



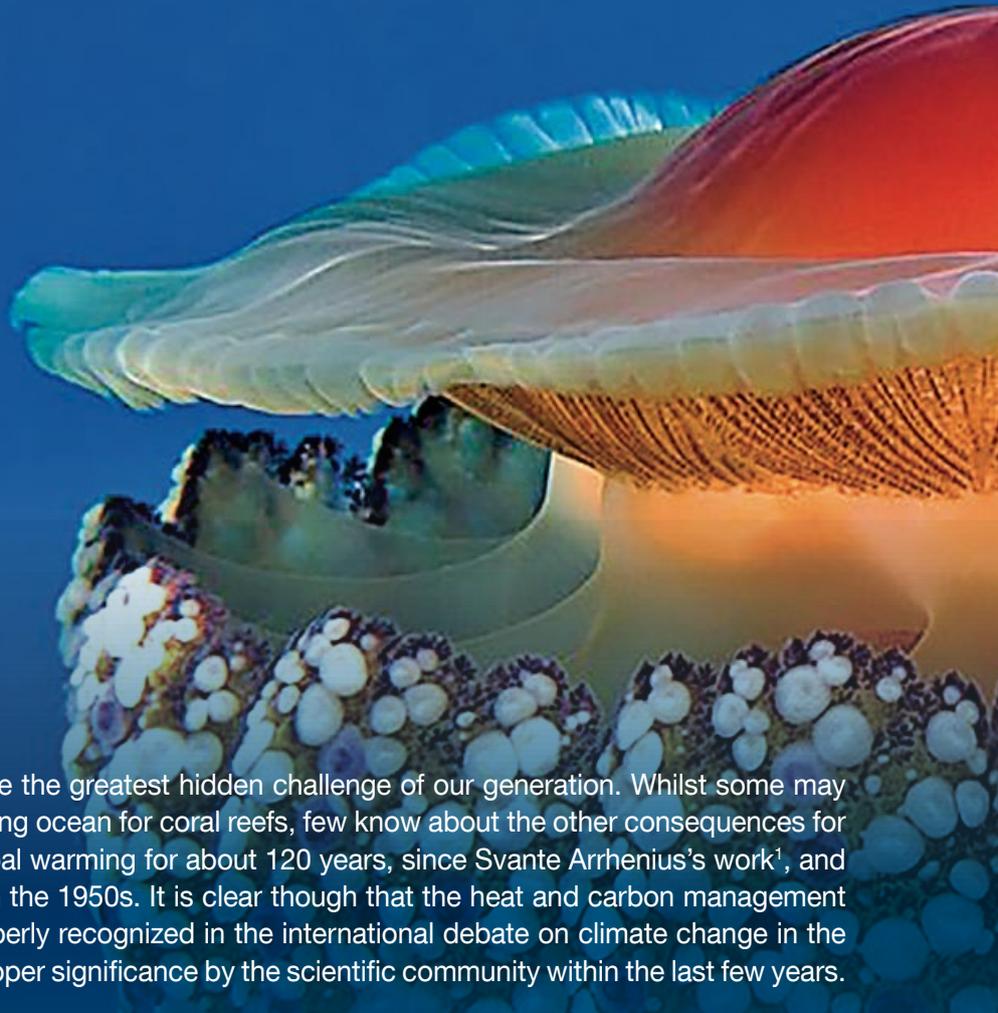
Ocean warming: causes, scale, effects and consequences

And why it should matter to everyone



Executive Summary





Ocean warming may well turn out to be the greatest hidden challenge of our generation. Whilst some may be aware of the implications of a warming ocean for coral reefs, few know about the other consequences for the ocean. We have known about global warming for about 120 years, since Svante Arrhenius's work¹, and ocean warming from Rossby's work² in the 1950s. It is clear though that the heat and carbon management roles of the ocean have only been properly recognized in the international debate on climate change in the last decade or so, and afforded their proper significance by the scientific community within the last few years.

More than 93% of the enhanced heating since the 1970s due to the greenhouse effect and other human activities has been absorbed by the ocean, and data show a sustained and accelerating upward trend in ocean warming. The year 2015 has recently been confirmed the warmest within the 136-year extended reconstructed sea surface temperature records, and the fourth such record-breaking year since 2005. The scale of ocean warming is truly staggering with the numbers so large that it is difficult for most people to comprehend. If the same amount of heat that has gone into the top 2000m of the ocean between 1955-2010 had gone into the lower 10km of the atmosphere, then the Earth would have seen a warming of 36°C³. This reports explores the consequences of putting such massive amounts of energy into the ocean, the warming it is causing and resulting changes that are now taking place.

Until very recently, the debate on climate change has focused on specific themes such as land surface temperatures, melting ice caps in Greenland and Polar Regions, and shrinking glaciers in mountain ranges. It has only occasionally mentioned the ocean. When the ocean was included, the issues discussed generally related to dramatic changes to coral reefs, with water temperature rises turning beautifully-coloured reefs a ghostly white from bleaching. Ocean acidification also emerged as a 'new story' around 2004, with problems already being encountered due to changes in ocean chemistry, add ocean warming to the mix and there is a far bigger story to tell. It is only in recent years that the science on these cumulative ocean impacts has started to emerge and the stories documented in this report begun to be heard.

