1. The Central Role of Oceans in Planetary Survival and in Human Economic and Social Well-being: Choices for Decision-makers

The central tenet of this proposed Strategic Action Roadmap is that it is imperative that climate change impacts on oceans and coastal and SIDS populations be considered both within and outside the UNFCCC, both for our planetary survival and for human well-being.

Findings/Recommendation on the Central Role of Oceans in Climate

1.0 Recognize the central role of oceans in climate and the need to implement stringent reductions in greenhouse gas emissions to avoid disastrous consequences on coastal and island communities, marine ecosystems, and ocean chemistry.

Main Findings Regarding the Role of Oceans:

- The ocean and coasts provide critical ecosystem services, including biogeochemical and physical processes, making the ocean critical for planetary survival. Oceans and seas cycle over 28% of carbon dioxide emitted to the atmosphere from burning fossil fuels since 1750, produce 50% of the oxygen on Earth, store 50% of all naturally sequestered carbon, and absorbed 30% of the heat added to the global system since the 1970s.[20]

- Fisheries and aquaculture provide food for over 4 billion people and at least 50% of animal protein to 400 million people in the poorest countries. Fisheries and aquaculture alone support the livelihoods of 10-12% of the global population, including many vulnerable fishing and fish-farming communities.[21] Disruption of ocean processes could impact food security as well as livelihoods, such as those that are supported by coastal tourism.

- Oceans, seas, and coastal areas are experiencing an increased frequency and intensity of climate extremes, including stronger hurricanes, typhoons, and cyclones. Changes in ocean chemistry and temperature are causing ocean acidification, ocean deoxygenation, sea level rise, and fluctuations in ocean circulation and salinity. [22]

- As the concentration of greenhouse gasses increase, options to overcome or limit the risks on ocean ecosystems and on coastal and island populations will become fewer and less effective.

- Further scientific work is needed to understand the extent of climate change impacts between mean global temperature increases of 1.5 and 2.0ºC and thus help in decision-making.

- While emphasis must be placed on reducing CO_2 emissions in the future we know that impacts are already happening, so we must also consider adaptation strategies and corresponding financing measures for island and coastal populations.

- Two thirds of the ocean is within areas beyond national jurisdiction (ABNJ), and these areas play a key role in the processes discussed in this section. Therefore, successful policies must necessarily consider the preservation and sustainable management of ABNJ.

The Role of the Ocean in Planetary Survival and in Human Well-being

The ocean is the primary regulator of Earth's climate and weather, produces 50% of the oxygen in the atmosphere and fixes 50% of global primary production. The ocean is also an important recycler of waste and an enormous store of carbon, substantially greater than on land or in the atmosphere. It plays a key role in the global water and carbon cycles. It especially influences the climate through the regulation of the amount of CO_2 and heat in the atmosphere.[23] Currently, the ocean has taken up over 93% of the heat generated by warming of the Earth system over recent decades and all the water from melting ice.[24] Coastal ecosystems, such as man-groves, salt marshes, seagrass, and kelp beds take up, lay down, and store great amounts of carbon while also protecting shorelines from storms. Many of these planetary roles are literally priceless and are performed by a series of biogeochemical processes regulated by marine organisms as well as the important physical processes of ocean mixing, tides, currents, and air–sea exchange.

Socio-Economic Effects of Climate Change on Oceans

The ocean provides enormous and diverse resources. It covers 70% of the planet, contributes ~96% of the living space on Earth, providing diverse habitats for 25% of eukaryotic organisms.[25] The ocean is of great economic, social, and cultural significance to all countries, including 183 coastal countries and island states. The substantial alteration in ocean physics and basic chemistry, and subsequent ocean warming, acidification, deoxygenation, storm frequency and intensity, and sea level rise—all emanating from climate change—are likely to have wide implications for life in the ocean with far-reaching socio-economic consequences.[26] Warming-induced deoxygenation will also lead to a significant reduction in the size of fishes and overall production.[27] Even countries or regions far from the coast will still experience the ocean's influence. For example, most of the rain that falls on land originates in tropical oceans.

