Journal of Climate Change, Vol. 7, No. 3 (2021), pp. 69-82.
DOI 10.3233/JCC210020

Climate Change as Observed in the Bay of Bengal

Rajalakshmi P.R.* and Hema Achyuthan
Institute for Ocean Management, Anna University, Chennai - 600 025
✉ r_ragee@yahoo.co.in

Received June 24, 2021; revised and accepted July 30, 2021

Abstract: The Bay of Bengal covers a vast expanse of area, it being warmer, holds signatures of climate change. Its impact and the parameters have been studied in terms of rise in temperature, sea level change, increased rainfall, drought, heat waves, the intensity of tropical cyclones, ocean acidification and ocean productivity. In the last 45 years, sea surface temperature (SST) has risen by 0.2 to 0.3°C and is projected to rise further by 2.0 to 3.5°C by the end of this century. As a result, the sea level is expected to also rise 37 cm by 2050. The Bay of Bengal is witnessing an increase in the intensity of cyclones in the last two decades. Floods and droughts have increased over the years and are a growing threat to plant and animal life. Ocean acidification and increase in the sea surface temperature have made many fish species a major part of the coastal food chain vulnerable to its productivity. Hence, the collection of real time data and its continuous monitoring of the Bay of Bengal is essential to predict and project the future climate change to its accuracy both in space and time.

Keywords: Tropical cyclones; Sea level rise; Sea Surface Temperature; Ocean acidification.

Introduction

The theory of climate change involving CO_2 variations is viewed as one of the major mechanisms for understanding climate variability of the geological past, including the Archean, the Cretaceous periods (Kichl and Dickinson, 1986; Barron and Washington, 1984), and the ice ages of the Pleistocene (Jouzel et al., 1987; Barnola et al., 1987). The important non-CO_2 trace gases that govern climate change include CFCs, CH_4, N_2O, ozone (O_3), and more than a dozen synthetic chemicals (Wang et al., 1986; Ramanathan, 1987; Tricot and Berger, 1987; Brihl and Crutzen, 1988). These developments set the stage for a number of recent theoretical and climate model studies (Bolle et al., 1986). According to the 2019 Intergovernmental Panel on Climate Change's (IPCC's) *Third Special Report on The Ocean and Cryosphere in a Changing Climate* (Srocc), the global ocean has absorbed 90% of the excess heat generated by greenhouse gas (GHG) emissions since the baseline year of 1970.

It is noted that higher temperatures have a greater negative impact for poorer districts: a 1°C rise in temperature leads to a nearly 4.7 percent fall in the growth rate of district per capita income. Access to developmental infrastructure, urbanisation, access to credit, and greater energy access plays a significant role in mitigating the negative impact of climatic parameters (Sandhanai et al., 2020). A detailed literature survey also indicates that a broad strategy to mitigate the negative impact of climate change is to focus on investment in human capital and improvement of infrastructure, especially in carbon-intensive regions and hotspots which are more prone to climate damages (Mani et al., 2018).

The Bay of Bengal (BOB), the largest bay in the world, forms the major coastline of Bangladesh, India, Myanmar, and Sri Lanka. These countries receive

*Corresponding Author

rainfall during the northeast and southwest monsoon but dominantly during the southwest monsoons. The large inflow of fresh water from precipitation and runoff results in strong near-surface stratification of waters and sediments in the BOB. In the BOB, low-level Findlater jet wind-forced processes have a minor impact on the heat budget while diffusion overwhelms other oceanic processes and the reason for this lies in the asymmetry of the wind field in the north Indian ocean. The weak winds over the BOB force a relatively sluggish oceanic circulation in the BOB, making it difficult for overturning or coastal pumping to remove heat from the control volume. It is the difference in the structure and magnitude of winds that keep the mean temperature of the top 50 m of the bay warmer (Shenoi et al., 2004) hence the warmer BOB gains greater significance with respect to climate change. In this paper, we discuss the factors responsible for climate change in the Bay of Bengal and its effects. The aim of this paper is to address the effect of climate change on the BOB by studying several parameters rather than focussing on a single factor. The purpose of integrating all climate change indicators is to help us in understanding the impact of climate change in a better way so that necessary adaptive and mitigative measures can be planned accordingly. Understanding the complex interactions and feedback mechanisms between climate and marine ecosystems is an important stage towards predicting and dealing with the consequences of change for the coupled biosphere-geosphere-humanosphere (Brierley and Kingsford, 2009).

Onset of Climate Change

Abram et al. (2016) studied the global warming trend and the time lag taken for the earth to witness climate change. The similarity of post-AD 1800 trends in the tropical Indian and western Atlantic oceans with those in Europe, Asia and North America (Table 1), indicates that the industrial-era warming of the tropical oceans has progressed at a rate similar to the warming of the Northern Hemisphere mid-latitude continents. By contrast, rates of century-scale warming since AD 1800 in the Southern Hemisphere regional reconstructions are slower than that for the tropical oceans and Northern Hemisphere continents. This difference is related to the delayed onset of warming in Australasia (region which comprises Australia, New Zealand, and some neighbouring islands) and South America reconstructions, but is also consistent with instrumental evidence of hemispheric asymmetries in the rate of twentieth-century warming (Figure 1a, b). Even though the industrial era began in 1750 as per IPCC 3rd report, paleoclimate time-of-emergence assessment indicates that the early onset and rapid rate of warming resulted in the emergence of climate change only since the 1930s; approximately 100 years after the sustained, significant warming began. The time when a climate-change signal exceeds the range of climate variability is known as the ‘time of emergence’ (Hawkins and Sutton, 2012).

Factors that Indicate Climate Change in the Bay of Bengal

Sea Surface Temperature (SST)

Analysis of global sea surface temperatures indicates an increase in the temperature range of 0.2-0.3°C since 1900 (Folland and Parker, 1990). Rising atmospheric greenhouse gas concentrations have increased the global average temperatures by ~0.2°C per decade over the past 30 years (Hansen et al., 2006) with most of this added energy being absorbed by the world’s oceans. As a result, the heat content of the upper 700 m of the global ocean has increased by 14 × 1022 J since 1975 (Levitua et al., 2009) while the average temperature of the upper layers of the ocean has increased by 0.6°C over the past 100 years (IPCC, 2007). As per the Intergovernmental Panel on Climate Change (IPCC, 2007) report, during 1980-2015 the average global surface temperature rose by 0.9°C.

Observed changes in water mass properties by Mitra et al. (2009) during 1980-2007 suggested that:

- Surface water temperature in the deltaic complex of Indian Sundarbans experienced a gradual increase from 1980 through 2007 at a rate of 0.5°C per decade. This rate is much higher than the globally observed warming rate of 0.06°C per decade, and the IPCC documented rate of 0.2°C per decade in the Indian Ocean during 1970-99.
- The waters of the western rivers (Hooghly and Muri Ganga) are fresher now than in the 80’s and 90’s, probably, primarily due to the increased amount of meltwater from the Gangotri Glacier which is receding at the rate of 23 m/year.
- The waters in the eastern sector of the Indian Sundarbans show increasing salination due to siltation, mixing with ocean water and possible global warming leading to evaporation while being deprived of the meltwater.