Whether ocean warming impacts a particular group of organisms, alters the structures of ecosystems such as coral reefs, changes the very essence of environmental conditions, or indeed influences weather, it impacts on everyone to some degree as we are an ocean planet. It has profound implications not just for ecosystems but also for the significant number of coastal communities and valuable economies that depend on a healthy ocean. Up to now, the ocean has shielded us from the worst impacts of climate change by absorbing

1 <http://www.lenntech.com/greenhouse-effect/global-warming-history.htm>

2 https://www.aip.org/history/climate/oceans.htm#M_13_

3 Whitmarsh, F., Zika, J., and Cazaja, A. 2015. Ocean heat uptake and the global surface temperature record, Grantham Institute, Briefing paper No 14.



Increases in ocean temperature may broaden the reproductive periods of mid-latitude jellyfish, and improve winter survival of tropical species expanding to temperate waters, therefore boosting both alien and native outbreaks.
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significant parts of the heat and CO_2 . This regulating function, however, happens at the profound cost to alterations of the ocean's physics and chemistry that lead especially to ocean warming and acidification, and consequently sea-level rise.

This report represents the most recent and comprehensive review on ocean warming; it builds on the IPCC's 2013 assessment, promotes their messages, and adds in new information published since then – over 25% of the peer reviewed papers quoted here have been published since 2014 - as well as highlighting lesser-known consequences of ocean warming on species, ecosystems and services. It is hoped that this report will help generate far greater awareness and scrutiny of ocean warming and its impacts in the future. To build up the report, leading scientists from around the world were invited to join with colleagues to contribute individual chapters or sections. Each chapter has been subject to peer review and tells in the scientist's own words the scale, nature and consequences of changes being driven by ocean warming, often in association with other stressors such as ocean acidification and deoxygenation. It contains many recommendations from the scientists on capability gaps and research issues that need to be resolved if we are to tackle the impacts of ocean warming with greater confidence in the future.

We hope that the timing of this report after COP21 in Paris in late 2015 will enhance awareness of the fact that despite greater recognition now being given to the ocean in climate discussions, the scale and nature of changes continues to grow. Since the process was started to compile this report, IPCC has agreed to prepare a special report on climate change and oceans and the cryosphere. The papers in this report will, we hope, help that process and shape further thinking on the scale and consequences of climate change in our seas. Alongside this work a second report is in production, which will use the knowledge on ocean warming to re-evaluate the risks to society from the growing changes that are now being seen.

Above all though this report is the story of ocean warming and its consequences for all of us. It outlines cautionary tales about changes that are now underway in the ocean, often hidden and unseen, but nevertheless of great consequence. A warming ocean is one where changes to ecosystems, chemistry and processes are generating risks to the benefits we and many other species receive and depend on during our lives: changes that are not theory, but now a reality supported by hard facts. For this reason, the relationship we have with the ocean matters more than ever and we hope this report will be instrumental in inspiring greater action to care for it.

Facts at a glance - a catalogue of change⁴

SOME OF THE MAJOR FINDINGS, IMPACTS AND CONSEQUENCES FOR WEATHER, OCEAN, ECOSYSTEMS AND SPECIES.

KEY WARMING FACTS

By absorbing a disproportionate amount of heat from global warming and by taking up the rapidly increasing emissions of carbon dioxide, the ocean has shielded the world from even more rapid changes in climate. The crucial role that the ocean plays in climate regulation as the major heat, carbon and water reservoir of the world has not until now been generally recognized or appreciated by the public or policy makers.

More than 93% of the enhanced heating since the 1970s due to the greenhouse effect and other human activities has been absorbed by the ocean, even affecting the deep ocean. If the same amount of heat that has gone into the top 2000m of the ocean between 1955-2010 had gone into the lower 10km of the atmosphere, then the Earth would have seen a warming of 36°C.

Sea surface temperature, ocean heat content, sea-level rise, melting of glaciers and ice sheets, CO₂ emissions and atmospheric concentrations are increasing at an accelerating rate with significant consequences for humanity and the marine species and ecosystems of the ocean.

There is likely to be an increase in mean global ocean temperature of 1-4°C by 2100. The greatest ocean warming overall is occurring in the Southern Hemisphere and is contributing to the subsurface melting of Antarctic ice shelves. Since the 1990s the atmosphere in the polar regions has been warming at about twice the average rate of global warming.

