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Present Scenario of Ocean Warming (OW) and Ocean Acidification (OA) in the Coastal and Marine Waters of the Bay of Bengal, Bangladesh and Implications of OW and OA on Fisheries and Seafood of Bangladesh: A First Regional Review Study

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Abstract: Bangladesh is one of the most vulnerable countries in the world to climate change. However, data relevant to ocean warming (OW) and ocean acidification (OA) are not readily available. This is the first study to review the available data relating to OW and OA covering the three parts (eastern, central and western parts) of the coastal marine waters (CMWs) of the Bay of Bengal (BoB), Bangladesh. The review compared the data collected from the three parts of the BoB, Bangladesh with the data and information of previous research carried out within the Indian subcontinent of the BoB (2000-2023). The present research provides an overview of water quality data relevant to OW and OA and the correlation among different water quality parameters. Our research found that the sea surface temperature is increasing and pH levels are decreasing in the BoB, Bangladesh. The current pH in BoB, Bangladesh is still alkaline, with an overall mean pH of 7.58 compared with the global ocean pH of 8.1. DO (overall mean: 6.09 mg/L), Ωarg (overall mean: 2.27) and Ωcal (overall mean: 3.59) levels were found to be within the safe thresholds for marine biota (fish, crustaceans, mussels, oysters, corals and echinoderms). Conversely, nitrate levels (mean: 2.29 mg/L) were found to be high, the concentration of which may enhance nitrogen pollution, algal blooms and hypoxia in the BoB, Bangladesh. The implications of OW and OA on Bangladesh's fisheries and seafood have been briefly discussed.

Keywords: Ocean warming; Ocean acidification; Water quality; Temperature; pH; Ωarg; Ωcal; Bay of Bengal; Bangladesh.

Introduction

The ocean absorbs more than 90% of global heat caused by the emissions of greenhouse gases resulting in ocean warming (OW) (Durack et al., 2018). The average global sea surface temperature has increased by 0.72°C between pre-industrial times (1870–1899) and recent years (2005–2014) (Gattuso et al., 2015). In fact, the top

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2,000 m of the global ocean has significantly warmed since the 1950s (Venegas et al., 2023). The rise in sea surface temperature could cause substantial impacts on fisheries, aquaculture, and seafood security across the globe. For example, fish species would shift towards the poles from the tropical areas to the temperate areas (to escape heat/OW). In addition, coral bleaching and coral mortalities could occur (Genner et al., 2017; Kibria et al., 2021a). Warmer temperatures would cause a decrease in dissolved oxygen levels that may affect fish's growth, reproductive success, and survival (Muir and Allinson, 2007; Kibria et al., 2021a).

The ocean is the primary sink of CO_2 (Durack et al., 2018; Kibria et al., 2021b), and the increasing anthropogenic CO_2 in the atmosphere is being absorbed into the oceans, resulting in a decrease in the pH of the ocean water, this phenomenon is known as Ocean Acidification (OA) (Caldeira and Wickett, 2003). The lowering of pH (or OA) is one of the most critical anthropogenic threats to marine life, in particular to calcifying organisms, that require calcium carbonate for their skeletons and shells including krill, pteropods, molluscs, corals, echinoderms, and fish and some phytoplankton (Kibria et al., 2017). OA could not only impact commercial fisheries and shellfish production but could also threaten protein supply, food security and livelihoods for millions of the world's poorest people (Kibria and Haroon, 2017; Kibria et al., 2017; Kibria et al., 2021b).

Bangladesh is one of the most vulnerable countries in the world to climate change. Currently, only limited and insufficient data and information are available on the OW and OA of Bangladesh. Such data and information are inadequate to predict/ assess the impact of OW and OA on fisheries, seafood and coastal and marine aquatic ecosystems. The main objectives of this article were:

- To review the past data and information relevant to ocean warming (OW) and ocean acidification (OA) for two decades (2000-2023) of coastal and marine waters (CMWs) covering the eastern, central, and western parts of the Bay of Bengal (BoB) of Bangladesh
- To evaluate the possible impacts of OW and OA on commercial fisheries and seafood organisms of the BoB of Bangladesh.

Materials and Methods

Field Survey and Baseline Data Collection

The Bay of Bengal (BoB) encompasses the northeastern part of the Indian Ocean, and it is bordered by land to the north, east and west by Bangladesh, Myanmar, and India, respectively. According to geology, the Indian plate drifted, the eastern Gondwana broke up, and eventually, the Indian plate collided with the Eurasian (Tibetan) and Burmese plates to form the Bengal Basin and the nearby BoB. It is well known for the great commercial value of its fish and fisheries landings, as well as for its huge semidiurnal tides and the effect they have on mixing. In this study according to geomorphologic and tidal features, the coastal region of Bangladesh was separated into three portions (Rana et al., 2023). A field survey was conducted to collect water quality data from different coastal and marine parts of the BoB of Bangladesh. Water quality from the three parts of the BoB (eastern, central and western) was measured and compared with others to evaluate the present scenario of OW and OA. These three areas were

i. The Eastern part (23°25.12' N, 90°13.12 E) covers Chattogram coastal areas;
ii. The Central part (23°77.71' N, 90°39.95' covers Noakhali and Barisal coastal areas and
iii. The Western part (23°41.39' N, 90°20.39' E) covers Khulna coastal areas (Figure 1).

Based on GPS coordinates, the following study map (Figure 1) was created using ArcGIS (Version 10.8.1).

Sampling Design

To visualize the scenario of OW and OA of CMWs of Bangladesh, water quality parameters were measured *in-situ* data from different parts of the selected sampling area during the 24 months. Afterwards, it was cross-checked with related scientific studies on OW and OA (high temperature and low pH) through the 'Google Scholar', 'Scopus', and 'Science Direct' databases of two decades (2000-2023). Related data and information on OW and OA impacts on CMWs, and interactive effects on fisheries are scanty. Meanwhile, information was collected from the following keywords in our search: (i) "Ocean acidification + coastal and marine water"; (ii) "Ocean warming + coastal and marine water"; (iii) "Ocean acidification + ocean warming + waters (coastal, marine) + fisheries + Bangladesh".Two decades of data were analysed in 5-year intervals (2000, 2005, 2010, 2015, 2020).

