ENVIRONMENT AND DEVELOPMENT DIVISION

Ocean and Climate Synergies

From ocean warming to rising sea levels

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Abstract

This working paper compiles major impacts of climate change on the ocean, focusing on ocean warming, rising sea levels and ocean acidification. It compiles the reports and projections about ocean and climate in the Asia-Pacific region, emphasizing on extreme weather events, heatwave, coral bleaching, fish migration, degradation of the marine ecosystems, and biodiversity. It also provides sea-level calculations based on satellite data and statistical tools with Asia and Pacific regional examples.

Keywords: Warming, Sea-level, Heatwave, Acidification, Coral bleaching, Fish-migration

1. Introduction

Climate change and its impact on the ocean

The ocean contains 99% of the living space on the planet and serves as a vital component of the global climate system. The climate is driven by interactions within and between the ocean, the atmosphere, and the continental landmasses, contributing to cloud formation, precipitation, and seasonal winds that drive important weather events, such as monsoons (Talley et al., 2011). Due to the enormous capacity of water to store heat and the ability of oceanic flows to redistribute this heat horizontally and vertically, the ocean acts as a heat distribution pump, moving huge volumes of warm water and air towards the poles and cold water and air towards the tropics (Talley et al., 2011). However, since seawater absorbs more than 4000 times as much heat as air per unit volume, changes in oceanic heat content have profound and long-lasting effects on global and regional climate (Volkov, 2018).

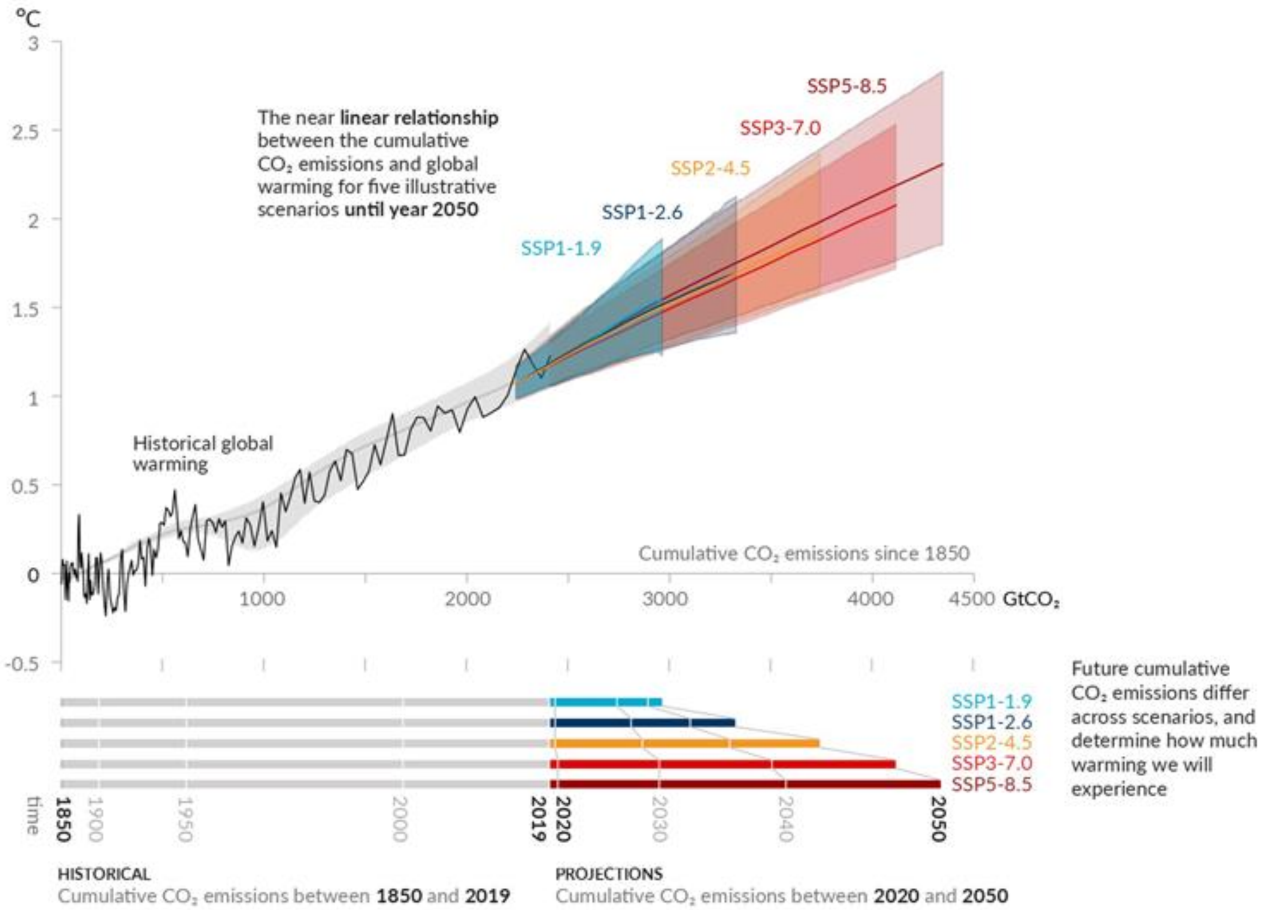
Since the 20th century, climate change has undeniably been the world's most prominent environmental issue. Each of the last four decades has been successively warmer than any decade that preceded it since 1850. The global mean surface temperature of the Earth (2001-2020) has increased by 0.99°C (0.84 - 1.1°C) than 1850-1900 (IPCC, 2021). This warming is mainly driven by increased greenhouse gas emissions (significant contribution from CO_2, CH_4, N_2O) generated by human activities. The concentrations of atmospheric CO_2 rose to 410 ppm (annual average) since 2011. According to NOAA, the current global monthly mean CO_2 is 413.9 ppm on October 2021.

Over the past six decades, the land and ocean have taken up about 56% per year (globally) of CO_2 emissions from human activities (IPCC, 2021). The IPCC (2014) report states that CO_2 concentrations will likely rise to around 450 ppm by 2030. As the global surface temperature rises as a result of CO_2 emission (Fig. 1), the Earth may experience global mean temperature rises of 3.7 °C to 7.8 °C (relative to the 1986–2005 average) by 2100, if CO_2 emission continues to rise and reaches roughly 750 ppm to 1300 ppm (IPCC, 2021). This human-induced warming has reached an alarming state that causes irreversible changes to the glaciers, ice sheets and ocean, and poses a critical threat on a global scale. The resultant sea-level rise by the significant loss of mass from ice sheets and glaciers will cause destructive coastal erosion, wetland flooding, aquifer and agricultural soil contamination, loss of habitat and imminent threat to coastal communities.

The ocean currently absorbs about 30% of all anthropogenic CO_2 emissions (Gruber et al., 2019) and 90% of the heat added to Earth's climate system (Bindoff et al., 2007), thereby substantially moderating the effects of climate change globally. However, global warming and anthropogenic CO_2 emissions have amplified the stress on the ocean, causing the ocean to warm, rise and become acidic. These changes threaten to alter the abundance and distribution of life throughout the ocean, as well as millions of people who rely on the ocean and its life for their sustenance and livelihoods.

Marine species are directly threatened by rising temperatures, and shifts in the abundance and distribution of marine species may have a significant impact on ecosystems (Brierley and Kingsford, 2009). Tropical species, for example, often live near the upper physiological limit of their temperature range (Tewksbury et al., 2008);

Figure 1: Projected changes, impacts and risks for ocean ecosystems Near-linear relationship between cumulative CO_2 emissions and the increase in global surface temperature



Source: IPCC, 2021

Notes: Shared Socioeconomic Pathway 1-1.9 (SSP1-1.9) scenario reflects most closely a 1.5◦C target under the Paris Agreement. SSP1-2.6 is comparable to RCP-2.6 (Representative Concentration Pathway-2.6), representing a scenario to limit warming below 2 ◦C, whereas SSP5-8.5 comparable to RCP-8.5 represent a scenario with high GHG emissions.

therefore, migration may be the only viable survival strategy for many species as the waters continue to warm. Changes in aquatic communities have already been noticed (Perry et al., 2005; Ghosh et al., 2020). These alterations will certainly have far-reaching consequences for both local fishing communities and industrial fishing nations, who may find themselves unable to adapt. Changes in species abundance and distribution inside or across boundaries could result in major disputes.

Coastal landscapes and adjacent areas (within 200 km from the ocean) provide a home for half of the world's population (UN Atlas of the Oceans, 2011), and they are exposed to face forthcoming risks from extreme weather events compared to other communities. The rising sea level can pose many challenges in the coastal population, such as the risk of flooding, seawater intrusion, increased storm wave frequency and further consequences. It is estimated that losses from flood damage due to a sea-level rise of 1.3 m could equal 4% of global gross domestic product (currently US$4 trillion) annually (Ichinko et al., 2019). At present, global infrastructure valued at US$100 trillion is at risk and underinsured (Kuwae and Crooks, 2020). People in the low-lying coastal zones (680 million people) and Small Island Developing States (65 million people) are more vulnerable to these changes, with more frequent storm surges and flooding, which exacerbates the existing vulnerabilities (IPCC, 2019). This is extremely worrisome because coastal fisheries and tourism contribute to food security and employment.

To address these expected challenges, increasing the resilience of the coastal infrastructure is one possible step towards sustainable development. Whereas the legacy of the historical development, the culture of existing communities, and the financial means of each country must be considered while planning the coastal infrastucture. The regional contribution from international development funds is needed to protect failing infrastructures in developing countries and effective coastal management. To minimize the stressors on the ocean, national governments and other actors needs to increase their climate change mitigation efforts through the adoption of effective policies and commitments (NDCs) and through international cooperation to keep the average global warming increase well below 2 °C.

Coastal blue carbon ecosystems, such as mangroves, salt marshes and seagrasses, can help reduce the risks and impacts of climate change, with multiple co-benefits. Conservation of these habitats would sustain the wide range of ecosystem services they provide and assist with climate adaptation by improving critical habitats for biodiversity, enhancing local fisheries production, protecting coastal communities from sea-level rise and storm events, and promoting carbon storage. This working paper focuses on the climate-related impacts on the ocean in Asia and the Pacific region, with a focus on sea-level rise. The COVID-19 pandemic has caused a temporary halt to economic activities, as well as the closure of certain industries, resulting in a substantial, albeit temporary, reduction in GHG emissions. The recovery phase provides an opportunity to promote more resilient and sustainable practices to build back better with a more ocean-sensitive approach.

Key points

• Global surface temperature increase by human-induced greenhouse gas emission, significantly increased the pressure on the ocean, causing it to warm, rise and become acidic.

• These changes threaten marine life, with a significant impact on ecosystems, and affect millions of people who rely on the ocean for food and livelihood. For instance, as the temperature rises, fish migrate as a survival strategy. Changes in aquatic communities have far-reaching consequences for both local fishing communities and industrial fishing nations.