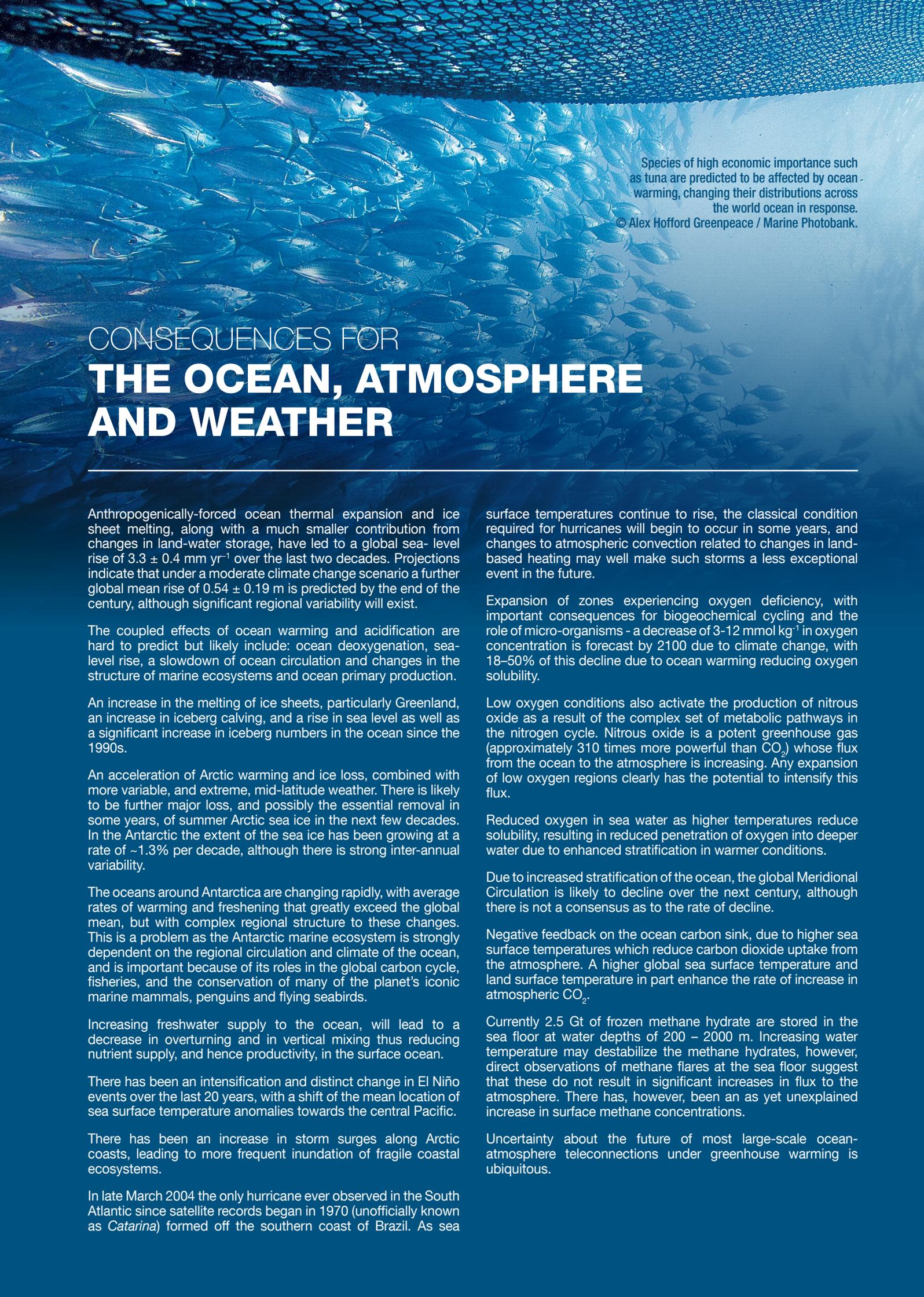
Increases in the atmospheric and upper ocean water temperatures are not quickly transferred to the deep sea, but the deep water masses are warming, now storing 16-89% more heat, including in the deep Mediterranean Sea, now 0.12°C warmer than a few decades ago. This increase in deep ocean water temperature is projected to continue for centuries after the atmospheric temperatures have levelled off or even decreased.

The heat content of the upper 700 m of the global ocean is the equivalent of ~ 240 times the human global energy consumption in 2013. The heat and CO₂ accumulated in the ocean are not permanently locked away, but can be released back to the atmosphere when the ocean surface is anomalously warm, giving a positive rapid feed-back to global warming.

While global hurricane frequency has not changed significantly there are now more severe hurricanes (Saffir-Simpson scale 3-5) than several decades ago, with an increase in these severe systems at a rate of ~ 25-30% per °C of global warming. It appears likely that the probability of strong hurricanes occurring will increase, although there may be a point in the warming process beyond which this trend halts.

⁴ For precise details and context for every fact please refer to the main scientific report downloadable from the web site address given at the end of this summary





Species of high economic importance such as tuna are predicted to be affected by ocean warming, changing their distributions across the world ocean in response.

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CONSEQUENCES FOR THE OCEAN, ATMOSPHERE AND WEATHER

Anthropogenically-forced ocean thermal expansion and ice sheet melting, along with a much smaller contribution from changes in land-water storage, have led to a global sea-level rise of $3.3 \pm 0.4 \text{ mm yr}^{-1}$ over the last two decades. Projections indicate that under a moderate climate change scenario a further global mean rise of $0.54 \pm 0.19 \text{ m}$ is predicted by the end of the century, although significant regional variability will exist.

The coupled effects of ocean warming and acidification are hard to predict but likely include: ocean deoxygenation, sea-level rise, a slowdown of ocean circulation and changes in the structure of marine ecosystems and ocean primary production.

