Dynamics of air–sea carbon dioxide fluxes and their trends in the global context

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This article reviews the dynamics of CO2 fluxes in the global scenario. Most of the available techniques for sea-surface CO2 partial-pressure estimation are regional models that depend on the key regulating parameters of partial pressures. Global-scenario of fluxes reveals a contrasting trend, indicating subpolar- and polar-waters dominated by physical forcings in winter, releasing CO2 whereas a biological drawdown of atmospheric CO2 in summer. In the tropical oceans, thermal-regulation weakens biological forcing leading to influx in winter and outflux in summer. The Atlantic Ocean acts as an intense sink (–815 to –1295 mmol C m\(^{-2}\) yr\(^{-1}\)); the strong source in the Pacific-equatorial belt is balanced by temperate sinks. The Indian Ocean as a whole acts as a sink (–8.41 \times 10^{15} \text{ mmol C yr}^{-1}) whereas the northwestern sub-basin acts as a source (2.04 \times 10^{15} \text{ mmol C yr}^{-1}). The net global ocean uptake is 50 \times 10^{15} \text{ mmol C yr}^{-1} where the physical- and biological-forcings along with seasonality play crucial roles in the flux direction.

Keywords: Carbon dioxide fluxes, earth system, global scenario, ocean–atmosphere interface, seasonal variability.

Carbon dioxide (CO2) though constitutes only a minor fraction (0.04%) of the volume of air, is the highest contributing greenhouse gas (GHG) to global warming, thus acting as one of the major factors in the radiative climate forcing\(^1\). CO2 gas emissions contribute about 77% of the anthropogenic GHG emissions and 63% of the direct radiative forcing\(^2\). About 50% of this added CO2 concentration in the atmosphere is being absorbed by the oceans, serving as the global CO2 storage. The role of oceans in regulating the global climate is significantly affected by the spatial and seasonal variations in the CO2 gas exchange process at the marine–atmosphere interface (Figure 1). Analysis of the regional controls on the direction of these fluxes is important in understanding the capacity of various oceanic regions in balancing the global CO2 concentrations\(^3,4\). CO2 flux can be divided into two constituents; the exchange of natural CO2 and the uptake of anthropogenic CO2 emissions. CO2 is released to the atmosphere from natural sources like biological respiration, organic decomposition, volcanic activities and chemical weathering as well as man-made sources like land-use change, cement production and fossil-fuel burning associated with manufacturing and industry, households and public buildings, and transport\(^5,6\).

The CO2 dissolved in the ocean occurs mainly in three inorganic forms, namely free aqueous carbon dioxide (CO2aq), bicarbonate ion (HCO\(_3^-\)) and carbonate ion (CO\(_3^{2-}\)), where HCO\(_3^-\) represents majority of the ocean inorganic carbon. The chemistry of this process as given in the literature\(^4,6\) is shown in eqs (1)–(4). A minor percentage of the diffused CO2 exists as carbonic acid which is about 0.3% of the aqueous CO2

\[
\begin{align*}
\text{CO}_2(g) & \rightarrow \text{CO}_2(aq), \quad (1) \\
\text{CO}_2(aq) + \text{H}_2\text{O}(l) & \leftrightarrow \text{H}_2\text{CO}_3(aq), \quad (2) \\
\text{H}_2\text{CO}_3 & \leftrightarrow \text{H}^+ + \text{HCO}_3^-, \quad (3) \\
\text{HCO}_3^- & \leftrightarrow \text{H}^+ + \text{CO}_3^{2-}. \quad (4)
\end{align*}
\]

These interspecies transitions occur in favour of maintaining a constant oceanic pH, thereby acting as a buffer system. Such dissolved CO2 in the surface ocean layer is transported into deeper layers through physical and biological carbon pumps, which reduces the surface water carbon dioxide partial pressures (pCO2) so as to enhance further uptake of atmospheric CO2 (Figure 2). The physical pump functions through downward mixing and downwelling processes and the biological pump involves gravitational settling of the fixed surface water carbon in biogenic debris. The physical pump also helps in maintaining the surface water pCO2 balance through upwelling of CO2-rich deep waters\(^1\).

Importance of the ocean–atmospheric CO2 fluxes

Studies have been carried out globally to understand the factors and mechanisms that govern the air–sea exchange of CO2. The concentration of CO2 gas in the atmosphere and ocean surface is the chief factor governing the flux direction\(^6,7\). This concentration is regulated by the physical, chemical and biological processes in the marine environment. These processes and their impacts vary regionally and seasonally, thereby impacting the spatial and seasonal trends in the CO2 fluxes. Even though the global ocean acts as a net CO2 sink, the regional fluctuations in the...
CO$_2$ exchange have potential repercussions on the global trends of CO$_2$ fluxes\(^3\). The ocean–atmosphere interactions and their vital role in the regulation of global biogeochemical cycles significantly contribute to the global climate system. Such natural cycles are continuously being interrupted by anthropogenic activities such as emission of GHGs like CO$_2$ and other lethal trace gases. Analysis of the transport, transformation and recycling of stored carbon in the ocean is essential in understanding carbon cycling in the marine–atmospheric system and thereby its significance in the global climate\(^7\). The ongoing reduction of ocean pH following the uptake of atmospheric CO$_2$ is referred to as ocean acidification, where the increase in the oceanic CO$_2$ leads to a decrease in the carbonate ion and increase in bicarbonate ion concentration. Such reduction in the carbonate concentration results in the reduction of CaCO$_3$ stability, leading to the deficiency of CaCO$_3$ for the marine calcifying organisms\(^4,8\). The ocean serves as the major reservoir of anthropogenic CO$_2$ as it holds about 93% of the carbon compared to the other reservoirs. Effective regulations for GHG emissions require accurate modelling of the global carbon cycle to understand the role of the ocean as the global CO$_2$ sink\(^4\).

**Carbon dioxide partial pressures as indicators of CO$_2$ fluxes**

The CO$_2$ flux is primarily defined by the CO$_2$ gas transfer velocity, seawater solubility of CO$_2$ and the difference in the CO$_2$ partial pressures at the sea surface and the air above, represented as $\delta$pcO$_2$. Among these, pCO$_2$ is the thermochemical steering factor for the net air–sea CO$_2$ flux, determining the flux direction at the ocean–atmospheric interface. Compared to atmospheric pCO$_2$, spatial and seasonal fluctuations are more prominent in the seawater pCO$_2$, making it the principal factor in flux determination\(^9\).
Accuracy of the CO$_2$ flux estimation thus depends on the spatio-temporal resolution of the measured pCO$_2$. Efforts have been made worldwide to obtain pCO$_2$ with better resolution using buoys and ship-board measurements. However, the spatial resolution of the present measurement network is far coarser (<250 km grid), which emphasizes the need for improved extrapolation techniques. Subsequently Landschutzer et al. have generated observational-based global monthly gridded sea-surface pCO$_2$ from 1982 to 2015. Figure 3 represents the seasonal pCO$_2$ map in the global context. The maximum value observed in the equatorial Pacific Ocean in all the seasons ranges between 450 and 475 μatm, whereas the Arctic Ocean exhibits minimum values ranging from 250 to 275 μatm in summer. In addition, low pCO$_2$ values (275–300 μatm) were observed in the Southern Ocean in the spring and winter seasons.

**Estimation of carbon dioxide partial pressures of seawater**

The seawater partial pressures are primarily regulated by thermal variations and biologically induced CO$_2$ concentration changes in the water, while other important factors acting in combination with these are sea surface salinity (SSS), nutrient concentration and mixed layer depth. The significance of these parameters on controlling the partial pressures depends on the biogeochemistry of the oceanic regions.