Water Quality Parameters Analysis Relevant to OW and OA

Relevant water parameters, namely sea surface temperature (SST), pH, the partial pressure of carbon dioxide (pCO_2), total alkalinity (TA), sea surface

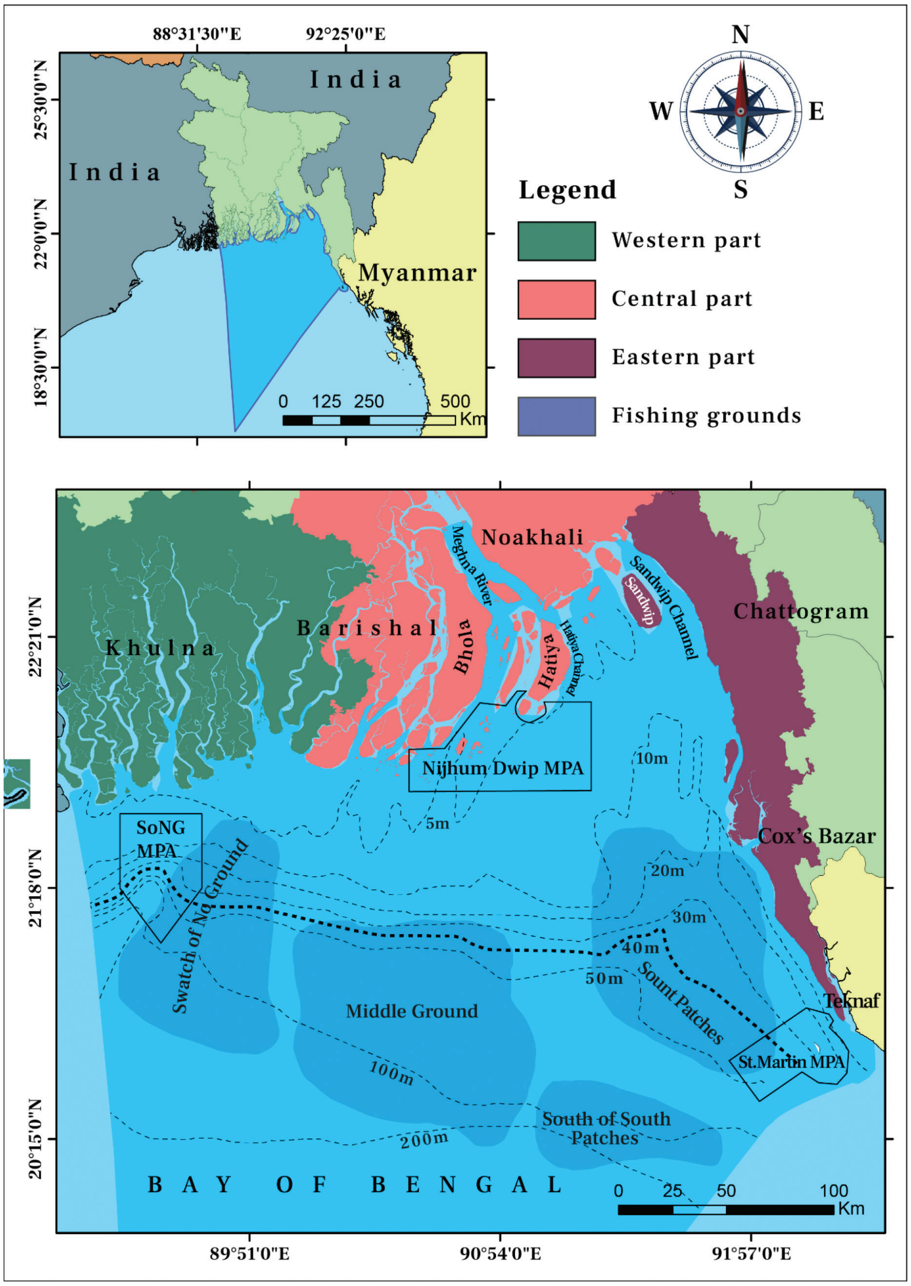

Figure 1: Study map for collecting water quality samples located in the coastal marine waters (CMWs) environment of Bangladesh adjacent to the Bay of Bengal (BoB). The three coastal parts of the BoB included in the study are shown in different colours on the map: Eastern (violet), Central (pink) and Western (dark green).

salinity (SSS), electric conductivity (EC), dissolved oxygen (DO), total dissolved solids (TDS), bicarbonate (HCO_3^-) and some related nutrients (nitrate-NO_3^-, phosphate PO_4^{2-}, and ammonia- NH_4^+) were measured to express the OA and OW scenario of Bangladesh (Table 1). DO, SST, pH and EC were measured using a Multi-parameter (Model: Hanna HI-98194). The TA and TDS were measured using a Multi-parameter (Model: Hanna HI-9829), and SSS was measured using a Refractometer (Model: Hanna HI-96822). Nutrients (NO_3^-, PO_4^{2-}, NH_4^+) were measured with Model: Hanna HI-83325. The applied indices to predict the acid-base concentrations (total dissolved inorganic carbon (DIC), total alkalinity (TA), H and pCO_2 concentration) in seawater were calculated by MatLab (Version 6.1.0.451) csys.m program (Zeebe and Wolf-Gladrow, 2001) and using saturation state solubility constants were k1 and k2 (Mehrbach et al., 1973). The bicarbonate (HCO_3^-), Carbonate (CO_3^{2-}), and aragonite saturation state (Ωarg) and calcite saturation state (Ωcal) of CMWs were also calculated following the solubility formula (Mehrbach et al., 1973, modified by Zeebe and Wolf-Gladrow, 2001).

Statistical Analysis

Pearson's correlation was run to assess the direction and degrees of relationship between the OA and OW and to relate the calculated seawater parameters. Pearson's product-moment correlation was run to assess the degrees and direction of the relationship among the water quality data with a 95% confidence interval. The normality of calculated data was estimated by the Shapiro-Wilks test ($p > 0.05$). The varimax rotated factor (R-mode), principal component analysis (PCA), and dendrogram using centroid linkage were performed using SPSS v.27. Mean values were expressed with standard deviation (Mean±SD). All analyses were performed using R-Studio programming and SPSS v. 27.

Results and Discussion (Regional Trend Results)

Sea Surface Temperature (SST)

Sea surface temperature (SST) is the temperature of the top few millimetres of the ocean. SST is an indicator of climate change (USEPA, 2003a). SST varied in the three parts of the BoB, Bangladesh (overall mean: 31.34°C) compared with other studies (25.2°C-27.7°C) (Table 1 and Figure 2). The increasing SST trend observed in this research is in line with several researchers. For example, Thangaradjou et al. (2014) reported the SST of the central Bay of Bengal, in India is in the range of 25.4 °C to 32.1°C which is close to our results of 31.34°Cin the BoB of Bangladesh.

Dissolved Oxygen (DO)

Dissolved oxygen (DO) measures how much oxygen is dissolved in the water. DO is one of the most important indicators of water quality and is vital for aquatic life. DO vary in the three parts of the BoB of Bangladesh (overall mean: 6.09 mg/L) compared with other studies (5.72 mg/L-6.5 mg/L) (Table 1 and Figure 2). A hypoxic environment occurs when the amount of dissolved oxygen in water is less than two milligrams per litre (<2 mg/L) (Wu, 2002). DO levels in the three studied parts of BoB, Bangladesh (the overall mean is 6.09 mg/L) which is safe for marine biota, including fish, crustaceans and molluscs (Kibria et al., 2021a,b). However, global warming is expected to reduce overall ocean oxygen levels, resulting in increased hypoxia (Breitburg et al., 2018; Kibria et al., 2021a).