• Coastal landscapes and adjacent areas are more exposed to face forthcoming risks from extreme weather events.

• These challenges can be addressed through improved resilience of the coastal infrastructure, conservation of blue carbon, climate adaptation through effective policymaking and increased international corporation.

2. The global perspective

THE OCEAN ECONOMY DIRECTLY EMPLOYS AROUND 31 MILLION PEOPLE GLOBALLY, WITH A MARKET VALUE OF APPROXIMATELY USD 1.5 TRILLION IN 2010, POTENTIALLY DOUBLING BY 2030 (OECD, 2016). Service sectors, such as tourism and fisheries, provide financial resources for national budgets and most employment and food security for households in coastal communities. Activities such as fishing, tourism, trade, aquaculture, seaweed harvesting, among others, depend on marine sustainability. However, recent ocean assessments reveal a cycle of decline in ocean health, with changes and losses in the structure, function and benefits obtained from marine systems (UNGA, 2017).

OCEAN WARMING

IPCC's Fifth Assessment Report (AR5) estimated that it is indisputable that global sea-surface temperature (SST) has increased since the beginning of the 20th century. At the ocean surface, the temperature has, on average, increased by 0.71°C from the 19th century. The SST is projected to increase up to 0.87°C in RCP-2.6 and up to 2.82°C in the RCP-8.5 scenario (IPCC, 2019). Warming is generally surface intensified; however, subsurface layers substantially contribute to the increase in the oceanic heat content. Since 1993, the rate of ocean warming has more than doubled due to anthropogenic forcing. The ocean warming has likely continued in the abyssal and deep ocean below 2000 m, especially in the Southern hemisphere and Southern Ocean (IPCC, 2019). Global rainfall patterns shift with rising temperatures (Henderson et al., 2015; IPCC, 2021) and increase the prevalence of extreme events such as storms, hurricanes, tornadoes, severe thunderstorms, floods, and hail; this trend is expected to continue (Walsh et al., 2016).

First and foremost, the sea level increases as the ocean warms and expands. The global mean sea level increased by 0.2 m (0.15 to 0.25) between 1901 and 2018, with an average rate of 3.7 (3.4 to 4.2) mm yr^{-1} between 2006 and 2018 (IPCC, 2021). According to satellite and in situ data, only around a third of the current sea level rise is attributed to thermal expansion. Melting ice sheets and glaciers account for the remaining two-thirds. The warmer ocean may enhance basal melting and thinning of ice shelves and marine-terminating glaciers, significantly contributing to sea-level rise (Denis, 2018). The rising sea level poses a direct threat to coastal regions in developed and developing countries, as well as low-lying coastal zones, including Small Island Developing States less than 10 metres above sea level with higher inundation levels, mounting water tables, extreme flood frequency, greater erosion, saltwater intrusion, and ecological changes in coastal resources. It increases the vulnerabilities of the coastal communities that depend on marine sources for their food and livelihood. These coastal zones are under imminent threat by the loss of coastal resources, infrastructure, agricultural land, and associated declines in economic, ecological, and cultural values.

The average sea-level rise is projected to be 24–30 cm by 2065 and 40–63 cm by 2100 under various scenarios compared to 1986–2005 (Allen et al., 2014; Pachauri et al., 2014). This is extremely worrying because accelerating sea-level rise could submerge parts of low-lying coastal lands and SIDS (Dasgupta et al., 2007), whereas a number of islands in the Pacific are already submerged, including 11 in the Solomon Islands and several in Pohnpei (Federated States of Micronesia) (Albert et al., 2016; Nunn et al., 2017). It is predicted that between 0.66 to 1.7 million people in the Pacific will be forced to migrate owing to rising sea levels by 2050, including from atoll islands in the Marshall Islands, Tuvalu, and Kiribati (Church et al., 2013). Very large proportions of the population of Bangladesh (46%) and the Netherlands (70%) are likely to be forced to relocate (Lalit Kumar et al., 2020). By 2100, coastal properties worth $238 billion to $507 billion in the United States alone are likely to be below sea level (National Report, The Economic Risks of Climate Change in the United States).

THE EFFECTS OF WARMING ON MARINE FAUNA

Warming of the sea surface makes the surface layer (upper 200 m) less dense, inhibiting the exchange between surface and deeper layers and causing more stratification in the water column. In response to increased stratification, open ocean nutrient cycles are being disturbed (stratification prevents micro and macronutrient mixing from the bottom layer, leading to depletion in the surface) and thereby impacts primary producers. Climate models project that net primary productivity will very likely decline, especially in the tropical region (7–16%) decrease is predicted for RCP-8.5 (IPCC, 2019). Moreover, the probable decrease in the sinking flux of organic matter will minimise organic carbon supply to deep-sea ecosystems. The reduction in the food supply is projected to lead to a significant decrease in biomass of benthic biota over in the abyssal seafloor by 2100 (Bindoff et al., 2019). These ocean changes affect marine organisms at multiple trophic levels, with deleterious effects on marine ecosystems.

Marine fauna, including mammals, are vulnerable to climate change as temperature is a crucial defining component of their habitat. Reports show that the North Pacific Ocean, the Greenland Sea, and the Barents Sea host the species most vulnerable to ocean warming (Albouy et al., 2020). Some marine species are exclusively found in warm tropical waters, some in the temperate zones and some only at the poles. Under warming scenarios, certain species move further poleward or become more successful at adapting to changes, while others may be unable to adapt due to ecological or geographical barriers (especially in the tropical region) and become extinct (Tagliari et al., 2021). For instance, Bryde's whales (Balaenoptera brydei), a widely spread subtropical and tropical species, were increasingly detected in the cooler waters of Southern California from 2000–2010 (Kerosky et al., 2012). Increased temperature seasonality in the tropics, on the other hand, could drive many species adapted to low seasonality to extinction (Tagliari et al., 2021). In addition, changes in ocean temperatures may affect the life cycles of prey of marine mammals, resulting in mismatches between prey abundance and that of predators. The circumstances could be hazardous for migratory marine species that travel large distances between feeding and breeding sites (Elliott and Simmonds, 2007; Lascelles et al., 2014). Thus, an increase in ocean temperature can have direct impacts on the survival rates of marine fauna (Burek et al., 2008) by increasing the stress of organisms, fostering the development of pathogens, and increasing the propagation of pathogens to new species by causing species to experience range shifts (Evans et al., 2013).

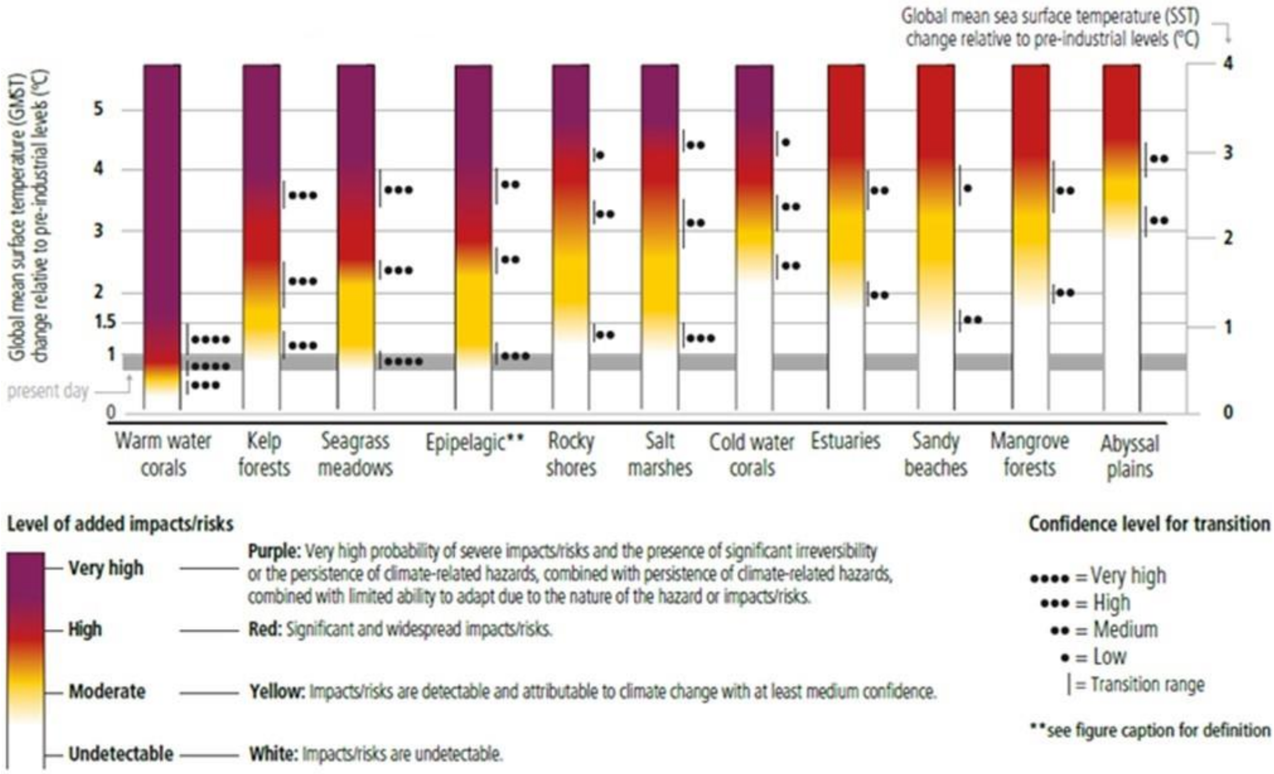
Burns (2002) noted the importance of the zooplankton species krill and its relationship to the extent of sea-ice and the algae associated with it, which are a critical food resource for krill (Euphausiacea), in a case study from Antarctica, where temperatures in some areas have risen by 4-5°C. In the warming scenario, salps (Salpa thompsoni), which are more tolerant of warmer, lower-nutrient water, tend to dominate and outcompete krill in locations where the sea ice has disappeared. The spread of salps over krill had far-reaching consequences for the Southern Ocean food web, including penguins, albatrosses, seals, and whales, all of which are susceptible to krill shortages despite their extensive foraging ranges (Atkinson et al., 2004). This case study clearly indicates the distinctive role of each species to balance the food web and the need to conserve vulnerable species.

THE EFFECTS OF WARMING AND SEA-LEVEL RISE IN COASTAL ECOSYSTEMS

Considering the coastal ecosystems, the global wetland area has declined by nearly 50% relative to the pre-industrial level due to warming, sea-level rise, extreme climate events and other human impacts. Coral reefs, seagrass meadows and kelp forests will face moderate to high risk at a temperature above 1.5°C global sea surface warming. And the distributions of seagrass meadows and kelp forests are contracting at low latitudes, whereas inundation, coastline erosion and salinisation are causing shifts in plant species distributions (Bindoff et al., 2019). Intertidal rocky shores are also expected to be at very high risk (above 3°C) under the RCP-8.5 scenario. These ecosystems have low to moderate adaptive capacity, as they are susceptible to ocean temperatures and acidification (Fig. 2). Similarly, warming-related mangrove encroachment into subtropical salt marshes has been observed in the past 50 years. In addition, increased nutrient (due to sea-level rise) and organic matter loads in estuaries since the 1970s have exacerbated the effects of warming on bacterial respiration and eutrophication, leading to the expansion of hypoxic areas (Limburg et al., 2020).