**Remote sensing approach in partial pressure estimation**

The key parameters governing the upper ocean biophysical processes are sea surface temperature (SST) and marine chlorophyll (Chl $a$) concentration, and their precise measurements can be done on global as well as regional scale for world oceans using satellite remote sensors. Therefore, efforts have been made worldwide to derive various biophysical parameters potentially affecting the CO$_2$ partial pressures from SST and Chl $a$. For example, seawater pCO$_2$ was estimated by eq. (5) using total alkalinity and dissolved inorganic carbon.

$$p_{CO2w} = g \times (2 \times DIC - TA) + h. \quad (5)$$

where pCO$_2w$ is the partial pressure of CO$_2$ in water, DIC the dissolved inorganic carbon, TA the total alkalinity,
Nutrient concentration was calculated as given in eq. (7) from SST and Chl \( a \)
\[
N = \alpha \times \text{SST} + \beta \times \text{SST}^2 + \gamma \times \text{Chl} + \delta \times \text{Chl}^2 + \epsilon.
\]

Lee et al. \cite{15} derived dissolved inorganic carbon using SST and nutrient concentration, as given in eq. (8).
\[
\text{DIC} = a \times \text{SST} + b \times \text{SST}^2 + c \times N + d,
\]

where \( a, b, c, d, e, f, g, \alpha, \beta, \gamma, \delta \) and \( \epsilon \) mentioned in eqs (5)–(8) are estimated constant parameters from least square method. The eqs (5)–(8) were combined to develop a semi-empirical quadratic relation given in eq. (9) for deriving sea surface \( \text{pCO}_2 \) as a function of SST and chlorophyll concentration \cite{10}.
\[
\text{pCO}_2\text{sw} = A \times \text{SST} + B \times \text{SST}^2 + C \times \text{Chl} + D \times \text{Chl}^2 + E,
\]

where \( A, B, C, D \) and \( E \) are constants estimated through least square procedure from \( \text{pCO}_2\text{sw} \), Chl \( a \) and SST measurements. Monthly averaged satellite data for SST and Chl \( a \) were obtained from OCTS (Ocean Colour and Temperature Sensor) on-board ADEOS (Advanced Earth Observation Satellite) platform to develop monthly \( \text{pCO}_2 \) maps for subarctic and subtropical oceanic regions.

Other studies that incorporated satellite data for \( \text{pCO}_2 \) determination include application of statistical regression techniques on SST data from NOAA (National Oceanic and Atmospheric Administration) AVHRR (Advanced Very-High-Resolution Radiometer) and Chl \( a \) from SeaWiFS (Sea-Viewing Wide Field-of-View Sensor) by Sarma et al. \cite{16} for the North Pacific Ocean; deriving partial pressure for northern South China Sea by Zhu et al. \cite{17} using SST and Chl \( a \) retrieved from AVHRR and SeaWiFS respectively; mapping \( \text{pCO}_2 \) over Huanghai and Bohai Sea by Zui et al. \cite{18} from Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) SST and SeaWiFS Chl \( a \); using SST from AMSR-E (Advanced Microwave Scanning Radiometer-Earth Observing System) on-board Aqua and Chl \( a \) from SeaWiFS and MODIS onboard Terra and Aqua by Liu and Xie \cite{19} for calculation of partial pressure for global oceans; use of SST and Chl \( a \) from MODIS for Hooghly estuary by Padhy et al. \cite{12} and that by Jang et al. \cite{20} where Chl \( a \), coloured dissolved organic matter (CDOM) and band reflectance from Geostationary Ocean Color Imager (GOCI) on-board COMS (Communication, Ocean and Meteorological Satellite) satellite were used over East Sea.

### Techniques for \( \text{pCO}_2 \) estimation

Stephens et al. \cite{21} developed sea-surface \( \text{pCO}_2 \) maps for the North Pacific by deriving statistical relationships between the ship-measured \( \text{pCO}_2 \) and SST, and applying them for the entire region using satellite-derived SST with a root mean square error of \( \pm 17 \) \( \mu \text{atm} \). The derived relation is given in eq. (10)
\[
\ln[\text{pCO}_2(10^\circ\text{C})] = A + B \times \text{SST} + C \times \text{SST}^2 + D \times \text{longitude}.
\]

Seasonal and inter-annual relationships between the CO2 fugacity and SST from ship measurements were derived by Cosca et al. \cite{22} for the central and eastern equatorial Pacific Ocean for El-Niño cool and warm event and non-El-Niño cool and warm event periods. The RMS values were \( \pm 20.3 \) and \( \pm 16.6 \) \( \mu \text{atm} \) for El-Niño warm and cool seasons respectively; \( \pm 28.8 \) and \( \pm 30.2 \) \( \mu \text{atm} \) for non-El-Niño warm and cool seasons respectively. The linear statistical algorithm obtained is represented in eq. (11)
\[
\text{fCO}_2 = A + B \times \text{SST}.
\]

The seawater CO2 partial pressures in the North Pacific Ocean were derived from ship measurements of Chl \( a \) and SST \cite{10} and \( \text{pCO}_2 \) maps for the region were developed using satellite-derived Chl \( a \) and SST. The RMS value for the satellite-derived \( \text{pCO}_2 \) was \( \pm 21 \) \( \mu \text{atm} \). The incorporation of Chl \( a \) along with SST in the \( \text{pCO}_2 \) derivation reduced the RMS error compared to the previous study by Stephens et al. \cite{21}, who developed \( \text{pCO}_2 \) maps from SST data in this region. The algorithm developed by Ono et al. \cite{16} for sea-surface \( \text{pCO}_2 \) is given in eq. (9).

Distribution of sea-surface \( \text{pCO}_2 \) in the North Pacific Ocean was mapped by Sarma et al. \cite{16} from satellite-derived Chl \( a \), SST and SSS applying multiple regression equations developed from \textit{in situ} data. The RMS error obtained for the satellite-derived \( \text{pCO}_2 \) was 17–23 \( \mu \text{atm} \). The algorithms were developed for spring and summer periods, and the general form of the algorithm is given in eq. (12)
\[
\text{pCO}_2 = A - B \times \text{SST} + C \times \text{SSS} - D \times \text{Chl} a.
\]

Zhu et al. \cite{17} estimated the sea-surface CO2 partial pressures and CO2 fluxes in the northern South China Sea using statistical relationship derived from \textit{in situ} measurements of SST and Chl \( a \) and \( \text{pCO}_2 \) maps were developed from the satellite-derived SST and chlorophyll. Two algorithms were developed using regression analysis for deriving sea-surface \( \text{pCO}_2 \), the first with \textit{in situ} SST data, and
the other with in situ SST and chlorophyll measurements. The satellite-derived pCO$_2$ was compared with the in situ values, which showed an RMS error of 4.6 μatm for the two-parameter algorithm, while it was found to be 25.1 μatm for the SST-based relation.

