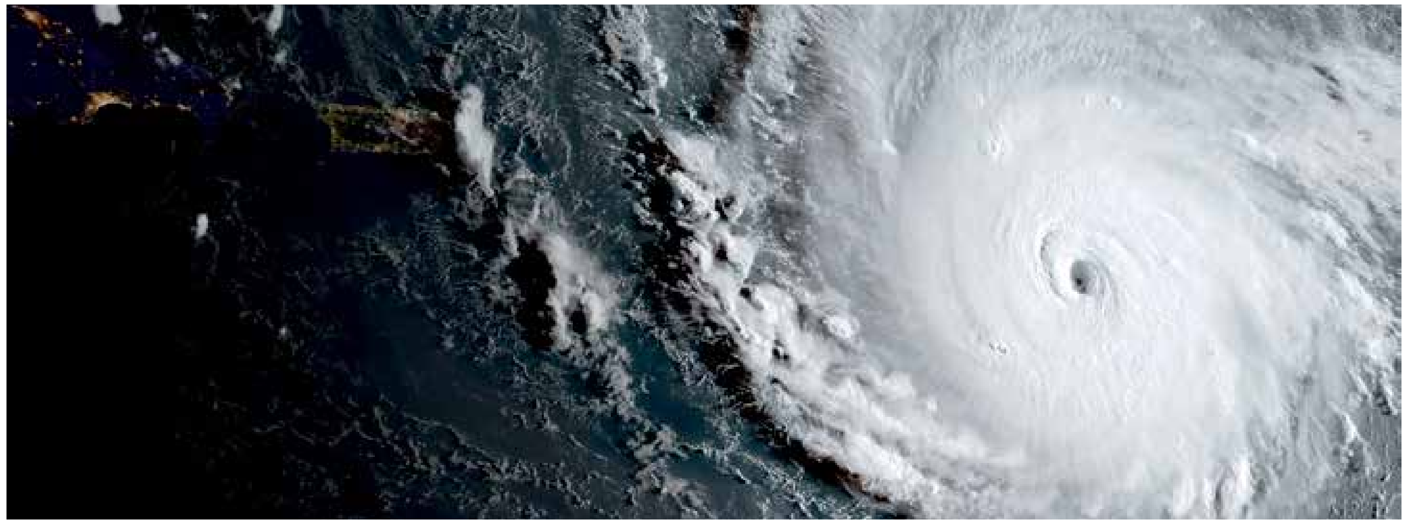
Although there is considerable uncertainty about some aspects of the impact of ETCs, the flood damage potential of ETCs is increasing due to various loss-relevant factors. For example, there is an increasing flood risk due to positive trends in precipitation, likely as a result of increased temperature 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.

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

The frequency, intensity and spatiotemporal 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).



Hurricane Irma, September 2017. © NOAA

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 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].

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[10] https://www.reuters.com/article/us-chile-salmon/chile-algal-bloom-kills-170000-salmon-raising-concern-idUSKBN15O2LS

Fisherman on a beach blanketed with dead sardines in Tolten, Temuco, Chile, May 2016. © Felix Marquez/AP/Rex/Shutterstock

3.3. Changes in asset risk

The growing importance of the blue economy at global, regional 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 natural 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 substantial 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 traditional 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.

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 social 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 additional 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 financial impacts and model ocean risk?" We begin to answer this question in the next section.

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

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 experiment-derived 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.

To 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 high-resolution 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].

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[11] http://www.globalreefrecord.org

[12] http://catlinseaviewsurvey.com

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 cost-benefit 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.

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[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.

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.