Ocean and coastal areas are estimated to contribute US$3-6 trillion to the global economy.[28] For example, 90% of all goods (by volume) are transported via marine shipping, reinforcing the importance of the ocean and coasts to the global economy. Tropical coral reef ecosystems alone provide food, income, and coastal protection for around 500 million people throughout tropical coastal areas.[29] Healthy marine ecosystems also attract income from recreation, leisure and tourism, provide important aesthetic and spiritual experience and inspiration for culture, art and design as well as education and research. Ocean ecosystems are increasingly being explored for pharmaceutical and genetic products, as well as rare and precious metals.[30] Losing coral reefs could cost the tourism industry USD $1.9-12 billion per year.[31]

Fisheries and aquaculture provide essential proteins and nutrients to over 4 billion around the global, an especially important source in countries with low animal protein intake and livelihoods for hundreds of millions of people.[32] Aquaculture of both finfish and shellfish is increasingly important to world food security and the provision of both captured and cultured seafood results from a combination of primary and secondary production, biogeochemical cycling, and food web dynamics. The changing physics and chemistry of the ocean will disrupt these processes and create impacts throughout the supply chain, increasing risk for food and livelihood insecurity.[33] An overall reduction in marine diversity and abundances is expected to occur in a high CO_2 ocean;[34] nevertheless, not all species will be negatively affected. Some marine species that may be favoured also provide societal benefits, e.g. sea-grasses,[35] but some “nuisance” species, such as jellyfish, seem generally tolerant of ocean acidification and could increase in occurrence.[36]

World fisheries already face multiple challenges but some are now further subject to the combined global scale stressors of ocean acidification, warming, and deoxygenation.[37] As these increase with increased CO_2 emissions, so will the risk to fisheries and aqua-culture. For example, increasing water temperatures as well as deoxygenation will likely result in changes in distributions of marine species;[38] with most marine species ranges being driven toward the higher latitudes and habitat compression; leaving serious deficits in tropical countries where marine fish availability is predicted to decrease by as much as 40%.[39] This will have cascading effects on economic growth and jobs created through fisheries. For example, one model has projected a 21% drop in annual landed value, a 50% decline in fisheries-related jobs and an annual loss of US$311 million in 14 West African economies.[40]

Fisheries are not the only valuable resources in the oceans. Raw materials such as aggregates, oil, gas, minerals and water are extracted from the ocean and increasingly we harvest energy from ocean tides, waves and winds. Ocean ecosystems are increasingly being explored for pharmaceutical and genetic products. For example, patent claims on the genetic material of marine organisms grow an average of 12% per year.[41]

However, coastal and island populations are some of the most vulnerable populations to climate change impacts.[42] Oceans, seas, and coastal areas experience an increased frequency and intensity of climate extremes, including stronger hurricanes, typhoons, and cyclones. They are also subject to ocean warming, acidification and deoxygenation, sea level rise, and fluctuations in ocean circulation and salinity. Due to warming conditions, outbreaks of some water-borne diseases and infections, such as cholera, *Vibrio* and Ciguatera, may become more common as species' ranges shift.[43] By 2050, it is estimated that 50-200 million people worldwide will be displaced due to the negative impacts of climate change, threatening food security, livelihoods, and peace.[44]

The effects of climate change are numerous. The effects vary globally and are all related. Whilst recognizing there are many important aspects, here we highlight four central issues: sea level rise and Pacific islands and coastal cities, changes to fisheries and aquaculture and attendant threats to global food security, ocean acidification, and ocean deoxygenation. These issues are summarized below and detailed in Boxes 1.1-1.5.

Sea Level Rise

Although the Pacific island and other small island developing states (SIDS) contributed little to climate change, sea level rise poses a threat to their survival and security—it has the potential to change coastlines, displace millions, and inundate coastal areas with sea water, ruining water supplies and crops (see Box 1.1). For 136 large coastal cities, the threat of sea level rise could necessitate the need to upgrade coastal defences, and could lead to retreat or abandonment of the city (see Box 1.2).

Fisheries and Aquaculture and Food Security

Climate change will have significant impacts on the four dimensions of food security through fisheries and aquaculture: varying the availability of aquatic foods, varying the stability of the fish supply, altering livelihoods due to altered access to aquatic foods and direct risks to safety at sea and fisheries and aquaculture infrastructure, and affecting the use of aquatic products and nutritional benefits from those products (see Box 1.3).

Ocean Acidification

While the socio-economic impacts of ocean acidification will vary locally, fisheries, coral reefs, and molluscs will be impacted, as well as sensitive areas such as the Arctic. The impact of ocean acidification on entire food chains and complex ecosystems remains poorly understood. Similarly, substantial additional research is required to understand how ocean acidification will compound other marine stressors, such as over fishing, pollution, rising temperatures and stratification. Action to understand, monitor, and respond to ocean acidification needs to be prioritized to reduce the effects on the economy and food security (see Box 1.4).