Potential of Hydrogen (pH)

The change in pH is an indicator of ocean acidification and is related to the amount of carbon dioxide dissolved in the water (NOAA, 2024). CO_2 dissolves in water and produces weak carbonic acid (H_2CO_3), which causes a decrease in ocean pH. This is called 'Ocean acidification' (OA) (Kibria et al., 2021b). pH varied in the three parts of the BoB of Bangladesh (overall mean 7.58) compared with other studies (7.05-7.3) (Table 1 and Figure 2). Our results show that water quality in the studied areas is still alkaline with a pH above 7.0 (mean: 7.58). The ocean's average pH is currently around 8.1, which is also alkaline (USEPA, 2023b). Rashid et al. (2013) reported that the average pH of the Bay of Bengal, Bangladesh, is 7.75, which is also very close to our results of 7.58.

Total Alkalinity (TA)

Alkalinity refers to water's ability to neutralise the acid. Total alkalinity (TA) is an indicator of OA. Alkalinity and pH are closely related. TA varied in the three parts of the BoB of Bangladesh (overall mean: 148.49 mg/L) compared to other studies (135 mg/L-202.5 mg/L) (Table 1 and Figure 2). According to Millero et al. (1998), the distribution of TA in the major oceans is a function of latitude. The latitudes at which maxima are observed (20°S and 30°N) coincide with those of the Atlantic Ocean where it varies between 250.9 mg/L and 82.0 mg/L) (Millero et al., 1998). Compared to the TA of the Atlantic Ocean, TA was observed in BoB, Bangladesh, comparatively lower (mean: 148.49 mg/L). Although alkalinity and pH are closely related, the lower alkalinity in Bangladesh could be related to the lower pH observed in Bangladesh.

Partial Pressure of Carbon Dioxide (pCO_2)

pCO_2 is an indicator of ocean acidification. CO_2 is often reported as a partial pressure (pCO_2) in natural waters. The pCO_2 is a function of its concentration in gas or dissolved phases. The seawater pCO_2 is related to the temperature, the total amount of CO_2 dissolved in seawater, and the pH of seawater (Takahashi and Sutherland, 2019). The pCO_2 varied in the three parts of the BoB of Bangladesh (overall mean: 262.85 µatm) compared to other studies (143.99 µatm-271 µatm) (Table 1 and Figure 2). Currently, the pCO_2 level in the global ocean varies between 100 µatm and 1000 µatm (Takahashi and Sutherland, 2019). Our pCO_2 result (39.45 µatm to 1122 µatm) in the BoB, Bangladesh, also agrees with Takahashi and Sutherland, 2019 (Table 1).

Table 1: A summary showing water quality parameters of different parts of coastal marine waters (CMWs) of the Bay of Bengal (BoB), Bangladesh covering eastern, central and western parts of the Bay of Bengal, Bangladesh (two decades 2000-2023; result in avg±SD)

Parameters	*Eastern part*	*Central part*	*Western part*	*References*
SST (°C)	27.7±1.2	25.2±6.4	25.4±6.17	Sarma et al., 2018; Sridevi and Sarma, 2021
	30.0 ± 3.50	34.04 ± 0.50	26.00 ± 5.44	This study
pH	7.3 ± 0.67	7.09 ± 1.09	7.05 ± 0.42	Sridevi and Sarma, 2021; Rana et al., 2023
	7.40 ± 0.27	7.50 ± 0.40	7.85 ± 0.12	This study
DO (mg/L)	6.5±0.89	5.72±1.75	6.45±0.85	Rashid et al., 2013
	6.70 ± 0.69	5.29 ± 2.03	6.30 ± 0.80	This study
SSS (psu)	31.80 ± 1.83	30.28 ± 2.13	30.67 ± 3.5	Kumar et al., 2016; Sridevi and Sarma, 2021
	27.02 ± 6.00	30.2 ± 3.0	29.50 ± 3.50	This study
TA (mg/L)	202.5 ± 32.5	135 ± 19.5	128.50 ± 37.24	Sabine et al., 2000; Roxy et al., 2015
	125.00 ± 5.00	195.45 ± 59.40	125.04 ± 3.80	This study
TDS (mg/L)	27.14 ± 4.35	30.40 ± 3.35	51.55 ± 3.24	Rashid et al., 2013
	26.25 ± 4.35	36.60 ± 3.35	51.05 ± 3.24	This study
EC (µS/cm)	46800.8±6600.3	48673.03±1435.02	567423.77±4563.67	Rashid et al., 2013
	41800.80±6600.32	60709.34 ± 204.07	54447.18±356.93	This study
pCO_2 (µatm)	143.99 ± 102.27	271 ± 56.5	222.5 ± 80.5	Lueker et al., 2000; Sarma et al., 2012
	337.50 ± 62.50	322.51 ± 30.65	128.55 ± 37.24	This study
HCO_3^- (µmolkg^{-1})	137.75 ± 33.66	651.69 ± 157.65	750.82 ± 370.36	Sabine et al., 2000; Rana et al., 2023
	2820.13±161.59	2484.30±101.70	136.97±17.55	This study
CO_3^{2-} (µmolkg^{-1})	133.84 ± 45.77	138.54 ± 43.09	137.75 ± 33.66	Rana et al., 2023
	125.67 ± 56.09	131.45 ± 51.98	156.38 ± 49.67	This study
DIC (µmolkg^{-1})	946.87 ± 385.33	792.54 ± 179.58	891.93 ± 387.43	Sarma et al., 2012; Rana et al., 2023
	1046.12±405.23	967.04±367.07	897.67±347.91	This study
Ωarg	2.28 ± 0.76	2.34 ± 0.68	2.35 ± 0.55	Sabine et al., 2000; Rana et al., 2023
	2.13 ± 0.56	2.33 ± 0.65	2.35 ± 0.71	This study
Ωcal	3.54 ± 1.11	3.66 ± 1.03	3.70 ± 0.86	Sabine et al., 2000; Rana et al., 2023
	3.78 ± 1.06	3.56 ± 0.98	3.44 ± 1.17	This study
NO_3^- (mg/L)	4.7±2.5	0.94±0.32	0.658±0.58	Sarma et al., 2020; Rana et al., 2023
	4.71 ± 2.52	0.11 ± 0.09	2.06 ± 0.18	This study
PO_4^{2-} (mg/L)	4.7 ± 2.5	0.33 ± 0.08	0.14 ± 0.012	Sarma et al., 2020; Rana et al., 2023
	0.98 ± 0.32	0.92 ± 0.45	0.89 ± 0.64	This study
NH_4^+ (mg/L)	0.84 ± 0.82	0.62 ± 0.1	0.016 ± 0.002	Sarma et al., 2020; Rana et al., 2023
	0.50 ± 0.01	1.04 ± 0.43	0.05 ± 0.03	This study

Note: NH_4^+ = Ammonia; Ωarg = Aragonite saturation state; Ωcal= Calcite saturation state; HCO_3^-= Bicarbonate; CO_3^{2-}= Carbonate; DO= Dissolved oxygen; EC= Electric conductivity; pCO_2 = partial pressure of carbon dioxide; DIC = Dissolved inorganic carbon; NO_3^-= Nitrate; PO_4^{2-} = Phosphate; SST = Sea surface temperature; SSS = Sea surface salinity; TA = Total alkalinity; TDS = Total dissolved solids].