SST has increased by 0.2°C to 0.3°C along the Indian coast in the last 45 years, and it is projected to increase by 2.0°C to 3.5°C by the end of the century

Table 1: Onset, rate and emergence of industrial-era warming in reconstructions and simulations (After - Abram et al., 2016)

	Year of onset of sustained, significant warming trends		*Century-scale trend distribution (°C per century)*		*Year of emergence*
	Reconstructions	*Simulations*	*Reconstructions*		*Reconstructions*
			AD 1500-1799	*Since AD 1800*	
Arctic	1831	1843 (1819-1880)	-0.11 (-0.41-0.07)	1.07 (0.92-1.26)	1930
Europe	1852	1888 (1840-1987)	0.02 (-0.39-0.33)	0.46 (0.29-0.58)	1994[ℜ]
Asia	1849	1833 (1807-1999)	0.00 (-0.18-0.10)	0.48 (0.35-0.54)	1987[ℜ]
North America	1847	1859 (1823-1900)	0.01 (-0.38-0.15)	0.48 (0.29-0.52)	§
Western Atlantic Ocean	1828	1836 (1811-1879)	-0.11 (-0.21-0.01)	0.41 (0.27-0.51)	1948
Western Pacific Ocean	1834	1830 (1818-1836)	-0.09 (-0.13-0.02)	0.27 (0.19-0.35)	1962
Indian Ocean	1827	1830 (1814-1838)	-0.14 (-0.31-0.04)	0.51 (0.39-0.54)	1962
Australasia	1904*	1832 (1808-1833)	0.00 (-0.04 - 0.05)	0.07 (0.02-0.23)	1959
South America	1896	1840 (1802-1880)	-0.02 (-0.11-0.21)	0.20 (-0.02-0.38)	§
Antarctica	†	1839 (1819-1851)	-0.05 (-0.15-0.09)	-0.06 (-0.14-0.07)	§

Note: Statistics represent changes in surface air temperature (SAT) for continental reconstruction regions and sea surface temperature (SST) for tropical ocean regions. The values given are medians (inter-model medians for the simulations), with the 25% - 75% ranges in parentheses. The reconstructed median years of onset and emergence are determined using 15-50-yr filter widths.

* Compared with a median warming onset of AD 1886 in the original Australasia 2k reconstruction[4] that includes marine SST-sensitive records

† Sustained, significant warming never achieved in reconstruction

ℜ Emergence of industrial-era warming above the AD 1622-1799 (reference interval) variability was within 20 years of the end of the reconstruction, making permanent emergence uncertain.

§ Emergence was not achieved in reconstruction.

(Vivekanandan, 2011; Vivekanandan et al., 2016). Thirty years of SST data analysis presented by Meghal Shah et al. (2016) exhibited a gradual increase from 1980 to 2000 except during December. It revealed a sharper increase from 1980 to 1990 and then to 2000 in the BOB. Studies carried out by Dinesh Babu et al. (2020) on the variations in SST in the Indian seas from 1976 to 2015 (40 years) revealed that SST increased by 0.60°C along north-eastern India and by 0.69°C along the south-eastern India (Figure 2). This study also presented that the rate of change in SST along the east coast was 0.005 and 0.001 yr^{-1} for the southeast and northeast, respectively. A significant rate of increase in SST was observed during the last decade that resulted in comparatively higher climate-related disturbances. By the end of this century, the Arabian Sea and the Bay of Bengal are predicted to be the foremost marine areas with a rise in temperature by 4°C and 40 percent precipitation under the highest emission scenario. The increase in temperature and, in turn, precipitations will have a large impact on the coastal ecosystem such as the mangroves. Mangroves in tropical regions are sensitive to global warming, which impacts the extent and composition of mangroves (Vivekanandan, 2011). The occurrence of harmful algal blooms has become more frequent, intense and widespread and often cause considerable mortality of fish in the Arabian Sea and the Bay of Bengal (Gomes et al., 2014; Martin and Shaji, 2015; Vivekanandan, 2011) and thus there is a relationship between the increased surface temperature and the incidence of infectious diseases (e.g., dengue fever; Paul and Tham, 2015).

Rise in Sea Level

The greenhouse gases released into the atmosphere are absorbed by the ocean and this increases the heat content of the ocean which leads to thermal expansion of the oceans as well as increased meltwater and discharged ice from terrestrial glaciers and ice sheets have increased ocean volume and hence sea level (Rahmstorf et al.,

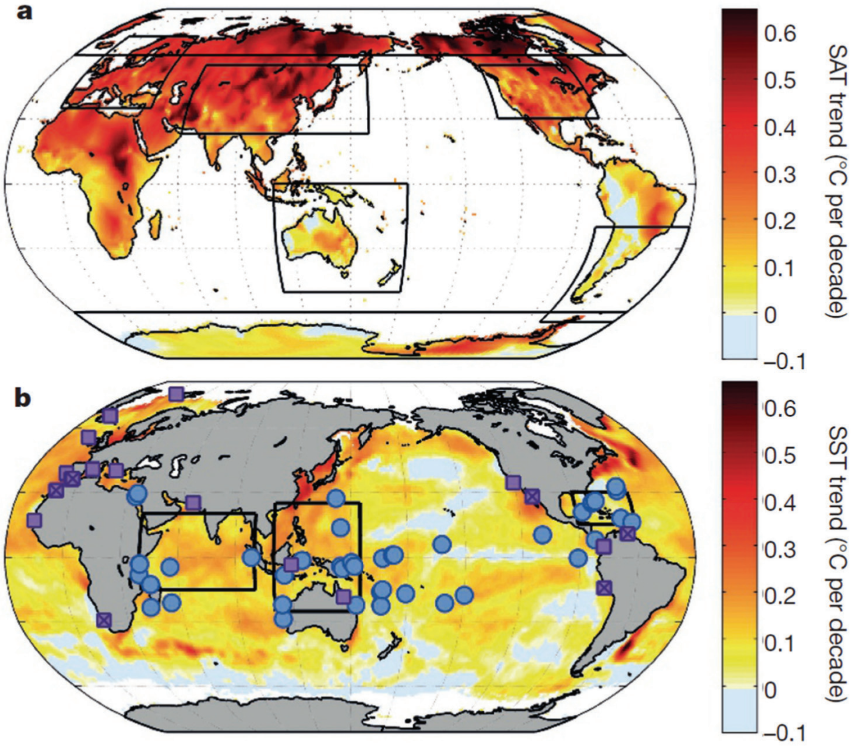

Figure 1: Terrestrial and marine paleoclimate reconstructions. a, b, (After - Abram et al., 2016). Instrumental temperature trends over the period ad 1961–2010 for surface air temperature (SAT; a) and sea surface temperature (SST; b).

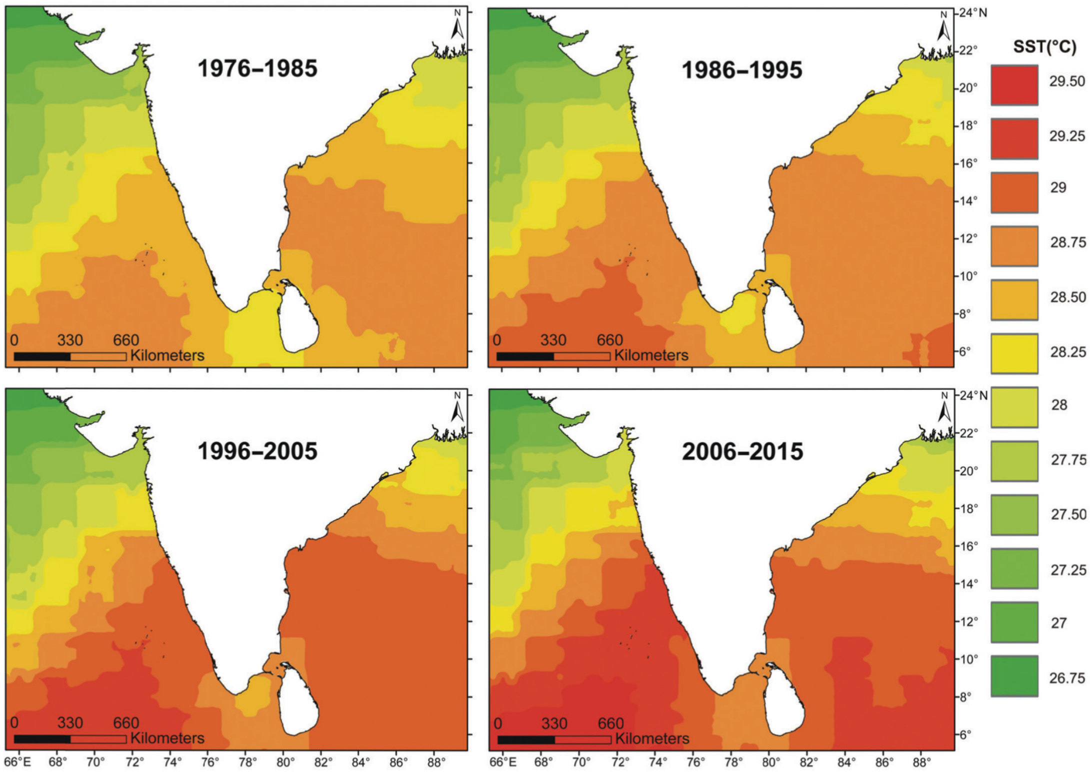

Figure 2: Rapid rate of warming in the Bay of Bengal (After Dineshbabu et al., 2020).