However, these vegetated coastal habitats are responsible for sequestering about 70% of the carbon permanently stored in the marine realm and can significantly impact global blue carbon stocks (Nellemann et al., 2009). For instance, cutting down mangrove forests have considerable climate cost as the carbon storage gets exposed. Studies estimate that the total amount of carbon held in the world's mangroves was around 4.19 billion tons in 2012, with Indonesia, Brazil, Malaysia and Papua New Guinea accounting for more than 50% of the global stock. Yet, 2% of global mangrove carbon was already lost between 2000 and 2012, equivalent to a maximum potential of 316,996,250 t of CO_2 emissions (Hamilton and Friess, 2018). This requires urgent climate action, for example, an estimate from Indonesia suggests that stopping mangrove deforestation would reduce the country's land-use emissions by 10-31% (Murdiyarso et al., 2015). Sustaining blue carbon sinks is crucial for ecosystem-based adaptation strategies that reduce vulnerabilities of coastal communities and maintain habitat for marine flora and fauna, resulting in economic revenue, increased food security, and improved coastal lifestyles.

Table 2: Projected changes, impacts and risks for ocean ecosystems



Source: IPCC, 2019

OCEAN ACIDIFICATION

The open ocean surface water pH has been observed to be declining by 0.017–0.027 pH units per decade since the late 1980s in response to increased CO_2 absorption from the atmosphere. These changes in pH have reduced the stability of mineral forms of calcium carbonate due to a lowering of carbonate ion concentrations (Box. 1), most notably in the upwelling and high-latitude regions of the ocean (IPCC, 2019). Ocean acidification alters the sensory abilities of some species (Hester et al., 2008; Munday et al., 2009) and threatens the ability of others to build their skeletons or shells (Fabry et al., 2008), and affects the marine food cycle. It has to be noted that though the overall change in ocean pH appears small (0.1 pH units over the past 150 years), this is a 26% increase in the concentration of hydrogen ions.

Experimental evidence shows a reduction in carbonate ions with ocean acidification is biologically significant since it can affect the rate at which marine organisms, such as corals, oysters, and other calcifying species (e.g. Pteropod (Limacina helicina), Coccolithophores (Emiliania huxleyi)) build their calcareous structures (Kroeker et al., 2013; NOAA report, 2010; Orr et al., 2005). The panel of photographs shows what happens to a pteropod, a shelled free-swimming marine snail exposed to ocean water adjusted to seawater pH projected for the year 2100 (pH 7.8). Its shell dissolves after approximately 45 days in this environmental condition (Fig. 3).

Ocean acidification is likely to cause major shifts in marine ecosystems and food webs, including losing most coral reefs globally. The decline in species and even extinctions are expected by the end of this century if ocean acidification continues unabated. Further consequences of ocean acidification include the reduction in fisheries and tourism, impacts on human health due to changes in nutritional content and decreased coastal protection.

HABITAT DEGRADATION AND LOSS

Coral reefs are significant ecosystems found in a wide range of environments, such as "warm-water" coral reefs, in the shallow region (especially in the coastal areas of the Pacific, Indian, and Atlantic oceans), "mesophotic" (low light) coral reefs locations up to 40-150 m depth and "cold water" corals reefs found in dark depths (2000 m or more). Coral reefs occupy 0.1% of the ocean's bottom, yet, are home to more than a quarter of all marine life (crustaceans, reptiles, seaweeds, bacteria, fungi, and over 4000 species of fish) (Fisher et al., 2015). These ecosystems sustain coastal economies that depend on reefs-related tourism, serve as a source for bioprospecting, develop novel pharmaceuticals, and supply food for hundreds of millions of people (World Wildlife Fund, 2020). The asset value of coral reefs has been estimated as close to $1 trillion (Hoegh-Guldberg, 2015), with the economic value of goods and services from coral reefs exceeding $375 billion annually, with benefits flowing to over 500 million people in at least 90 countries worldwide (Burke et al., 2011; Gattuso et al., 2014).

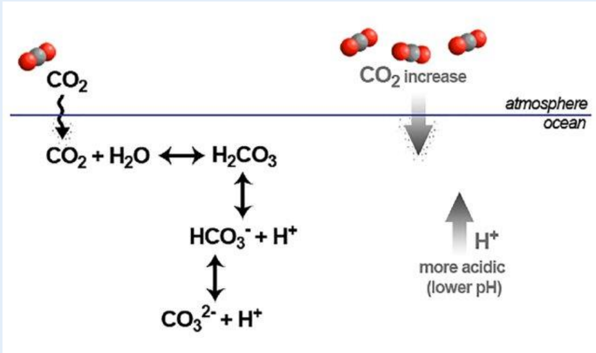
Figure 3: In a lab experiment, sea butterfly (pteropod) shell placed in seawater at a pH of 7.8 slowly dissolves over 45 days. Panels from the top represent 0 days, 15 days, 30 days and 45 days respectively.

Source: NOAA report 2010; Orr et al., 2005. Photo credit: David Liittschwager, National Geographic Images

Box 1: Inorganic carbon cycling in the ocean and pH.

As more CO_2 enters the ocean, it reacts with water increasing hydrogen ion concentration, thus decreasing ocean pH even in a very small amount.

The distribution of carbonate species in the ocean varies with pH, and at average seawater pH of 8.1, the dominant species are HCO_3^- (bicarbonate ion) ≈ 90%, CO_3^{2-} (carbonate ion) ≈ 10 % and CO_2(aq)/ H_2CO_3 (carbonic acid) ≈ (<1%). As more CO_2 absorbs by the ocean, the balance between the carbonate species will change, with the concentration of CO_2(aq) and HCO_3^- increasing and CO_3^{2-} decreasing, resulting in less precipitation or dissolution of calcium carbonate ($CaCO_3$) (especially aragonite, less crystalline $CaCO_3$ which makes corals and shells).



Source: Perretti et al., 2018

According to Reefs at Risk Revisited (Burke et al., 2011), a report by the World Resources Institute, 75% of the world's coral reefs are at risk from local and global stresses. More than 50% of the world's reefs have died in the last 30 years, and more than 90% of the remaining reefs are projected to die by 2050 (Secore International, n.d.). Studies reveal that almost all coral reefs will degrade from their current state, even if global warming remains below 2°C, and the remaining shallow coral reef communities will differ in species composition and diversity from present reefs. Multiple hazards of warming, acidification, deoxygenation, and a decrease in the influx of organic carbon from the surface ocean will reduce calcification and exacerbate the bioerosion and dissolution of the non-living component of cold-water coral as well (Bindoff et al., 2019).

The drivers of the destruction of coral reefs also include hurricanes, El Niño and local threats such as overfishing, destructive fishing techniques, coastal development, pollution, and careless tourism. These declines in coral reef health will greatly diminish the services they provide to society, such as food provision, coastal protection, and tourism. However, reefs are remarkably resilient and can recover in the absence of large-scale disturbances. After a 1998 mass coral bleaching event, hard coral cover rebounded to pre-1998 levels within a decade. "If we halt and reverse ocean warming through global cooperation, we give coral reefs a chance to come back from the brink. It will, however, take nothing less than ambitious, immediate, and well-funded climate and ocean action to save the world's coral reefs" (UN News, Global perspective Human stories).

The consequences of warming, sea-level rise and ocean acidification result in population declines in marine species and affect marine biodiversity. Whereas the pressure from illegal, unreported, and unregulated fishing will likely cause further reductions or extinctions. Marine pollution, especially from plastics and microplastics, will significantly impact fish abundance, and it is reported that if the pollution continues at this rate, the amount of plastic debris in the ocean could triple by 2050. The pollution by anthropogenic activities further makes the system more vulnerable by bioaccumulation of organic and trace metal pollutants and bio-toxicity.

Key points

• The rising sea surface temperature has altered rainfall patterns and increased the prevalence of extreme weather events. Coastal regions and low lying coastal zones are under diresct threat.

• It is estimated that between 0.66 to 1.7 million people in the Pacific islands and 46% population of Bangladesh may be forced to migrate owing to rising sea levels by 2050, along with the loss of coastal resources and infrastructure.

• Warming causes stratified water columns with less biological productivity leading to reduction of food supply to deep-sea ecosystems and thereby decrease in biomass of benthic biota.

• Marine fauna, including mammals, are vulnerable to climate change as the temperature is a crucial defining component of their habitat, and extinction or reduction of even one species affects the balance of the food web in the marine ecosystem.

• Extreme climate events and human impacts caused considerable decline to coastal ecosystems that store carbon and provide habitat for marine fauna along with multiple co-benefits.

• Increased human-induced CO_2 emissions significantly reduced the pH of the ocean, thereby reducing the stability of mineral forms of calcium carbonate (including corals) and threatening the ability of species to build their skeletons or shells.

3. Challenges for Asia and the Pacific

The Asia-Pacific region is biologically diverse with 71% of the world's coral reefs (Hoegh-Guldberg, 2009), 45% of the world's mangroves (Giri et al., 2011), 66% of the world's fisheries production and 89% of aquaculture production (FAO, 2020). The Asia-Pacific region is home to over 200 million people who rely on fishery resources for food and income. Asia accounts for 84% of the global population working in fisheries and aquaculture (FAO, 2016). In addition to fishing, tourism contributes significantly to almost all Pacific Island countries as a significant source of employment and foreign exchange, in which Fiji (40% GDP from tourism), with its established network of resorts and beach attractions, dominated the market, while the Solomon Islands received just over 20,000 international visitors. Tourism revenues as a percentage of GDP were 7.3% for Kiribati, 6.4% for the Solomon Islands, 17.8% for Tuvalu and 31.7% for Vanuatu in 2018.[1] In terms of employment, Vanuatu had the highest share of tourism employees (34.5%), followed by Kiribati (15.5%), Solomon Islands (11%) and Tuvalu (2.3%).[2]

OCEAN HEALTH INDEX IN THE REGION

The Ocean Health Index for the Asia-Pacific region indicates that more benefits could be gained, or that current methods jeopardize the delivery of future benefits. The Ocean Health Index for each coastal country's exclusive economic zone in Asia and the Pacific and that in the high seas is represented in the figure, where the situation in the high sea is even more precarious. SDG 14 will require transformative action and innovative approaches since the health of the ocean in the region has deteriorated further (ESCAP, 2018).

