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GUEST EDITORIAL

Sustainable management of our coasts in the era of climate change

Anthropocene Earth has warmed by at least a degree centigrade. The IPCC 2019 Special Report on 'Ocean and Cryosphere in a Changing Climate' underscores the necessity for limiting global warming to at least the level agreed to in the Paris accord 2015. It is estimated that oceans have absorbed 90% of the heat added to the climate system since 1970. Melting glaciers and continental ice sheets together with the thermal expansion of sea water, are causing sea-level rise. While the sea-level has risen globally ~15 cm during 20th century, it is known to be currently rising more rapidly at 3.6 mm/year. Sea-level could rise by 30–60 cm by 2100, even if global warming is controlled below 2°C. While contribution of glacial melting and sea water warming are the major causes for sea-level rise, contribution of terrestrial water for the rise is small (0.12 mm/year between 1993 and 2010) (Wada, Y. *et al.*, *Nature Climate Change*, 2016, doi:10.1038/NCLIMATE30011). The fact is that in general sea-level has risen more than what researchers could model based on known sources.

The rate of sea-level change differs widely, due to ocean dynamics, local uplift/submergence of land, etc. An estimate based on historical data from tide gauges installed at major ports in India has shown that, on an average, the mean sea-level along Indian coasts has risen at 1.29 mm/year during the past few decades (Unnikrishnan, A. S. and Shankar, D., *Global Planet. Change*, 2007, doi:10.1016/j.gloplacha.2006.11.029).

Attribution of coastal impacts on people due to sea-level rise remains difficult, because the impacts are exacerbated by anthropogenic non-climatic drivers. Scott and Strauss (*Nature Commun.*, 2020, https://doi.org/10.1038/s41467-019-12808) argued that the population which would get affected due to raising sea-level is underestimated because coastal elevation data estimated from NASA's Shuttle Radar Topography Mission (SRTM) are inaccurate. They estimated the errors in SRTM elevations using accurate measurments of coastal elevation for US coasts and extrapolated to other coasts to observe that the usage of SRTM data underestimated the coastal population that would experience flooding due to sea-level rise by at least three times. For the Indian coast, underestimation reported was of the order of 6 to 7 times. Since the SRTM data is unsatisfactory, the Indian National Centre for Ocean Information Services (INCOIS) mapped the elevation for Indian mainland coast using Airborne Laser Terrain Mapping (ALTM). Though the final data is yet to be readied, a quick comparison of the SRTM and the ALTM elevations for Mumbai indicated that the error in the SRTM elevation is 3.75 m. For Mumabi city, the area having elevation ≤1.0 m above MSL works out to 71.00 km^2 as per SRTM data and that using ALTM works out to 5.00 km^2. It is found that about 8.9% of coastal mainland – the coastal stretch between MSL line and ~2 km inland – has elevation ≤1.0 m. Such areas are highly vulnerable for temporary/permanent flooding by sea-level rise and therefore are at greater risk; especially, for a city like Mumbai which finds it difficult to drain excess rain water during high tides. Based on intermediate carbon emissions scenario (RCP 4.5), Scott and Strauss estimated that the rise in the sea-level will be about 50–70 cm by 2100. Therefore, about 10 million people living along the Indian coastline will be exposed to inundation. Another consequence of sea-level rise is coastal erosion. The satellite data (1990–2018) suggested that about 37% of Indian coastline eroded and 28% accreted (Kankara, R. S. *et al.*, National assessment of shoreline changes along the Indian coast, 2018).

The warming oceans and rising sea-level have increased the frequency and strength of cyclones and associated storm-surges inundating greater stretches of coastal areas, especially the low-lying coastal tracts. The IPCC Special Report records that the number of category 5 cyclones has increased in recent decades. During the past 30 years, the intensity of land-fall of extremely severe cyclones from Bay of Bengal has increased at an average rate of 8% per decade (Singh, K. S. *et al.*, *Theor. Appl. Climatol.*, 2020; https://doi.org/10.1007/s00704-020-03510-y). The intensity of cyclones over the Arabian Sea is no exception to this trend in recent decades (Evan, A. T. *et al.*, *Nature*, 2011, **479**, 94–97). In the northern Indian Ocean, more intense cyclones are moving faster relative to less intense (Mohapatra, M. and Sharma, M., *Mausam*, 2019, **70**, 635–666) and they are intensifying rapidly from one stage to another within short duration (Singh, V. K. and Roxy, M. K., *Earth Sci. Rev.*, 2021, preprint-https://arxiv.org/abs/2012.04384). Cyclone *Ockhi* formed over Arabian Sea, in November 2017, intensified rapidly from a depression to a cyclonic storm within 9 hours (Singh, V. K. *et al*., *Curr. Sci.*, 2020, **119**, 771–779). Due to the shift in the locations of cyclone genesis over the warm waters in the east in Bay of Bengal, they travel longer over ocean drawing more thermal energy and often intensifies rapidly (Balaji, M. *et al*., *Int. J. Climatol.*, 2018, **38**, 2819–2837). While 14% of the cyclones formed to the east of 90°E became category 3 or above cyclones during 1981–1995, that percentage increased to 42% in 1996–2010 (Balaguru, K. *et al*., *Geophys. Res. Lett.*, 2014; doi:10.1002/2014GL060197). During 2018–2020, 10 cyclonic storms developed over the Arabian Sea and 11 over the Bay of Bengal. According to IMD's categorization, 7 out of 10 cyclones formed over Arabian Sea and 6 out of 11 formed over Bay were in the category of Very Severe Cyclonic Storms (VSCS), indicating that the cyclones over the north Indian Ocean are getting stronger with higher destruction potential. The storm-surges associated with the intense cyclonic storms, exacerbated with the rising sea-level, will put large populations, infrastructure and strategic installations on or near the coast at greater risk of flooding.