Relationship of pCO$_2$ and SST is given in eq. (13)

$$pCO_2 = A \times SST^2 - B \times SST + C.$$  \hspace{1cm} \text{(13)}

Equation (14) showing the pCO$_2$ relationship with SST and Chl $a$

$$pCO_2 = A \times SST^2 + B \times Chl \times a^2 - C \times SST - D \times Chl \times a + E.$$ \hspace{1cm} \text{(14)}

Ship-board measurements of pCO$_{2sw}$, SST and salinity were used to develop the partial pressure algorithm for seawater from SST, salinity and time component by Takamura et al. over the eastern and western North Pacific Ocean. The time parameter was introduced to address the temporal variations. The relation can be expressed as follows

$$pCO_{2sw} = a_0 + a_1 \times SST + a_2 \times SSS + a_3 \times t,$$ \hspace{1cm} \text{(15)}

where $t$ is the time elapsed (months), and maximum significance among the parameters on the variability of partial pressure is exhibited by SSS. The RMS error obtained for the eastern North Pacific Ocean was ±11.3 μatm. For the western region, separate temperature conditions were considered for statistical analysis, where the error obtained was ±13.4 μatm for <17.5°C and ±12.1 μatm for ≥17.5°C.

Zui et al. studied the seasonal variability of seawater pCO$_2$ in the Huanghai and Bohai Sea in relation to SST and Chl $a$ using ship measurements. The study proposed an empirical relation between pCO$_2$, SST and Chl $a$ to develop pCO$_2$ maps using satellite data. The satellite-derived pCO$_2$ value showed an RMS error of 13.45 μatm. The algorithm was developed for different SST ranges, viz. SST < 12°C, 12°C ≤ SST ≤ 23°C, and SST > 23°C. The basic form of the algorithm can be written as follows

$$pCO_2 = A \times SST + B \times SST^2 - C \times Chl \times a + D \times Chl \times a^2 + E(T).$$ \hspace{1cm} \text{(16)}

Carbon dioxide fugacity in the East Sea was derived from in situ measurements of dissolved organic matter, SST, salinity, mixed layer depth (MLD), Chl $a$ and band reflectance. The fCO$_2$ was derived using multivariate non-linear regression (MNR), where SST showed maximum correlation with pCO$_2$ distribution and the major contributing factors for fCO$_2$ variations were SST, salinity and MLD. The MNR algorithm is represented in eq. (17).

$$fCO_2 = \sum_{i=1}^{n} k_i x_i + \sum_{j=1}^{n-1} \sum_{m=j+1}^{n} k_{jm} x_j x_m + \sum_{j=1}^{n} k_j x_j^2,$$ \hspace{1cm} \text{(17)}

where $n$ is the number of input parameters, $x_i$ each input parameter and $k$ is the coefficient associated with each term. The RMSE obtained for validation of the algorithm was 10.59 μatm.

Seawater pCO$_2$, SST and SSS time-series data for the Bay of Bengal (BoB) open ocean waters have been used to derive multiple linear regression models. The empirical relation obtained was applied on satellite SST and SSS to develop the pCO$_2$ map for the case 1 waters of BoB. The relation is given in eq. (18)

$$pCO_2 = 11.81 \times SST + 11.71 \times SSS - 337.1,$$ \hspace{1cm} \text{(18)}

where RMSE for the validation of the derived pCO$_2$ was 9.22 μatm.

**Air–sea CO$_2$ fluxes distribution – case studies**

Assessment of the spatial and temporal distribution of CO$_2$ fluxes is important in understanding the efficiency of the ocean to control excess quantities of CO$_2$ gas released into the atmosphere and balancing the atmospheric CO$_2$ concentration. The capacity of the oceans to act as the anthropogenic CO$_2$ sink will be reduced eventually, up-setting the seawater carbonate speciation and the marine carbon cycle. The quantification and analysis of CO$_2$ fluxes between ocean and atmosphere will provide information regarding the past and current trends in CO$_2$ gas regulation by the oceans.

**Indian Ocean**

A study on CO$_2$ emissions over the Arabian Sea (AS) showed a supersaturation of pCO$_2$ during the southwest (SW) monsoon leading to strong outflux to the atmosphere. Extreme supersaturation levels reaching up to 750 μatm were found along the Omani coast and high pCO$_2$ values of around 525 μatm along with cold upwelled waters were observed about 300 NM (nautical miles) off the coast due to Ekman pumping. Variations in the flux densities were evident from the coastal region towards the open ocean with values ranging from 43,435 mmol m$^{-2}$ yr$^{-1}$ in the coast to 730 mmol m$^{-2}$ yr$^{-1}$ in the open-ocean waters. The SW monsoon has a significant role in the annual CO$_2$ emissions to the atmosphere with total emissions ranging from 0.672 to 1.73 × 10$^{13}$ mmol C. The wind forcing in combination with intense coastal upwelling during this season makes the Arabian Sea a major CO$_2$ source.

Analysis of temporal variations in CO$_2$ partial pressures and CO$_2$ fluxes over the Arabian Sea was done by Goet et al. using continuous pCO$_2$ measurements of seawater and atmosphere for the year 1995. Strong physical forcing due to the seasonal monsoons plays a major role in regulating the Arabian Sea partial pressures. Variations in pCO$_2$ were found to be very small in the offshore
regions with values less than 40 μatm while that of coastal areas crossed around 260 μatm. The monthly and annual fluxes were calculated using SST, wind speed and pCO₂ data. The mean monthly values ranged from 99.6 to 528 mmol m⁻² yr⁻¹ for most of the year, while they showed significantly higher values during the SW monsoon with values reaching up to 3753.6 mmol m⁻² yr⁻¹ along the coast of Oman resulting from the strong upwelling. The Arabian Sea was found to act as an annual CO₂ source to the atmosphere with annual emissions of 0.159 × 10¹⁵ mmol C yr⁻¹.

Sarma et al.29 analysed the seasonal and interannual variations in pCO₂ and total CO₂ (TCO₂) in the central and eastern Arabian Sea. The total CO₂ was determined by coulometric methods, and pCO₂ was computed from TCO₂ and pH. Seasonal changes in the TCO₂ were observed with variations in ocean circulation and primary production. TCO₂ values were found high during winter and low in the SW monsoon season. This was attributed to the winter convective mixing bringing subsurface CO₂ to the upper ocean and accelerated primary production during SW monsoon resulting from nutrient enrichment. Seawater pCO₂ was higher in all the seasons compared to the atmosphere in the Arabian Sea, except during the SW monsoon on the Indian coast. The analysis revealed that the Arabian Sea acts as a perennial CO₂ source during almost all seasons with annual emissions of 1.02 × 10¹⁵ mmol C yr⁻¹ to the atmosphere.

Data collected during the Indian and US JGOFS programme, and Indian Land–Ocean Interactions in the Coastal Zone process study program were used to analyse the sea-surface pCO₂ and air–sea CO₂ fluxes30. Dissolved inorganic carbon content was derived from SST, salinity and chlorophyll using multiple linear regression. Total alkalinity from salinity and surface pCO₂ from carbonate dissociation constants were computed. High variability was observed in the seasonal and spatial partial pressure distributions and CO₂ fluxes in the Arabian Sea. A rise in the partial pressures was observed on the western coast during the SW monsoon induced by the intense upwelling. The highest surface partial pressure values were observed during the SW monsoon with about 700 μatm in the upwelling region of the western coast and >480 μatm along the SW coast of India. In the open ocean, high partial pressures were found in the northern Arabian Sea with values >420 μatm. An increase in the SST by 2°–3°C was observed in the fall monsoon compared to the SW monsoon. This resulted in a decrease in surface pCO₂ levels to 360–380 μatm in the western coastal regions, particularly the Arabian coast due to stratification and biological processes triggered by high nutrient availability and subsequent elevated chlorophyll content. A lowered partial pressure range 370–380 μatm was noticed in the central Arabian Sea owing to the increase in SST and increased bacterial respiration. Lower pCO₂ values were found along the SW coast of India during the northeast (NE) monsoon resulting from the inflow of low-saline waters from the BoB. The decrease in partial pressures caused a lowering of the coastal pCO₂ values to <360 μatm, while the central Arabian Sea showed a partial pressure range 380–420 μatm. The spring intermonsoon was characterized by increased coastal partial pressures from <360 μatm to about 370–380 μatm, resulting from the reversed surface circulation breaking off the influence of low-saline water mass. Analysis of the CO₂ flux distribution showed stronger emissions from the western coast and the annual emissions from the Arabian Sea were about 2.04 × 10¹⁵ mmol C yr⁻¹, thereby acting as a CO₂ source.