2007). This is a chain reaction with cause-and-effect parameters interrelated. The major impact of increased ocean temperature causes the increment in sea level, as per the IPCC report, and nearly about 190 mm sea level got changed up to 2000 (Henderson et al., 2018). The Assessment Report 4 of the IPCC projected that global sea levels will rise by up to ~ 60 cm by 2100 as a result of ocean warming and glaciers melting. Applying the Representative Concentration Pathway RCP 4.5 scenario and 40 cm under RCP 8.5 by 2050, with respect to 2005 and with Coupled Model Intercomparison Project CMIP5-simulations; Kusche et al. (2016) estimated that the absolute sea level in Bay of Bengal may rise additionally by 37 cm.

And hence the impacts of this sea level rise will be:

- Loss of fragile habitat near coastal lands and increase in salinisation covering larger areas and population displacement along the coast
- Will affect agriculture sector (e.g., loss of yield and create a high percentage of unemployment)
- Reduce fresh water availability
- Erosion of sandy beaches
- Hamper coastal tourism (Shukla et al., 2003; Leatherman et al., 1997).

Apart from the increment in sea level rise, in the areas where a very negligible amount of fresh water is added, the salinity of that area will also increase owing to high evaporation.

The oceans that are closer to ice cover or glacial areas will experience lower salinity due to the melting of ice caps and glacial activity because of higher atmospheric temperature and this will negatively influence oceanic flora and fauna. The impact of the rise in temperature will also melt the glaciers in the mountains which will lead to Glacial Lake Outburst Floods (GLOFs). A GLOF refers to the flooding that occurs when the water dammed by a glacier or a moraine is released suddenly. One such major disaster struck Uttarakhand's Chamoli district on February 7, 2021 in the form of an avalanche and deluge, after a portion of the Nanda Devi glacier broke off. The sudden flood in the middle of the day in the Dhauli Ganga, Rishi Ganga and Alaknanda rivers – all intricately linked tributaries of the Ganga – triggered widespread panic and large-scale devastation in the high mountain areas.

Increase in the Intensity of Tropical Cyclones

Tropical storms play a vital role in climate change by pumping a considerable quantity of heat from the ocean into the atmosphere each year, by generating mixing that brings cold deep water to the surface and through evaporation (Trenberth and Fasullo, 2007). These storms act as a release valve for solar heat caught above the sea in the humid, cloudy conditions of the summer tropics and are generated when surface water temperatures reach a threshold of ~26°C over a depth of ~50-100 m.

BOB is marginally conducive to tropical cyclone (TC) formation, with an average of three to four storms annually (Alam et al., 2003). The recent storms that struck the western and eastern coast of India were catastrophic. Tauktae cyclone made landfall on the Gujarat coast on 17^{th} May 2021 and precipitated copious rains inland closely followed by Yaas storm (26^{th} May 2021) that brought heavy rains and winds along the Odisha, Bengal and Bangladesh coast.

The India Meteorological Department (IMD), established in 1875 provides data for all meteorological statistics and forecasts on severe weather phenomena like tropical cyclones, heavy rains, cold and heat waves, etc. The classification of the low-pressure systems by IMD is mentioned in Table 2 (IMD, 2003). Based on IMD's long term data sets on TC, the maximum number of TC are in the month of October and November (Figure 3) and the number of depressions (D) shows a decreasing trend after 1950 whereas severe cyclonic storm (SCS) shows an increasing trend after 1960 (Figure 4).

Girishkumar and Ravichandran (2012) studied the difference between the storms that formed over BOB during the period 1981 to 1995 (27 storms) and 1996 to 2010 (24 storms). They noted that during 1981-1995, eight storms achieved TC strength or higher out of a total of 27 storms, for a conversion rate of nearly 30%. On the other hand, 10 out of the 24 total storms attained TC strength or higher between 1996 and 2010, resulting in a higher conversion rate of about 42%. An interesting feature of the BOB TC formation is the zonal asymmetry. Only three out of the 18 TCs formed to the west of 90°E, while an overwhelming 15 TCs formed to the east of 90°E. The difference is much starker for major TCs (MTCs). All seven MTCs that occurred in the BOB formed east of the 90°E longitude. This geographical dependence of TCs has been attributed to the longer time spent over the warm ocean of storms that form to the east of 90°E. Next, considering only the storms that formed to the east of 90°E, six out of the 14 storms that formed before 1995 achieved TC strength or higher, while nine out of the 12 storms that formed after 1995 attained a strength of the TC or higher, with conversion rates of 42% and 75% before and after 1995, respectively. Similarly, for MTCs, the conversion rates are 14% (two out of 14) and 42% (five

Table 2: Classification of cyclonic disturbance (Source IMD 2003)

Classification of cyclonic disturbance	*Maximum sustained surface wind speed (MSW)*	
	Knots	*km h−1*
Low-pressure area	< 17	< 31
Depression (D)	17-27	31-50
Deep depression (DD)	28-33	51-62
Cyclonic Storm (CS)	34-47	63-88
Severe Cyclonic Storm (SCS)	48-63	89-117
Very Severe Cyclonic Storm (VSCS)	64-89	118-165
Extremely Severe Cyclonic Storm (ESCS)	90-119	166-221
Super Cyclonic Storm (SuCS)	≥120	≥222

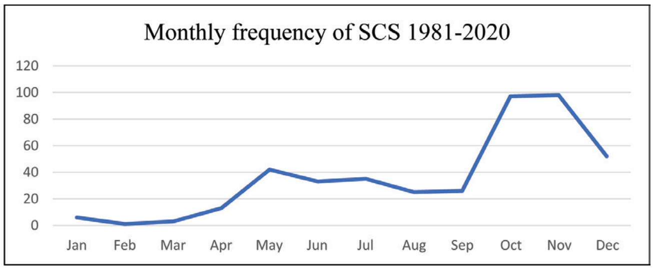

Figure 3: Monthly frequency of SCS 1981-2020.

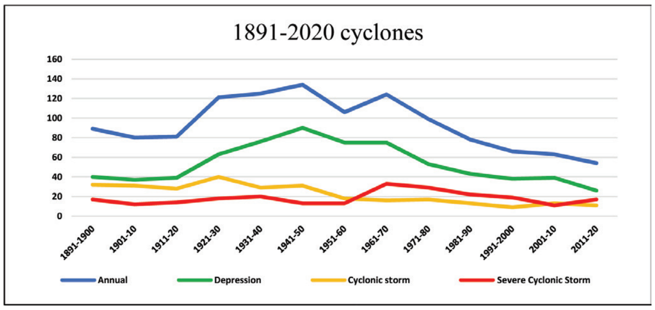

Figure 4: Cyclones in Bay of Bengal 1891-2020.