Ocean Deoxygenation

There are several anthropogenic factors which are contributing to increasing ocean deoxygenation. Although the activity most commonly associated with this phenomenon is eutrophication due to manufactured fertilizers, ocean warming has a significant impact on the solubility of oxygen in the ocean. The impacts of deoxygenation on aquatic ecosystems is dramatic, and has widespread consequences for several nutrient cycles. Further research is urgently needed to understand and monitor the causes, impacts, and potential solutions associated with deoxygenation (see Box 1.5).

Box 1.1 Sea Level Rise and the Pacific Islands Region: Threats to Survival and National Security

For the Pacific Islands region, anthropogenic climate change and its impacts are a matter of survival and national security. The Pacific Islands region is vast—containing about 10% of the global ocean—and has more than 33,000 islands. The Pacific Islands is home to a diverse range of peoples whose lifestyles have adapted to their environment over millennia. The ocean regulates weather and climate but this has been drastically affected by climate change. Sea level rise in particular represents an existential risk. Within the Pacific islands are four of the six lowest countries on Earth –-the atoll countries of Tuvalu, Kiribati, Republic of the Marshall Islands, and Tokelau. On average, the highest point in each country is between 3 to 4 metres. Additionally, some of the low lying outer islands of many Pacific Island countries are equally vulnerable. The IPCC predicts a sea level rise of up to one metre by 2100 under RCP 8.5, and by 2300 the projection is for a rise of 3 metres. If a business as usual scenario is allowed to continue, what is the world saying to these low-lying island countries?

This region contributes less than 0.03% of the world's total green-house gas emissions, yet it is amongst the most vulnerable to its impacts and the first to feel the impacts of climate change—the Pacific islands are on the frontline. The Pacific way of life is changing; sea level rise has ruined homes, gardens, water sources, buildings and infrastructure across the island region. Food security is threatened by salt water inundation, over-topping by waves, and by droughts. As each cyclone season app-roaches, the threat of extreme weather events causes widespread angst and trepidation.

Recent research has demonstrated that sea level rise is neither simple nor predictable, nor is the rise uniform across the region. Some islands actually appear to be increasing in horizontal size, due to the complicated processes of accretion and siltation, while others are rising or falling due to tectonic forces unrelated to sea level rise. Increasing in size doesn't necessarily mean increasing in height. The image of islands disappearing is thus overly simplistic, and does not reflect the overall range of climate change impacts. Long before islands disappear under the waves, how-ever, they will be uninhabitable, due to saltwater contamination of scarce groundwater supplies which provide the main potable water for atoll communities, which will make it impossible to grow food crops.

Apart from low-lying atolls, even the high volcanic islands of the Pacific will be impacted by sea level rise as most populations live along narrow vulnerable coastal zones sur-rounding steep interiors. Faced with inexorable rising waters, many Pacific islanders have resorted to building sea walls to keep out the hungry tides, but this is rarely successful, as the sand and sediment is scoured away by wave action. President Anote Tong of Kiribati has promoted the concept of an early 'migration with dignity,' and his government has purchased land in Fiji to resettle climate refugees.

The small-islands chapter[45] of the IPCC's fifth assessment report in 2014 found that rising seas present "severe sea flood and erosion risks for low-lying coastal areas and atoll islands." It highlighted one projection that a 50-centimetre rise in sea level could displace 1.2 million people from low-lying islands in the Caribbean Sea and the Indian and Pacific oceans; that number almost doubles if the sea level rises by 2 metres.

As islanders watch their homes being battered by waves, possessions washed out to sea, suffer the health effects of diminishing potable water, or witness their root crops dying from salt water inundation, we often hear: "we didn't cause this problem but we are suffering from the effects–we are being punished for what others have done." While much is un-certain, it is highly unlikely that the children growing up in the atolls of the Pacific islands will grow old there.

Box 1.2 Sea Level Rise and Coastal Cities

The risk of sea level rise for coastal cities is immediate and long term. Climate mitigation can stabilize the rate of sea level rise, which makes adaptation more feasible. However, even if the global temperature is stabilized, sea level will continue to rise for many centuries as the deep ocean slowly warms and the large ice sheets reach a new equilibrium: this has been termed the commitment to sea level rise. For coastal areas and cities, mitigation and adaptation must be considered together as sea level rise necessitates an adaptation response.[46]

Adaptation limits of coastal cities are not easily predictable. The rise in mean sea level raises the likelihood of catastrophic floods and extreme events which damage and trigger a possible response: abandonment, defense upgrading or another response entirely. Limits to adaptation can be grouped into physical and engineering limits, economic and financial limits, and socio-political limits.[47]