Figure 2: Showing the different water quality parameters linked to ocean warming (OW) and ocean acidification (OA) in the coastal marine waters (CMWs) of the Bay of Bengal, Bangladesh (2000-2023).

Bicarbonate (HCO_3^-)

Most of the inorganic carbon dissolved in the ocean exists in the form of bicarbonate **(**HCO_3^-). Bicarbonate accounts for about 92% of the CO_2 dissolved in the ocean. Bicarbonate plays a critical role in either increasing or decreasing the pH of seawater by releasing or incorporating hydrogen ions into the various carbon compounds (Webb, 2024). Bicarbonate varied in the three parts of the BoB of Bangladesh (overall mean: 1813.8 μmolkg^{-1} or 208.7 mg/L) compared to other studies (137.75 μmolkg^{-1} -750.82 μmolkg^{-1}) (Table 1 and Figure 2). Rashid et al. (2013) reported that the average bicarbonate of the Bay of Bengal, Bangladesh, is 138.9 mg/L, closer to our results of 208.7 mg/L^{1}).

Carbonate (CO_3^{2-})

In the seawater, bicarbonate dissociates into carbonate ions (CO_3^{2-}). Carbonate accounts for about 7% of the CO_2 dissolved in the ocean (Webb, 2024). Carbonate ions are essential for oysters, clams, sea urchins, corals, and calcareous plankton. Carbonate varied in the three parts of the BoB of Bangladesh (overall mean: 137.83 μmolkg^{-1}) compared to other studies (133.84 μmolkg^{-1} -138.54 μmolkg^{-1}) (Table 1 and Figure 2). It is reported that the CO_3^{2-} concentration varied from 272 to 379 μmolkg^{-1} in the seawater of the BoB (Sabine et al., 2000; Sarma et al., 2021). Our study found CO_3^{2-} concentration in the Bay of Bengal, Bangladesh, in the range of 100.05 μmolkg^{-1} to 205.06 μmolkg$^{-1,}$ lower than that shown in the study of Sarma et al. (2021) and Sabine et al. (2000).

Dissolved Inorganic Carbon (DIC)

Dissolved inorganic carbon (DIC) (DIC = ΣCO_2; i.e., dissolved $CO_2 + HCO_3^- + CO_3^{2-}$), refers to the total amount of CO_2, HCO_3^- and CO_3^{2-} in natural water

(Cole and Prairie, 2014). The ratio of CO_2 to HCO_3^- and CO_3^{2-} is the major pH control in most natural waters (Cole et al., 2021). DIC varied in the three parts of the BoB of Bangladesh (overall mean: 970.28 µmol kg^{-1}) compared to other studies (792.54 µmolkg^{-1} – 946.87 µmolkg^{-1}) (Table 1 and Figure 2). The average dissolved inorganic carbon concentration in the ocean is ~2300 µmolkg^- (Zeebe and Wolf-Gladrow, 2001). This research found DIC levels in the BoB of Bangladesh are an average of 970.28 µmolkg^{-1}. The low pH (mean 7.85) found in our study may be related to the lower DIC (970.28 µmolkg^{-1}) in the BoB, Bangladesh.

Aragonite Saturation State (Ωarg) and Calcite Saturation State (Ωcal)

Ωarg and Ωcal are indicators of OA. The saturation state "Omega (Ω)" describes the level of calcium carbonate in seawater. There are two forms of calcium carbonate: aragonite and calcite. The shells and skeletons of many marine organisms are made from either aragonite or calcite. The lower saturation level ($\Omega<1$ or undersaturation state) harms marine biota as building and maintaining their protective skeletons and shells is more difficult. Whereas, when the saturation level is more than 1 ($\Omega>1$ or supersaturation state), the condition is favourable for shell formation (USEPA, 2023c). Ωarg varied in the three parts of the BoB of Bangladesh (overall mean: 2.27) compared to other studies (2.28-2.35) (Table 1). Ωcal also varied in the three parts of the BoB of Bangladesh (overall mean: 3.59) compared with other studies (3.54-3.70) (Table 1). Our results of Ωarg 2.27 and Ωcal 3.59 are above the calcium carbonate (aragonite and calcite) threshold of $\Omega>1$ for marine biota. This means that Bangladesh's aragonite and calcite levels are currently safe for $CaCO_3$-required marine biota (krill, pteropods, molluscs, corals, and echinoderms).

Nutrients: Nitrate (NO_3^-), Phosphate (PO_4^{2-})

Nitrate (NO_3^-)and phosphate (PO_4^{2-}), are dissolved nutrients. These nutrients are essential for the growth of aquatic plants. However, high concentrations of these nutrients in water may cause nutrients pollution resulting in algal blooms and hypoxia in the oceans (Kibria et al., 2021b). The nitrate contents varied in the three parts of the BoB of Bangladesh (overall mean 2.29 mg/L) compared to other studies (Nitrate: 0.658 mg/L-4.7 mg/L) (Table 1 and Figure 1). In the marine environment, the limiting nutrient for algal blooms is nitrogen (Kibria et al., 2021b). The nitrogen threshold for algal blooms is known to be above 0.3 mg/L (UM, 2016). The nitrate concentration detected in our study (mean 2.29 mg/L) may cause nitrogen pollution resulting in algal blooms and hypoxia (low dissolved oxygen) in the Bangladesh part of BoB as it is above the threshold of 0.3 mg//L. The high nitrate found in our study in the BoB, Bangladesh, could be related to the open discharge of effluents into the rivers and coastal areas of Bangladesh (Kibria et al., 2021b).

Discussion Relating to Correlation Among Water Quality Parameters Related to Ocean Warming (OW) and Ocean Acidification (OA)

Correlation Among Different Water Quality Parameters

The present study found that a range of parameters including SST, SSS, DO, TA, TDS, and EC govern the pH of CMWs (BoB, Bangladesh). It further found that SST and SSS were the principal drivers that affected the pH, while TA acted as a buffering character. Pearson's correlation coefficient matrices were used to relate the analysed parameters, and the results are presented in Table 2. The ranges of correlation coefficient lie between −1 and +1. A moderate relationship is between 0.5 and 0.8, and a substantial correlation is considered when it is above 0.8 (Ahammed and Harvey, 2004; Islam et al., 2022).