A study carried out in 27 estuaries along the Indian coast by Sarma et al.31 reported that the CO₂ emissions were 4–5 times higher in the monsoon season than the dry period. The pCO₂ values ranged from 300 to 18,492 μatm. The monsoonal fluxes were about 0.0363 × 10¹⁵ mmol C, while the annual CO₂ emissions from the estuaries were 0.0436 × 10¹⁵ mmol C yr⁻¹. The high fluxes during the wet period are attributed to the high organic matter content in the estuaries due to the monsoonal river discharge and subsequently increased rates of microbial aerobic respiration. The occurrence of phytoplankton blooms drawing down the CO₂ levels and the increase in light penetration with decreased suspended sediment concentration in summer account for the reduced summer fluxes.

Observations on the western continental shelf of BoB by Sarma et al.32 showed that the sources and sinks of CO₂ in the shelf region are dependent on the river discharges and the distribution of the discharged water by the East India Coastal Current (EICC). The CO₂ partial pressures in SW coast are regulated by the peninsular river discharge and in NW region by the Ganges river discharge. The partial pressures were found to be lower than that of the atmospheric levels in the NW region, whereas the SW coast exhibited supersaturation. The lower values in the NW region were caused by the comparatively low salinity due to freshwater discharge and higher productivity than the SW coast. The CO₂ fluxes for the SW region were 2847 mmol m⁻² yr⁻¹, thus acting as a CO₂ source and for the NW region were −3978.5 mmol m⁻² yr⁻¹, thereby acting as a sink. The mean fluxes for the entire western coast were about 73 mmol m⁻² yr⁻¹, which suggests that the coast acts as a net annual source.

A study of the atmospheric CO₂ sinks in the southern Indian Ocean by Valsala et al.33 examined the seasonal, interannual and interdecadal variability of the CO₂ fluxes. They reported that the southern tropical-to-subtropical Indian Ocean region is a broad zone of subduction, where the subducting water mass traps and carries atmospheric trace gases from the atmosphere. Highest concentration of anthropogenic CO₂ was found to be at 150 m depth between 15°S and 50°S. The study area was divided into two distinct zones, namely north and south located at
Seasonal and interannual variability study of the CO₂ fluxes over the Indian Ocean from 1990 to 2009 was estimated by Sarma et al.34 as part of the Regional Carbon Cycle Assessment and Process (RECCAP). The fluxes in the northern Indian Ocean (18°S–30°N) were regulated by the solubility pump, while both the biological and solubility pumps equally dominated the southern region (44°–18°S). The results suggested that the southern Indian Ocean acts as a net annual CO₂ sink with flux value $-9.77 \times 10^{15}$ mmol C yr$^{-1}$ and the northern counterpart acts as a net source with annual mean value $2.95 \times 10^{15}$ mmol C yr$^{-1}$. The entire Indian Ocean acts as a net sink for atmospheric CO₂ with annual flux value $-8.41 \times 10^{15}$ mmol C yr$^{-1}$. The monsoonal wind action and upwelling processes in the northern Indian Ocean contribute to CO₂ release, whereas the low saline waters in the southern region enhance CO₂ uptake.

Seasonal and interannual variability study of the CO₂ flux by Valsala and Maksyutov35 simulated CO₂ flux over the northern Indian Ocean by coupling the biogeochemical model with an ocean tracer transport model which is based on 30-year reanalysis ocean data such as ocean currents, temperature and salinity. Maximum variability was observed in the coastal AS and southern Peninsula India (SP). The modelled CO₂ flux values showed an annual emission scenario of $(2.72 \pm 0.909) \times 10^{15}$ mmol C yr$^{-1}$. The CO₂ flux anomalies in AS and SP were then correlated with two major climate anomalies, i.e. ENSO (El Niño-Southern Oscillation) and Indian Ocean Dipole/Zonal Mode (IODZM). It was observed that a strong correlation of CO₂ flux in AS and SP with IODZM is accompanied by a weak correlation of the flux with ENSO and vice versa. The surface-water pCO$_2$ was calculated from dissolved inorganic carbon (DIC), temperature, alkalinity and salinity. Analysis of the effects of these components on the flux showed an increase in the temperature effect with a positive correlation between the flux and IODZM and vice versa in AS, whereas the CO₂ emission in SP was mainly controlled by changes in DIC. The DIC effect in SP was found to weaken during a negative correlation between CO₂ emission and ENSO.

Time-series estimation of chemical processes in the upper 100 m water column was carried out in the Visakhapatnam region on the western coast of BoB36. Measurements were made for temperature, salinity, DIC, TA and nutrients to derive the seawater pCO$_2$ and the atmospheric pCO$_2$ was measured directly using a pCO$_2$ sensor. The seawater pCO$_2$ values showed an increasing trend with a depth ranging from 450 μm at the surface to 1300 μm at 100 m depth. The CO₂ fluxes were estimated empirically from the CO₂ solubility, gas-transfer velocity and partial-pressure difference between air and seawater. The calculated fluxes suggest that the region acts as a net CO₂ source to the atmosphere with average values of 0.186 mmol C m$^{-2}$ yr$^{-1}$. The strong wind mixing of the sea-surface water was found to be a significant contributing factor for the fluxes in this region.

Valsala and Murtugudde37 analysed the intraseasonal and mesoscale variations occurring in the CO₂ gas transfer during boreal summer (June–September) over the western Arabian Sea. The oceanic circulation triggered by the fluctuations in the atmospheric circulation in this season induces intense upwelling, eddy formation, increased salinity levels and consequently elevated levels of nutrients and carbon content in the surface waters of the Somali coast. The study used a biogeochemical model called Ocean Tracer Transport Model (OTTM) based on reanalysis ocean data and surface fluxes. The sea-surface pCO$_2$ was observed to undergo consistent intraseasonal variability in this region driven by the changes in SST and DIC content. The analysis showed a correlation of 0.86 between pCO₂ variability and temperature, which was found to decrease with increased upwelling and Ekman pumping. The pCO₂ variability during the boreal summer accounts for 40% of the mean monthly CO₂ flux variability in this season. The seasonal co-variability of the outflux of CO₂ gas with decreased SST can be explained by the increase in DIC resulting from intense upwelling. The study also establishes the significance of ocean dynamics in the pCO₂ and CO₂ flux intraseasonal variability by analysing the response of SST, DIC, alkalinity, pCO₂ and biological pumps to the dynamic processes in the ocean system.