In addition to the increased inundation of the coast during extreme conditions like a tsunami or storm-surge, the raise in sea-level also affects the water table, the flora and fauna. Sea water intrusion will turn the land unsuitable for crops. The coral reefs though can grow upwards with gradual rise in sea-level, they get damaged by the wash off and deposit of sediments and bleaching due to increasing temperature and decreasing pH of ocean water.

In addition to the effects of climate change, the coasts also are under constant anthropogenic pressure due to building of structures on the coast for protection, commerce, communication, recreation, etc. These activities affect the natural processes leading to a wide range of issues including loss of biodiversity, high levels of pollution, coastal erosion and displacement of settlements. Often, the effects on coasts are immediate, fast and more devastating, leading to permanent damages. Fortunately, most of the damages are avoidable or reversible, if proper planning and scientific studies are carried out. For example, lost beach in Puducherry due to the construction of a fishing harbour and the eroded beach of Kadalur could be re-grown through proper engineering intervention following scientific investigations by the National Institute of Ocean Technology. Extensive data created by the National Centre for Sustainable Coastal Management including the data on sediment cells, are useful to develop models for understanding the effects of coastal projects on the coasts. A green infrastructure approach (mangroves, reefs, shrubby vegetation) can help sustenance of natural barriers, reduce erosion and flooding while maintaining natural shoreline processes.

While human intervention can be managed and regulated, it is not easy to prevent the adversities on coasts that arise due to climate change. It will take a couple of centuries to halt and reverse effects of climate change even if the Paris accord is put into action. It is, therefore, not wrong to assume that coasts will have to deal with the intensified cyclones, raising sea-levels, increased inundations, higher levels of flooding, etc. in the years to come.

Therefore, the important question before us is, how can we protect our coastal areas from the adversities arising from sea-level rise, intense cyclones and flooding? Preventive planning, adaptive management and allocation of land for future use, keeping in mind the probable adversities due to changing climate, are the way forward. The first step towards implementing these approaches is better understanding of the coasts and their surroundings based on the data on pre-existing conditions of the coast and their surroundings, ongoing changes and the ability to foresee the likely changes due to climate change. Next step is creation of data base on the risk levels of coasts, ecosystems, existing human settlements and infrastructure. The Coastal Vulnerability Index Maps at 1 : 100,000 scale created by INCOIS (https://incois.gov.in/portal/cvi/index.html) considering the rate of sea-level rise, the rate of shoreline change, coastal slope, elevation, geomorphology, significant wave height and tidal range and the Multi-hazard Vulnerability Maps at 1 : 25,000 for storm-surges and tsunamis (https://incois.gov.in/portal/multihazard) provide useful information on Indian coasts. Modern concepts like marine spatial planning proposed by the Intergovernmental Oceanographic Commission (IOC) of UNESCO as a public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives which are usually specified through a political process would be the right way to approach this situation. The marine spatial planning brings together multiple users of the coasts including energy, industry, government, conservation, local population and recreation to make informed and coordinated decisions on how to use the marine resources sustainably. This would also help in avoiding conflicts between traditional users of coasts and developmental activities while ensuring sustainability of resources and conservation of environment, ecosystem and biodiversity.

Though human activities and aspirations are now the primary drivers of coastal ecosystems, the effects of climate change like warming of oceans, rising sea-levels, and the increasing number of intense cyclones and associated storm-surges cannot be ignored for sustainable development of the coasts. One is the physical task of protecting the vast vulnerable coasts. The other is addressing the social reparations of the combined effects. This is where we need new learning and close cooperation among all stakeholders, because the success of management depends ultimately on guarantying the safety of life and property and the sustenance of environment and livelihood of the population.

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