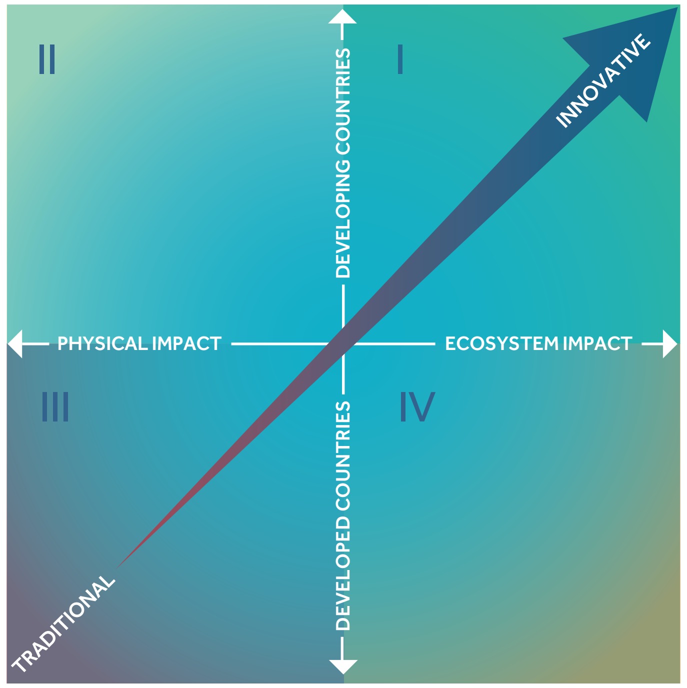

Figure 10: Conceptual diagram illustrating the continuum of ocean risk insurance products based on a country's development level and the type of insured asset. Each quadrant represents a different business segment with different risk transfer solutions. The diagonal provides a very general sense of the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

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[14] http://www.insuresilience.org/

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-agreed-upon 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 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 (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.

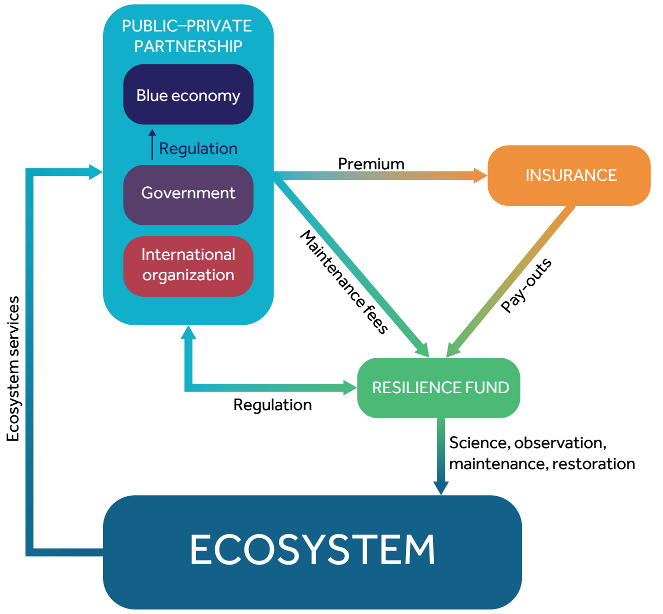

Figure 11 : Possible structure of resilience funds in developing countries for sustainable ecosystem services and their insurance elements

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.

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.

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[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 240,000km^2 of coral reef, 130,000km^2 of mangroves, and 37,000km^2 of saltmarshes.

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.