VULNERABILITIES OF SIDS IN THE PACIFIC

The SIDS in the Pacific Ocean cover nearly 528,090 km^2 of land (0.39%) spread throughout the ocean, with a combined exclusive economic zone (EEZ) of approximately 30 million km^2 (Carlos et al., 2008). These Islands supply one-third of the world's tuna with a first-sale value of over $4 billion per year (World Bank, 2014). The influence of fisheries permeates every aspect of life in low-lying coastal zones and islands in the Asia-Pacific region. Much of these economies' nutrition, welfare, culture, employment, and recreation depend on the resources between the shoreline and the outer reef. Moreover, the average fish consumption in Pacific SIDS is two to three times higher than the global average fish consumption per capita (Gillett, 2016).

Sea-level rise will directly impact people living in these regions as the population distribution is mainly concentrated close to the shoreline. For instance, 98% of the people of Kiribati, 98% of Marshall Islands, and 99% of Tuvalu live within 500m of the coast. Furthermore, data from 12 Pacific countries (Cook Islands, Kiribati, Marshall Islands, Nauru, Niue, Palau, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu) show that around 55% of the population in these countries live within 500 m of the coast, with 20% residing within 100 m (Kumar et al., 2018).

[1] Tourism receipt data are for 2018 and taken from the SPTO's Annual Review of Tourist Arrivals in Pacific Island Countries 2018.

[2] Employment data are for 2018 and from ESCAP (2020).

In the Pacific, under the RCP-4.5 scenario, sea level is projected to increase 0.5 to 0.6 m by 2100 compared to 1986 to 2005 (Church et al., 2013). However, an increase of even 32 cm sea-level rise is projected to have severe consequences for the social and ecological systems on low coral atolls (Pearce, 2000). In addition, the intensity of tropical cyclones is likely to increase with increasing temperatures and precipitation (Christensen et al., 2013; CSIRO, 2015). Wave actions, storm surges, sea-level rise, and river flooding can damage coastal assets, infrastructure, freshwater supply and, in turn, have adverse effects on various sectors such as agriculture, tourism, public health, and hydro-electricity production (Campbell and Barnett, 2010).

Kumar and Taylor (2015) have shown that 57% of all infrastructure in 12 Pacific Island countries are within 500 m of the coast, with 20% being within 100 m. This exposes a substantial proportion of national infrastructure in these island countries to coastal climate change impacts. Ocean warming and acidification are expected to have major effects on the distribution of fish habitats and fish stocks. In contrast, stormy weather and more intense cyclones make fishing trips unsafe and less productive. This will most likely affect the fish supply, depriving fishers of income and potentially threatening the economic security of island communities (FAO, 2008). SIDS are highly vulnerable to external economic and financial shocks, at least 35% more than other developing countries. Compared with other regions in the world, the number of COVID-19 cases in the Pacific was relatively low in 2020. However, SIDS experienced an estimated fall in GDP of 9% in 2020, compared with a 3.3% decline in other developing countries based on IMF projections data. The pandemic severely affected employment, labour mobility and livelihoods across the region, exposing and exacerbating vulnerabilities and socioeconomic challenges that are expected to have long-lasting impacts, particularly in relation to education and gender equality issues. For instance, SIDS suffered an estimated 70% drop in travel receipts in 2020. The UN World Tourism Organisation estimates that it could take up to four years for international tourism, an essential source of jobs and livelihoods, to recover to levels observed in 2019.

On top of that, the Pacific region was able to adapt to the constraints of COVID-19 and strengthened the capacity to deliver services and support through virtual platforms or through greater reliance on locally based partners (Pacific community results report, 2020). SIDS are pioneers in designing and implementing green financial instruments to bolster debt resilience, especially climate adaptation and mitigation.

INCREASED PROBABILITY OF HEATWAVES AND FISH MIGRATION

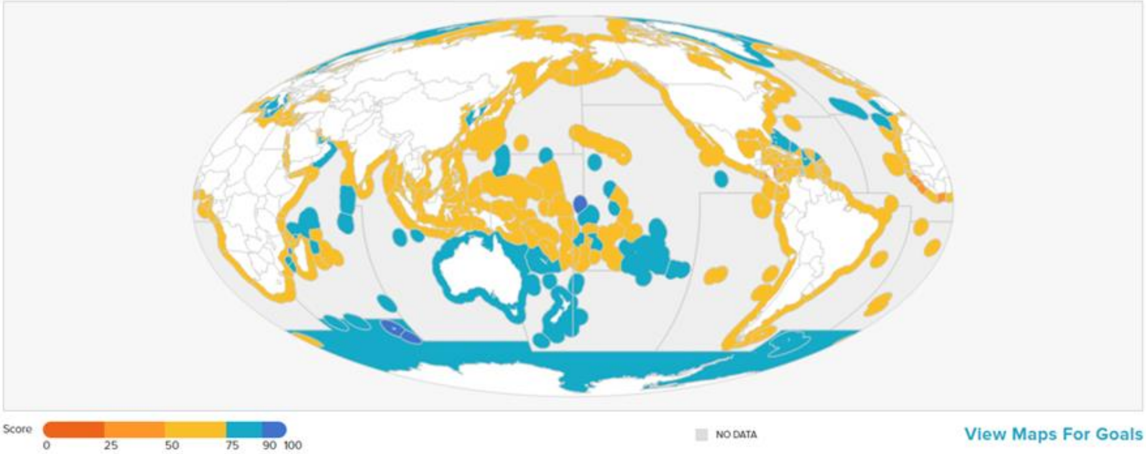
Considering the Asia-Pacific region, the fastest surface warming since 1950 has occurred in the Indian Ocean and the Northern Pacific Ocean. The stratified surface layer with variation in wind patterns causes stagnant ocean conditions and helps to increase water temperature, leading to the formation of heat waves (especially in the North Pacific and near Australia). Marine heatwaves have become more common during the last century, increasing 54% in annual marine heatwave days globally from 1925 to 2016. The prime example of the marine heatwave is "The blob," which occurred in the North-Eastern Pacific Ocean in 2014–2016. It was characterised by anomalous SSTs of more than 3°C above normal. The blob caused damage to marine ecosystems, causing abnormally low near-surface chlorophyll biomass (indicating fewer nutrients to feed marine life) and enormous extinction of sea lions, whales, and seabirds, with mass fish migration (Miyama et al., 2021). The South-Western Pacific region also experienced intense heatwave events during 2016, 2019 and 2020. Heatwave events in 2016 caused mass fish mortality in the South-West of Fiji with an intensity of +2.8°C (Holbrook et al., 2021). Modelling studies in the region report intense warming in the subsurface layers of the western Pacific as well (Hu et al., 2021). Moreover, simulated ocean warming and changes in primary productivity during the 21st century are projected to alter the community structure of marine organisms, reduce global marine animal biomass and the maximum potential catches of fish stocks.

In the Asia-Pacific region, oceanic fisheries target four tuna species such as skipjack, yellowfin, bigeye, and South Pacific albacore, making critical contributions to economic development, government revenue, and livelihoods in most nations. These tuna species are sensitive to water temperature. They are expected to respond directly to oxygen, ocean currents, stratification of the water column and location of the Western Pacific Warm Pool, and are influenced indirectly by changes in the food web (Bromhead et al., 2015; Lehodey et al., 2011). Concentrations of these stocks usually shift from year to year between areas further to the west in El Niño years and those further east in La Niña years. However, due to climate change, tuna in the Pacific Ocean is likely to move progressively to the east, leading to a slow transfer of resources further away from EEZ. Thus, contributions from tuna to the economies of dependent human communities in the Western Pacific (SIDS) will decline, as tuna will be forced to migrate to the open ocean of the high seas, away from the jurisdiction of any country.

Pacific Island nations and territories charge (Fig. 5) foreign fishing operators to access their waters and heavily depend on this revenue. Their governments charge tuna fishing access fees to distant nations of between US$7.1 million and $134 million, providing an average of 37% of total government revenue (ranging from 4-84%). The projected movement of tuna stocks will cause a fall in annual government revenue of these small island States of up to 17%. In addition, the decline in marine animal biomass and fish catch potential due to climate change will further elevate the risk of impacts on income, livelihood, and food security. This loss will hurt these developing economies, which need fisheries revenue to maintain essential public services such as hospitals, roads, and schools[3].

[3] https://www.uow.edu.au/media/2021/climate-change-is-causing-tuna-to-migrate-.php

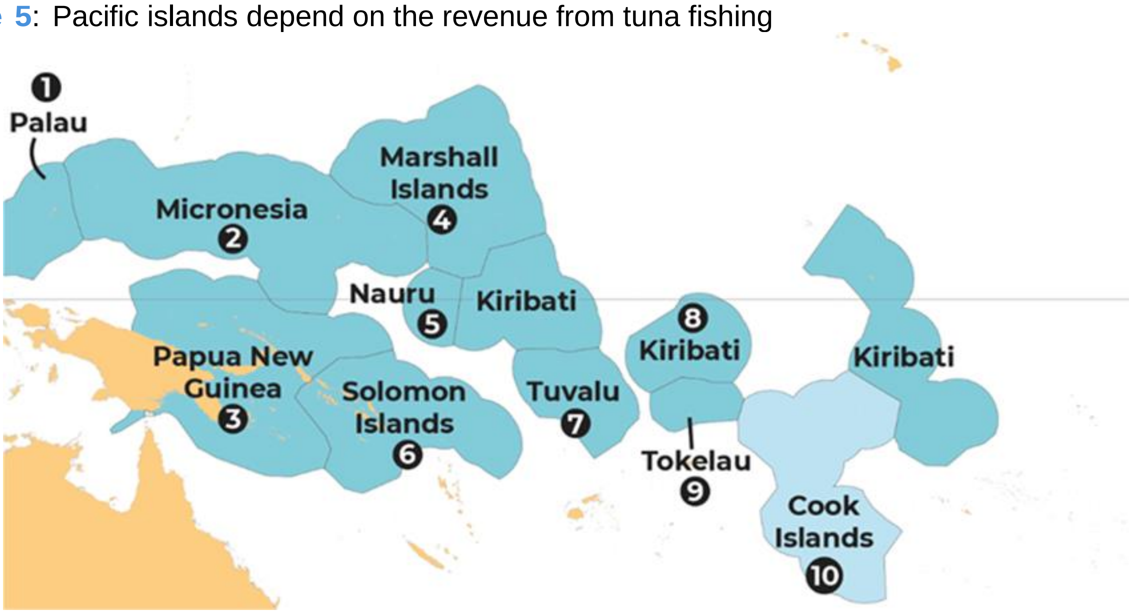
Figure 4: Ocean Health Index: Asia-Pacific exclusive economic zones



Source: National Center for Ecological Analysis and Synthesis and Conservation International (http://www.oceanhealthindex.org/regionscores/ maps

Note: Ocean health index is an assessment framework to comprehensively evaluate ocean health and score them from 0-100.

