

**CARBON DIOXIDE EXCHANGES BETWEEN
THE ATMOSPHERE AND SEAWATER AT THE
NORTHERN STRAITS OF
MALACCA USING THE EDDY COVARIANCE
METHOD AND REMOTE SENSING**

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UNIVERSITI SAINS MALAYSIA

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by

ABDULGHANI ESSAYAH MUSBAH SWESI

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TABLE OF CONTENTS

ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF SYMBOLS	xi
LIST OF ABBREVIATIONS	xii
LIST OF EQUATIONS	xiii
ABSTRAK	xiv
ABSTRACT	xvi
CHAPTER 1 INTRODUCTION	1
1.1 Carbon Dioxide Flux and the Coastal Ecosystem.....	1
1.2 Problem Statement	5
1.3 Research Questions and Objectives	6
1.4 Research Significance and Novelty of the research.....	7
1.5 Thesis Outline	8
CHAPTER 2 LITERATURE REVIEW	11
2.1 Background of Study.....	11
2.2 Carbon Dioxide Fluxes in Coastal Environments	16
2.3 Influence of Monsoons on CO ₂ Flux	19
2.4 Photosynthetic Active Radiation and <i>Chl-α</i>	22
2.5 Wavelet Analysis of CO ₂ Flux and Environmental Parameters.....	26
2.6 Environmental Drivers of CO ₂ Flux and Interrelated Factors	27
2.7 Upwelling and Downwelling Processes and CO ₂ Flux.....	31
2.8 Climatological Trends in CO ₂ Flux.....	34
2.9 Eddy Covariance Application in the Coastal Area	36

CHAPTER 3	METHODOLOGY.....	39
3.1	Conceptual Framework of Methodology	39
3.2	Site Description	40
3.3	The Flux and Environmental Factors Measurement System	45
3.4	The Remote Sensing Data	48
3.5	Eddy Covariance Data Processing: Footprint and Quality Control	50
3.6	Measurement Uncertainty of the CO ₂ Flux.....	57
3.7	Statistical Analysis	59
CHAPTER 4	RESULTS AND DISCUSSION	62
4.1	General Role of the Tropical Coast as a CO ₂ Sink and Source	62
4.2	Variations of FCO₂ and it's Influencing Factors	63
4.2.1	Monsoons and FCO₂	63
4.2.2	Monsoons, <i>Chl-α</i> , and Environmental Factors in the monthly timescale.....	70
4.2.3	Carbon Dioxide Flux, Chlorophyll- α , and Environmental Factors on the Annual Timescale.....	81
4.2.4	Monthly and Annually Oscillations of FCO₂ and Environmental Parameters through Wavelet Analysis	86
4.2.5	Environmental Drivers of FCO₂ on Monthly and Annual Timescales.....	93
4.3	Upwelling -Downwelling Effects on FCO₂	101
4.3.1	Monsoons and the Upwelling and Downwelling Processes	101
4.3.2	Daily Averaged Seawater Temperature, <i>Chl-α</i> , and Wind Trends in Upwelling-Downwelling Conditions.....	111
4.3.3	Effects of the Upwelling-Downwelling (NEM-SWM) Phenomenon on FCO₂	117
4.3.4	Climatological Hourly Trends of FCO₂ in Upwelling and Downwelling Conditions in Upwelling-Downwelling (NEM-SWM) Periods.....	122
4.3.5	Impacts of CO ₂ Exchange on Coastal Fisheries and Ecosystem Health	127

CHAPTER 5	CONCLUSION AND RECOMMENDATIONS	130
5.1	Conclusion.....	130
5.2	Recommendations for Future Research	132
REFERENCES.....		134

LIST OF TABLES

	Page
Table 2.1 Literature values of the net CO ₂ flux in the South China Sea and Southeast Asia oceans. The Chukchi Sea is included for comparison. The primary method used to estimate the flux is the bulk transfer method using the sea–air difference.	18
Table 4.1 Correlation matrix of the CO ₂ flux and environmental factors on the monthly and yearly timescales (**p-value < 0.0001, *p-value < 0.001, *p-value < 0.01).	77
Table 4.2 Yearly averaged <i>FCO2</i> and environmental factors.	85
Table 4.3 Correlation coefficient matrix for the CO ₂ flux and environmental parameters on the overall, Upwelling-Northeast Monsoon (NEM), and Downwelling-Southwest Monsoon (SWM) daily timescales. Note that “***” is for p-value < 0.001, “**” is for p-value < 0.01, and “*” is for p-value < 0.1.	115