An increase in the melting of ice sheets, particularly Greenland, an increase in iceberg calving, and a rise in sea level as well as a significant increase in iceberg numbers in the ocean since the 1990s.

An acceleration of Arctic warming and ice loss, combined with more variable, and extreme, mid-latitude weather. There is likely to be further major loss, and possibly the essential removal in some years, of summer Arctic sea ice in the next few decades. In the Antarctic the extent of the sea ice has been growing at a rate of $\sim 1.3\%$ per decade, although there is strong inter-annual variability.

The oceans around Antarctica are changing rapidly, with average rates of warming and freshening that greatly exceed the global mean, but with complex regional structure to these changes. This is a problem as the Antarctic marine ecosystem is strongly dependent on the regional circulation and climate of the ocean, and is important because of its roles in the global carbon cycle, fisheries, and the conservation of many of the planet's iconic marine mammals, penguins and flying seabirds.

Increasing freshwater supply to the ocean, will lead to a decrease in overturning and in vertical mixing thus reducing nutrient supply, and hence productivity, in the surface ocean.

There has been an intensification and distinct change in El Niño events over the last 20 years, with a shift of the mean location of sea surface temperature anomalies towards the central Pacific.

There has been an increase in storm surges along Arctic coasts, leading to more frequent inundation of fragile coastal ecosystems.

In late March 2004 the only hurricane ever observed in the South Atlantic since satellite records began in 1970 (unofficially known as *Catarina*) formed off the southern coast of Brazil. As sea

surface temperatures continue to rise, the classical condition required for hurricanes will begin to occur in some years, and changes to atmospheric convection related to changes in land-based heating may well make such storms a less exceptional event in the future.

Expansion of zones experiencing oxygen deficiency, with important consequences for biogeochemical cycling and the role of micro-organisms - a decrease of $3\text{-}12 \text{ mmol kg}^{-1}$ in oxygen concentration is forecast by 2100 due to climate change, with 18–50% of this decline due to ocean warming reducing oxygen solubility.

Low oxygen conditions also activate the production of nitrous oxide as a result of the complex set of metabolic pathways in the nitrogen cycle. Nitrous oxide is a potent greenhouse gas (approximately 310 times more powerful than CO_2) whose flux from the ocean to the atmosphere is increasing. Any expansion of low oxygen regions clearly has the potential to intensify this flux.

Reduced oxygen in sea water as higher temperatures reduce solubility, resulting in reduced penetration of oxygen into deeper water due to enhanced stratification in warmer conditions.

Due to increased stratification of the ocean, the global Meridional Circulation is likely to decline over the next century, although there is not a consensus as to the rate of decline.

Negative feedback on the ocean carbon sink, due to higher sea surface temperatures which reduce carbon dioxide uptake from the atmosphere. A higher global sea surface temperature and land surface temperature in part enhance the rate of increase in atmospheric CO_2 .

Currently 2.5 Gt of frozen methane hydrate are stored in the sea floor at water depths of 200 – 2000 m. Increasing water temperature may destabilize the methane hydrates, however, direct observations of methane flares at the sea floor suggest that these do not result in significant increases in flux to the atmosphere. There has, however, been an as yet unexplained increase in surface methane concentrations.

Uncertainty about the future of most large-scale ocean-atmosphere teleconnections under greenhouse warming is ubiquitous.



Iconic polar species are increasingly at risk as ice cover substantially reduces as a result of warming.
© Paul Nicklen, SeaLegacy

CONSEQUENCES FOR COASTAL AND MARINE ECOSYSTEMS

In the Arctic changes are highly variable and site specific, but as the sea ice withdraws the availability of ice-associated zooplankton and other invertebrates will be affected which will have an impact on the Arctic food chain. Sub-Arctic species will expand north and compete with Arctic species, reductions in distribution and abundance amongst seals and walrus populations will happen, and pack ice breeding seals will experience reproductive failure.

Coastal areas have warmed 35% faster than in the open ocean since 1960 and are more susceptible to impacts directly from warming, sea-level rise, changes in storms and increased land runoff than any other ocean realm. Changes have now occurred in rocky shore species ranges, distribution, abundance and phenology, leading to promotion of nuisance and fouling species, reduced diversity of native species, and eventual changes in ecosystem functioning.

Ocean warming has caused significant changes in seaweed distribution, especially at Arctic and temperate latitudes. Gradual warming, marine heatwaves and over-grazing by range-shifting herbivores have forced and augmented regime-shifts in at least seven regions across four continents. In places, highly complex productive seaweed forests have been replaced by structurally simple coralline crusts, filamentous turfs or small fleshy seaweeds.

Low latitude saltmarsh distributions will decline due to expansion of mangrove forest, while high latitude marshes will expand onto mud flats.

Within saltmarshes, because individual species respond differently, changes to future community composition is uncertain. Increased plant production is likely, which will generally improve ecosystem services but other aspects are highly uncertain such as carbon sequestration capacity, which may increase, and the likely increase in methane emissions, thus affecting climate-motivated restoration activities.

Persistent, structurally complex seagrass species do not recover quickly from major mortality incidents, as clonal propagation is slow and recruitment from sexual reproduction is limited. Thus, a global phase shift to more ephemeral, opportunistic seagrass species, macroalgae or bare sediment is likely, consequently reducing future seagrass ecosystem services.