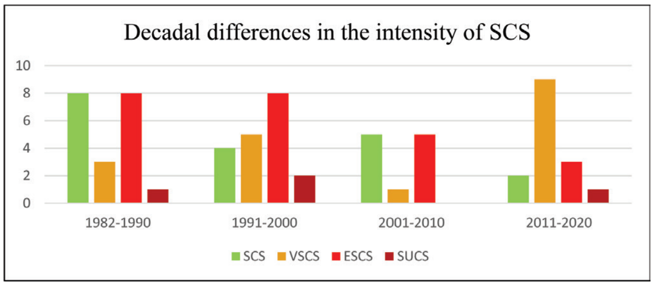

Figure 5: Decadal differences in the intensity of SCS 1982 to 2020.

out of 12) before and after 1995, respectively. These numbers suggest a stronger tendency of storms that intensified during 1996-2010 compared to the period between 1981 and 1995. The decadal TCs comparison for the period between 1982 and 2020 also indicates that the intensity of SCS has increased. Most of the SCS categories from 2011 to 2020 fall under VSCS (Figure 5). More recently, Super cyclone Amphan (May 2020) left at least 80 people dead in West Bengal and over 45 lakes were drastically affected in Odisha. It was the strongest storm to have formed in the BOB since the Super cyclone of 1999 that ravaged Paradip in Odisha.

A study by Balaguru et al. (2014) revealed that the intensity of MTCs increased in the BOB between 1981 and 2010. Their analysis on various oceanic and atmospheric parameters indicated that the large-scale environment for TC intensification was more favourable in the eastern BOB for the period 1996-2010 compared to 1981-1995. The main conclusions from their study are in general agreement with those of Elsner et al. (2008), who showed an upward trend in the formation of the strongest TCs in the northern Indian Ocean basin and relate it to global warming-induced rising SSTs.

Extreme Events

As the planet experiences global warming, climate changes will express themselves most obviously through water – i.e. through increased periods of drought and flooding, melting glaciers and changing rain and snowfall patterns. A warming climate also contributes to the intensity of heat waves by increasing the chances of very hot days and nights. It also increases evaporation on land, which can worsen drought and create conditions more prone to wildfire and a long wildfire season. El Niño events favour drought in many tropical and subtropical land areas, while La Niña events promote wetter conditions in many places.

These short-term and regional variations are expected to become more extreme in a warming climate.

Droughts

Droughts over India have been typically associated with prolonged periods of abnormally low monsoon rainfall that can last over a season or longer and extend over large spatial scales across the country (Sikka, 1999). The slow evolutionary nature of monsoon droughts and enhanced surface dryness exert significant impacts on water availability, agriculture and socio-economic activities over India (Asoka et al., 2017; Pai et al., 2017). India experienced an increase in intensity and percentage of area affected by moderate droughts along with frequent occurrence of multi-year droughts during recent decades (Niranjan Kumar et al., 2013; Mallya et al., 2016). The Standardized Precipitation Evapotranspiration Index (SPEI) over India for the period 1901–2016 analysed by Mujumdar et al. (2020) identified that the frequency and spatial extent of droughts over the country have increased significantly along with an increase in intensity, mainly confining to the central parts including the Indo-Gangetic plains of India, during 1951-2016. These changes have been observed in association with the decline in monsoon rainfall, which is likely due to an increase in anthropogenic aerosol emissions in the northern hemisphere, regional land-use changes as well as warming of the Indian Ocean.

Future projections using the regional as well as global climate models indicate a high likelihood of an increase in frequency, intensity and area under drought conditions covering large parts of India, and this is with medium confidence due to large spread in model projections (Aadhar and Mishra, 2018; Preethi et al., 2019). Though the climate models project an enhanced mean monsoon rainfall, the projected increase in droughts could be due to the larger interannual variability of rainfall and the increase in atmospheric water vapour demand (potential evapotranspiration) over the country (Scheff and Frierson, 2014; Jayasankar et al., 2015; Sharmila et al., 2015; Krishnan et al., 2016).

Floods

Flooding is an overflowing of water onto land that is normally dry. Floods can happen during heavy rains, when ocean waves come on shore, when the snow melts quickly, or when dams or levees break. Flash floods are the most dangerous kind of floods because they combine the destructive power of a flood with incredible speed. Flash floods occur when heavy rainfall exceeds the ability of the ground to absorb it. Droughts and floods across India are known to have complex linkages with the space-time distribution of monsoon rainfall and socio-economic demand (Sikka, 1999). Every year, nearly 8 million hectares of land area are affected by floods over India (Ray et al., 2019). The majority of floods in India are closely associated with heavy rainfall events, and not all of these heavy rain events translate into floods. Low pressure systems during the monsoon season or active monsoon conditions or monsoon breaks are the root cause of extreme floods in the South Asian rivers (Ramaswamy, 1962; Dhar and Nandargi, 2003).

The analysis of severe flood events using the flood database of Dartmouth Flood Observatory by Mujumdar et al. (2020) indicates a statistically significant increasing trend (1 flood event per decade) in the frequency of severe flood events over India during the period 1985-2019. Increase in extreme rainfall events (Goswami et al., 2006; Rajeevan et al., 2008; Guhathakurta et al., 2011), rate of intensification of cyclones into severe cyclones (Niyas et al., 2009; Kishtawal et al., 2012) and prolonged breaks (Kumar et al., 2009) are suggested to be the possible reasons for the intensification of river floods during the post-1950 period.

The increasing trend in floods is also possibly attributed to long-term climate variability (Ward et al., 2016; Najibi and Devineni, 2018). Chennai city is more prone to tropical disturbances, and cyclones, which often leads to flooding of major rivers and clogging of drainage systems (Boyaj et al., 2018). A major flood event that occurred in December, 2015 was reported as one of the most disastrous floods in the history of the region. Tamil Nadu and Puducherry observed an unusual prolonged wet spell during 1-17 January, 2021 (IMD report 8th Feb, 2021). It shows that rainfall was much higher than normal during most of the dates till 16 Jan, 2021(Figure 6). This heavy rainfall is attributed to the Western Disturbance.

The flood risk has increased over the East coast, West Bengal, eastern Uttar Pradesh, Gujarat and Konkan region, as well as a majority of urban areas such as Mumbai, Kolkata and Chennai (Guhathakurta et al., 2011). Analysis of precipitation Extremes under 1.5 and 2.0 °C global warming levels (GWL), committed under the "Paris Agreement", suggested a rise in the short duration rainfall extremes and associated flood risk urban areas of India (Ali and Mishra, 2018).

Ocean Acidification

The oceans are not only planet's heat sink, but also absorb approximately one-third of the carbon dioxide produced by human activities. The major impact of increased CO_2 concentration in ocean water is ocean

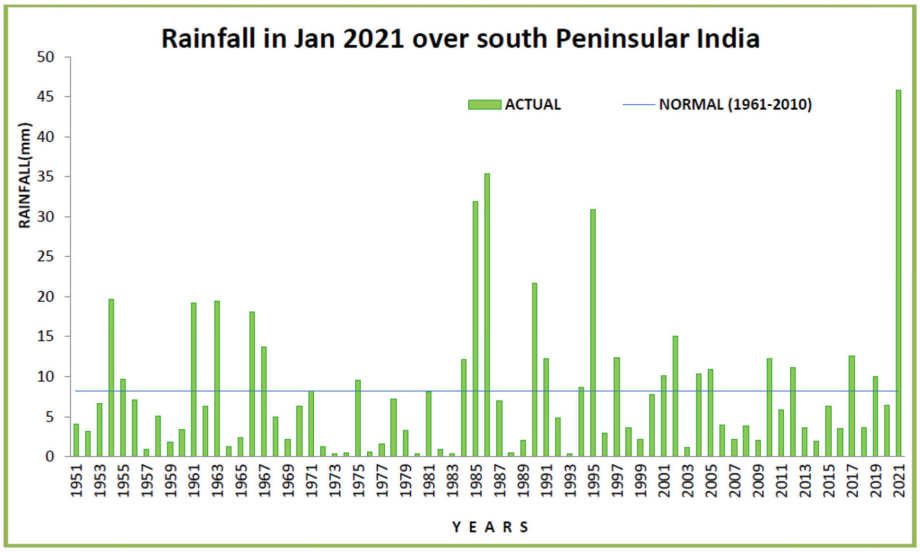

Figure 6: Cumulative Monthly Area weighted rainfall of Jan, over Peninsular India for the period 1951-2021 (Source: IMD).

acidification. It is estimated that since the start of the Industrial Revolution, surface ocean pH has declined from approximately 8.2 to 8.1, an effective increase in acidity ([H+]) of 30%, and a comparable magnitude change is expected by 2050 depending upon future CO_2 emissions (Orr et al., 2005). The absorption of anthropogenic CO_2 has acidified the surface layers of the ocean, with a steady decrease of 0.02 pH units per decade over the past 30 years and an overall decrease since the pre-industrial period of 0.1 pH units (Doney et al., 2009).