A CO₂ flux pattern study between seawater and air over the southern BoB reported high seasonal variations in the physico-chemical and biological parameters38. The summer season was characterized by intense light penetration due to low cloud cover, reduced nutrient concentration due to the absence of river discharge and vertical mixing, consequent decrease in biological production, lowering of surface pCO$_2$ and negative CO₂ fluxes. The summer trends in the physical, chemical and biological factors reversed during the monsoon season with strong wind action and enhanced upwelling contributing to high pCO₂ values and sea-to-air fluxes. The annual CO₂ flux variability ranged from $-1752$ to $4088$ mmol C m$^{-2}$ yr$^{-1}$ with an annual mean of 73 mmol C m$^{-2}$ yr$^{-1}$. The seawater pCO$_2$ values showed an increasing trend with a depth ranging from 450 μm at the surface to 1300 μm at 100 m depth. The CO₂ fluxes were estimated empirically from the CO₂ solubility, gas-transfer velocity and partial-pressure difference between air and seawater. The calculated fluxes suggest that the region acts as a net CO₂ source to the atmosphere with average values of 0.186 mmol C m$^{-2}$ yr$^{-1}$. The strong wind mixing of the sea-surface water was found to be a significant contributing factor for the fluxes in this region.
CO₂ partial pressure and flux measurements were made in the Hooghly estuary by Padhy et al. using in situ measurements and satellite data. SST and Chl a were used to derive the seawater partial pressure which revealed supersaturation levels. The high riverine fluxes account for high DIC levels in this region, contributing to enhanced pCO₂ levels. The winter pCO₂ levels ranged from 340 to 375 μatm and summer values were found to be about 450 μatm. The comparatively lower values in winter are attributed to the lowering of salinity by the river discharge and weak wind action. The average annual CO₂ fluxes were about 4.5 × 10⁴ mmol C m⁻² yr⁻¹, proving the region as a CO₂ source.

**Pacific Ocean**

Midorikawa et al.³⁹ analysed the CO₂ partial pressure distribution and concentration of DIC and nutrients in the western subarctic North Pacific region. The fluxes derived during winter to summer were about 5840 mmol m⁻² yr⁻¹, and during summer to autumn about –1460 mmol m⁻² yr⁻¹. The high fluxes during the winter to summer season is due to high DIC in the mixed layer and deep vertical mixing. The decreased CO₂ partial pressures due to increased biological consumption and the comparatively low wind speed during summer season have resulted in the reversal of fluxes during the summer to the autumn period.

CO₂ fugacity measurements of surface water were carried out by Feely et al.⁴⁰ in the equatorial Pacific Ocean, which showed a CO₂ supersaturation of seawater with average value of 473 μatm. The higher partial pressure values were attributed to enhanced upwelling in the region which resulted in about 20–40 μatm higher than normal values with the highest values obtained in the southern equatorial Pacific, where the upwelling was intense. The drawdown of CO₂ by the primary productivity of the ocean was counterbalanced by upwelling and surface warming, thus maintaining the sea-to-air fluxes. A relationship between the CO₂ gas transfer and wind speed was developed along with estimates of air–sea partial pressure differences to derive CO₂ fluxes. The average CO₂ flux was 3.7 × 10³ mmol m⁻² yr⁻¹. The variability in fluxes was contributed mainly by the partial pressure changes in this region, where the influence of wind field and gas transfer variability was found to be less.

Interannual and decadal flux variability over the equatorial Pacific Ocean was studied by Feely et al.⁴¹ using ship measurements of SST and CO₂ fugacity collected during the period November 1981 to June 2004, which included five El Niño and four La Nina events. An increase in the sea-surface CO₂ was observed at a similar rate to that of atmospheric CO₂, indicating an active exchange of air–sea CO₂ in the equatorial waters. A major inter-annual ENSO variability was observed for the entire region from the analysis of seawater fugacity in combination with SST and wind data, while seasonal changes were noted to be weak in the eastern Pacific. A prominent increase in fCO₂sw (CO₂ fugacity of seawater) was observed over the entire study period and a slight intensification of the CO₂ outflux after the 1997–1998 warm-to-cold regime shift resulting from the Pacific Decadal Oscillation (PDO).

Ship measurements of SST, salinity, sea surface and atmospheric CO₂ from the NW and northeast Pacific were analysed by Takamura et al.²⁷ to study the interannual and seasonal variability in the CO₂ fluxes from 1999 to 2006. In both western and eastern North Pacific, the fluxes showed minimum values during late summer (August/September) and reached a maximum during late winter (January/February). The summer flux values over the western region ranged from ~73 to 219 mmol m⁻² yr⁻¹, where the flux maximum during the winter exhibited a range 2993–4161 mmol m⁻² yr⁻¹. The eastern region had the minimum flux range within –1058.5 to –657 mmol m⁻² yr⁻¹ during summer and maximum range 1898 to 2482 mmol m⁻² yr⁻¹ in winter. The fluxes from air to seawater were found to increase over the period of study where the western North Pacific showed a comparatively higher rate of 69 ± 18.25 mmol m⁻² yr⁻¹, indicating a much stronger CO₂ sink than the eastern region with a flux rate of 32.85 ± 10.95 mmol m⁻² yr⁻¹.

Climatic impacts on the CO₂ flux variability in the northern Pacific Ocean were studied by Valsala et al.⁴² for the period 1980–2004. CO₂ flux data were analysed for spatio-temporal variability over the study area, followed by a comparative analysis of interannual variability with the seasonal changes. Spatial flux variability induced by PDO, generated by the SST anomalies in the North Pacific, was analysed using correlation analysis between monthly anomalies of CO₂ fluxes and PDO index. The analysis revealed small spatial variability of fluxes in relation to PDO, which was attributed to the weak interannual flux anomalies in the North Pacific. Flux anomalies were noticed in the subtropical gyre, where PDO-accompanied SST cooling had resulted in CO₂ absorption and eventual generation of the sink, thus establishing an active flux response to climate variability. It was observed that thermocline shifts associated with PDO were reflected in subsurface DIC levels.

Valsala et al.⁴³ studied the seawater pCO₂ and CO₂ fluxes over the equatorial Pacific for seasonal, interannual and multi-decadal variability for the period 1961–2005. They used the biogeochemical model based on the reanalysis ocean products to study the seasonal cycle and spatio-temporal characteristics of the pCO₂ and CO₂ fluxes during the ENSO period, both individual and combined effects of the wind and ocean dynamics on the variability of pCO₂ and CO₂ fluxes, effect of the canonical and Modoki ENSOs on the fluxes and also the carbon dynamics variability and its association with PDO. The analysis revealed a dominance of ENSO on the interannual flux
variability. A reduction in CO₂ emission was observed in the central to eastern equatorial Pacific during the El Niño period. The effect of canonical El Niño was found mainly between 160°W and 110°W, while the El Niño–Modoki dominated over the western (160°E–160°W) and far eastern (110°–90°W) equatorial Pacific. A correlation of pCO₂ was observed with the canonical El Niño to the east of 140°W and with the El Niño–Modoki to the west of 140°W. A nonlinear relationship between the pCO₂ and CO₂ fluxes was introduced in some parts of the equatorial Pacific by individual as well as combined influence of the ENSO-induced wind and ocean dynamics. Abrupt shifts were observed in the equatorial Pacific CO₂ sinks during the 45-yr study period. The multi-decadal variability caused an increased uptake of atmospheric CO₂ from 1961 to 1982, followed by a reduction until 2000 and again a strengthening of the sinking process thereafter. The study concluded that PDO and El Niño–Modoki are the major controlling factors of the pCO₂ and CO₂ flux multi-decadal variability, while the interannual variability is dominated by the canonical El Niño events.