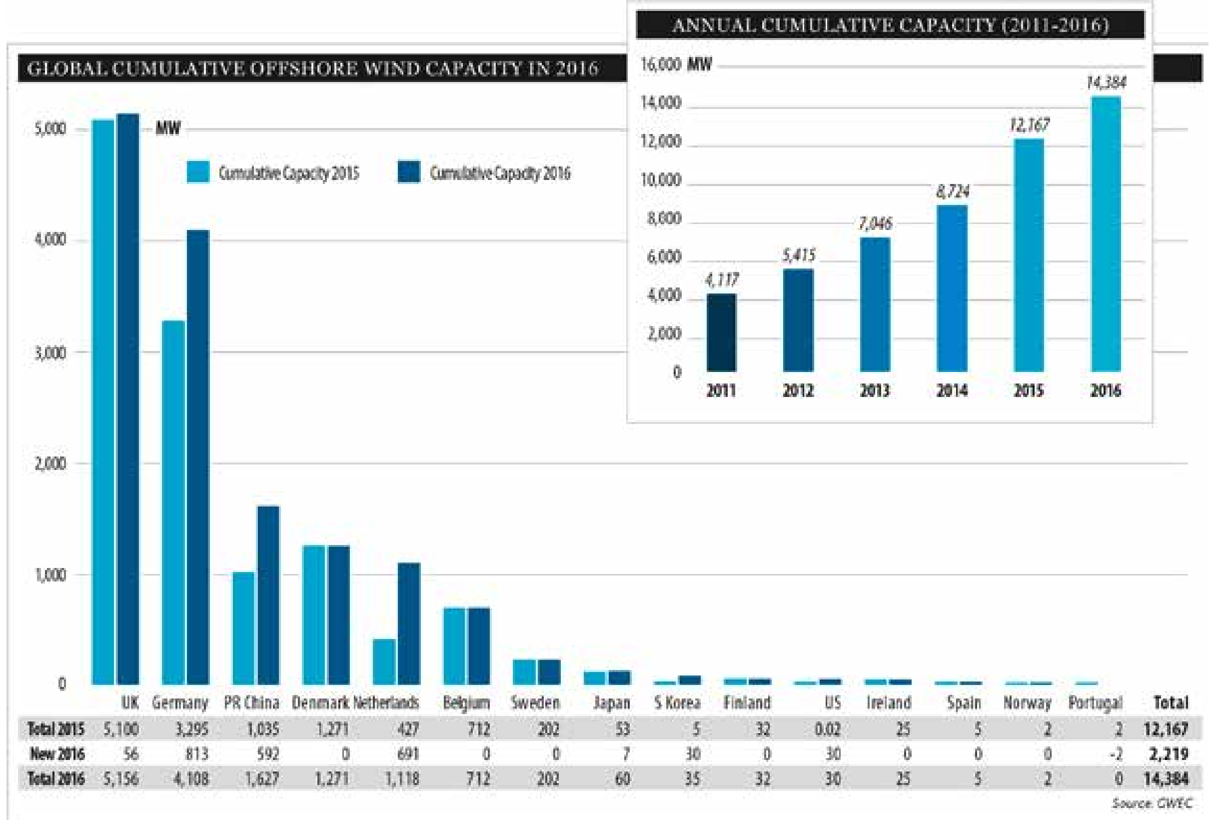
A second common feature of sovereign-level insurance products is the involvement of multiple countries to take advantage of geographic diversification. Existing examples include CCRIF in the Caribbean, PCRAFI in the Pacific and ARC in Africa. In all of these regions, countries with coastlines will likely 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.

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].



	UK	Germany	PR China	Denmark	Netherlands	Belgium	Sweden	Japan	S Korea	Finland	US	Ireland	Spain	Norway	Portugal	Total
Total 2015	5,100	3,295	1,035	1,271	427	712	202	53	5	32	0.02	25	5	2	2	**12,167**
New 2016	56	813	592	0	691	0	0	7	30	0	30	0	0	0	-2	**2,219**
Total 2016	5,156	4,108	1,627	1,271	1,118	712	202	60	35	32	30	25	5	2	0	**14,384**

Source: GWEC

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.

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.

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[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.

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.

Large harbor cranes loading container ships in the port of Rotterdam. © VanderWolf Images/Shutterstock

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 developing 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

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[20] https://www.willistowerswatson.com/en/press/2018/03/willis-towers-watson-launches-the-global-ecosystem-resilience-facility

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 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.

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[21] http://www.wavespartnership.org/en/natural-capital-accounting

[22] http://www.un.org/sustainabledevelopment/oceans/

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

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 Pseudo-nitzschia, 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.

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[23] https://www.theguardian.com/environment/2016/mar/10/chiles-salmon-farms-lose-800m-as-algal-bloom-kills-millions-of-fish

[24] http://haedat.iode.org

Appendix 2: Coral reef bleaching

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 capacity of corals to form their limestone skeleton in the reef-building 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 start-ups[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.

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[25] http://www.globalreefrecord.org

[26] http://www.monacolife.net/monaco-claims-worldwide-first-in-printed-reefs

[27] http://www.coralvita.co

[28] http://www.sustainableoceans.com.au

[29] http://www.reefdesignlab.com

[30] https://boskalis.com/csr/cases/3d-printed-reefs.html

A marine biologist assesses coral bleaching at Airport Reef, American Samoa. © The Ocean Agency/XL Catlin Seaview Survey

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