There are a number of potential consequences of OA (Raven et al., 2005; Doney et al., 2009), but one that is believed significant is its impact on the solubility of the mineral calcium carbonate ($CaCO_3$). As the ocean acidifies, carbonate chemistry shifts such that the concentration of bicarbonate increases, but that carbonate decreases. As a result, the solubility of $CaCO_3$ will increase, with potentially serious consequences for organisms using it for structural purposes (Orr et al., 2005; Fabry et al., 2008; Gangstø et al., 2011). The calcification process directly impacted a reduction in cell size of some phytoplankton species. Fish embryos and larvae are more sensitive to pH change than juveniles and adults (Brown and Sadler, 1989). Eggs of the pelagic fishes might be more susceptible to pH change. The increased level of dissolved CO_2 also reduces the pH of animal tissue (Portner et al., 2004) and it may affect marine fish physiology. Worldwide many more reports provide evidence regarding the reduction of phytoplankton cell size (Forster et al., 2012) (Figure 7).

The study on observed changes in water mass properties by Mitra et al. (2009) reveals that the surface

Figure 7: Ocean acidification effects- (A) Coccolithofores calcification, (B) Coral Bleaching, (C) Cell size reduction events (After Forster et al., 2012).

water pH decreased (-0.015/decade) in the western sector of the mangrove-dominated Indian Sundarbans. This is probably due to increased anthropogenic impact. However, on the eastern side, the pH shows an oscillating behaviour where it increases from 1980-90, 1996-98 and 2006-07. More study on this aspect is needed to quantify the effects produced by local effluents and increased run-off induced by climate change. Coral bleaching is likely to be an annual event in the future and reefs could soon start to decline and become only a remnant in the Indian seas between 2050 and 2060 (Vivekanandan, 2011).

Productivity

In any aquatic water body food web dynamics, biogeochemical cycles and fisheries productivity; primary productivity plays a major role, as they are the sole energy provider to the aquatic fauna present in that water body (Chassot et al., 2010; Passow and Carlson, 2012). Variation in temperature can also have impacts on key biological processes. For example, the distribution and abundance of phytoplankton communities throughout the world, as well as their phonology and productivity, are changing in response to warming, acidifying, and stratifying oceans (Doney et al., 2009; Polovina, 2008). Warming has also been found to decrease the size of individual phytoplankton (Morán et al., 2010) further altering the functioning and biogeochemistry of shallow pelagic ecosystems and, in particular, reducing their potential for carbon sequestration.

Overall, these changes in the primary production of the oceans have profound implications for the marine biosphere, carbon sinks, and biogeochemistry of the Earth (Falkowski et al., 2000). Temperature changes influence the changes in species distribution and composition, and there are several models on the distribution and abundance of species in relation to temperature (Hare et al., 2012). The rise in sea surface temperature affects the ocean's productivity as the temperature has a fundamental effect on biological processes simply by its influence on molecular kinetic energy (i.e., Maxwell-Boltzmann energy distribution), which determines the rate of fundamental processes such as enzyme reactions, diffusion, and membrane transport (Hochachka and Somero, 2002). Moderate increases in temperature increase metabolic rates, which ultimately determine life history traits, population growth, and ecosystem processes (Connor et al., 2007). Beyond the optimal range, however, acclimatisation fails, mortality risk increases, fitness is reduced, and populations decline or are driven to local extinction (Hochachka and Somero, 2002). Animal metabolism is temperature-dependent (Hochachka and Somero, 2002) and consequent ecological processes such as predator-prey interactions are likely to be altered as warming occurs (Sanford, 1999).

The Bay of Bengal is a region of relatively low biological productivity. The strong stratification that exists between the mixed layer and the thermocline (Vinayachandran et al., 2002) inhibits the upwelling of nutrients and makes the region strongly oligotrophic during summer (Prasanna Kumar et al., 2002). These factors contribute to the low productivity during the summer monsoon (Gomes et al., 2000; Kumar et al., 2002). In contrast, during the Northeast Monsoon, there are high chlorophyll concentrations over a large part of the western Bay of Bengal, and this has been observed from the 5 years weekly SeaWiFS satellite data from 1996 to 2001 (Vinayachandran and Mathew, 2003) and in hydrographic observations (Gomes et al., 2000). Gomes et al. (2000) also noted that better light conditions prevailed at that time than during the summer. These observations, as well as the modelling study, suggest that the productivity of the Bay of Bengal could be higher during the Northeast Monsoon. Jayalakshmi et al. (2013) has also reported an increase of 3.8 μM in the nitrate concentration at a cyclonic eddy region in the southwestern BOB during northern winter.

On the east coast of India, the fishing pressure is not allayed by productivity, and stocks became vulnerable along this coast. The high catch of oil sardine along the southeast coast may not be sustainable for long periods of time in the face of existing fishing pressure. Species with restricted geographic distribution, such as Bombay duck and golden anchovy are highly vulnerable to climate change. The exposure to climate variabilities, along with fishing pressure, increases the risk of the stock becoming depleted or collapsing. Fishes with a longer life span, lower growth rate (e.g., large tunas) and low fecundity (eg. Sharks) are found to be more vulnerable to climate change and existing fishing pressures. Of the attributes scored, phonology appeared to be more valuable as a measure for assessing the sensitivity of the shrimp species to climate change. Estuarine phases during the life cycles of some shrimp (e.g., *Fenneropeneaus indicus*, *Penaeus monodon*) make them more susceptible to disturbances, in river flow and current patterns, and thus to the effects of climate change. Indian species such as *F. Indicus* may suffer a collapse if adequate conservation measures are not undertaken. Stake net fishery and estuarine pollution also affect the recruitment of this species (Pecl et al., 2014). *P. monodon* displays high vulnerability along the Bay of Bengal coast. Tropical cyclones destroy the coastal embankment infrastructure and increase the salinity. This salinity intrusion and sea level rise creates a harmful effect on existing fish species. Water salinity exceeds the expected salinity level that is especially required for fresh water fish production. So, salinity intrusion has threatened fresh water fisheries and at the same time, creating opportunities for catching and cultivating brackish and marine species (World Fish Centre, 2007).

The Sundarbans mangrove forest located in the Gangetic delta (Ganges-Brahmaputra-Meghna) of India and Bangladesh is the largest single chunk of contiguous mangrove forest in the world (Gittings and Akonda, 1982). The Sunderbans have been playing a very important role as a protecting wall against the devastating cyclones and tidal surges by deflecting and reducing energy. The mangrove supports the offshore and deep-sea fisheries by playing a significant role as a nursery ground for many deep-sea fishes and shrimps including the *P. Monodon*, which is the major species of the industrial bottom trawl fishery of Bangladesh (Islam and Haque, 2004). Over 120 species of fish are commonly caught by commercial fishermen in the Sundarbans area (Seidensticker and Hai, 1983). Sundarbans are highly vulnerable to sea level rise and will submerge even with the 1-meter rise of the sea level (World Bank Report, 2000).