Time-series data of high-resolution CO₂ flux were obtained by Sutton et al. over the Pacific Ocean from moored observations of sea-surface pCO₂ and wind speed measurements. These moorings are situated in four specific locations of north and south subtropical oligotrophic region, subtropical and subarctic North Pacific regions. Atmospheric and seawater pCO₂, SST and salinity were measured from four locations using a moored autonomous pCO₂ system set-up in open-ocean buoys located in the subtropical North and South Pacific and subarctic North Pacific regions. Total alkalinity was calculated using SST and salinity, which was further used along with the seawater pCO₂ to calculate DIC. The CO₂ flux was calculated using gas transfer velocity, CO₂ solubility and pCO₂ difference between seawater and atmosphere. The analysis showed an eventual shift of this oceanic region from an annual sink to a source of CO₂, which was attributed to elevated levels of sea-surface pCO₂ resulting from thermal anomalies in the North Pacific region. The subtropical North Pacific location proved as the strongest sink with ~647.7 mmol C m⁻² yr⁻¹ and the southern subtropical oligotrophic region was the only source with 106.8 mmol C m⁻² yr⁻¹.

Atlantic Ocean

Interannual CO₂ flux variability over the northern North Atlantic Sea for the period 1981–2001 during winter season was analysed by Olsen et al. The data analysis was carried out from October to March for calculating the fluxes using seawater CO₂ fugacity, CO₂ mole fraction, gridded datasets of SST, sea-level pressure and wind speed. A net annual air-to-sea CO₂ flux of 1.818×10¹⁵ mmol was obtained for the winter season for the study period with an interannual variability of ±0.7%. This variability was attributed mainly to the variations in wind speed and atmospheric CO₂ fugacity. The air–sea CO₂ flux was also found to be sensitive towards the variations in the North Atlantic Oscillation (NAO) and an increased CO₂ influx to the ocean with an increase in NAO index was observed.

A study on the interannual variability in the CO₂ sinks in the North Atlantic subtropical gyre over a two decadal period was carried out by Bates. Oceanic CO₂ was monitored continuously from 1983 to 2005, which showed an annual increasing trend in DIC and pCO₂ with an increase in atmospheric CO₂ concentration, followed by a subsequent decrease in seawater pH, carbonate concentration and CaCO₃ saturation states. An imbalance in the seasonal CO₂ sink and source rates was also observed attributed to the comparatively higher CO₂ uptake in winter than the summer outflux, proving this region as a CO₂ sink. The net air–sea CO₂ flux was estimated to be in the range ~815 to ~1295 mmol C m⁻² yr⁻¹. The occurrence of hurricane events enhanced the fluxes during summer season. The fluxes also exhibited a correlation with NAO variability in the summer and fall seasons. However, poor correlations were found in the case of the winter fluxes with NAO or Arctic Oscillation (AO), whereas they showed higher values during the El-Niño years. An increase of 5–17% in the net annual CO₂ flux rate was also observed during the study period.

Oliveira et al. carried out a study on the CO₂ fluxes over coastal and open-ocean waters of the southern Atlantic Ocean during the austral winter period of 2015. They analysed the eddy covariance measured in situ CO₂ fluxes for 13 and 14 July 2015 in three sub-regions of the study area, namely the Brazilian southeast coastal region (BCR), the region influenced by the Brazil current (BC) and the open ocean (OPO). The results showed a contrasting flux trend over the three selected study regions. The BC and BCR regions were found to act as a carbon sink, as shown by the measured negative flux values from these regions. It was noticed that an intensified mixing process at the ocean–atmosphere interface in the BC region induced by intense winds in this oceanic part favoured CO₂ absorption by the ocean waters, which was again strengthened by the temperature difference between the sea surface and atmosphere at the marine–atmospheric boundary layer (MABL). The presence of coastal upwelling was found to be the consequence of CO₂ sinking in the BCR region. Here the low values of SST and SSS were observed to increase the CO₂ solubility of surface waters, resulting in enhanced primary productivity. In contrast to BC and BCR, the OPO region lacks the CO₂ sink as a result of the decreased sea level pressure and weakened wind speeds triggering vertical movements in the MABL over this area leading to a decrease in atmospheric CO₂. As a result, the OPO region acts as a CO₂ source to the atmosphere. The study region exhibited a
mean sinking behaviour in the flux trends during the sampling period caused by the combined impact of large-scale atmospheric processes and local atmospheric modulations due to SST variations. The authors suggested the inclusion of further in situ data with better spatial and temporal resolution for enhanced understanding of the carbon budget over the southwest Atlantic region.55

Orselli et al.48 studied the significance of the Agulhas eddies in the air–sea CO2 fluxes over the south Atlantic Ocean using in situ measurements from six eddies and their surrounding waters carried out as a part of the FORSA (Following Ocean Rings in the South Atlantic) cruise during 27 June to 15 July 2015. The study area was divided into the eastern and western basins, with the Mid-Atlantic Ridge acting as the boundary. The sea surface and atmospheric CO2 partial pressures were calculated from the measured parameters like temperature, salinity and CO2 mole fraction for both seawater and overlying air. The surface temperature, salinity and seawater CO2 partial pressure values were comparatively less in the eastern basin, while low values of atmospheric partial pressures were obtained in the western basin. Eastern basin fluxes were observed to be regulated by physical forcing mechanisms driven by the Agulhas eddies, whereas biological dominance could be considered in the case of flux trends in the western basin. The difference in the ocean and atmospheric partial pressures was calculated to be –39.1 μatm, proving the oceanic region to be a sink for atmospheric CO2 with a mean flux value of −1372.4 mmol m⁻² yr⁻¹. Temperature domination in CO2 absorption was observed during the study period and the contribution of Agulhas eddy in this CO2 uptake was found to be –262 × 10⁷ mmol C yr⁻¹.

Studies over other oceanic regions

The study of seasonal variations in CO2 and nutrients in the high-latitude oceanic regions by Takahashi et al.25 examined the CO2 and nutrient concentration, and pCO2 data to define their seasonal relationship and compare the inter-ocean variations of these parameters. The springtime phytoplankton blooms in the North Atlantic Ocean were found to reduce the surface pCO2, nutrient and CO2 concentrations which lasted only until the exhaustion of the available nutrients. Such processes were limited only to the high-latitude waters north of 40° N. In the North Pacific, the seasonal variations in the CO2 and nutrient concentrations occurred as a gradual process, while a partial consumption of nutrients was observed in the subarctic North Pacific and the Southern Ocean regions. The concentration of CO2 and nutrients and the surface pCO2 showed higher values during winter in the subpolar and polar waters of South Atlantic, North Pacific, North and South Atlantic Oceans compared to the summer season. The high-latitude areas of North Atlantic, North Pacific and Weddel Sea acted as sources of CO2 to the atmosphere in winter and sinks in summer. This seasonality in the fluxes was attributed to intense winter upwelling and increased summertime photosynthesis. However, in the case of tropical waters, CO2 uptake from the atmosphere was found to occur during winter while outfluxes were observed in summer. Here, temperature was the key element regulating the seasonal pCO2 fluctuations due to weakening of biological factors. The combined effect of subtropical cooling and strong photosynthetic consumption of CO2 in the subpolar waters resulted in the generation of an intense sink in the subtropical convergence region.

Estimation of global CO2 fluxes by Takahashi et al.49 involved the measurement of partial pressure differences between air and ocean surface for around 250,000 global observations. Distribution of global monthly pCO2 differences was constructed from the lateral advection–diffusion transport equation, and the net CO2 flux was calculated from the partial pressure and CO2 gas transfer coefficients. An annual net uptake of 13.6–30.45 × 10¹⁵ mmol C yr⁻¹ by the oceans was estimated, and the analysis revealed the temperate and polar regions as CO2 sinks while equatorial region as the source. The Atlantic Ocean was found to be the most intense sink, accounting for about 60% of the global CO2 uptake. The Pacific equatorial belt was a strong CO2 source which was balanced by the temperate sinks; thus the Pacific Ocean was observed to be neutral in terms of flux. The contribution from both the Indian Ocean and Southern Ocean combined for the CO2 uptake was 20%.