In 2005, there were 136 large coastal cities with a population exceeding one million people and a collective population of 400 million people. All these coastal cities are threatened by flooding from the sea and these risks are increasing due to growing exposure (people and assets), rising sea levels due to climate change, and in some cities, significant coastal subsidence due to human agency (drainage and groundwater withdrawals from susceptible soils). Flood risks grow with sea-level rise as it raises the likelihood of extreme sea levels.[48]

In those 136 large coastal cities over the next 50 years, damages could rise from US$6 billion/year to US$52 billion/year solely due to increase in population, property and its value. With additional climate change and subsidence, global losses could approach US$1 trillion or more per year if flood defenses are not upgraded. Even if protection levels are maintained (i.e. flood probability is kept the same thanks to upgraded defenses), annual losses will grow as individual floods become more severe due to flood depths increasing with relative sea level rise.[49]

To maintain present levels of flood risk (average losses per year), protection will need to be upgraded to reduce flood probabilities below present values. Even with upgraded protection, the magnitude of losses when flood events do occur would increase for the reasons stated above. Beyond a 50 year time frame, sea levels will continue to rise and protection will have to be progressively upgraded into the future with uncertain consequences. If protection limits are reached, some cities may have to be abandoned. Other cities would have to retreat by reconfiguring the city to the new land-water interface.[50]

Few cities have been subject to studies that quantify the sea level rise threshold at which cities will be abandoned. One exception is London and the Thames estuary. Though a less extensive sea level rise is projected to 2100, for London and the Thames estuary, the key adaptation threshold is 5 meters of mean sea-level rise. For higher sea level rise, due to limits of sea walls and tidal barriers, the River Thames would need to be diverted or pumped to the sea.[51]

In the Netherlands, the Delta Programme considered sea level rise of 4 meters by 2200, and concluded that continuation of dyke-raising and beach and dune nourishment with sand could still be effective.[52]

New York City has also considered risks of sea level rise in its adaptation strategies. Sea level rise combined with storm surges is likely to give rise to greater flooding of low-lying neighborhoods and infrastructure, increased structural damage, and impaired city operations. The extent and location of changes is being mapped out, allowing the development of adaptation res-ponses and increasing the city’s resilience to sea level rise.[53]

London’s Thames Estuary 2100 (TE2100) plan, the Dutch Delta Programme and New York City have defined adaptive pathways into the future, which include a portfolio of adaptation measures which can be progressively and flexibility applied to manage flood and other risks as sea level rises, and promote urban resilience. This is a best practice proactive approach and could be applied widely to the coastal cities global as they identify adaptation and resilience approaches.

Box 1.3. Climate Change Impacts on Fisheries and Aquaculture and Peoples' Livelihoods: Growing Threats to Global Food Security

Over 800 million people depend, directly or indirectly, on fisheries and aquaculture for their livelihoods. Fish products are among the most widely-traded foods, with more than 37% by volume of world production traded internationally. In addition, fish provide essential nutrition for 4 billion people and at least 50% of animal protein and essential minerals to 400 million people in the poorest countries.[54] But climate change is bringing an ocean of change to the world's fisheries, which are already in crisis from over-fishing and poor management.

Dimensions and Scales of Likely Impacts on Fisheries and Aquaculture including Livelihoods of Fishing Communities

Climate variability and change are compounding threats to the sustain-ability of capture fisheries and aquaculture development. Impacts occur as a result of both gradual warming and associated physical changes as well as from frequency, intensity and location of extreme events, and take place in the context of other global socio-economic pressures on natural resources. Urgent adaptation measures are required in response to opportunities and threats to food and livelihood provision due to climatic variations.

Ecosystem Impacts

In a warmed world, aquatic eco-system productivity is likely to be reduced in most tropical and subtropical oceans, seas and lakes and increased in high latitudes. Increased temperatures will affect fish physiological processes resulting in both positive and negative effects on fisheries and aquaculture systems. Coral reef systems, housing one out of four marine species, will be at increased risk of coral bleaching.

Climate change is already affecting the seasonality of particular biological processes, radically altering marine and freshwater food webs, with unpredictable consequences for fish production. Increased risks of species invasions and spreading of vector-borne diseases provide additional concerns.

Differential warming between land and oceans and between polar and tropical regions may affect the intensity, frequency and seasonality of climate patterns (e.g. El Niño) and extreme events (e.g. floods, droughts, storms) affecting the stability of marine and fresh-water resources adapted to or affected by these. Rising sea levels displace brackish and fresh waters in river deltas, wiping out some aquaculture practices and destroying wetlands.