Tidal freshwater forest area declines due to salinity intrusion and geomorphic constraints.

The direct effects of the projected temperature increase driving ocean warming are likely to be mostly beneficial to mangroves, with a shift poleward and increasing mangrove productivity and biodiversity particularly at higher latitudes. There will be loss or narrowing to mangrove habitats, and species composition changes, due to sea-level rise, leading to fragmentation.

There will be a reduction in mangrove diversity, photosynthesis and growth and impacts on associated fauna with low adaptive capacity with reduced rainfall and humidity.

Where the current rate of sea-level rise exceeds the soil surface elevation gain, mangroves with low tidal range and low sediment supply could be submerged as early as 2070, such as in the Gulf of Thailand, the south-east coast of Sumatra, the north coasts of Java and Papua New Guinea and the Solomon Islands.

The rate of warming in coral reef areas has increased from ~0.04°C/decade over the past century to 0.2°C/decade over recent decades (1985-2012). Across this period, reefs were exposed to prolonged high temperatures that caused bleaching, approximately once every six years. However, within the last three decades, as the planet has warmed the frequency of bleaching stress has increased three-fold.

The latest climate models predict that ocean warming will cause annual coral bleaching for almost all reefs by 2050. They also predict that disease is as likely to be a future cause of coral mortality as coral bleaching. Unabated temperature increases will produce serious consequences for coral reef ecosystems and dependent communities. The proportion of reefs in which ocean chemistry will allow coral reefs to grow has decreased from 98% (ca. 1780) to 38% (ca. 2006) due to ocean acidification and this continues to drop.

The impacts of climate change on deep sea faunal communities are not fully known. It is hypothesized that long term changes in surface productivity, as a result of a warming ocean, will lead to fundamental changes in the deep sea community as they are reliant on this flux of material reaching the sea floor.



Ocean warming changes are happening on many familiar rocky shore ecosystems around the world.
© John M Baxter

CONSEQUENCES FOR **COASTAL AND MARINE SPECIES**

Increased role of microbial species in ocean food webs, removing food available for species higher up the food chain, and with a consequential important role in overall responses to climate change, including potential decreased efficiency of the ocean's carbon-storage capacity.

Poleward movement of:

- plankton - during the last 50 years there has been a northerly movement of some warmer water plankton by 10° latitude in the north-east Atlantic and a similar retreat of colder water plankton northwards (a mean poleward movement of between 200–250 km per decade).
- deeper water movement of jellyfish, with geographical (spatial) adjustment to species' optimum ecological niche/thermal preference. Increases in cooler climes may have a positive feedback on warming whilst elsewhere may provide opportunities for Harmful Algal Blooms or invasive species. The tropics are affected by defaunation of jellyfish species, unless thermal tolerance evolves.
- seaweeds - cool-water species have been contracting and warm-water species extending their range edges, leading to poleward range expansion of warm-water seaweeds and other species including sub-tropical and tropical herbivores. Recent range-changes have been from 26 km to 1,250 km.
- fishes shifting 10s to 100s of km per decade to follow habitat with suitable temperature, resulting in species invasions and local extinctions, shifts in community structure, with increasing dominance of warmer-water species, disturbance of trophic interactions, shift in fishing grounds of target species and may increase bycatch when overlaps of distributions of target and non-target species increases, and reduced effectiveness of conservation measures such as MPAs. Where some species move to deeper water this will reduce catchability by surface fisheries, and increase catchability by deep water fisheries.
- seabirds, especially in non-breeding seasons, and large declines in populations of many seabird species in all regions of the planet, with notable declines in populations of seabirds that specialize in foraging at the ice edge. Poleward shifts of breeding distributions, but for most seabird species with greater losses at the low latitude edge than gained at the high latitude edge. Extinction of some breeding colonies. Increased breeding failures of seabirds, especially of burrow-nesting species (due to burrow flooding), and increased winter mortality of cormorants. Increased wind speeds may reduce breeding success of terns, increase costs of flight for many seabirds that use

flapping flight with some negative impact on population size, but reduce costs of flight for gliding seabirds that may allow those species to expand their distributions.

- turtles, as breeding beaches become unfavourable and conditions cause shifts in breeding ranges and changes in post-hatchling migrations and distribution linked to changes in ocean currents and temperature and the availability and abundance of food e.g. jellyfish.
- more mobile marine mammals and other more regional changes in feeding and breeding grounds result in penetration of species into new areas, and potentially into new conflicts with human activities such as fishing. Changes in distribution also bring previously isolated populations into contact with the potential for enhanced disease transmission.

Loss of breeding grounds through direct physical impacts of storms and sea-level rise on species such as turtles and indirect losses as species forced to move to retain optimal thermal conditions for survival such as fish.

Impacts on breeding success on many species of birds and marine mammals through a variety of effects such as storminess, sea-level rise, increased rainfall, habitat availability and food availability and distribution. For some taxa, such as highly migratory whales, this can result in a mismatch in occurrence of productivity peaks and their arrival, which may negatively impact their reproduction.