Figure 5: Pacific islands depend on the revenue from tuna fishing



Source: https://www.uow.edu.au/media/2021
Note: These are major 10 Islands depend on the revenue from Tuna fishing

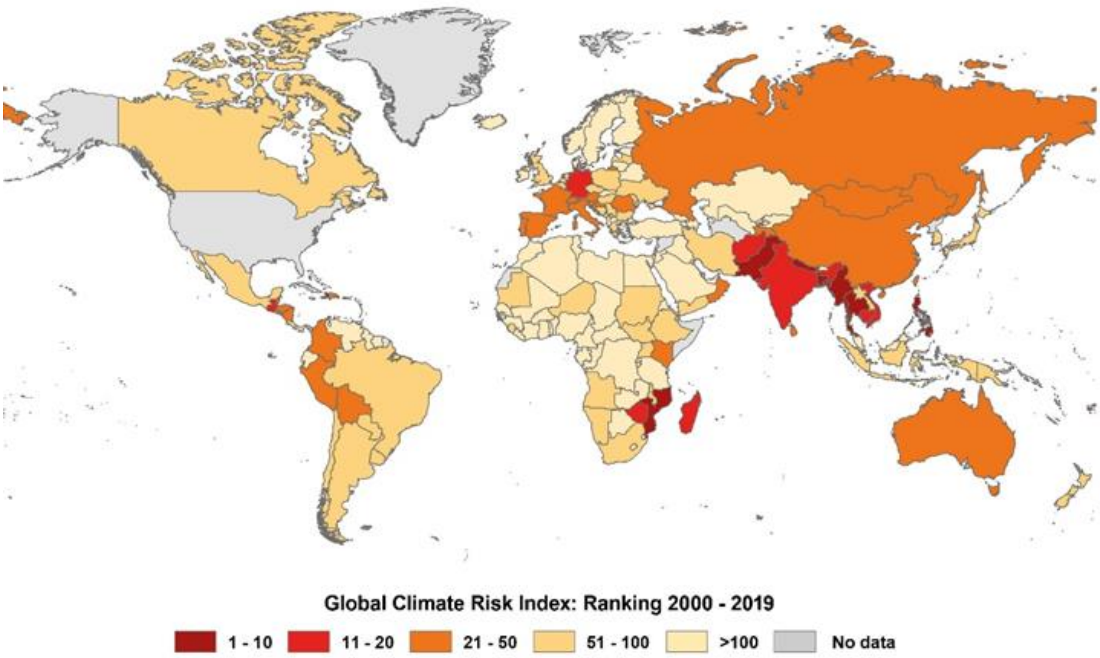
Advanced studies on tuna migration predict that the biomass of the major three species of tuna (skipjack, yellowfin, bigeye) in the combined jurisdictions of these ten Pacific Island states would decrease by an average of 13% (up to 20%) under the RCP-8.5 scenario. But if emissions were kept to the lower RCP-4.5 scenario, the effects are expected to be far less pronounced, with an average decrease in biomass of just 1% (Bell et al., 2021). While both climate scenarios result in average losses of both tuna catches and revenue, lower emissions scenarios lead to drastically smaller losses, underscoring the importance of climate action.

INCREASED PROBABILITY OF HEATWAVES AND FISH MIGRATION

The risks associated with extreme events will increase as the global mean temperature rises (IPCC, 2014). The *El Niño*–Southern Oscillation (ENSO; recurs about every 2–7 years) in the tropical Pacific can further lead to disruptive heat waves, droughts, and floods worldwide. According to the Global Climate Risk Index (CRI) 2021[4], over 475,000 people lost their lives worldwide, and losses of US$2.56 trillion (in terms of Purchasing Power Parities, excluding the United States of America) were incurred as a direct result of more than 11,000 extreme weather events during 2000-2019 (www.germanwatch.org/en/cri). The index of most affected countries in 2019 shows Japan, the Islamic Republic of Afghanistan and India in the top 10 positions with high CRI scores (average weighted ranking), indicating the warning sign that they are at risk of either frequent extreme weather events, or rare but extraordinary catastrophes. In 2019, Japan was hit by typhoons (Hagibis, Faxai), causing economic damage estimated at US$ 25 billion, heatwave and extremely high temperature (39.5°C) causing thousands of heat-related hospitalisations (18,000) and even deaths. The Islamic Republic of Afghanistan experienced several floods and landslides throughout the year caused by heavy rainfall, whereas India faced floods caused by intense rainfall and eight tropical cyclones.

[4] Global climate risk index 2021, Who Suffers Most from Extreme Weather Events? (Eckstein et al., 2021)

Figure 6: World map of global climate risk index (CRI) 2000-2019.



Source: Germanwatch Körperschaft. (n.d.). Global Climate Risk Index. 2021ermanwatch; Eckstein et al., 2021

In contrast, considering the 10 countries most affected in the period 2000-2019 by extreme weather events, Myanmar, Philippines, Bangladesh, Pakistan, Thailand, and Nepal are there in the list, whereas more countries and island States are there in the top 20 list indicates the magnitude of imminent risk in the region.[3]

Pacific Island countries are particularly vulnerable to health impacts from changing climate due to their unique geologic, social, and economic characteristics (Hanna and McIver, 2014). Comparatively small in size and isolation, their tropical locations, often stagnant economies, and limited health infrastructure are some reasons. The direct impacts include damages to health infrastructure, deaths, and traumatic injuries occurring during extreme events and physiological effects from heatwaves. For example, in 2015, Cyclone Pam caused severe damages to the healthcare system of Vanuatu, destroying 21 of 24 health facilities(hospitals, health centres, and dispensaries) across 22 affected islands in the most affected province (Esler, 2015). With severe impacts projected for local economies and livelihoods of people, resulting in human mobility and cross-border displacement and migration (Perch-Nielsen et al., 2008). Climate change can drive human mobility in specific contexts, particularly in low-lying coastal areas. Significant migrations from rural atolls to coastal towns and cities or larger islands have occurred over the past decades in the Pacific Island region (Campbell and Warrick, 2014).

IMPACTS OF WARMING, SEA-LEVEL RISE AND, ACIDIFICATION ON ECOSYSTEMS

Warmer air and sea surface temperatures, ocean acidification, rising sea levels and altered rainfall patterns are expected to reduce significantly the habitats that provide shelter and food for coastal fish and shellfish. Anthropogenic CO_2 has caused a decrease of 0.06 pH units in the tropical Pacific since the beginning of the industrial era (Howes et al., 2018). Currently, the pH of the tropical Pacific Ocean is decreasing at a rate of 0.02 units per decade, and it is projected to decrease by 0.15 units relative to 1986–2005 by 2050 (Hoegh-Guldberg, 2014). This declining pH corresponds to a decrease in dissolved carbonate ions (CO_3^{2-}), leading to a lower potential for $CaCO_3$ precipitation. According to IPCC AR5, under the RCP-8.5 scenario, the aragonite saturation states in the subtropical gyre region will continuously decrease to around 800 ppm by 2100, which will impact the calcification process with detrimental effects for many shallow-water organisms (Hoegh-Guldberg, 2014). The combined impacts of increasing temperature, sea-level rise and alteration of ocean layer thickness will affect the nutrient supply, lagoon flushing, and ocean acidity and ultimately affect plankton productivity and survival of corals (FAO, 2008).

CORAL REEFS IN THE REGION

Warm-water coral reefs (coral reefs in shallow regions) are prominent ecosystems in coastal areas of the Pacific and Indian oceans. Southeast Asia contains nearly 100,000 square kilometres of coral reefs, accounting for nearly 34% of the world's total. These reefs feature the highest levels of marine biodiversity on the planet, with over 600 of the over 800 reef-building coral species. However, about 60% of coral reefs in the region are at risk from coral bleaching and destructive human activities (Policy brief, SDG 14, ESCAP). The coral cover is projected to decline from the current maximum of 40% to 15 to 30% by 2035 and 10% to 20% by 2050, primarily due to the acidification of the ocean and increasing sea surface temperature (Bruno and Selig, 2007; Hoegh-Guldberg, 2014). This will also negatively affect the ability of corals to compete with microalgae for space; hence, microalgae are likely to smother a significant proportion of corals by 2035. This pressure on coral reefs will also affect the reproduction of coral reef fish species, numbers of which are projected to decrease 20% by 2050 (Bell et al., 2013).

According to the Sixth Status of Corals of the World: 2020 Report, there has been a steady decrease in hard coral cover since 2010, with the worst impacts occurring in South Asia, Australia, the Pacific, East Asia, the Western Indian Ocean, and the Gulf of Oman. Simultaneously, rising sea surface temperatures have triggered unprecedented mass bleaching of corals. Mass fish kills were observed on the Coral Coast of Fiji and Vanuatu, owing to increased water temperatures of 35°C and over 30°C, respectively (Howes et al., 2018). During 2015–2016, record temperatures (above 30°C) triggered a pan-tropical episode of coral bleaching in the Great Barrier Reef (>60% of corals bleached) (Fig. 7), the third global-scale event since mass bleaching was first documented in the 1980s (Hughes et al., 2017). The Pacific was also hit by a severe heatwave in 2019. The Great Barrier Reef region of Australia saw another big heatwave in 2020, and the high temperatures damaged the whole reef, resulting in widespread coral bleaching, the the third such incident in the previous five years[5]. The increased heatwave and ENSO events (Toth et al., 2019) in the region demands immediate global action to curb future warming to secure a future for coral reefs and marine biodiversity.

EFFECTS ON BIODIVERSITY

The limited amount of suitable habitat and limited capacity for rapid adaptation of small islands make the consequences of accelerating climate change likely to be severe for the region's biodiversity (Taylor and Kumar, 2016). Sea-level rise poses a significant threat to the restricted species ranges on smaller and atoll islands (Taylor and Kumar, 2016). Since the early 1980s, the occurrence of harmful algal blooms and pathogenic organisms (e.g.,

[5] https://public.wmo.int/

Vibrio) has increased in coastal areas in response to warming, deoxygenation and eutrophication, with negative impacts on food provisioning, tourism, the economy and human health. These impacts depend on species-specific responses to the interactive effects of climate change and other human drivers (e.g., pollution). Human communities in poorly monitored areas are among the most vulnerable to these biological hazards. In rocky intertidal shores, sessile calcified organisms (e.g., barnacles and mussels) are susceptible to extreme temperature events and acidification. A reduction in their biodiversity and abundance have been observed in naturally acidified rocky reef ecosystems.

Marine turtles have been among the great survivors of dramatic climate changes and fluctuating sea levels; turtles are expected to be little affected by sea-level rise as their nesting should occur above the new tide levels. The situation will be very different with low elevation sand islands, which occurs widely in the Pacific Islands nations, the Caribbean, the Maldives, and the Great Barrier Reef. At these low elevation sand beaches, the combined impact of erosion and flooding of the nesting habitat is expected to cause increases in egg mortality and eventually loss of some nesting beaches. It is uncertain whether reef-building processes will keep pace with sea-level rise to renourish the beaches naturally. Turtles that lose their nesting beaches are expected to seek out new nesting sites.