Marine fishes that are vulnerable to climate change along the eastern and western coast of India have been identified by Dineshbabu et al. (2020). Species with high vulnerability along the east coast of India are *Metapenaeus monoceros, Parastomateus niger, Plicofollis tenuispinis, Carcharinus limbatus, Decapterus russelli, Fenneropeneaus indicus, Katsuwonus pelamis, Nemipterus japonicus, Penaeus monodon, Sardinella gibbose, Saurida tumbil, Saurida undosquamis, Scomberomorus commerson, Sphyraena jello, Thunnus albacares and Trichiurus lepturus.* The Indian fishing industry is sustained by resilient species (sardines, mackerel, and threadfin bream) that are widely distributed with high fecundity and adaptive capacity. Fisherfolk has generally adapted to the ongoing changes that have occurred in the distribution, abundance and species composition of commercial resources.

Observations and Climate Change Projections for India

From the mid-twentieth century; India has witnessed a rise in average temperature; a decrease in monsoon precipitation; a rise in extreme temperature and rainfall events, droughts, and sea levels; and an increase in the intensity of severe cyclones, alongside other changes in the monsoon system. In spite of witnessing the growing threats of climate change, no serious measures have been undertaken to mitigate or reduce the greenhouse gases, consumption of fossil fuels, deforestation, etc., and hence the impacts of climate change reveal an increasing trend for the near future.

According to the report of the Ministry of Earth Sciences, Government of India on “Assessment of climate change over the Indian region (2020)” by the end of twenty-first century the average temperature over India is projected to rise by approximately 4.4°C relatives to the recent past (1976-2005 average[3]). On account of these increases in temperatures heat waves over India are projected to be 3 to 4 times higher by the end of twenty-first century as compared to the 1976-2005 baseline period. The SST of the tropical Indian Ocean has risen by 1°C on average during 1951-2015, markedly higher than the global average SST warming of 0.7°C, over the same period and is projected to continue to rise during the twenty first century. Sea-level rise in the North Indian Ocean (NIO) occurred at a rate of 1.06-1.75 mm per year during 1874-2004 and has accelerated to 3.3 mm per year in the last two and a half decades (1993-2017), which is comparable to the current rate of global mean sea-level rise and is projected to rise by approximately 300 mm relative to the average over 1986-2005.

Climate models project a rise in the intensity of tropical cyclones in the NIO basin during the twenty-first century. For more precise prediction, observational data like temperature, rainfall, SST, chlorophyll, etc. need to be collected periodically at closer intervals and the extreme events need to be monitored for their intensity, periodicity and recurrence. The broad scope of climate change impacts demands a detailed study that unites diverse disciplines and successful adaptation and mitigation efforts that is able to rapidly respond to evolving climate change (IPCC, 2014).

Conclusions

It is to be noted that the threats posed by climate change are multi-sectoral, so regional scale risk assessment and multi-disciplinary approach is the need of the hour programme that requires to be undertaken from the grass root levels. It is also important to frame stringent laws to combat the impact of climate change for developing adaptation and mitigation measures.

Reduction in the consumption of fossil fuels, greenhouse gases and switching on to clean energy sources can help in reducing the impacts of climate change. In addition to oceans, forests also help in the absorption of carbon. Peatlands are better carbon sinks as large amounts of carbon in plant tissues are locked away in peat soils. Peat lands in India occupy roughly 320 - 1000 square kilometre area which should be protected and prevented from further degradation. The carbon stored in coastal and marine ecosystems is known as blue carbon. Coastal ecosystems such as mangroves, tidal marshes and seagrass meadows sequester and store more carbon per unit area than terrestrial forests and are now being recognised for their role in mitigating climate change. These ecosystems also provide essential benefits for climate change adaptation, including coastal protection and food security for many coastal communities. However, if the ecosystems get degraded or damaged, their carbon sink capacity is lost or gets adversely affected. The carbon stored is released, resulting in emissions of carbon dioxide (CO_2) that contribute to climate change. Therefore, dedicated conservation efforts can ensure that coastal ecosystems continue to play their role as long-term carbon sinks.

Acknowledgements

The authors thank the Department of Science and Technology (DST), (DST-WOS-A sanction No.SR/WOS-A/EA-27/2019), New Delhi and Institute for Ocean Management, Anna University, Chennai, for their kind support and extending necessary facilities.

References

Aadhar, S. and Mishra, V., 2018. Impact of climate change on drought frequency over India. *Book Climate Change and Water Resources in India. Publisher: Ministry of Environment, Forest and Climate Change (MoEF and CC), Government of India*.

Abram, N.J., McGregor, H.V., Tierney, J.E., Evans, M.N., McKay, N.P. and Kaufman, D.S., 2016. Early onset of industrial-era warming across the oceans and continents. *Nature*, **536(7617):** 411-418.

Alam, M.M., Hossain, M.A. and Shafee, S., 2003. Frequency of Bay of Bengal cyclonic storms and depressions crossing different coastal zones. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, **23(9):** 1119-1125.

Ali, H. and Mishra, V., 2018. Increase in subdaily precipitation extremes in India under 1.5 and 2.0 C warming worlds. *Geophysical Research Letters*, **45(14):** 6972-6982.

Asoka, A., Gleeson, T., Wada, Y. and Mishra, V., 2017. Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. *Nature Geoscience*, **10(2):** 109-117.

Balaguru, K., Taraphdar, S., Leung, L.R. and Foltz, G.R., 2014. Increase in the intensity of postmonsoon Bay of Bengal tropical cyclones. *Geophysical Research Letters*, **41(10):** 3594-3601.

Barnola, J.M., Raynaud, D.Y.S.N., Korotkevich, Y.S. and Lorius, C., 1987. Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature*, **329(6138):** 408-414.

Barron, E.J. and Washington, W.M., 1984. The role of geographic variables in explaining paleoclimates: Results from Cretaceous climate model sensitivity studies. *Journal of Geophysical Research: Atmospheres*, **89(D1):** 1267-1279.

Bolle, H.J., Seiler, W. and Bolin, B., 1986. Other greenhouse gases and aerosols: assessing their role for atmospheric radiative transfer. *The Greenhouse Effect, Climatic change and Ecosystems (Editors: B Bolin, B.R Doos, B Warrick and D Jager) John Wiley and Sons: New York*.

Boyaj, A., Ashok, K., Ghosh, S., Devanand, A. and Dandu, G., 2018. The Chennai extreme rainfall event in 2015: The Bay of Bengal connection. *Climate Dynamics*, **50(7):** 2867-2879.

Brierley, A.S. and Kingsford, M.J., 2009. Impacts of climate change on marine organisms and ecosystems. *Current Biology*, **19(14):** R602-R614.

Brown, D.J.A., 1989. Fish survival in acid waters. *Acid Toxicity and Aquatic Animals*, 31-44.

Brühl, C. and Crutzen, P.J., 1988. Scenarios of possible changes in atmospheric temperatures and ozone concentrations due to man's activities, estimated with a one-dimensional coupled photochemical climate model. *Climate Dynamics*, **2(3):** 173-203.

Chassot, E., Bonhommeau, S., Dulvy, N.K., Mélin, F., Watson, R., Gascuel, D. and Le Pape, O., 2010. Global marine primary production constrains fisheries catches. *Ecology Letters*, **13(4):** 495-505.

Dey, M.M., Kambewa, P., Prein, M., Jamu, D., Paraguas, F.J., Pemsl, D.E. and Briones, R.M., 2007. WorldFish Centre. Impact of the development and dissemination of integrated aquaculture–agriculture technologies in Malawi. *International Research on Natural Resource Management: Advances in Impact Assessments. FAO/CAB International, Wallingford*, 118-146.