Changes in foraging strategy as a result of changes in prey distribution and abundance. In species such as turtles this will influence fitness and therefore reproductive capacity.

Seasonality shifts in plankton leading to potential mismatch between plankton, fish and other marine wildlife. Similarly, in fish, altered spawning, migration and dispersal patterns may lead to mismatch in prey and predator occurrences and thus trophic interactions.

Sex ratio shifts in turtles as warmer temperatures alter the sex ratios of offspring.

Whole marine ecosystem shifts as species respond to shifting boundaries in ocean temperature and decoupling of community structure.

Reduction in the physical size of species such as plankton in response to food and nutrient limitations. Similarly, in fish, leading to reduced fecundity, altered trophic interactions and decreased fisheries yield.

CONCLUSIONS AND RECOMMENDATIONS

Marked biological manifestations of the impacts from ocean warming and other stressors in the ocean have taken the form of changes in biogeographical, phenological, biodiversity, community size changes, and species abundance changes as well as whole ecological regime shifts. Such regime shifts often interfere, or are predicted to interfere, with the benefits we depend on from the ocean. More precise interactions, such as the relative importance of direct physiological effects and indirect effects through other abiotic pathways and species interactions remain largely unknown. Multiple stressors (warming, acidification and oxygen reductions) interact cumulatively, and exposure to one stressor (such as warming) can affect the tolerance of a species to another stressor. There is a worrying lack of detailed experiments of thermal limits on survival, reproduction and growth of pathogenic organisms and their carriers that are being favoured by ocean warming. The problem is that we know ocean warming is driving change in the ocean – this is well documented. The speed of change in the ocean, such as the poleward range shifts in marine systems, is happening between 1.5 and 5 times faster than on land. Such range shifts are potentially irreversible with great impacts on ecosystems – but the consequences of these changes, decades down the line, are far less clear.



Whilst rising CO₂ levels and increasing warming can occasionally have positive effects, the overwhelming evidence and predictions shown in this report are for a cocktail of negative effects, which we are only just starting to understand, but about which we know enough to be very concerned. The warning signs are clear to see. These range from the persistence of jellyfish blooms and their increasing frequency of occurrence, year after year, through to the current prevalence of bleaching of coral reefs around the world, but also the increasing confidence of predictions that all coral reefs will be so affected by 2050, unless we change our ways, and quickly. Ocean warming and climate change are ultimately contributing to global homogenization of biodiversity, as vulnerable species become extinct and “non-native” species from different biogeographic regions spread, overlap, and become established across the world’s ocean. Predictions are for a decrease of biodiversity in warm-water regions, but as much as a 300% increase in polar regions. Biomass losses in deep sea areas in the north-east Atlantic for example may reach 40% and for biodiversity hotspots, such as seamounts, even 80%.

Overall, ocean primary production is expected to continue to change, however, the global patterns of these changes are difficult to project, but regional evidence suggests that carbon cycling and storage will be fundamentally altered in some specific

coastal situations, e.g. saltmarshes and mangroves. Existing projections suggest an increase in productivity in high latitude systems like the Arctic and Southern Ocean and a decrease in productivity in the tropics and mid-latitudes. Ocean warming is causing the expansion of zones experiencing oxygen deficiency, with important consequences for biogeochemical cycling and an increased role for the microbial world, and especially bacteria, archaea and viruses, at the expense of eukaryotes which are generally more sensitive to reduced oxygen levels. This will likely make the already dominant role of microbes in the functioning of the marine ecosystems even more pronounced in a scenario of a warming ocean. Declines in the amount of oxygen will make the demands of water-breathing organisms, such as fishes and invertebrates, increasingly difficult to meet under global warming scenarios, and will stimulate the production of nitrous oxide which is a potent greenhouse gas approximately 310 times more powerful than CO₂. It also has one of the longest atmosphere lifetimes of the greenhouse gases, lasting for up to 150 years. There is evidence that the flux of nitrous oxide from the ocean to the atmosphere is increasing.

All these changes and predictions for the future matter from moral, social, ecological and economic perspectives. The value of our relationship with the ocean sometimes seems difficult to cost, but is the ultimate relationship that enables life to exist on Earth. Estimates of worth vary but range from the services value of seaweeds at US\$ 30,000 ha⁻¹yr⁻¹ through to US\$ 5-10 trillion yr⁻¹ for the services provided by rocky shores. In terms of economic losses, where this is quantified, it runs from millions to trillions of dollars a year. For example, the current tourism costs associated with the loss of corals from warming and acidification have been estimated as high as US\$ 12 billion per year, with annual estimated costs from the loss of reef ecosystem services rising to US\$ 1 trillion by 2100, directly and indirectly affecting many of the benefits we have so far taken for granted.

Alongside the high economic impacts from recent extreme storm event impacts, other *single* event economic losses related to ocean warming impacts already run from the tens to hundreds of million dollars. A major outbreak of Paralytic Shellfish Poisoning in 2012 and 2015 along 200km of coastline of Tasmania triggered a global product recall and loss to the local economy of AU\$ 23million. A single coral bleaching event in South-east Asia suggested an economic loss of services to dive tourists in the order of US\$ 49-74 million for the six-month period during and following bleaching, whilst more recently the 2016 unusually strong El Niño pattern triggered the largest ever reported algal blooms and aquaculture fish kills in Chile causing losses of US\$ 800million.