Key points

• A significant proportion of the population in the Asia-Pacific region rely on fishery resources and tourism services for food and income, and all these activities depend on marine sustainability.

• The ocean health index in the region (both for the country's exclusive economic zone and in the high seas) is deteriorating, and innovative approaches are needed.

• According to the Global Climate Risk Index (CRI) 2021, more than 475,000 people died and US$2.56 trillion was lost as a direct result of more than 11,000 extreme weather events between 2000 and 2019. Myanmar, Philippines, Bangladesh, Pakistan, Thailand, and Nepal are among the top ten countries most affected from 2000 to 2019, while more countries and island states appear in the top 20 list, demonstrating the scale of the region's immediate risk.

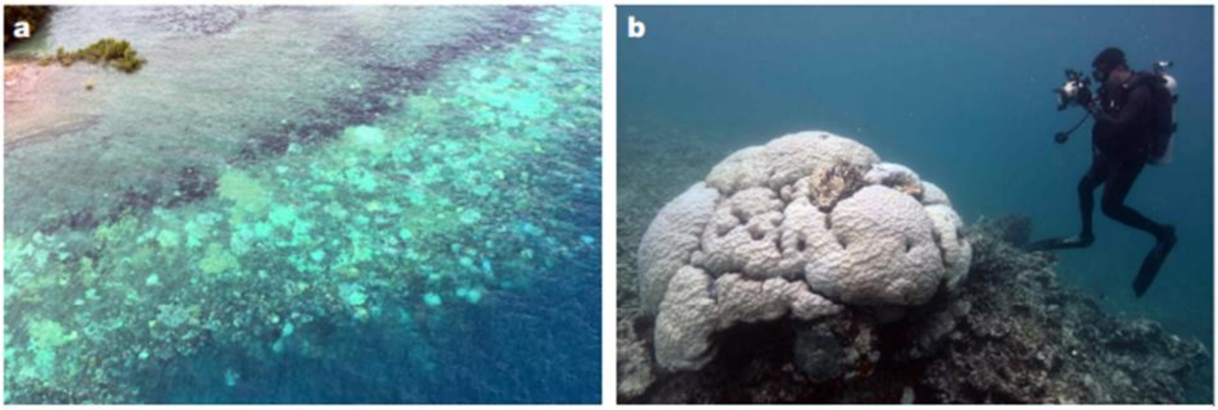
• Small Island Developing States in the region are more vulnerable to climate change, especially sea-level rise, as the population distribution is mainly concentrated close to the shoreline and are mostly reliant on ocean resources and tourism. Observed tuna migration from the EEZ of island states, harsh weather, and the COVID-19 have deprived fishers of their livelihoods and may threaten the economic security of island communities.

• The combined effects of warming, sea-level rise, acidification (pH dropping at a rate of 0.02 units per decade), and heatwaves will affect nutrient supply, lagoon flushing, and, eventually, ecosystem health in the region.

• The severe consecutive heatwave events in the South-Western Pacific significantly damaged the warm water corals in the region, resulting in widespread coral bleaching.

• Sea-level rise poses a significant threat to the restricted species ranges on smaller and atoll islands owing to the limited amount of suitable habitat and limited capacity for rapid adaptation of small islands.

Figure 7: Coral bleaching in Western Pacific during 2016 heatwave event.



Source : Hughes et al., 2017
Note: (a), March 2016, aerial image of extreme bleaching in Princess Charlotte Bay, North-East Australia. On the reef flat and crest, nearly all the corals have bleached. Bleaching happens when environmental stress kills algae symbionts (Symbiodinium spp.) in a coral host, revealing the coral's underlying white skeleton. (b), On the Northern Great Barrier Reef in 2016, severe bleaching devastated even the largest and oldest corals, including this slow-growing Porites colony.

4. Sea-level rise: Case studies in selected countries

GLOBAL MEAN SEA-LEVEL ROSE FASTER IN THE 20TH CENTURY THAN IN ANY PRIOR CENTURY OVER THE LAST THREE MILLENNIA. THE OCEAN THERMAL EXPANSION (38%) AND MASS LOSS FROM GLACIERS (41%) DOMINATE THE TOTAL CHANGE FROM 1901 TO 2018, WHEREAS ICE SHEET MASS LOSS HAS INCREASED AND ACCOUNTS FOR ABOUT 35% OF THE SEA LEVEL INCREASE DURING 2006–2018 (IPCC, 2021).

The studies on mass loss estimates from individual glaciers (Hugonnet et al., 2021) show that during the last 20 years, the highest regional mass-loss rates (>720 kg m^{-2} yr^{-1}) were observed in the Southern Andes, New Zealand, Alaska, Central Europe, and Iceland. It is projected that nearly all glacier mass in low latitudes, such as Central Europe, Caucasus, Western Canada and USA, North Asia, Scandinavia, and New Zealand will likely disappear; if warming is sustained in levels between 3°C and 5°C (IPCC, 2021).

At the basin scale, sea levels rose fastest in the Western Pacific and slowest in the Eastern Pacific over 1993–2018. Regional differences in sea-level rise occur due to ocean dynamics, especially climate events, such as El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), changes in earth gravity, rotation, and many other features. Furthermore, due to relative sea-level rise, extreme sea-level events that occurred once per century in the recent past are projected to occur at least annually at more than half of all tide gauge locations by 2100. Relative sea-level rise contributes to increases in the frequency and severity of coastal flooding in low-lying areas and coastal erosion along most sandy coasts (IPCC, 2021). The Asia-Pacific region is at imminent risk of sea-level rise, especially in the case of SIDS, as an average of 13% of Pacific SIDS' land lies less than 5 metres above sea level. In the Maldives, Kiribati, and Tuvalu, , 99% of land lies less than 5 metres above sea level[6].

Considering the imminent risk due to climate change, the low-lying coastal zones in the Asia-Pacific region acted as a focal theme for various research based on the risks of atoll island erosion under increased wave heights and accelerated sea-level rise (Oppenheimer et al., 2019). Some studies suggested that these islands may become uninhabitable by 2060-2090 under the RCP- 8.5 scenario due to annual flooding (Giardino et al., 2018; Storlazzi et al., 2018), whereas others have proposed that vertical accretion of shoreline systems may limit future flooding and its consequences for settlements (e.g., Beetham and Kench, 2018; Tuck et al., 2019). A recent publication from Duvat et al. (2020) suggested that these studies overlooked the effects of drivers other than sea-level rise and reported that the cumulative risk arising from multiple drivers (sea-level rise; changes in rainfall, ocean-atmosphere oscillations and tropical cyclone intensity; ocean warming and acidification) would be highest in the Western Pacific which will experience increased island destabilisation together with an increased threat to freshwater, and decreased land-based and marine food supply from reef dependent fish, and tuna-like resources. Whereas

[6] UNCTAD/PRESS/PR/2021/012.

risk accumulation will occur at a lower rate in the Central Pacific (lower pressure on land, with more limited cascading effects and increase in pelagic fish stocks) and the Central Indian Ocean (mostly experiencing increased land destabilisation and reef degradation).

EVALUATION OF SEA-LEVEL RISE

Sea level is defined as the level of the sea after averaging out the short-term variations due to wind waves. According to specific disciplines in Earth Sciences, there are many terms to represent the surface of the sea: from oceanography, meteorology to geodesy. Sea surface height (SSH) is commonly found in the satellite altimetry dataset as the height was measured above the geoid. Another related term is sea-surface topography, where sea level is described by calculating the undulation from Earth's magnetic fields and the mean sea surface. By observing the components of the ocean, the sea level can be estimated as increasing, decreasing or in certain warm/cold phases. However, the sea level rise is influenced by the wider ocean and climate spectrums over a more extended period.

The processes that occur in the ocean affect the dynamics of the climate and vice versa. The air-sea interaction is a key concept in Earth system science, where various elements in the planet are connected to each other, maybe much more closely than usually thought. The Walker circulation in the atmosphere, which generates easterly trade winds that move the 'warm pool' in the Pacific, initiates El Nino–Southern Oscillation (ENSO) events. Equatorial Kelvin waves, on the other hand, transport water from the 'warm pool' to the eastern part of the ocean, causing the thermocline to deepen. This results in impacts on fish catches; for reference, the terms El Niño (the boy) and La Niña (the girl) were coined by local South American fisherfolk, who noticed this ocean phenomena. The sea surface temperature anomaly of the east-central tropical Pacific is regularly monitored by the National Oceanographic and Atmospheric Administration (NOAA), and the anomaly value is called Ocean Nino Index (ONI). When ONI shows +0.5 or above, it indicates the ongoing El Niño, whereas the value of -0.5 or below signals La Niña. Generally, the El Niño or warm phase of ENSO contributes to a lower mean sea surface in the Pacific, and the cold phase (La Niña) precedes a higher mean sea surface with more than a three-months lag. Several climate modes formed in other major oceans resemble ENSO, such as the Indian Ocean Dipole (IOD), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO).

However, the variability of sea level in other regions (mesoscale variability) might display contrasting results. Understanding which processes have a more dominant role in the observed changes requires complex methods (Milne et al., 2009). In some areas, the allosteric change (the sea-level change due to diverse density associated with salinity) might be crucial, but in other parts of the ocean, the thermosteric effect could give more significant contribution to the ocean dynamics (Fig. 8). Therefore, statistical techniques are deployed to examine the climate change effect more thoroughly. Two of the most popular methods are Empirical Orthogonal Function (EOF)[7] or Principal Component Analysis (PCA) and linear regression[8].

EOF and PCA separate variations of sea level based on its mode; climate events that range from

[7] Signal analysis with a low pass filter is conducted to separate the low-frequency data.

[8] A linear regression line has an equation of the form $Y = a + bX$, where X is the explanatory variable and Y is the dependent variable.

seasonal (i.e., monsoons) to interannual (ENSO) occurrences could be detected from their signals. Linear regression is very useful to project the sea level rise rate for decades, with a maintained margin of error. Another less common method is Anderson-Darling, which may be useful to assess the distribution of normal values. Statistical methods bridge the gap in data-sparse availability from satellite altimetry, tide gauge stations and model reanalysis. The sea-level rise calculated from selected locations in the Asia-Pacific region is further discussed below.