Dhar, O.N. and Nandargi, S., 2003. Hydrometeorological aspects of floods in India. *Natural Hazards*, **28(1):** 1-33.

Dineshbabu, A.P., Zacharia, P.U., Sujitha, T., Shoba, J.K., Rajesh, K.M., Vivekanandan, E., ... and Ninan, R.G., 2020. Assessment of stock vulnerability of Indian marine fishes to past changes in climate and options for adaptation. *Climate Research*, **79(3):** 175-192.

do Rosário Gomes, H., Goes, J.I., Matondkar, S.P., Buskey, E.J., Basu, S., Parab, S. and Thoppil, P., 2014. Massive outbreaks of Noctiluca scintillans blooms in the Arabian Sea due to spread of hypoxia. *Nature Communications*, **5(1):** 1-8.

Doney, S.C., Fabry, V.J., Feely, R.A. and Kleypas, J.A., 2009. Ocean acidification: The other CO_2 problem. *Annual Review of Marine Science*, **1:** 169-192.

Elsner, J.B., Kossin, J.P. and Jagger, T.H., 2008. The increasing intensity of the strongest tropical cyclones. *Nature*, **455(7209):** 92-95.

Fabry, V.J., Seibel, B.A., Feely, R.A., and Orr, J.C., 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science*, **65(3):** 414-432.

Falkowski, P., Scholes, R.J., Boyle, E.E.A., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Högberg P., Linder S. and Mackenzie F.T., 2000. The global carbon cycle: A test of our knowledge of earth as a system. *Science*, **290(5490):** 291-296.

Folland, C. K. and Parker, D.E., 1990. Observed variations of sea surface temperature. *In: Climate-Ocean Interaction* (pp. 21-52). Springer, Dordrecht.

Gangstø, R., Joos, F. and Gehlen, M., 2011. Sensitivity of pelagic calcification to ocean acidification. *Biogeosciences*, **8(2):** 433-458.

Girishkumar, M.S. and Ravichandran, M., 2012. The influences of ENSO on tropical cyclone activity in the Bay of Bengal during October–December. *Journal of Geophysical Research: Oceans*, **117(C2)**.

Gittins, S.P. and Akonda, A.W., 1982. What survives in Bangladesh?. *Oryx*, **16(3):** 275-282.

Gomes, H.R., Goes, J.I. and Saino, T., 2000. Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. *Continental Shelf Research*, **20(3):** 313-330.

Goswami, B.N., Venugopal, V., Sengupta, D., Madhusoodanan, M.S. and Xavier, P.K., 2006. Increasing trend of extreme rain events over India in a warming environment. *Science*, **314(5804):** 1442-1445.

Greenwood, N., Forster, R.M., Créach, V., Painting, S.J., Dennis, A., Cutchey, Silva T., Sivyer, D.B. and Jickells, T., 2012. Seasonal and interannual variation of the phytoplankton and copepod dynamics in Liverpool Bay. *Ocean Dynamics*, **62(2):** 307-320.

Guhathakurta, P., Sreejith, O. P., and Menon, P. A. (2011). Impact of climate change on extreme rainfall events and flood risk in India. *Journal of Earth System Science*, **120(3):** 359-373.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W. and Medina-Elizade, M. (2006). Global temperature change. *Proceedings of the National Academy of Sciences*, **103(39):** 14288-14293.

Hare, J.A., Manderson, J.P., Nye, J.A., Alexander, M.A., Auster, P.J., Borggaard, D.L., Capotondi, A.M., Damon-Randall, K.B., Heupel, E., Mateo, I. and O'Brien, L., 2012. Cusk (Brosme brosme) and climate change: Assessing the threat to a candidate marine fish species under the US Endangered Species Act. *ICES Journal of Marine Science*, **69(10):** 1753-1768.

Hawkins, E. and Sutton, R., 2012. Time of emergence of climate signals. *Geophysical Research Letters*, **39(1)**.

Henderson, R.M., Reinert, S.A., Dekhtyar, P. and Migdal, A., 2015. Climate change in 2018: Implications for business. Harvard Business School Publishing, Boston, 2018, 39.

Hochachka, P.W. and Somero, G.N., 2002. *Biochemical adaptation: Mechanism and process in physiological evolution*. Oxford University Press.

India Meteorological Department (IMD), 2003. Cyclone Manual, IMD, New Delhi.

Islam, M. S. and Haque, M., 2004. The mangrove-based coastal and nearshore fisheries of Bangladesh: ecology, exploitation and management. *Reviews in Fish Biology and Fisheries*, **14(2):** 153-180.

Jayalakshmi, K.J., Sabu, P., Devi, C.A. and Sanjeevan, V.N., 2015. Response of micro-and mesozooplankton in the southwestern Bay of Bengal to a cyclonic eddy during the winter monsoon, 2005. *Environmental monitoring and assessment*, **187(7):** 1-18.

Jayasankar, C.B., Surendran, S. and Rajendran, K., 2015. Robust signals of future projections of Indian summer monsoon rainfall by IPCC AR5 climate models: Role of seasonal cycle and interannual variability. *Geophysical Research Letters*, **42(9):** 3513-3520.

Jouzel, J., Russell, G.L., Suozzo, R.J., Koster, R.D., White, J.W.C. and Broecker, W.S., 1987. Simulations of the HDO and H2 18O atmospheric cycles using the NASA GISS general circulation model: The seasonal cycle for present-day conditions. *Journal of Geophysical Research: Atmospheres*, **92(D12):** 14739-14760.

Kiehl, J.T. and Dickinson, R.E.,1987. A study of the radiative effects of enhanced atmospheric CO_2 and CH4 on early Earth surface temperatures. *Journal of Geophysical Research: Atmospheres*, **92(D3):** 2991-2998.

Kishtawal, C.M., Jaiswal, N., Singh, R. and Niyogi, D., 2012. Tropical cyclone intensification trends during satellite era (1986–2010). *Geophysical Research Letters*, **39(10)**.

Krishnan, R., Sabin, T.P., Vellore, R., Mujumdar, M., Sanjay, J., Goswami, B.N., Hourdin, F., Dufresne, J.L. and Terray, P., 2016. Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. *Climate Dynamics*, **47(3):** 1007-1027.

Krishnan, R., Sanjay, J., Gnanaseelan, C., Mujumdar, M., Kulkarni, A. and Chakraborty, S., 2020. *Assessment of Climate Change over the Indian Region: A Report of the Ministry of Earth Sciences (MoES), Government of India* (p. 226). Springer Nature.

Kumar, K.N., Rajeevan, M., Pai, D.S., Srivastava, A.K. and Preethi, B., 2013. On the observed variability of monsoon droughts over India. *Weather and Climate Extremes*, **1:** 42-50.

Kumar, M.R., Krishnan, R., Sankar, S., Unnikrishnan, A.S. and Pai, D.S., 2009. Increasing trend of "break-monsoon" conditions over India—role of ocean–atmosphere processes in the Indian Ocean. *IEEE Geoscience and Remote Sensing Letters*, **6(2):** 332-336.

Kusche, J., Uebbing, B., Rietbroek, R., Shum, C.K. and Khan, Z.H., 2016. Sea level budget in the Bay of Bengal (2002–2014) from GRACE and altimetry. *Journal of Geophysical Research: Oceans*, *121*(2), 1194-1217.

Leatherman, S. P. and Beller-Simms, N. (1997). Sea-level rise and small island states: An overview. *Journal of Coastal Research*, 1-16.

Levitus, S., Antonov, J.I., Boyer, T. P., Locarnini, R.A., Garcia, H.E. and Mishonov, A.V., 2009. Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophysical Research Letters*, **36(7)**.

Mallya, G., Mishra, V., Niyogi, D., Tripathi, S. and Govindaraju, R.S., 2016. Trends and variability of droughts over the Indian monsoon region. *Weather and Climate Extremes*, **12:** 43-68.