There are also early signs that human health is already being impacted by enhanced survival and spread of tropical diseases with increasing temperatures, particularly pathogenic species of bacteria in the genus *Vibrio* (one of which causes cholera) and Harmful Algal Bloom species that cause a variety of neurological illnesses (such as Ciguatera). From a purely ocean perspective, 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 for infections of wounds exposed during recreational (e.g. bathing) activities.



Ocean warming is changing the distribution and occurrence of prey species, affecting the survival and reproduction of seabirds further up the food chain. © John M Baxter

There is already a fundamental concern for the economic effects and consequences ocean warming will have on global fisheries and aquaculture. Together they play a vital but often poorly acknowledged role in global food security, providing 4.3 billion people with ~15% of their average per capita intake of animal protein. By 2050, an additional 75 million tonnes of fish will be needed to help feed more than 9 billion people, but warming of the world's ocean could disrupt these important initiatives with projected decreases in fisheries production in some countries and increases in others. Similarly, the prime locations for mariculture are expected to be altered by ocean warming, resulting in changes in yield patterns among countries.

The costs of this for countries could be high as we know key species are vulnerable to ocean warming impacts, such as tuna, and they account for 8% of the US\$ 129 billion value of internationally traded fishery products. Rapid population growth, fish exports and poor fisheries management also affect availability of fish in many developing countries. These drivers often create a gap between how much fish is needed for good nutrition and local fish harvests. The main effects of ocean warming will be to alter (increase or decrease) the gap, with the greatest changes expected in tropical and subtropical countries. Closing this gap will require the expansion of environmentally sustainable mariculture (and freshwater aquaculture), or even re-allocating some of the catch of large and small pelagic fish taken by industrial fleets to small-scale fishers, and/or arranging for industrial fleets to land more of their catch in local ports. From the community perspective, the greatest human losses will likely fall upon those people who rely upon the ocean for day-to-day subsistence – typically in these poorest coastal nations.

With issues of such importance at stake, we need to vastly improve the science and knowledge available as we move forward into an increasingly compromised ocean world. This is a common conclusion of many of the scientists involved with this

report. As the global community through action, or sadly and probably inaction, increasingly commits itself to a high carbon future, knowledge of ocean warming and biological interactions will become invaluable in working out how we cope with the impacts and changes that become evident and prevalent, and impact and alter our way of life.

With the realization that ocean ecosystems are vulnerable to human threats such as overfishing, climate change, eutrophication, habitat destruction, pollution and species introductions there is an increasing imperative to observe ocean biology in a more integrated fashion in order to provide the long-term baselines needed for management actions and research. Historical datasets will need to be maintained and where possible expanded into new areas of the world's ocean where there are little or no sustained observations, including the open and the deep ocean and seabed Area. Many new international research initiatives such as Global Earth Observation System of Systems (GEOSS) and Group on Earth Observations Biodiversity Observation Network (GEOBON) are being set up to address these issues and monitor these changes. Future biological monitoring of these open-ocean ecosystems, through an integrated and sustained observational approach, will be essential to understand the continuing impacts of ocean warming and other stressors on oceanic systems.

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 repeated problem in this respect is being able to resolve sufficient detail to make models more applicable at the regional scale. Inadequacies in such systems already pose great challenges, for example, for estimating effects of climate change on Antarctic marine ecosystems and for projecting future change. This is a widespread problem as there is a failure of the range of existing climate models to reach adequate consensus on future change in processes of air-sea interaction. Such uncertainty is an abiding feature of predictions of the future, and is why the improvement of climate model representation of the feedbacks in the climate system between the ocean and atmosphere is therefore a priority for more successful prediction.

More comprehensive observations may allow us through international collaboration to mitigate and adaptively manage some of their more detrimental impacts. More studies are needed in this respect. The impacts of ocean warming and other stressors will drive a new paradigm in ecological restoration towards active management and restoration. This will increasingly drive approaches from just 'protect' towards more active intervention to recover or restore, with a focus on sustaining resistance or increasing resilience in natural systems and their services, and increasing adaptive capacity. Increasing human interventions on the ecologically-sensitive design of artificial structures may become increasingly important as natural habitats are "squeezed" by sea-level rise. The viability of reducing impacts of warming by managing additional local stressors such as eutrophication, pollution and commercial and overfishing needs more investigation, but is clearly already a part of the strategy to sustain ocean benefits moving forwards. The rationale being that the more ecosystems are impacted, the less they will be resilient to gradual and on-set change. Alongside this are simple needs such as good resolution maps of the distribution worldwide of ecosystems, habitats and species to put all such observations, plans, and actions into operation. It is perhaps surprising to many that we have yet to successfully complete even this most basic of steps. None of this, however, should detract from the urgency or need to reduce global CO₂ emissions which lies centrally at the heart of what the international community must achieve.