A statistically significant correlation was observed among the parameters in the CMWs of BoB, Bangladesh. The Principal Components Analysis (PCA), and Correspondence Analysis (CA) signify the inter-parameter relationship of water quality parameters. SST, pH, DO, SSS, TA, HCO_3^- and NH_4^+ were loaded positively on PC1 (Table 3) and constituted Cluster 1 (Figure 3). It also showed a significant positive association in the correlation analysis. pCO_2, TDS, EC, and PO_4^{2-} loaded positively on PC2 (Table 3) and grouped in Cluster 2 (Figure 4) showed a positive correlation among them. The strong correlation specifies CMW's common sources of origin, which can be derived from geogenic sources, especially from freshwater intrusion and bicarbonate mineral dissolutions. PC1, which accounted for 56.921% of the total variance, demonstrated the highest and strong positive loadings of the factors mainly due to pH and TA (PC1> 0.8), moderate positive loadings of SST, DO, SSS, HCO_3^- (PC1: 0.7-0.8) and NH_4^+ (PC1: 0.5) weak negative loading (Table 3). These parameters are attributed to the acidic (low alkaline) water present in the coastal area of Bangladesh.

Table 2: Pearson's correlation coefficient values of water parameters of CMWs of Bangladesh [-1 meaning a total negative linear correlation, 0 being no correlation, and + 1 meaning a total positive correlation; 0.5-0.8 moderate relationship; >0.8 = a strong relationship]

	SST	*pH*	*DO*	*SSS*	*TA*	*pCO_2*	*TDS*	*EC*	*HCO_3^-*	*NO_3^-*	*PO_4^{2-}*	*NH_4^+*
SST	1											
pH	.570**	1										
DO	.364	.672**	1									
SSS	.493*	.612**	.663**	1								
TA	.551**	.530**	.443*	.209	1							
pCO_2	.550**	.418*	.200	.309	.164	1						
TDS	.438*	.236	.141	.282	.360	.566**	1					
EC	.056	-.182	-.283	-.377	-.101	.132	.092	1				
HCO_3^-	.490*	.464*	.345	.311	.135	.156	-.021	-.124	1			
NO_3^-	.270	.265	.060	.282	.321	.148	-.036	-.107	.103	1		
PO_4^{2-}	.033	.456*	.460*	.415*	.316	-.231	.015	-.287	.010	.331	1	
NH_4^+	.477*	.552**	.423*	.501*	.189	.410	.088	-.264	.352	.060	.131	1

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

Table 3: Varimax rotated factor loadings and communalities of water quality parameters (strong and moderate loadings are in boldface) [-1 meaning a total negative linear correlation, 0 = no correlation, and + 1 meaning a total positive correlation; 0.5-0.8 moderate relationship; >0.8 = a strong relationship]

Parameters (R-mode)	*PC1*	*PC2*	*PC3*	*Communalities*
Sea Surface Temperature	.768	.436	.124	.089
pH	**.862**	-.088	-.061	-.026
DO	**.729**	-.300	-.186	-.311
Sea Surface Salinity	**.717**	-.215	-.445	.152
Total Alkalinity	**.806**	.025	**.524**	-.195
PCO_2	.471	**.665**	-.380	.240
TDS	.480	**.567**	-.116	-.142
EC	-.249	**.590**	.299	.047
HCO_3^-	.796	.040	**.539**	-.194
NO_3^-	.390	-.184	.315	.824
PO_4^{2-}	.471	**-.674**	.053	.064
NH_4^+	**.587**	.022	-.472	-.003
Eigenvalue	4.893	1.937	1.388	
% of the total variance	56.921	16.143	11.566	
Cumulative % of variance	56.921	73.064	84.63	

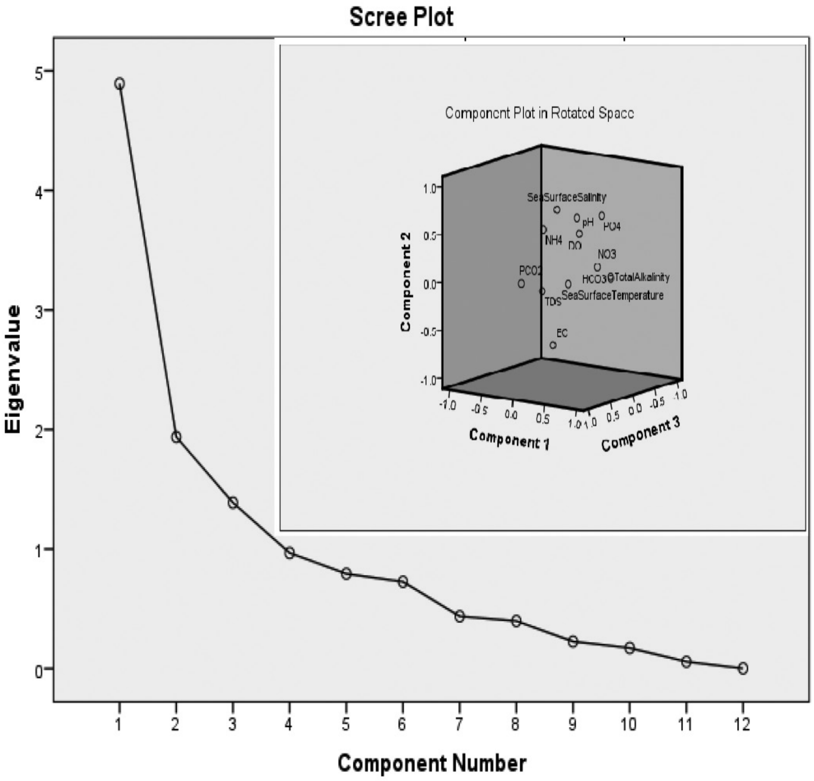

Figure 3: Principal component analysis (PCA) of CMW parameters is done by using a scree plot of the characteristic roots (eigenvalues) and a component plot in a rotated space.