Sea level rise, glacier melting, ocean acidification and changes in precipitation, groundwater and river flows will significantly affect coral reefs, wetlands, rivers, lakes and estuaries, requiring adapting measures to exploit opportunities and minimize impacts on fisheries and aquaculture systems.

Impacts on Livelihoods

Changes in distribution, species composition, productivity, risks and habitats will require changes in fishing practices and aquaculture operations, as well as in the location of fish landing, farming and processing facilities. Extreme events will impact infrastructure, ranging from landing and farming sites to processing facilities and transport routes. They will also affect safety at sea and settlements, with communities living in low-lying areas at particular risk. Water stress and competition for water resources will affect aqua-culture operations and in-land fisheries production, and are likely to increase conflicts among water-dependent activities. Livelihood strategies will have to be modified for instance with changes in fishers migration patterns due to changes in timing of fishing activities.

Reduced livelihood options, especially in the coastal regions, inside and outside the fishery sector will force occupational changes and may increase social pressures. Livelihood diversification is an established means of risk transfer and reduction in the face of shocks, but reduced options for diversification will negatively affect livelihood outcomes. There are particular gender dimensions to impacts and vulnerabilities to these impacts, including competition for resource access, risk from extreme events and occupational change in areas such as markets, distribution and processing, in which women currently play a significant role.

Box 1.4. Ocean Acidification: The Other CO_2 Problem[55]

What Is It: Ocean acidification, sometimes called "the other CO_2 problem," describes a series of chemical changes caused when excess atmospheric CO_2 is absorbed by seawater.[56] Since the 1850s, mean surface seawater pH has decreased by 0.1 units, equivalent to a 26% increase in acidity. While ocean acidification events have occurred before, the ocean is currently acidifying faster than it has in the past 300 million years.[57]

The Science: As seawater pH decreases, carbonate ion (CO_3^{2-}) concentration decreases as well, making it harder to form minerals such as calcium carbonate ($CaCO_3$). Furthermore, if concentrations become low enough, it can cause these minerals to dissolve. Calcifying organisms such as corals, pteropods, molluscs, and some species of phytoplankton form their shells and skeletons out of calcium carbonate, and are there-fore particularly sensitive to changes in seawater carbonate chemistry.[58] Moreover, experimental, field and modelling studies have shown a wide variety of possible impacts, both positive and negative, on survival, reproduction, growth, abundance, behaviour, photosynthesis and other processes.[59]

Models project that ocean acidification will continue into the future under most emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC). Projections show a decline in global-mean surface pH of 0.41-0.43 units or a100-150% increase in acidity by 2100 based the business as usual scenario (RCP8.5).[60]

Impacts: While the impacts of ocean acidification on marine ecosystems are not fully under-stood, there will undoubtedly be significant social and economic impacts.

Coral reefs are marine biodiversity hotspots providing habitat for numerous species and fisheries, coastal protection, and are the basis of an important tourism industry in many countries. Coral reefs provide food, revenue and protection for almost 500 million people[61] and their annual value has been evaluated to be 30 billion US dollars.[62] Coral reefs and their associated services are among the most sensitive ecosystems to ocean acidification.[63] Brander et al. (2012) estimated that damages due to ocean acidification could reach 870 billion US dollars in 2100.[64] This is exacerbated by the fact that coral reefs and their associated services are already threatened by numerous stressors such as ocean warming, pollution, tourism and overfishing.

Fisheries are directly or indirectly affected by ocean acidification through effects on habitats or food webs (impacts on prey or predators of species of commercial interest). High-latitude pteropods, an important food source for many commercial species such as salmon, seem to be particularly vulnerable to ocean acidification.[65]

Some bivalve molluscs also appear to be particularly sensitive to ocean acidification. Oyster hatcheries in the States of Washington and Oregon in the United States, which represent a 270 million US dollars industry and employ 3200 people, suddenly faced increased mortality rates of juvenile oysters in 2008. The decline was linked to corrosive conditions of the surrounding seawater.[66] In this area, upwelling events bring deep water, naturally rich in CO_2, to the surface, and ocean acidification causes these waters to become increasingly corrosive.

The Arctic Ocean is especially vulnerable to ocean acidification.[67] Due to large freshwater inputs from rivers and melting ice, the Arctic Ocean is less effective at chemically neutralizing acidification. Freshwater in the Arctic increases with global warming, while decreasing sea ice means more open water, allowing for greater absorption of carbon dioxide. Furthermore, the Arctic Ocean is cold, which increases the absorption of carbon dioxide. The Arctic food web is short, and key marine species may be disadvantaged to extinction.[68]

While socio-economic impacts of ocean acidification will depend on local vulnerabilities, adaptation capacity and mitigation strategies, communities that are already heavily impacted by climate change and have few possibilities to adapt, such as the Small Island Developing States (SIDS), might be particularly sensitive. Across the Pacific region, small-scale fisheries provide vital income for around 50% of coastal households and also comprise 50-90% of dietary protein.[69] Unabated ocean acidification has the potential to severely impact the region's coral reefs in the near future, and thus will have significant negative impacts on the region's economy and food security.