LIST OF FIGURES

		Page
Figure 2.1	Conceptual framework of air-sea CO ₂ exchange in the coastal region.	20
Figure 3.1	Conceptual framework of methodology research.....	40
Figure 3.2	The Muka Head Station's (MY-MKH) location is in the tropical coastal ocean of the Straits of Malacca (5°26'53''N,100°11'36''E). The station is equipped with eddy covariance and Biomet systems.	43
Figure 3.3	The eddy covariance system for CO ₂ flux measurements with the Biomet system at the Muka Head Station.	47
Figure 3.4	a) The flux footprint around the station; the percentages denote the contribution to the flux, e.g., the 10% contour shows the location of the peak flux contributor at 90%; b) the covariance spectra curve colored purple for $z/L = -2.01$, an unstable atmospheric surface layer, and spectra curve colored green for $z/L = 0.08$, a stable ASL; c) the windrose for u^*	53
Figure 4.1	Monthly-averaged atmospheric surface layer parameters from 2016 to 2020: CO ₂ flux, FCO_2 , and wind speed, U , The solid blue line is the monthly averaged trend, while the red dashed line is the annual averaged trend.....	68
Figure 4.2	Monthly-averaged atmospheric surface layer parameters from 2016 to 2020: friction velocity, u^* , and z/L . The solid blue line is the monthly averaged trend, while the red dashed line is the annual averaged trend.	69
Figure 4.3	Monthly-averaged values from 2016 to 2020: PAR, and $Chl-\alpha$. The solid blue line is the monthly averaged trend, whereas the red dashed line is the annually averaged trend.	78

Figure 4.4	Monthly-averaged values from 2016 to 2020: T_a , and RH. The solid blue line is the monthly averaged trend, whereas the red dashed line is the annually averaged trend.	79
Figure 4.5	Monthly-averaged values from 2016 to 2020: T_s , and SST from MODIS. The solid blue line is the monthly averaged trend, whereas the red dashed line is the annually averaged trend.	80
Figure 4.6	Wavelet analysis results of 2016 to 2020 monthly of FCO_2 , The power color bar and the corresponding power plot in the right panel are the power spectrum density, whereas the red-dashed and bolded yellow contour lines are the 95% confidence spectrum. The shaded regions indicate areas with high edge effects.	87
Figure 4.7	Wavelet analysis results of 2016 to 2020 monthly for $Chl-a$. The power color bar and the corresponding power plot in the right panel are the power spectrum density, while the red-dashed and bolded yellow contour lines are the 95% confidence spectrum. The shaded regions indicate areas with high edge effects.	89
Figure 4.8	Wavelet analysis results of 2016 to 2020 monthly for PAR . The power color bar and the corresponding power plot in the right panel are the power spectrum density, while the red-dashed and bolded yellow contour lines are the 95% confidence spectrum. The shaded regions indicate areas with high edge effects.	91
Figure 4.9	Wavelet analysis results of 2016 to 2020 monthly TS datasets. The power color bar and the corresponding power plot in the right panel are the power spectrum density, while the red-dashed and bolded yellow contour lines are the 95% confidence spectrum. The shaded regions indicate areas with high edge effects.	92
Figure 4.10	Correlation plots of the FCO_2 and environmental parameters on the monthly timescale.	97
Figure 4.11	Carbon dioxide flux and its controlling factors in the coastal sea in different monsoons.	101

Figure 4.12	Visual comparison of the monthly averaged distribution of (a) sea surface temperature, SST, in °C, (b) wind speed, U , in m s^{-1} , and (c) $Chl-\alpha$ concentration, $Chl-\alpha$, in mg m^{-3} , in the Malacca Strait during the upwelling month of January from 2018 to 2020. The red box indicates the location of the study site. The northeasterly winds of the monsoon triggered the upwelling process, which reduced the SST and enhanced the $Chl-\alpha$ concentration.	104
Figure 4.13	Visual comparison of the monthly averaged distribution of (a) sea surface temperature, SST, in °C, (b) wind speed, U , in m s^{-1} , and (c) $Chl-\alpha$ concentration, $Chl-\alpha$, in mg m^{-3} , in the Malacca Strait during the downwelling month of January from 2018 to 2020. The red box indicates the location of the study site. The southwesterly winds of the monsoon triggered the downwelling process, which moved warm waters to the location and increased SST while dampening the $chl-\alpha$ concentration.	105
Figure 4.14	Schematics of the dynamics of the (a) upwelling (Northeast Monsoon) and (b) downwelling (Southwest Monsoon) processes of the tropical coastal waters around the Muka Head station. It highlights the effects of wind on cold and warm water movements and its influence on nutrient availability and phytoplankton migration (denoted as blue, green, yellow, etc. icons) and the resulting CO_2 exchange between the sea and the atmosphere.	107
Figure 4.15	Day-of-year (DOY) daily averaged <i>in-situ</i> seawater temperature, TS (°C).	113
Figure 4.16	Day-of-year (DOY) daily averaged for satellite-derived chlorophyll- α concentration, $Chl-\alpha$ (mg m^{-3}).	114
Figure 4.17	Day-of-year (DOY) daily averaged <i>in-situ</i> wind speed, U	114
Figure 4.18	(a) Day-of-year (DOY) daily averaged FCO_2 ($\text{mmol m}^{-2} \text{d}^{-1}$) for 365 days. The green line is the loess-smoothed trend through the grey dots, the daily averaged values. Red (blue) box highlights upwelling (downwelling) in January (Northeast Monsoon, NEM) and June (Southwest Monsoon, SWM); (b) scatter plots showing the linear	