Key recommendations based on the evidence presented in this report are:

- 1. Recognition of impact severity.** There is a need for a much better recognition of the unequivocal scientific evidence of impacts on key marine and coastal organisms, ecosystems, and services that are already detectable, with predictions of high to very high risk of impact to be expected by 2100, even under the low emissions scenario (RCP2.6). These impacts will occur across all latitudes, making this a global concern beyond the usual North/South divide.
- 2. Concerted joined-up global policy action for ocean protection.** There is a need to join up action across global conventions with respect to climate change and environmental protection. Action must be taken in light of these findings on ocean warming to accelerate and dramatically scale-up area-based, effective, and full protection of marine ecosystems, and to better implement sustainability measures across the entire ocean. Similarly, species assessment and advice, such as IUCN's Red List, must ensure that ocean warming impacts are fully integrated into assessments, findings and actions.
- 3. Ensure comprehensive protection and management.** There is a need to ensure that we rapidly fill gaps in protective regimes, such as protecting the High Seas and the seabed Area – the ocean and sea floor beyond the jurisdiction of any single country – under a new Implementing Agreement under the Law of the Sea, as well as expanding global conventions to be truly 'global' – such as expanding the World Heritage Convention to take action across the High Seas and seabed Area.
- 4. Updated risk assessments.** A re-evaluation is needed on the risks that impacts from ocean warming and other stressors pose to humanity, to the viability of the very species and ecosystems involved, and to the provisioning of goods and services we derive from them. As documented in this report vast change is underway and will be locked in for many decades – there is an urgency to determine what risk this holds for now and for the future so we can mitigate, plan and adapt accordingly.
- 5. Updated economic analysis.** New and updated economic analysis is needed on the scale, nature and effects of impacts from ocean warming and other stressors. This is both in terms of the severity of impacts that are being felt, and are being predicted, but also on how such impacts may affect regional economies as high worth services are affected (e.g. coral reefs, kelp forests, mangroves, seagrass, etc.) and the distribution of valued assets diminish or increase (e.g. economically valuable species such as tuna, krill, etc.).
- 6. Closing gaps in fundamental science and capability needs.** There is a need to rapidly assess science, observing and modelling capacity and their needs in light of the widespread changes happening from ocean warming and other stressors. This report has repeatedly highlighted fundamental and massive gaps in our understanding that already compromise even our basic ability to understand and predict with any confidence what changes already underway may mean to our wellbeing. Whilst some of the ocean warming-related science and capability needs right now may not sit easily against other priorities for governments, as the planet changes, we may regret the day we didn't take action early enough to obtain the essential data we will need in the future.
- 7. Achieving rapid and substantial cuts in greenhouse gases.** Greenhouse gas mitigation at the global scale is the overarching solution that will determine the future of all other solutions (protect, repair, adapt). As a result, rapid and substantial reductions of greenhouse gas emissions are required. Through the implementation of the Paris Agreement under the UNFCCC Parties should now put forward rapid and substantial reductions of greenhouse gases, and consider ocean impacts in the so-called "nationally determined contributions" (NDCs) outlining national best efforts towards a sustainable low carbon future. The concerns among the scientific community is that as atmospheric CO₂ increases, the options for the ocean (i.e. mitigate, protect, repair, adapt) become fewer and less effective. Time is not on our side and delays in taking action on greenhouse gas reductions close off future prospects that could otherwise help us cope with changes and impacts.

To conclude the evidence in this report shows a complex story of change in the ocean, change that is underway, is often already locked in for future decades, and is beginning to impact on all our lives whether it is obvious or not. This is no longer a single story of challenges to coral reefs, but stories of changes across species and at ecosystem scales, and across geographies and the entire world. It is pervasive change, driven by ocean warming and other stressors that are already operating across scales and in ways we only barely understand. It is critical that we sit up and recognize these issues and act, or we will be poorly prepared, if at all, for an uncertain changing future.

The ocean lies at the heart of the climate system and should thus be at the heart of climate discussions. We have perhaps become distracted by our daily issues on land, and have been ignoring the impact climate has been having on by far and away the majority of the living space on the planet – the ocean. A relevant architecture must now be developed to put the ocean at the heart of climate discussions. The scale and nature of impacts we are seeing are already running way ahead of what we know, and importantly, what we are apparently capable of acting on. Adaptation action is already needed to evolve short- and long-term management strategies for the ocean. This most likely will require increased levels of support and investment. Finally, and most critical, is the need to address atmospheric CO₂ and achieve rapid and significant reductions in what we emit. To do otherwise will be to 'sleepwalk ourselves into a nightmare', where no level of conservation action in the future will be enough to override the impacts in order to save many of the ocean's species, ecosystems and benefits we currently rely on and take for granted.

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Cover photos:

Clockwise from top: King penguins (*Aptenodytes patagonicus*) on Middle Beach (Brothers Point in distance), Macquarie Island, Southern Ocean. (© Robbie Kilpatrick/Australian Antarctic Division, November 2015, Image RS31770, Image Antarctica); a colony of black coral with small crabs moving amongst the branches (image courtesy of Department of BIS, UK); seagrass (*Zostera marina*) © SNH/Ben James; Hurricane Catarina on March 26th, 2004, off SE Brazil. Image courtesy of NASA.

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