The Bottom Line: The threat of ocean acidification needs to be highlighted and action needs to be prioritized. Ocean acidification will add to the stress already caused by increased ocean warming as well as other ocean stressors such as deoxygenation, pollution and overfishing, together increasing the risk to ecosystems and society. There is an urgent need for increased ocean acidification monitoring and research on impacts on commercial

Box 1.4. Continued

species, as well as efforts to assess the costs and effectiveness of adaptation measures, reduce local stress factors, and mainstream ocean acidification into global, regional and national policies and investment strategies. Without immediate and significant reductions in CO2 emissions, adaptation efforts will be at best short-term, as continued warming and acidification of the marine environment will exceed the conditions where vulnerable species can provide ecosystem services we have come to depend on.

Looking Ahead: In the next 5 years:
Establish and maintain long-term global ocean acidification monitoring networks, including the Global Ocean Acidification Observation Network (GOA-ON).

Carry out comprehensive baseline studies and vulnerability assessments at the regional, national, and local levels especially in SIDS regions.

Prioritize local action to a) include ocean acidification in local marine management policy, b) increase ecosystem resilience to ocean acidification through the removal of other stressors such as pollution and overfishing, c) consider and research potential pros and cons of adaptation strategies including use of ecosystem based adaptation, culture of more resilient strains of seafood and the control of seawater chemistry in aquaculture

Box 1.5. Ocean Warming and Deoxygenation: The Ocean is Losing its Breath

What is Deoxygenation? Oxygen is fundamental to most life on earth, including life in the oceans. Oxygen governs most biological and biogeochemical processes. When oxygen is lost from the open and coastal ocean we call this ocean deoxygenation. [70] It is a major result of ocean warming and can have deleterious impacts on marine organisms and ecosystems. Although there are areas of the ocean that are naturally low in oxygen, these areas are expanding and new areas are appearing as the ocean warms. [71]

How does it happen? The ocean is warming, throughout the water column, including in deep water. A warmer ocean holds less oxygen due to declining solubility of oxygen with increasing temperature. A warmer ocean also has reduced ventilation (transport of oxygen from the mixed layer to the ocean interior). Warming also increases the oxygen requirements of most organisms and reduces their tolerance to low oxygen concentrations.[72] The combination of lower solubility, reduced ventilation and increased respiration act to cause ocean deoxygenation. Other contributors to oxygen loss in the ocean are atmospheric iron and nitrogen fertilization of the open ocean, along with warming-induced dissociation of gas hydrates and climate-induced intensification of upwelling winds on continental margins. Other human activities (e.g. nutrient input from agriculture) can increase the rate, extent, and severity of ocean deoxygenation, particularly in coastal and estuarine water. The areas affected by ocean deoxygenation are vast. Since the 1960s over 4.5 million km^2 of the ocean has become deprived of oxygen (hypoxic) at 200 m water depth, over broad swaths of the tropical and subtropical oceans and NE Pacific. [73] Simultaneously, ocean warming increases vulnerability of coastal and estuarine areas to hypoxia (oxygen loss) from nutrient inputs. [74] However, more science is needed to discover the feedbacks associated with oxygen loss.

What are the Consequences? When oxygen levels become stressful, oxygen influences metabolic, physiological, reproductive, behavioral, and ecological processes. This ultimately shapes the composition, diversity, abundance and distribution of marine life and reduces the resilience of coastal populations to further climate change. Deoxygenation reduces the quality and quantity of habitat that wild fisheries species use and that is available for aquaculture production. Chronic exposure to insufficient oxygen also increases disease susceptibility, [75] interferes with reproduction, [76] and reduces growth rates.