Mani, M., Bandyopadhyay, S., Chonabayashi, S. and Markandya, A., 2018. *South Asia's hotspots: The impact of temperature and precipitation changes on living standards*. World Bank Publications.

Martin, M.V. and Shaji, C., 2015. On the eastward shift of winter surface chlorophyll-a bloom peak in the Bay of Bengal. *Journal of Geophysical Research: Oceans*, **120(3):** 2193-2211.

Mitra, A., Gangopadhyay, A., Dube, A., Schmidt, A.C. and Banerjee, K., 2009. Observed changes in water mass properties in the Indian Sundarbans (northwestern Bay of Bengal) during 1980–2007. *Current Science*, 1445-1452.

Morán, X.A.G., López-Urrutia, Á.N, Calvo-Díaz, A.L.E.J.A.N.D.R.A. and Li, W.K., 2010. Increasing importance of small phytoplankton in a warmer ocean. *Global Change Biology*, **16(3):** 1137-1144.

Mujumdar, M., Bhaskar, P., Ramarao, M.V.S., Uppara, U., Goswami, M., Borgaonkar, H., Chakraborty, S., Ram, S., Mishra, V., Rajeevan, M. and Niyogi, D., 2020. Droughts and Floods. *In: Assessment of Climate Change over the Indian Region*. Springer, Singapore, pp. 117-141.

Najibi, N. and Devineni, N., 2018. Recent trends in the frequency and duration of global floods. *Earth System Dynamics*, **9(2):** 757-783.

Niyas, N.T., Srivastava, A.K. and Hatwar, H.R., 2009. *Variability and trend in the cyclonic storms over north Indian Ocean*. National Climate Centre, Office of the Additional Director General of Meteorology (Research), India Meteorological Department.

O'Connor, M.I., Bruno, J.F., Gaines, S.D., Halpern, B.S., Lester, S.E., Kinlan, B.P. and Weiss, J.M., 2007. Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. *Proceedings of the National Academy of Sciences*, **104(4):** 1266-1271.

Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A. and Yool, A., 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437(7059):** 681-686.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R. ... and van Ypserle, J.P., 2014. *Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* (p. 151). IPCC.

Pai, D.S., Guhathakurta, P., Kulkarni, A. and Rajeevan, M.N., 2017. Variability of meteorological droughts over India. *In: Observed climate variability and change over the Indian Region,* Springer, Singapore (73-87).

Parry, M., Parry, M.L., Canziani, O., Palutikof, J., Van der Linden, P. and Hanson, C. (Eds.)., 2007. *Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC* (Vol. 4). Cambridge University Press.

Passow, U. and Carlson, C.A., 2012. The biological pump in a high CO_2 world. *Marine Ecology Progress Series*, **470:** 249-271.

Paul, B. and Tham, W.L., 2015. Interrelation between climate and dengue in Malaysia. *Health*, **7(06):** 672.

Pecl, G.T., Ward, T.M., Doubleday, Z.A., Clarke, S., Day, J., Dixon, C. ... and Stoklosa, R., 2014. Rapid assessment of fisheries species sensitivity to climate change. *Climatic Change*, **127(3):** 505-520.

Polovina, J.J., Howell, E.A. and Abecassis, M., 2008. Ocean's least productive waters are expanding. *Geophysical Research Letters*, **35(3)**.

Pörtner, H.O., Langenbuch, M. and Reipschläger, A., 2004. Biological impact of elevated ocean CO_2 concentrations: Lessons from animal physiology and earth history. *Journal of Oceanography*, **60(4):** 705-718.

Prasanna Kumar, S., Muraleedharan, P.M., Prasad, T.G., Gauns, M., Ramaiah, N., De Souza, S.N. ... and Madhupratap, M., 2002. Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea? *Geophysical Research Letters*, **29(24):** 88-1.

Preethi, B., Ramya, R., Patwardhan, S.K., Mujumdar, M. and Kripalani, R.H., 2019. Variability of Indian summer monsoon droughts in CMIP5 climate models. *Climate Dynamics*, **53(3):** 1937-1962.

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. *Science*, **315(5810):** 368-370.

Rajeevan, M., Bhate, J. and Jaswal, A.K., 2008. Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. *Geophysical Research Letters*, **35(18):** L18707.

Ramanathan, V., 1987. The role of earth radiation budget studies in climate and general circulation research. *Journal of Geophysical Research: Atmospheres*, **92(D4):** 4075-4095.

Ramaswamy, C., 1962. Breaks in the Indian summer monsoon as a phenomenon of interaction between the easterly and the sub-tropical westerly jet streams. *Tellus*, **14(3):** 337-349.

Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U. ... and Watson, A., 2005. *Ocean acidification due to increasing atmospheric carbon dioxide*. The Royal Society.

Ray, K., Pandey, P., Pandey, C., Dimri, A.P. and Kishore, K., 2019. On the recent floods in India. *Current Science*, **117(2):** 204-218.

Sandhani, M., Pattanayak, A. and Kumar, K.K., 2020. Impact of climate change on economic growth: A case study of India.

Sanford, E., 1999. Regulation of keystone predation by small changes in ocean temperature. *Science*, **283(5410):** 2095-2097.

Scheff, J. and Frierson, D.M., 2014. Scaling potential evapotranspiration with greenhouse warming. *Journal of Climate*, **27(4):** 1539-1558.

Seidensticker, J. and Hai, M.A., 1983. The Sundarbans wildlife management plan: Conservation in the Bangladesh coastal zone.

Sharmila, S., Joseph, S., Sahai, A.K., Abhilash, S. and Chattopadhyay, R., 2015. Future projection of Indian summer monsoon variability under climate change scenario: An assessment from CMIP5 climate models. *Global and Planetary Change*, **124:** 62-78.

Shenoi, S.S.C., Shankar, D. and Shetye, S.R., 2004. Remote forcing annihilates barrier layer in southeastern Arabian Sea. *Geophysical Research Letters*, **31(5)**.

Shukla, P.R., 2003. *Climate change and India: vulnerability assessment and adaptation*. Universities Press.

Sikka, D.R., 1999. *Monsoon drought in India* (No. 2). Center for Ocean-Land-Atmosphere Studies, Center for the Application of Research on the Environment (CARE).

Trenberth, K.E. and Fasullo, J., 2007. Water and energy budgets of hurricanes and implications for climate change. *Journal of Geophysical Research: Atmospheres*, **112(D23)**.

Tricot, C. and Berger, A., 1987. Modelling the equilibrium and transient responses of global temperature to past and future trace gas concentrations. *Climate Dynamics*, **2(1):** 39-61.

Vinayachandran, P.N. and Mathew, S., 2003. Phytoplankton bloom in the Bay of Bengal during the northeast monsoon and its intensification by cyclones. *Geophysical Research Letters*, **30(11)**.

Vinayachandran, P.N., Murty, V.S.N. and Ramesh Babu, V., 2002. Observations of barrier layer formation in the Bay of Bengal during summer monsoon. *Journal of Geophysical Research: Oceans*, **107(C12):** SRF-19.

Vivekanandan, E., 2011. Marine fisheries policy brief-3; climate change and indian marine fisheries. *CMFRI Special Publication*, **105:** 1-97.

Vivekanandan, E., Hermes, R. and O'Brien, C., 2016. Climate change effects in the Bay of Bengal large marine ecosystem. *Environmental Development*, **17:** 46-56.

Wang, W.C., Wuebbles, D.J., Washington, W.M., Isaacs, R.G. and Molnar, G., 1986. Trace gases and other potential perturbations to global climate. *Reviews of Geophysics*, **24(1):** 110-140.

Ward, P.J., Kummu, M. and Lall, U., 2016. Flood frequencies and durations and their response to El Niño Southern Oscillation: Global analysis. *Journal of Hydrology*, 539: 358-378.