A satellite-derived re-analysis of surface-ocean pH variability in the coastal waters of India

Vinaya Kumar Vase*, Rajan Kumar, Shikha Rahangdale, Sanjana Kartu, Harshad Solanki, Jayasankar Jayaraman, Ratheesh Kumar and Grinson George

Indian Council of Agricultural Research-Central Marine Fisheries Research Institute, Kochi 682 018, India

Monitoring pH variations in coastal waters is essential for maintaining marine life and developing strategies to combat ocean acidification caused by climate change. The present study examines pH changes on interannual and seasonal scales along the northwest (NW), southwest (SW), southeast (SE), and northeast (NE) coasts of India over 30 years (1993–2022) using satellite data. Results reveal a significant decline in pH levels ($R^2 = 0.727$) across Indian coastal waters, with notable regional differences. The northeastern coast showed the greatest pH stability and the smallest decrease ($R^2 = 0.798$), while the southwestern coast experienced the highest variability ($R^2 = 0.490$). These regional pH fluctuations suggest varying resilience to ocean acidification. The NE and SW coasts, with higher variability, may be more susceptible to environmental changes, underscoring the importance of targeted monitoring and mitigation measures. In contrast, the more stable trends along the SE and NW coasts present opportunities to explore long-term resilience mechanisms. Seasonal fluctuations were evident everywhere, with winter consistently showing higher pH values and monsoon seasons the lowest. Principal component analysis indicated that the first two components accounted for 85.7% of the variance, highlighting factors such as seasonal river inflows, biological activity, and monsoonal freshwater input. Overall, these findings emphasise the importance of region-specific coastal management strategies to address climate change impacts and human pressures, while also providing a baseline for tracking future ocean acidification trends and assessing their effects on marine biodiversity and ecosystem services.

Keywords: Acidification, coastal waters, Indian EEZ, satellite-derived data, spatial variability.

marine food webs[1]. The large uptake of CO_2 by the oceans decreases pH (measured as the negative logarithm of H^+ ion concentrations), resulting in the formation of carbonic acid that harms marine life[2]. The changes in water pH caused by biochemical and biogeochemical reactions mainly affect calcifying organisms due to the lower saturation of $CaCO_3$ in seawater[3]. The rate of acidification is higher in coastal areas than offshore regions due to nearby anthropogenic activities and land influence that alter carbonate chemistry[4].

The oceans are predicted to become more acidic due to the exceeding atmospheric concentrations of CO_2 at 415 ppmv, and this trend is expected to continue, surpassing the pre-industrial level of 280 ppmv (ref. 2). Several studies have projected a decline of upper ocean pH by 0.3–0.4 units by the end of the 21st century[5], which can reduce oceanic biological production[6]. Modelling experiments conducted by Caldeira and Wickett[7] and Orr[8] suggest a decrease in surface ocean pH of about 0.3 from current conditions by the end of this century, based on estimates of future CO_2 emissions. Spatial and seasonal dynamics in pH at the global scale and their potential impact on biogeochemical cycles and marine biota were studied[3,9–12]. Researchers employ a combination of satellite datasets, numerical models, and *in situ* observations to assess spatiotemporal trends in pH and its drivers, including anthropogenic CO_2 emissions and natural variability[13].

Although a few coastal pH measurements exist, the observations to study acidification in the Indian Ocean are unavailable at a basin scale to depict a comprehensive understanding of acidification[14]. The pH measurements were made sporadically at short periods and limited locations along the coastal waters of western India[15–18] and eastern India[19–21], which fails to bring a synoptic view of the variability of pH at spatial and temporal scales. Time-series monitoring of pH through field survey techniques is costly and time-consuming, especially for wider-area and long-term investigations[22]. To overcome these limitations