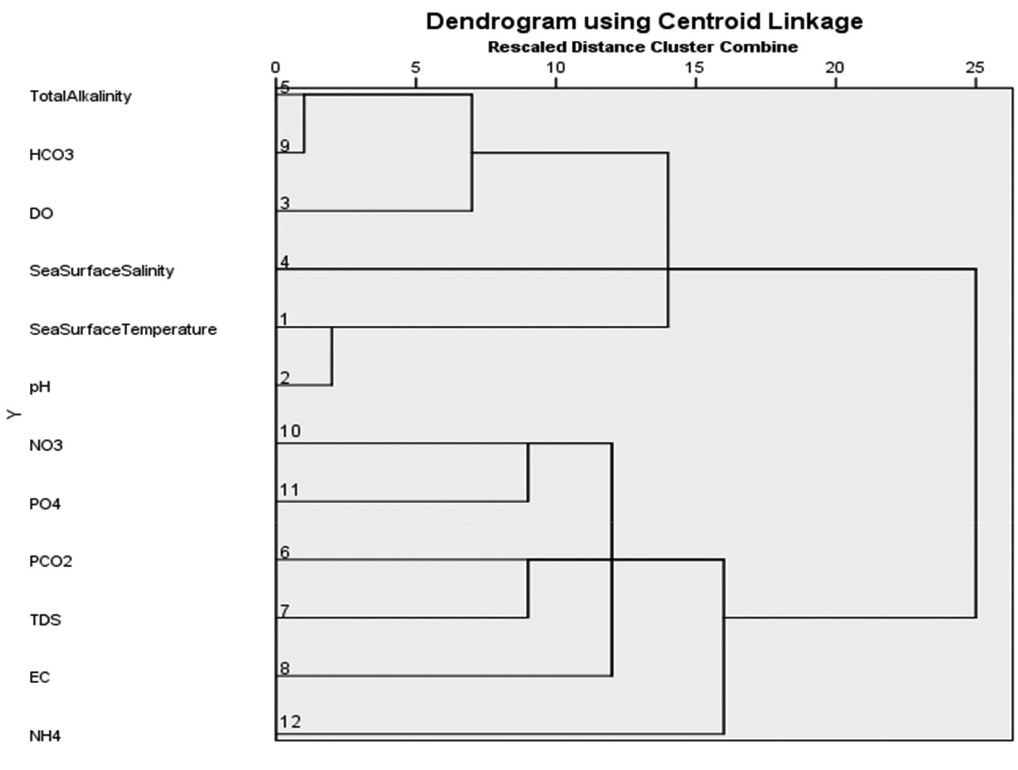

Figure 4: Dendrogram obtained by hierarchical clustering analysis for CMWs of Bangladesh. Based on Euclidean distances and maximum and minimum values of CMWs parameters. Data were square root transformed.

Implications of Ocean Warming (OW) and Ocean Acidification (OA) on Fisheries and Seafood of Bangladesh

Climate change could pose a significant threat to the fisheries and seafood of Bangladesh as explained below:

Ocean Warming (OW)

This review found that the sea surface temperature is an increasing trend in the BoB, Bangladesh. OW could affect the distribution and abundance of coastal and marine fish species in Bangladesh. For example, due to OW, fish may migrate away from Bangladesh to neighbouring countries or new territories. This would affect local fish production, affecting fish consumers, fishers, and the livelihoods of the people associated with the fishing business (Kibria et al., 2017). Furthermore, OW would cause reduction in dissolved oxygen (DO) in water bodies that can affect the growth, reproductive success and survival of fish and other marine organisms (Kibria et al, 2021) (Note: the oxygen solubility in water is inversely related to temperature; Kibria and Haroon, 2017). Moreover, increasing temperature due to OW could cause mass coral bleaching resulting mortalities (Hoegh-Guldberg et al., 2007). Such bleaching will have rapid impacts on the diversity and species composition of coral reef fish communities and other associated organisms. OW may also enhance the bioaccumulation potential of toxins in marine organisms. Bioaccumulation of pollutants such as heavy metals to marine organisms could be enhanced with increasing temperatures. Temperature-related increases in the uptake, bioaccumulation, and toxicity of metals (arsenic, copper, cobalt, cadmium, and lead) have been reported for several marine organisms, including crustaceans, echinoderms, and molluscs (Hutchins et al., 1996; Khan et al., 2006; Mubiana and Blust, 2007; Noyes et al., 2009; Kibria et al., 2013; Kibria et al., 2016; Kibria et al., 2021a,b). One positive effect is that OW would enhance algal growth that could be beneficial to filter-feeding species such as oysters, mussels and herbivorous fish – Rohi or Rohu (*Labeo rohita*). Nevertheless, there is a need to assess whether OW affects the migration pattern of Bangladesh's national anadromous hilsa fish, *Hilsa tenualosa.* About 86% of the world's total *H. tenualosa* supply originates in Bangladesh. If seafood products are contaminated with chemical micropollutants such as Cd, Pb, and Hg and exceed the recommended seafood safety guideline values, the seafood products can be rejected or recalled from the international market. This will immensely impact fishers, seafood frozen industries and countries that rely on seafood sales, such as Bangladesh (Kibria et al., 2021a).

Ocean Acidification (OA) (Low pH)

This review also found that the pH is declining in the BoB, Bangladesh. OA can adversely affect many marine organisms that require calcium carbonate for their skeletons and shells, such as corals, molluscs, pteropods, and some phytoplankton (Kibria et al., 2017). It is reported that OA caused tissue damage in many internal organs of cod fish larvae (liver, pancreas, kidney, eye, and the gut) (Frommel et al., 2012) and reduced survival and growth rates of early life stages of silverside fish (Baumann et al., 2012); therefore, it (like other chemical stressors) could cause a decline in valuable wild fisheries including in Bangladesh (Nugegoda and Kibria, 2016). In the case of Bangladesh, OA may also have significant consequences on the biodiversity of St. Martin's Coral Island (the only coral island locally known as Narikel Jinjira). St. Martin's Island is a biodiversity "hot spot" with 66 species of corals, 234 species of fish (of which 89 species are coral reef-associated), 187 species of molluscs, 12 species of crabs, and 154 species of marine algae including 10 species of seaweeds (Thompson and Islam, 2010; http://www.fao.org/docrep/field/003/ab727e/AB727E03.htm). Loss of biodiversity (corals, crabs, fish, molluscs, etc.) in St. Martin's Island due to OA would mean the loss of seafood security, tourism revenues, and livelihoods of people as fishing and tourism are the main occupations for the Island's 5,500 residents. However, OA would also enhance the productivity of seaweeds on the Island since CO_2 is a major component for the photosynthesis of plants and would help those Bangladesh people engaged in seaweed culture and harvesting business (e.g., dry seaweed export to China, Myanmar, and Singapore) (Kibria and Haroon, 2017).

Hypoxia

This review further found nutrients such as high nitrate levels in the BoB, Bangladesh. In the marine environment, the limiting nutrient for algae is nitrogen, the abundance of which can cause nitrogen pollution, resulting in algal blooms and hypoxia (low dissolved oxygen) (Kibria et al., 2021a,b). Hypoxia can cause reduced growth, reproduction, and death of fish, shrimp, and molluscs (Kibria, 2023). For example, Wu (2009) reported that hypoxia can impair fish reproduction, alter reproductive behaviours, reduce fertilisation and egg-hatching success, and cause endocrine disruption in fish (e.g., increase the incidence of malformations in fish and may alter sex differentiation and sex determination). Hence, hypoxic conditions could threaten the sustainability of natural fish populations and affect the fisheries and livelihoods of people in the fishing and seafood business in Bangladesh (Kibria et al., 2010; Kibria, 2023).

Prawns, shrimp, crabs, oysters, clams, mussels, and fish are important sources of protein, vitamins B6, B12, and omega-3 fatty acids for Bangladeshi people (Kibria et al., 2017). It also generates revenue through employment and exports, supporting the livelihoods of coastal people. Fish accounts for more than 60% of the animal protein consumed in Bangladesh (Kibria et al., 2021a). The above discussion (sections: Ocean Warming (OW), Ocean Acidification (OA) (Low pH), and Hypoxia) shows that the fisheries and seafood of Bangladesh could be significantly negatively affected due to OW and OA.