EVALUATION OF SEA-LEVEL RISE FROM SELECTED REGIONS

1. Overview of sea-level rise in the maritime continent

a. Spatial information of the maritime continent

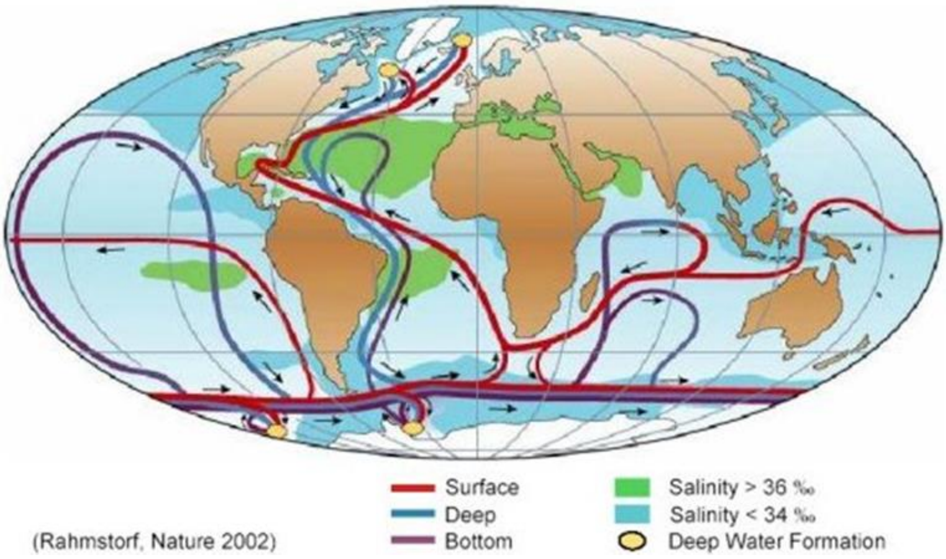
Maritime continent refers to the region in Southeast Asia that consists of countries such as Indonesia, Malaysia, and the Philippines. The primary area between the Indian and the Pacific Ocean plays a significant role in regulating regional and even global climate variability. The water passage known as Arlindo (Indonesian Through Flow) situated around the Makassar Strait has been a continuous source of oceanographic research. It allows the water masses to transport from the Pacific Ocean to the Indonesian seas and the Indian Ocean. Moreover, the passage is an integral part of the thermohaline circulation, also known as the Great Ocean Conveyor Belt. It is argued that the disturbance in any path of Arlindo would cause a striking fall of temperature over the North American region, as the less saline and denser water body could not sink at the Atlantic. This scenario highlights the importance of air-sea interaction to worldwide climate conditions.

b. Case study: Indonesia (Aceh and Sulawesi)

Aceh is situated near the Indian Ocean and the Andaman Sea. The water region is closely related to the South China Sea Summer Monsoon onset; thus, the sea-level dynamics could be defined by monthly, annual and interannual climate variability. Based on recent studies using satellite altimetry data from NASA, the sea-level rise in Aceh reached 4 cm or an increase of 0.16 cm for the last 25 years (Setiawan et al., 2019). To capture a synoptic view on the dynamics of sea level, a linear regression plot was constructed based on tide gauge data from the Sea Level Station Monitoring Facility of The Intergovernmental Oceanographic Commission of UNESCO (IOC). The tide gauge record of sea surface height of the Aceh region gives no visible trend from 2005 to 2018. The constant influence of IOD and South China Sea summer monsoon (SCSSM) that modulate the precipitation rate is likely the main cause of this result.

Due to the discrepancy between altimetry and tide gauge data, a fitted line plot was created to minimalize the scattered value and observe the most appropriate regression line. The 'noise' (monthly value) was averaged, which produced the 14 bars of sea level on the second graph. Harmonic pattern from the plot suggests a strong tidal influence over the region near the Indian Ocean. This matches the analysis from Setiawan et al., 2019, where the sea level movement is generated by the difference between high and low tide. Since tidal waves depend on coastal morphology and gravity, it is assumed that the increasing sea level mirrors the global rate, although it does not directly affect the Aceh region.

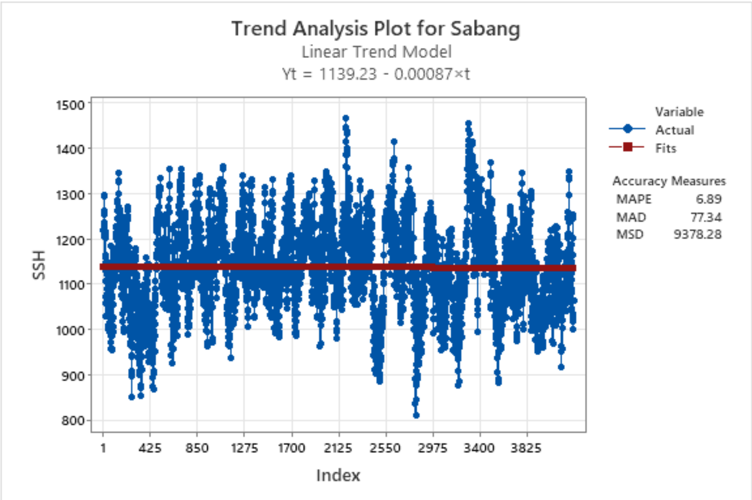
Figure 8: Illustration of global ocean circulation



Source: http://www.pik-potsdam.de/~stefan/thc_fact_sheet.html

Figure 9: (a) Trend analysis plot for Sabang and (b) fited line plot

a)



b)

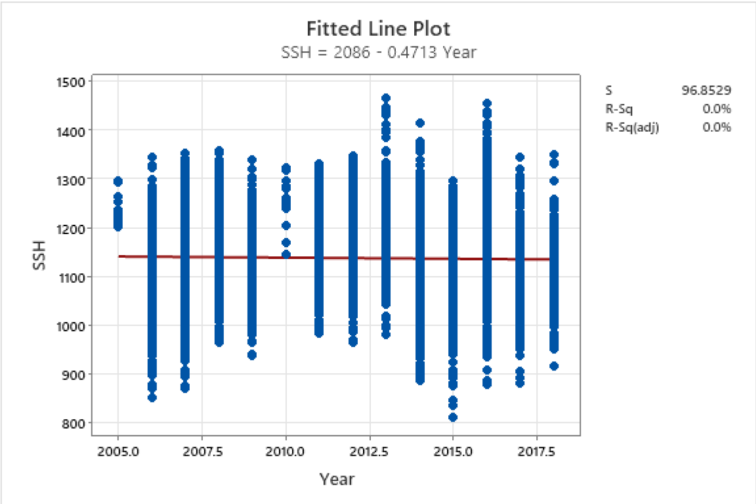


Figure 10: Trend analysis (linear regression model) plot for Viti Levu

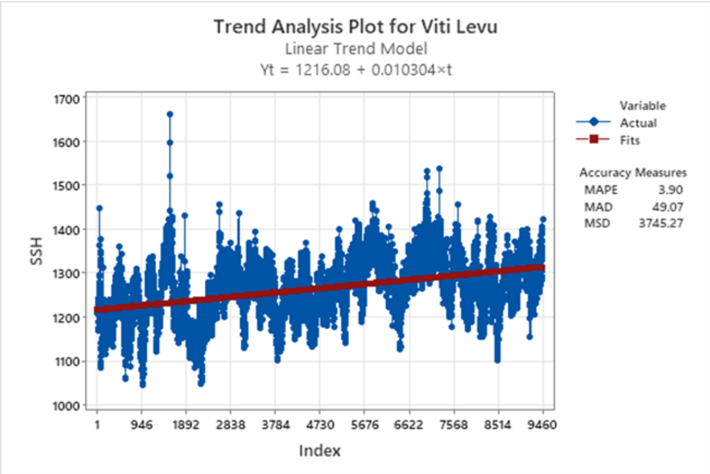
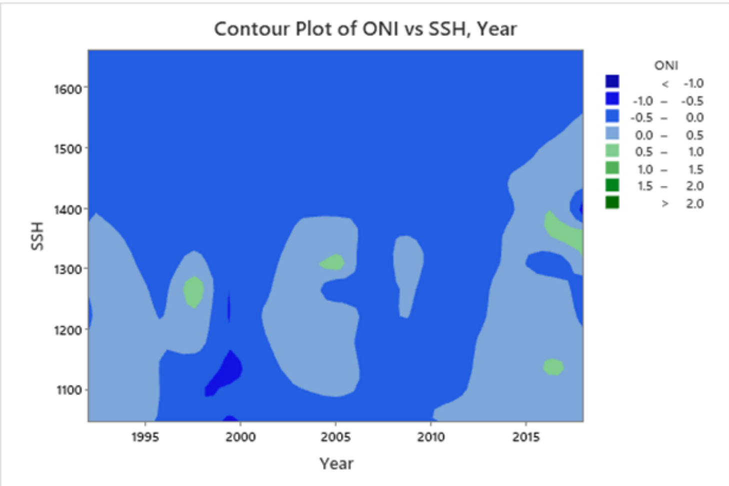


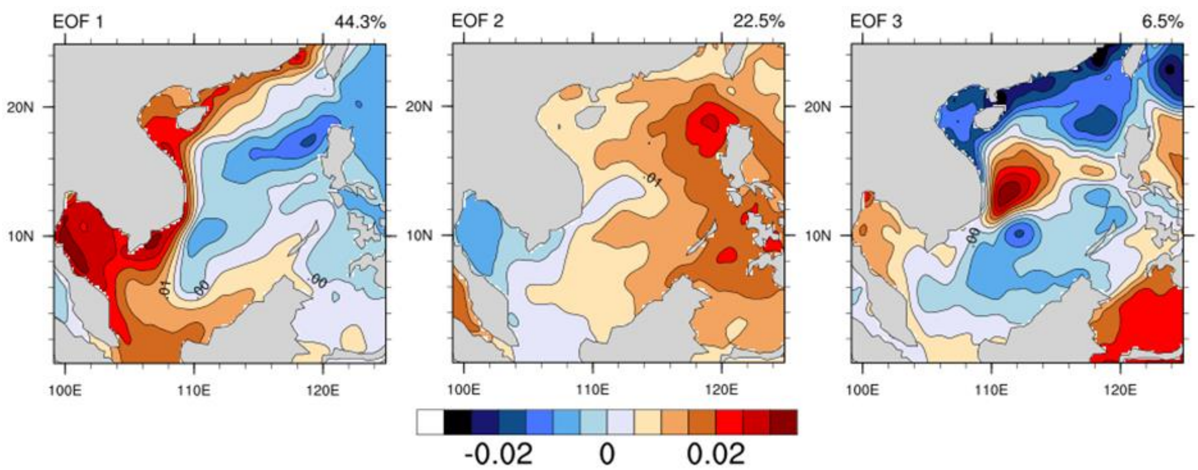
Figure 11: Correlation between El Niño index (ONI) with Sea Surface Height (SSH)



Note: The positive number (more than 0.5) of the Ocean Nino Index (ONI) indicates the ongoing strong El Niño, whereas the negative ONI (smaller than -0.5) shows the occurrence of a strong La Niña

Figure 12: (a) Empirical Orthogonal Function (EOF) of Sea Level in SCS.

a)