Predicted future declines in oxygenation will move ecosystems across biodiversity tipping points in some regions, including in coastal waters and at intermediate (100-1000 m) depths. [77] Fish and invertebrates are sensitive to water temperature and oxygen level for their survival and each organism has a range of ocean conditions that they can tolerate. Marine species are becoming increasingly exposed to conditions beyond their tolerance level. Some organisms show decreased growth and body size and compromised reproductive output. At the species level, some exhibit changes in distribution by moving to areas with more favorable conditions. Under a business-as-usual scenario, by 2050 relative to now, the maximum body size of fish communities is expected to decrease by 14-24%

Box 1.5. Continued.

globally. The distribution of fishes and invertebrates will shift poleward by 10s-100s km per decade or into deeper waters, resulting in local extinctions in tropical waters.[78] Loss of some species and expansion of species highly tolerant of low oxygen, from chemosynthetic bacteria to jellyfish and giant (Humboldt) squid often will alter food web interactions and change energy pathways in the ocean. From a human perspective, deoxygenation can reduce the abundance and mix of species that are important to food security and local economies.

Climate feedbacks. The oxygen content of the ocean and coastal waters also exerts an important influence on the biogeochemical cycles of nitrogen (N) phosphorus (P) and carbon (C) in the water column and sediments directly and through its effect on the types of benthic organisms that occur in an area. These changes in the sediment and water column can then alter the air-sea exchange of climatically important greenhouse gases (CO_2, N_2O, CH_4) and, as a result, may influence the climate on both long and short-term scales. With the expansion and intensification of the open ocean oxygen minimum zones, and the increasing emergence of low-oxygen sites in the coastal areas, it is most likely that deoxygenation will significantly increase oceanic emissions of N_2O in future, which in turn further warming the planet. Another potential consequence of deoxygenation is nitrogen loss through denitrification (and a similar process called anammox), leading to a potential reduction in nitrogen available for primary production in the open ocean. A less productive ocean is projected to have a lower capacity to sequester anthropogenic CO_2 from the atmosphere, hence the regulating role of the world's ocean will decrease. Warming may also dissociate large amounts gas hydrates, methane buried on continental margins, releasing a potent greenhouse gas into the ocean.

Are there Solutions? There is an urgent need to better understand the causes and consequences of ocean deoxygenation and to adapt and manage accordingly. Key actions to halt the loss of oxygen in the ocean are to:

(a) reduce the greenhouse gas and particulate (black carbon) emissions that cause atmospheric and ocean warming
(b) reduce nutrient inputs to the ocean that exacerbate oxygen loss,
(c) alleviate direct anthropogenic stressors (e.g. pollution, overfishing, invasive species, habitat loss, trawling or mining disturbance) that threaten resilience and increase vulnerability of marine ecosystems to deoxygenation
(d) adopt spatial planning and fisheries management strategies that identify deoxygenation vulnerabilities and protect species and habitats.
(e) expand ocean oxygen observations to improve mechanistic understanding and provide early warning systems, especially in countries where changes threaten fisheries, aquaculture and livelihoods,
(f) promote global awareness and the exchange of information about ocean deoxygenation, for example through the IOC's Global Ocean Oxygen Network (GO_2NE) and
(g) recognize ocean deoxygenation as one of multiple climate stressors and work to unify research across (i) coasts and the open ocean (ii) biology, geochemistry and physics, (iii) on warming, acidification and deoxygenation and (iv) across academic, industry, government and regulatory sectors.

Estimating the Risks of Climate Change on Oceans and on Coastal and Island Populations

A recent report (King et al., 2015) presents a need for a climate change risk assessment that aims to be holistic.[79] It emphasises that the risks of climate change are non-linear, for example, while average conditions may change gradually, the risks can increase rapidly. It also highlights that risks of climate change are amplified by feedbacks: e.g. rising temperatures melt ice; sea without ice absorbs more heat; and the temperatures rise faster. It also warns that the most significant risks may arise if thresholds are crossed beyond which certain kinds of adaptation are no longer possible. Although the Earth's climate has changed dramatically in the past, human civilization has seen few of those changes as the Earth's climate has been unusually stable during this period with little variation in global temperature and sea levels. We have taken advantage of this period of stability to grow crops, build cities, and develop a global economy. Greatest risks may arise from the interaction of the climate with complex human systems such as global food markets, governance arrangements within states, and international security. The risks to human interests will also depend on how successfully we can limit emissions and how we can adapt to these changes.

The original text of the UNFCCC adopted a long-term goal of keeping global average warming to "safe levels," which was specified as below 2°C above pre-industrial levels by the Copenhagen

Accord.[80] The choice of this policy target is a subjective policy informed by estimates of future climate impacts and relative difficulty of adaptation, and the judgment that there is a sufficiently high chance of being able to limit warming to this level. However, even the lowest emissions scenario (RCP2.6) has a more than a 33% chance of exceeding 2°C.