Conclusion

This review collected, collated, analysed, interpreted, synthesised, and documented the regional water quality parameters relevant to OW and OA covering the Bay of Bengal (BoB). It principally compared the water quality data collected from the three parts of the BoB, Bangladesh, with the data and information from previous research carried out within the Indian subcontinent of the BoB. This review found that the sea surface temperature is increasing, and pH levels are decreasing in the BoB, Bangladesh. This could be alarming because OW could affect Bangladesh's distribution and abundance of coastal and marine fish species. Due to OW, fish may migrate away from Bangladesh to neighbouring countries or new territories. On the other hand, OA can adversely affect marine organisms that require calcium carbonate for their skeletons and shells, such as corals, molluscs, pteropods, and some phytoplankton in Bangladesh. Importantly, high nitrate levels detected in the BoB, Bangladesh, can cause nutrient pollution, resulting in algal blooms and hypoxia (low dissolved oxygen). OW, OA and hypoxia could threaten fisheries, seafood, and livelihoods of people associated with the seafood business in Bangladesh. Measured are required to reduce greenhouse gas emissions that cause climate change. Some of the measures could be the reducing greenhouse gas emissions in all spheres of life, promotion of community awareness and education on climate change, introduction of climate change courses in schools, colleges, and universities, and the incorporation of climate change risks in all the current and future development projects/plans vital to minimise threats and risks of climate change on fisheries, aquaculture, and seafood security.

Conflicts of interest

There is no conflict of interest.

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References

Ahammed, R. and Harvey, N., 2004. Evaluation of environmental impact assessment procedures and practice in Bangladesh. Impact Assessment and Project Appraisal, **22(1):** 63-78.

Baumann, H., Talmage, S.C., Christopher J. and Gobler, C.J., 2012. Reduced early life growth and survival in a fish in direct response to increased carbon dioxide. *Nature Climate Change*, **2:** 38-41. DOI: 10.1038/NCLIMATE1291

Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., et al., 2018. Declining oxygen in the global ocean and coastal waters. *Science*, **359(6371):** eaam7240.

Caldeira, K. and Wickett, M.E., 2003. Anthropogenic carbon and ocean pH. *Nature*, **425(6956):** 365-365.

Cole, J.J. and Prairie, Y.T., 2014. Dissolved CO_2 in freshwater systems. *In:* Reference Module in Earth Systems and Environmental Sciences https://doi.org/10.1016/B978-0-12-409548-9.09399-4. DOI: 10.1038/NCLIMATE1324

Cole, J.J., Hararuk, O. and Solomon, C.T., 2021. Chapter 7 - The Carbon cycle: With a brief introduction to global biogeochemistry. p131-160. *In:* Fundamentals of Ecosystem Science 131. Elsevier Inc. https://doi.org/10.1016/B978-0-12-812762-9.00007-1

Durack, P.J., Gleckler, P.J., Purkey, S.G., Johnson, G.C., Lyman, J.M. and Boyer, T.P., 2018. Ocean warming: From the surface to the deep in observations and models. *Oceanography*, **31(2):** 41-51.

Frommel, A.Y., Maneja, R., Lowe, D., et al., 2012. Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. *Nature Climate Change*, **2(1):** 42-46.

Gattuso, J.P., Magnan, A., Billé, R., Cheung, W.W., Howes, E.L., Joos, F. and Turley, C., 2015. Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science*, **349(6243):** aac4722.

Genner, M.J., Freer, J.J. and Rutterford, L.A., 2017. Future of the sea: Biological responses to ocean warming. Foresight Future of the Sea Project, 30.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., et al., 2007. Coral reefs under rapid climate change and ocean acidification. *Science*, **318:** 1737–1742.

Hutchins, D.A., Teyssii, J.-L., Boisson, F., Fowler, S.W. and Fisher, N.S., 1996. Temperature effects on uptake and retention of contaminant radionuclides and trace metals by the brittle star *Ophiothrix fragilis*. *Mar. Environ. Res.*, **41:** 363-378.

Islam, M.S., Pervez, A., Asseri, A.H., Al-Mutair, M., Sumon, M.A.A., Taleb, M.A., et al., 2022. Diversity and seasonal succession of resident and migratory macrobenthic fauna of saltmarsh restoration site at Sonadia Island, Cox's Bazar, Bangladesh region. *Stud. Mar. Sci.*, **53:** 102460.

Khan, M.A.Q., Ahmed, S.A., Catalin, B., Khodadoust, A., Ajayi, O. and Vaughn, V., 2006. Effect of temperature on heavy metal toxicity to juvenile crayfish, *Orconecte simmunis* (Hagen). *Environ. Toxico.*, **21(5):** 513-520.

Kibria, G., 2023. Climate change and pollution challenges. Analysis and examples (e-book). 131 pages. https://www.researchgate.net/publication/367433646_Climate_Change_and_Pollution_Challenges_Analysis_and_Examples

Kibria, G., Haroon, A.K.Y. and Nugegoda, D., 2013. Climate Change and Agricultural food production: Impacts, vulnerabilities and remedies. New India Publishing Agency, New Delhi, India. 300 p. ISBN: 9789381450512; DOI:0.13140/2.1.3245.4081.

Kibria, G., Haroon, A.K.Y., Nugegoda, D. and Rose, G., 2010. Climate Change and Chemicals: Environmental Biological aspects. New India Publishing Agency. New Delhi. 470 p. ISBN: 9789380235301. DOI: 10.13140/2.1.4384.0963.

Kibria, G., Hossain, M.M., Mallick, D., Lau, T. and Wu, R., 2016. Trace/heavy metal pollution monitoring in estuary and coastal area of Bay of Bengal. Bangladesh and implicated impacts. *Mar. Pollu. Bull.*, **105:** 393-402. https://doi.org/10.10 16/j.marpolbul.2016.02.021.

Kibria, G. and Yousuf Haroon, A.K., 2017. Climate change impacts on wetlands of Bangladesh, its biodiversity and ecology, and actions and programs to reduce risks. Chapter 10. Wetland Science: Perspectives From South Asia, pp. 189-204.

Kibria, G., Haroon, A.K.Y. and Nugegoda, D., 2017. Climate change impacts on tropical and temperate fisheries, aquaculture, and seafood security and implications - A review. *Livestock Res. Rural. Dev*., **29(1):** 1-29.

Kibria, G., Nugegoda, D., Rose, G. and Haroon, A.K.Y., 2021a. Climate change impacts on pollutants mobilization and interactive effects of climate change and pollutants on toxicity and bioaccumulation of pollutants in estuarine and marine biota and linkage to seafood security. *Mar. Pollu. Bull.*, **167:** 112364.

Kibria, G., Haroon, A.K.Y., Rose, G., Hossain, M.M. and Nugegoda, D., 2021b. Pollution risks, impacts and management. *In:* Social, Economic, and Environmental Perspectives. Scientific Publishers, India. ISBN: 978-93-89184-96-9. 833 p. https://www.research gate.net/publication/338291667_Book_2021_Pollution_Risks_Impacts_and_Manage ment_Social_Economic_and_Environmental_Perspectives

Kumar, P.K., Paul, Y.S., Muraleedharan, K.R., Murty, V.S.N. and Preenu, P.N., 2016. Comparison of long-term variability of Sea Surface Temperature in the Arabian Sea and Bay of Bengal. *Reg. Stud. Mar. Sci*. **3:** 67-75.