2. Overview of sea-level rise in Pacific

a. Spatial information of small islands in the Pacific

Fiji is located in the South Pacific. The country has over 300 islands, and most of the population resides on the main island, Viti Levu. ENSO and PDO modulate the dominant portion of climate in Fiji, including its rainfall. By its nature and characteristics, the Pacific Ocean provides balanced precipitation and evaporation value that maintain the water mass in global circulation. A report by Mörner (2017) suggests that the present sea level rise in Fiji is non-existent due to the Earth forcing that alters the water mass circulation during the last 600 years. Other studies from Kelman (2017) describe possible scenarios that could take place in Fiji due to El Niño, including less rainfall, more frequent cyclones, and lower sea level. However, the ENSO linkage with historical sea level data in both papers is apparent. It is noteworthy how climate mode acts in smaller temporal and spatial scales.

b. Case study: Fiji (Viti Levu)

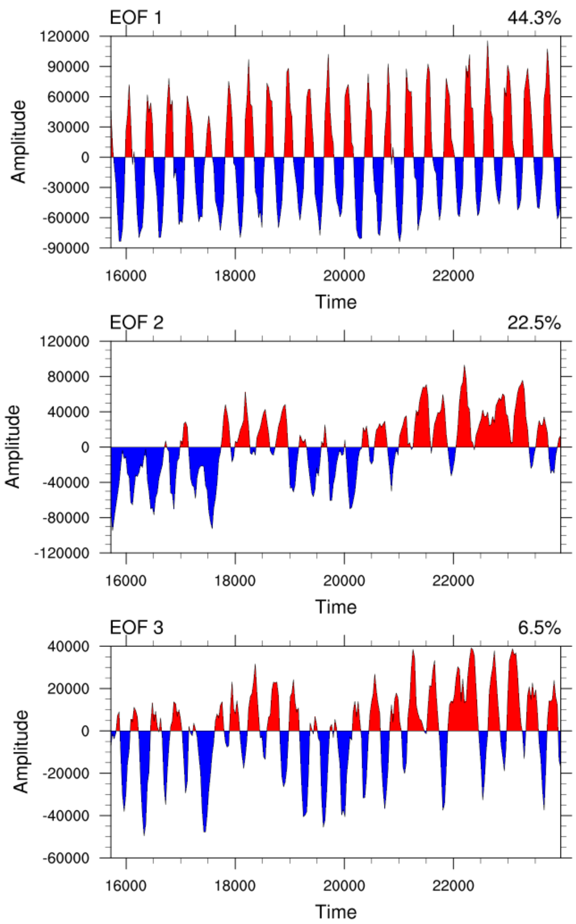
The linear regression model below shows the projection of sea surface height with lower than 3% error. Based on tide gauge records at Viti Levu station, there is an increasing trend of sea level in Fiji. Generally, the trade wind plays a vital role in the rising of sea level in the Pacific. Anthropogenic heat flux from activities such as industry, agriculture and landfills have a minor impact to sea level variability. On the other hand, ENSO features another contrasting correlation with sea-level variability. As displayed in the contour plot below, ENSO has had a growing influence on sea level height from 2015 onwards. The positive number (more than 0.5) of the Ocean Nino Index (ONI) indicates the ongoing strong El Niño, while the negative ONI (smaller than -0.5) shows the occurrence of a strong La Niña. The green dots that fit the positive correlation explain the above-average sea surface height during strong ENSO on the certain area off the coast of Viti Levu and below average on another region. It is expected that El Niño Southern Oscillation will accelerate the sea level rise in the Pacific for the next decades. The ocean-climate model might exert a more vital role in the future, based on statistical analysis in this study. In certain parts of Fiji, there might be more imminent threats of sea-level rise, and the risk of climate hazard could also befall other countries such as Kiribati, Vanuatu, and Samoa. There is not much to do to minimize the impact of ENSO or another large-scale mode. Rather, the most appropriate approach would be in collaboration of in situ data and research among countries in the Pacific Islands.

3. Overview of sea-level rise in Southeast Asia

a. Spatial information of Philippines

The Philippines is one of the archipelago countries situated in South China Sea (SCS). Besides its high economic value as a major marine transportation route, SCS is also known as the monsoon onset region. Besides seasonal variability, long-term signal could be traced by examining the water mass transport in certain areas in the SCS. For instance, the Kuroshio and Arlindo enter the South China Sea through Luzon Strait, displaying distinctive salinity and temperature. In order to obtain general spatial information about this region, the Empirical Orthogonal Function (EOF) and its counterpart, Principal Components Analysis (PCA) were conducted. The red marks in both disclose positive correlation while the negative correlation is represented by the blue color.

Figure 12: (b) Principal Components (PC) of Sea Level in SCS



It is shown that the first mode of EOF explains 44% of the variance in sea level of the SCS. This mode is closely related to seasonal and annual atmospheric events, such as monsoon and ENSO. There is a strong connection between the high level of the water column in the coastal area of mainland China and the Gulf of Thailand to the monsoon that occurs almost periodically. However, it is odd to see that the ENSO could exert a contrasting effect on sea level, just like the results in Fiji. The image EOF 3 shows both strong positive and negative correlations between climate events and sea level are spatially justified around Luzon Strait. Arguably, other driving mechanisms account for this variability, such as vertical land movement, thermal expansion, and freshwater influx.

b. <u>Case study: Davao</u>

Mesoscale variation is prominently demonstrated over the Philippines, including storm surges. Therefore, the calculation of sea level must take severe thunderstorms, hurricanes, and floods into accounts. It seems that there is a symmetrical pattern of sea surface modulation. Despite the increasing trend, the graph below indicates that during a certain period, the water balance in this region is disrupted. This is hardly possible since the area of the South China Sea, and Luzon is highly active. The trigger might lie on Glacial-Isostatic Adjustment (GIA). GIA is a technique used in oceanography to determine the vertical land movement on the tide gauge station. If GIA is added, then the trend might be justified. The sea level rate over the Philippines is increasing, only at a smaller rate or parallel with the global rate.

In order to obtain a more detailed description of sea surface dynamics, the Anderson-Darling (AD) normality test was performed. The extreme weather influence could be seen from the probability plot. Since the p-Value is so small (below 0.005), it is assumed that the sea level data are not normally distributed. This explains why contrasting signals on EOF modes were detected. The local forcing might exert a more dominant role in this region than ENSO in the near future.

In sum, the three case studies presented above show that sea-level rise has increasingly become an environmental concern in the region. As governments prepare national mitigation and adaptation strategies to climate change, sea-level rise in coastal communities must be included. Sea-level rise projections may inform local and national action plans to increase the resilience of affected communities and to protect the health and wellbeing of inhabitants. The quality and the quantity of data availability needs major improvement. Comprehensive projection of sea-level rise and climate change impact on regional scale necessitates enormous historical records and satellite observations; a growing concept called 'big data oceanography'. A wide collection of reliable measurements, along with improved altimetry data and ocean models, could be highly beneficial for policymakers to cope with sea-level rise threats in their respective countries and to formulate effective policies to address these challenges.

Key Points

• The sea-level rise is observed in Viti Levu, Sulawesi and Davao; no trend is detected in Aceh.

• ENSO becomes the dominant figure in accelerating sea-level rise through thermal expansion.

• More comprehensive data, especially from tide gauge stations, needs to be easily accessed by local governments to monitor the sea surface height, cope with the regional effect of climate changes, and protect the health and well-being of inhabitants.

• Comprehensive projection of sea-level rise and climate change impact on regional scale necessitates enormous historical records and satellite observations ('big data oceanography').

• A wide collection of reliable measurements, along with improved altimetry data and ocean models, could be highly beneficial for policymakers to cope with sea-level rise threats. in their respective countries and to formulate effective policies to address these challenges

Figure 13: Anderson-Darling probability of Sea Surface High in SCS.

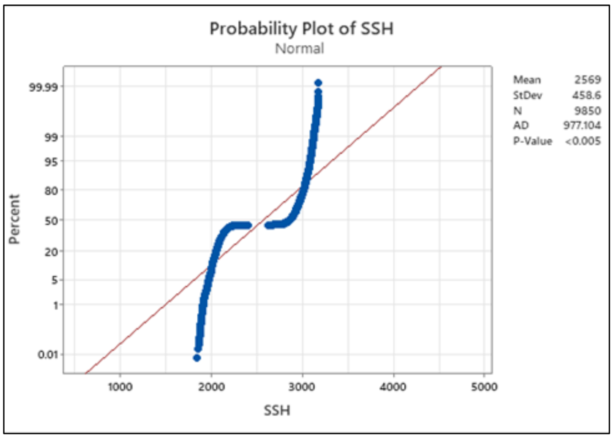
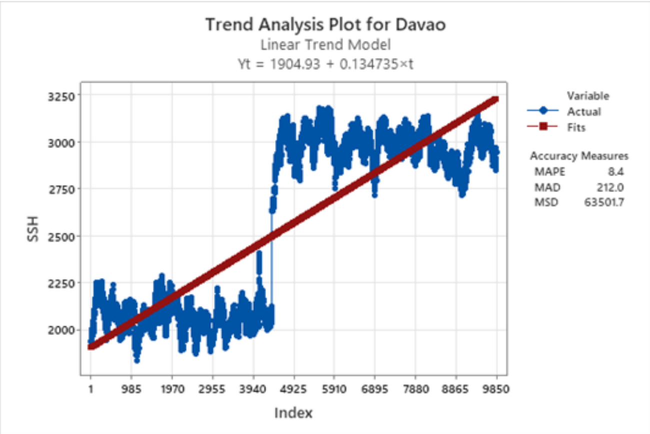


Figure 14: Trend analysis plot for Davao.



5. Conclusion

Ocean health is measurably deteriorating with global warming and anthropogenic CO2 emissions, and it is causing irreversible changes to the glaciers, ice sheets and ocean, and poses a critical threat by increasing sea-levels. Furthermore, it amplifies the stress on the ocean, causing the ocean to warm, stratify and become acidic. These changes alter the abundance and distribution of life throughout the ocean and negatively affect coastal ecosystems and the communities they serve.

The Asia-Pacific region is more affected by the following climate change impacts: i) the imminent threat of sea-level rise to the coastal areas, low lying coastal zones and SIDS, ii) frequent heatwave events in the Western Pacific, iii) increased risk of extreme weather events, iv) coral bleaching and degradation of coastal ecosystems/habitats (mangroves, seagrass, and salt marshes), v) migration of tuna and other fish stocks, which provides significant revenue, vi) loss of biodiversity and abundance owing to increased ocean stressors and less biological productivity.

Since the region is home to over 200 million people who depend on fishery resources and tourism for food and income, deterioration of ocean health, coastal infrastructure, and resources, along with harsh weather will substantially influence the coastal population. Low lying coastal zones and SIDS are more vulnerable to these changes as the population distribution is mainly concentrated close to the shoreline, whereas regions far from coastal zones are also affected by the extreme weather events.

The projected trajectories under various scenarios indicate that immediate action is required in the region to minimize or restrict the impending threats and to develop better policies and strategies to adapt to these changes. Reliable measurements, along with improved altimetry data and ocean models, would support policymakers in formulating effective policies to address these challenges.

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