Climatological monthly pCO2 data, seasonal effects of biological factors and temperature were used by Takahashi et al.9 to calculate the global air–sea CO2 fluxes, where the monthly and annual fluxes were estimated using mean monthly wind-speed data. The net annual uptake estimates were obtained as 50 × 10¹⁵ mmol C yr⁻¹ and the regions between 40° and 60° lat. were found to be the major CO2 sinks in both hemispheres consequent to the mixing of nutrient-rich subpolar cold waters with the poleward-flowing warm waters along with the biological CO2 uptake, subsequently resulting in decreased pCO2 in the subpolar waters. The high wind speed over the low-surface pCO2 waters also enhanced the oceanic CO2 uptake. Thermal and biological effects were observed to control the pCO2 seasonality for specific areas, whereas pCO2 seasonal maximum was regulated by thermal and physical forcing such as upwelling. The biological component dominated in the eastern equatorial Pacific, equatorial and subpolar waters, the northwestern Arabian Sea, Antarctic and the sub-Arctic North Pacific coastal waters, while the temperature component was found to influence the subtropical gyre areas.

Air–sea CO2 fluxes over the northern South China Sea were derived by Zhai et al.20 during spring, summer and autumn seasons. Data collection for temperature, pCO2,
and salinity was done during the ship measurements conducted for the summer of 2000, spring of 2001 and fall season of 2002. The surface-water partial pressures in the offshore region of about >100 km from the coast were found to be in the range 360–450 μatm, and were higher than that of the atmosphere in all three seasons. The sea-to-air difference in the partial pressures was observed to be about 0–50 μatm in the spring season, 0–90 μatm in autumn and 50–100 μatm in the summer season. The average flux values from the ocean to the atmosphere were 2555 mmol m⁻² yr⁻¹ for summer and in the range of average flux values from the ocean to the atmosphere. The formation of CO₂ fluxes showed that the Southern Ocean pressure changes dominated the DIC variations. The estimation of the seasonal variations in pCO₂ showed significant variations in pCO₂. The results were found to agree with the temperature and DIC-driven regulations in the summer CO₂ uptake by biological processes and winter release. The analysis showed that despite the outgassing in STZ and SAZ, these regions acted as sinks with flux values −7.95 × 10¹⁵ and −2.27 × 10¹⁵ mmol C yr⁻¹ respectively. While PFZ and SIZ were found to act as weak sources with negligible outgassing (0.227 × 10¹⁵ mmol C yr⁻¹), ASZ was a substantial CO₂ source, outgassing 8.18 × 10¹⁵ mmol C yr⁻¹.

Mongwe et al.⁵³ examined the significance of temperature and DIC in driving the seasonal cycle of CO₂ flux in the Southern Ocean. According to recent studies, the seasonality in CO₂ fluxes over this oceanic region is not well simulated by the Coupled Model Inter-comparison Project version 5 (CMIP5) as evident from a comparison with observational data. This study explains the bias in the CMIP5 model related to seasonal variations in SST and DIC. SST-related biases were grouped as group-SST, the most commonly observed bias, exhibiting an exaggerated rate of seasonal temperature variations during warming and cooling peaks in the spring and autumn seasons. Group-DIC bias showed exaggerated primary production scenarios, indicating a DIC-dominated flux variation. The study selected 10 CMIP5 models for analysis, based on the availability of the required parameters like pCO₂, CO₂ fluxes, SST, vertical temperature fields, surface DIC, annual DIC, mixed layer depth (MLD), surface oxygen, chlorophyll and net primary production (NPP). The analysis showed a low model sensitivity for the inter-basin CO₂ flux differences. The study reports that this is most likely due to the low sensitivity of the carbon cycle in these models compared to the observational data, towards the inter-basin difference in the driver parameters of the fluxes. This results in a zonal uniformity in the seasonal flux biases. Moreover, since the flux direction is dependent on the air–sea partial pressure difference and the sea-surface partial pressures are regulated by the SST and DIC concentrations, the ability of the model to simulate the flux seasonality is dependent on the sensitivity of the model towards the regulation of fluxes by variations in SST and DIC. As the CMIP5 models lack proper representation of inter-basin contrasts in the CO₂ fluxes and phytoplankton biomass compared to observational and remote sensing data, the study concludes with remarks explaining the need for further studies with the next-generation models such as CMIP6, giving a proper representation of carbon process parameterization and dynamics of the water column physics.

Dynamics and trends of air–sea CO₂ fluxes

The Indian Ocean, divided by the Indian peninsula into western and eastern sub-basins, is a unique oceanic region for studying the CO₂ fluxes. The northwestern Indian Ocean observed a supersaturation of pCO₂ during SW monsoon leading to strong outflux to the atmosphere. This was found to be attributed to the monsoonal wind forcing and intense coastal upwelling in this region, where the Somalia and Omani coasts were identified as the peak upwelling regions.⁵⁴ The circulation, mixing and
The Indian Ocean was identified as a net annual CO$_2$ sink open ocean enhances upwelling in the Arabian Sea, winds in the coastal areas and Ekman pumping in the source regions in the northeastern Indian Ocean are regulated by river discharge and coastal currents. The river discharges in BoB were found to have a significant influence on the mixed layer and barrier layer processes$^{57,58}$. Studies have reported upwelling regions triggered by strong monsoon winds around the Sri Lankan coast during summer monsoon and in BoB during NW monsoon$^{69,61}$, while the intensification of alongshore winds during summer monsoon induced strong upwelling along the coasts of Java and Sumatra, according to a study by Susanto et al.$^{62}$. The seasonal variability study of fluxes in the western BoB reported that the southwestern region acts as a source, whereas the northwestern part acted as a sink due to the freshwater-induced low surface salinity, and the entire western part was a net source. The western BoB was a CO$_2$ source resulting from strong wind action. The seasonality observations in the southern BoB fluxes showed that this region acts as a summer sink due to lack of vertical mixing and monsoonal source due to wind action and upwelling with a wide range from $-1752$ to $4088$ mmol C m$^{-2}$ yr$^{-1}$. A study on the Indian Ocean biophysical processes reported that the shallowing of thermocline by the climatological winds in the coastal areas and Ekman pumping in the open ocean enhances upwelling in the Arabian Sea, whereas BoB lacks a strong upwelling system$^{44}$. The entire Indian Ocean was identified as a net annual CO$_2$ sink by Sarma et al.$^{34}$ with an annual inward flux of $-8.41 \times 10^{15}$ mmol C yr$^{-1}$. The emissions were observed to be 4–5 times higher in the monsoon season compared to the dry period in the Indian coastal estuaries. A study of the Hooghly estuary revealed that the region acts as a net source of CO$_2$ with comparatively lower flux values in summer due to lowering of surface salinity and weak winds.