Lueker, T.J., Dickson, A.G. and Keeling, C.D., 2000. Ocean pCO_2 calculated from dissolved inorganic carbon, alkalinity, and equations for K1 and K2: Validation based on laboratory measurements of CO_2 in gas and seawater at equilibrium. *Marine Chemistry*, **70(1-3):** 105-119.

Mehrbach, C., Culberson, C.H., Hawley, J.E. and Pytkowicx, R.M., 1973. Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure 1. *Lim. Oceanog*, **18(6):** 897-907.

Millero, F., Lee, K. and Roche, M., 1998. Distribution of alkalinity in the surface waters of the major oceans. *Marine Chemistry* **60(1-2):** 111-130. https://doi.org/10.1016/S0304-4203(97)00084-4

Mubiana, V.K. and Blust, R., 2007. Effects of temperature on scope for growth and accumulation of Cd, Co, Cu and Pb by the marine bivalve, *Mytilus edulis. Marine Environ. Res.*, **63:** 219-235.

Muir, J. and Allison, E., 2007. The threat to fisheries and aquaculture from climate change - A policy brief. Policy brief. World Fish Centre. http://www.worldfishcenter.org/resource_centre/ClimateChange2.pdf.

NOAA., 2024. What is Ocean Acidification? National Oceanic and Atmospheric Administration. Last updated: 01/18/24 https://oceanservice.noaa.gov/facts/acidification.html#:~:text=Ocean%20acidification%20refers%20to%20a,CO2)%20from%20the%20atmosphere.

Noyes, P.D., McElwee, M.K., Hilary, D., Miller, H.D., et al., 2009. The toxicology of climate change: Environmental contaminants in a warming world. *Environ. Inter.*, **35:** 971-986.

Nugegoda, D. and Kibria, G., 2016. Effects of environmental chemicals on fish thyroid function: Implications for fisheries and aquaculture in Australia. *General Compar. Endocr.*, **244:** 40-53. doi: 10.1016/j.ygcen.2016.02.021

Rana, S., Hasan, M.N., Sultana, N., Hasan, S.J., Shimul, S.A. and Al Nahid, S.A., 2023. Acidification scenario of Cox's Bazar coast of the Bay of Bengal, Bangladesh and its influence on fish larvae abundance. *Heliyon*, **9(5):** e158555. doi: 10.1016/j.heliyon.2023.e15855.

Rashid, T., Hoque, S. and Akter, F., 2013. Ocean acidification in the Bay of Bengal. *Scientific Reports*, **2(3):** 699.

Roxy, M.K., Ritika, K., Terray, P., Murtugudde, R., Ashok, K. and Goswami, B.N., 2015. Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. *Nature Communications*, **6(1):** 7423.

Sabine, C.L., Wanninkhof, R., Key, R.M., Goyet, C. and Millero, F.J., 2000. Seasonal CO_2 fluxes in the tropical and subtropical Indian Ocean. *Mar. Chem*, **72(1):** 33-53.

Sarma, V. V. S.S., Krishna, M.S., Rao, V.D., Viswanadham, R., Kumar, N.A., Kumari, T.R., et al., 2012. Sources and sinks of CO_2 in the west coast of Bay of Bengal. *Tellus B: Chem. Physi. Meteorol.*, **64(1):** 10961.

Sarma, V.V.S.S., Kumari, V.R., Srinivas, T.N.R., Krishna, M.S., Ganapathi, P. and Murty, V.S.N., 2018. East India coastal current controls the dissolved inorganic carbon in the coastal Bay of Bengal. *Marine Chemistry*, **205:** 37-47.

Sarma, V.V.S.S., Krishna, M.S., Srinivas, T.N.R., Kumari, V.R., Yadav, K. and Kumar, M.D., 2021. Elevated acidification rates due to deposition of atmospheric pollutants in the coastal Bay of Bengal. *Geoph. Res Lett.*, **48(16):** e2021GL095159.

Sridevi, B. and Sarma, V.V.S.S., 2021. Role of river discharge and warming on ocean acidification and pCO_2 levels in the Bay of Bengal. *Tellus B: Chem. Phys. Meteorol*., **73(1):** 1-20.

Takahashi, T. and Sutherland, S.C., 2019. Global ocean surface water partial pressure of CO_2 Database: Measurements performed during 1957–2018 (Version 2018). NOAA/NCEI/OCADS. NDP-088(V2018). National Centers for Environmental Information. National Oceanic and Atmospheric Administration. 1315 East-West HwySilver Spring, MD 20910, USA, 17p. (accessed 21 February 2024).

Thangaradjou, T., Sarangi, R.K., Shanthi, R., Poornima, D., Raja, K., Saravanakumar, A. and Balasubramanian, S.T., 2014. Changes in nutrients ratio along the central Bay of Bengal coast and its influence on chlorophyll distribution. *J. Environ. Biol.*, **35(3):** 467.

Thompson, P.M. and Islam, M.A. (eds.) 2010. Environmental Profile of St. Martin's Island, United Nations Development Programme, Dhaka. http://samiasaif.weebly.com/uploads/1/6/7/9/16797564/environmental_profile_of_st_martins_island.pdf

UM (University of Massachusetts), 2016. Fact Sheets. Nitrogen Fact Sheet. Massachusetts Water Watch Partnership. Centre for Agriculture, Food and the Environment. https://www.umass.edu/mwwp/resources/factsheets.html#:~:text=Nitrate%20is%20usually%20the%20most,to%20support%20summer%20algae%20blooms.

USEPA., 2023a. Climate change Indicators: Sea surface temperature. https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature

USEPA., 2023b. Climate change indicators: Ocean acidity https://www.epa.gov/climate-indicators/climate-change-indicators-ocean-acidity#:~:text=Measurements%20made%20over%20the%20last,)%20(see%20Figure%201).

USEPA., 2023c. Understanding the science of ocean and coastal acidification. https://www.epa.gov/ocean-acidification/understanding-science-ocean-and-coastal-acidification#:~:text=Solutions%20with%20low%20pH%20are,and%20acidity%20is%20not%20direct

Venegas, R.M., Acevedo, J., Treml, E.A., Waldbusser, G.G. and Salisbury, J.E., 2023. Ocean acidification in the coastal zone from an organism's perspective: Multiple system parameters, frequency domains, and habitats. *Annu. Rev. Mar. Sci.*, **6:** 221-247.

Webb, P.M., 2024. 5.5: Carbon dioxide, pH, and ocean acidification (accessed 22 February 2024).

Wu, R.S., 2002. Hypoxia: From molecular responses to ecosystem responses. *Mar. Pollu. Bull.*, **45(1-12):** 35-45.

Wu, R.S.S., 2009. Effects of hypoxia on fish reproduction and development. *Fish Physio.*, **27(3):** 79-141.

Zeebe, R.E. and Wolf-Gladrow, D., 2001. CO_2 in seawater: Equilibrium, kinetics, isotopes (No. 65). Gulf Professional Publishing.

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