An assessment by Gattuso *et al.* (2015) of the risk of impacts of high and low CO_2 emissions scenarios on key ocean ecosystems and the goods and services they provide[81] took a holistic approach for the ocean by combining the risk of impact from the ocean warming, acidification, deoxygenation and sea-level rise. The authors called on the findings of the IPCC 5th Assessment report[82] and research published since then and also produced a policy brief.[83] Their assessment made it clear that this integrated risk was high or very high under high emissions (RCP 8.5, the current trajectory of business-as-usual CO_2 emissions) for key ecosystems or links in the food chain such as coral reefs, sea grass beds, bivalve shellfish, fin fish, krill and sea butterflies. Worryingly, the risk assessment found that even under the stringent emissions scenario (RCP2.6, the 2°C warming target), warm-water corals and mid latitude bivalves will be at high risk by 2100.

Impacts to the ocean's ecosystem services follow a parallel trajectory. Services such as coastal protection and capture fisheries are already affected by ocean warming and acidification. The risks of impacts to these services increase with continued emissions: They are predicted to remain moderate for the next 85 years for most services under stringent emission reductions, but the business as-usual scenario (RCP8.5) would put all ecosystem services considered at high or very high risk over the same time frame. These impacts will be cumulative or synergistic with other human impacts, such as overexploitation of living resources, habitat destruction, and pollution. The authors found that the management options to address ocean impacts become fewer and less effective. They conclude that the ocean provides compelling arguments for rapid reductions in CO_2 emissions and eventually atmospheric CO_2 drawdown and that any new global climate agreement that does not minimize the impacts on the ocean will be inadequate.[84]

Choices for Decision-makers

Evidence and scientific predictions show that climate change will cause adverse impacts on major social, economic, and environmental sectors in coastal countries and SIDS such as water resources, biological diversity, fisheries and aquaculture, agriculture, energy access, health, economy, tourism, and even human settlement and infrastructure. Most of these impacts have negative effects on GDP and reduce funds available for adaptation and development of capacities to face climate change impacts.[85]

The King et al. (2015) report underlines that the risks of climate change are both immediate and long-term, therefore, we must act both immediately and with a long-term view. A risk that grows over time will not be managed successfully if our horizons are short-term. Ultimately, the risks of climate change will only be under control when we have reduced further buildup of CO_2 in the atmosphere. So while we must do all in our power to reduce emissions now, we must also follow a path that increases our power to do more in the future.

The authors underline, as well, that climate change represents both national and global security risks and must be addressed and managed at the highest levels of authority—at the highest levels in national governments and at the global level, in institutions where heads of state meet to make decisions.

With regard to the impacts of climate change on the ocean and on coastal and island populations, as noted by many scientists and policy specialists,[86] and supported by the authors of this Strategic Action Roadmap:

- It is imperative that immediate and substantial reductions of CO_2 emissions take place starting in 2016 for the ocean to continue to perform its central role in planetary survival.

- As the concentration of greenhouse gasses increase, options to overcome or limit the risks on oceans and on coastal and island populations will become fewer and less effective, as risks are non-linear and small changes in emission concentrations could mean disproportionate risks to humans and the environment.

- Further scientific work is needed to understand the extent of climate change impacts between mean global temperature increases of 1.5 and 2.0°C and thus help in decision-making.

This is the challenge to the decision-makers. Money spent now to reduce emissions and mitigate the risks of climate change could save money on adaptation later. Risks of climate change are near term and long term, and delayed response means options for limiting impacts are reduced. Careful planning and fast action are both needed to ensure risks are minimized. The authors of the King et al., 2015 report conclude:

"It is clear to us that the risks posed by climate change to these objectives are very great. We are deeply concerned about what this means for the future of our families, our countries, and our civilization, all of which we care about. At present, our exposure to these risks is far higher than we would wish to tolerate. We do not believe the situation is hopeless. On the contrary, there is much that we can do. The risks of climate change cannot be entirely eliminated, but they can certainly be reduced."

"To win this battle, we must deploy equally powerful forces in favor of change: the power of human ingenuity, the power of technology, and the power of leadership. We must match the laws of physics with a will and a determination that is equally unyielding. The greatest risks of climate change arise when thresholds are crossed: what had been gradual becomes sudden; what had been inconvenient becomes intolerable. The greatest reductions in risk will be won in the same way. Gradual, incremental measures will not be enough: we must seek out non-linear, discontinuous, transformational change."

In this Strategic Action Roadmap, we address specific pathways, which can be pursued within and outside of the UNFCCC, to mitigate whenever/however possible the effects of climate change on oceans and coastal and island communities, to adapt to a changing climate, as well as mobilizing the requisite financing, and the essential capacity development, scientific monitoring, and public outreach.