Flux studies over the Pacific Ocean were carried out in the western subarctic North Pacific, equatorial Pacific, the northwest and northeast Pacific, subtropical North and South Pacific and subarctic North Pacific regions. Observations in the western subarctic North Pacific showed this region to be a CO$_2$ source during winter to summer, and as a sink during summer to autumn. The high sea-to-air fluxes were due to high DIC in the mixed layer, and the deep vertical mixing in winter and decreased sea-surface CO$_2$ partial pressures in summer resulted from the increased biological consumption and comparatively low wind speed. The equatorial Pacific Ocean showed a CO$_2$ supersaturation of seawater caused by enhanced upwelling in this region. Highest outflux values were obtained in the southern equatorial Pacific where the upwelling was intense thus counterbalancing the surface CO$_2$ consumption by the ocean primary productivity. Interannual and decadal flux variability studies over the equatorial Pacific Ocean revealed an active exchange of air–sea CO$_2$. The interannual ENSO variability was strong in the entire region, while the seasonal changes were weaker in the eastern Pacific. PDO was found to intensify the sea-to-air fluxes in the equatorial region, while SST cooling related to PDO in the subtropical gyre was observed to enhance CO$_2$ sinking. The western North Pacific showed a much stronger CO$_2$ sink with minimum values during late summer and maximum during late winter. The Pacific Ocean showed an eventual shift from an annual sink to a source resulting from elevated thermal anomalies in the North Pacific region. The western subarctic North Pacific showed the highest sea-to-air fluxes of $5840$ mmol m$^{-2}$ yr$^{-1}$ during winter$^{39}$, while maximum absorption by the sea surface was observed in the subtropical North Pacific with a flux value of $-647.7$ mmol C m$^{-2}$ yr$^{-1}$ (ref. 44).

The air–sea CO$_2$ flux over the northern North Atlantic Sea during winter season showed sensitivity towards variations in NAO where the air-to-sea fluxes tended to be stronger with an increase in the NAO index. An imbalance in the seasonal CO$_2$ sink and source rates was also observed in the North Atlantic subtropical gyre, which was interpreted to be caused by the relatively higher winter CO$_2$ uptake rates by the sea surface compared to the summer outflux, establishing this region as a CO$_2$ sink of $-815$ to $-1295$ mmol C m$^{-2}$ yr$^{-1}$ (ref. 46). Hurricanes and NAO were also found to contribute to flux variability. South Atlantic Ocean showed contrasting trends in the fluxes between coastal and open ocean waters$^{27}$, while the coastal region influenced by BC as well as BCR acts as a CO$_2$ sink, the open ocean waters found to be releasing CO$_2$ gas. The South Atlantic Ocean acts as a net CO$_2$ sink with a mean flux value of $-1372.4$ mmol C m$^{-2}$ yr$^{-1}$ (ref. 48).

The northern South China Sea was reported to be a CO$_2$ source during spring, summer and autumn seasons with a maximum value of $2555$ mmol m$^{-2}$ yr$^{-1}$ in summer$^{50}$. A temperature-induced seasonality was observed in the sea-surface partial pressures with the region acting as a net CO$_2$ source. The Southern Ocean is known to be weak-to-moderate global sink where a winter upwelling induced increase in CO$_2$ partial pressures is obtained in the Antarctic Zone, while winter cooling decreases the pCO$_2$ values in the Sub Antarctic Zone. The annual fluxes were around $-9.1 \times 10^{15}$ mmol C yr$^{-1}$ for the Southern Ocean waters$^{51}$. 

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The springtime phytoplankton blooms in the high-latitude oceanic regions reduce the surface CO₂ concentration. Higher values were observed during winter in the subpolar and polar waters of South Atlantic, North Pacific, North and South Atlantic Oceans. The seasonality in the fluxes was visible from the winter sources and summer sinks in the high-latitude areas of North Atlantic, North Pacific and Weddel Sea. This seasonality was accredited to the intense winter upwelling and increased summer photosynthesis. In tropical oceanic regions where the biological factors are comparatively weak, temperature determines the flux direction with CO₂ release from the ocean surface in summer and absorption in winter. A combination of the subtropical cooling and strong subpolar photosynthetic CO₂ consumption generates an intense sink in the subtropical convergence region. The major global CO₂ sinks were found to be located in the temperate and polar regions, whereas the equatorial region acted as a source. The Southern Ocean is a significant sink despite the upwelling regions around Antarctica. The Atlantic Ocean was found to be the most intense sink with 60% of the global CO₂ uptake, while the Indian Ocean and Southern Ocean combined contributed by 20%. The Pacific equatorial belt was identified as a strong CO₂ source, which was balanced by the temperate sinks. Fluxes in the eastern equatorial Pacific, equatorial and subpolar waters, the northwestern Arabian Sea, Antarctic and the Sub-Arctic North Pacific coastal waters were found to be controlled by biological factors, whereas temperature factor dominated the subtropical gyre areas. The annual uptake of CO₂ by global oceans was estimated to be $50 \times 10^{15} \text{mmol C yr}^{-1}$ (ref. 9).

**Conclusion**

The global ocean acts as a net CO₂ sink with flux value of $50 \times 10^{15} \text{mmol C yr}^{-1}$, with high-latitude areas behaving as sources of CO₂ to the atmosphere in winter and sinks in summer. Tropical oceans exhibit the reverse trend. This seasonal behaviour of fluxes in the subpolar and polar regions results from the intense winter upwelling and increased photosynthetic activity in summer. Temperature is the key regulating factor in the tropics where the biological forcing is weak. The western subarctic North Pacific is a source in winter influenced by the physical forcing and becomes a sink with the summer photosynthetic drawdown of CO₂ peaks. The western North Pacific, on the other hand, proved to be a strong sink with maximum absorption in winter. The Atlantic region was recognized as the strongest sink of $-815$ to $-1295 \text{mmol C m}^{-2} \text{yr}^{-1}$ in the North Atlantic subtropical gyre, while the Pacific Ocean has been remained a neutral basin in terms of the CO₂ fluxes, since the intense outwards fluxes occurring in the equatorial belt are balanced by the sink zones in the temperate region. However, it tends to switch from an annual sink to a source as a consequence of the thermal anomalies in the North Pacific. The Indian Ocean and the Southern Ocean also contribute to the global sinks; however, the western sub-basin of the northern Indian Ocean is an annual net source with fluxes of $2.04 \times 10^{15} \text{mmol C yr}^{-1}$. The strong subtropical convergence zone acts as a strong sink, resulting from the occurrence of subtropical cooling and photosynthetic CO₂ intake in the subpolar oceans. The spatial and seasonal variability of the global CO₂ fluxes is triggered by the intensity of the physical and biological forcings as well as the thermal variations in particular oceanic regions. While the equatorial, subpolar, Antarctic and Sub-Arctic regions are dominated by the biological factors, the subtropical zones are influenced by the thermal component.

From studies conducted over different oceanic regions, it can be observed that the Indian Ocean exhibits a peculiarity in terms of CO₂ gas transfer. Even though this oceanic region contributes to the global CO₂ sinks, there is a contrasting nature of CO₂ fluxes in between the western and eastern sub-basins of the northern Indian Ocean, which can be better explained in terms of the contrasting trends in ocean primary productivity, freshwater and nutrient availability which govern the physical, chemical and biological processes in these waters. While major nutrient source is the river-water influx for BoB waters, the Arabian Sea is enriched with nutrients through the eolian dust fluxes from the deserts of Somalia and Arabia, especially iron which is the limiting nutrient in oceanic waters. The strong wind mixing of the surface waters along with the upwelling processes well distribute the available nutrients in the Arabian Sea, whereas the weak wind forcing and strong surface stratification restrict the nutrients distribution in BoB waters. Such contrasting trends between these two sub-basins of the Indian Ocean need to be analysed in detail both spatially and temporally using satellite as well as field data analysis in order to understand the biogeochemistry of these waters and its importance in regulating the carbon fluxes.

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