relationships (red lines) between the **FCO₂** and chlorophyll- α , *Chl- α* . A moderate negative linear relationship ($r = -0.159$) was observed for upwelling-NEM, whereas no relationship ($r = -0.055$) was seen for downwelling-SWM..... 121

Figure 4.19 Climatological hourly averaged (a) seawater temperature, *TS* (°C), (b) wind speed, *U* (m s⁻¹), (c) CO₂ flux (mmol m⁻² d⁻¹), and (d) wind direction, *WD* (radian, where zero means from the north and negative and positive radians are from the northwest and northeast). Red and blue loess-smoothed curves denote the upwelling-northeast Monsoon (NEM) and downwelling-southwest Monsoon (SWM) months of January and Jun, respectively. Seawater temperature (*TS*) and *U* were lower (higher) and higher (lower) in the upwelling than their corresponding values in the downwelling months, respectively. (e) The CO₂ flux was mostly negative (positive) throughout 24 h in the upwelling (downwelling) season. The depth of the sea in the northeastern area differed significantly from that of the northwestern area. 124

LIST OF SYMBOLS

CO_2	Carbon dioxide
F_{CO_2}	Carbon dioxide flux
U	Wind speed
u_*	Friction velocity
SST	Sea surface temperature from MODIS-Aqua
$Chl-\alpha$	Chlorophyll- α concentration
PAR	Photosynthetically available radiation
$PPFD$	Photosynthetic photon flux density
CH_4	Methane
RH	Relative humidity
T_a	Air temperature
T_s	Sea surface temperature
z/L	Ratio of the height of the measurement to the Obukhov length
C	Carbon
$p\text{CO}_2$	partial pressure of carbon dioxide
H_2O	Water
HCO_3^-	Bicarbonate Ion
CO_3^{2-}	Carbonate Ion
Ca^{2+}	Calcium Ion
CaCO_3	Calcium Carbonate
SSS	Sea Surface Salinity
H_2	Hydrogen gas
r	Pearson's Correlation Coefficient

LIST OF ABBREVIATIONS

NEM	Northeast Monsoon
STM	Spring Transitional Monsoon
SWM	Southwest Monsoon
FTM	Fall Transitional Monsoon
NEE	Net Ecosystem Exchange
EC	Eddy Covariance
ET	Evapotranspiration
QC	Quality Control
UI	Upwelling Index
ITCZ	Intertropical Convergence Zone
MODIS-Aqua	Moderate Resolution Imaging Spectroradiometer Aqua
Rrs	Remote Reflectance
SOCAT	Surface Ocean CO ₂ Atlas
WPL	Webb Pearman and Leuning
ASL	Atmospheric Surface Layer
SMI	Standard Mapped Image
NASA	National Aeronautics and Space Administration
EOS	Earth Observing System
GMT	Greenwich Mean Time
WGS	World Geodetic System
OC3	Ocean Color 3
TSM	Total Suspended Matter
CDOM	Colored Dissolved Organic Material
RMSE	Root Mean Square Error
ENSO	El-Niño-Southern Oscillation
WA	Wavelet Analysis
SD	Standard Deviation
CWT	Continuous Wavelet Transform

LIST OF EQUATIONS

$$u_* = \tau \rho \quad 1$$

$$z/L = kz_* \theta v / g_* T_* u_*^2 \quad 2$$

$$FCO_2 = -w_*' c' \rho_{air} C \rho \quad 3$$

$$W_{a,b} = 1/a - \infty \infty f t \psi t - b a dt \quad 4$$

**PERTUKARAN KARBON DIOKSIDA ANTARA ATMOSFERA DAN
AIR LAUT DI UTARA SELAT MELAKA MENGGUNAKAN KAEDAH EDDY
COVARIANCE DAN PENDERIAAN JAUH**

ABSTRAK

Karbon dioksida (CO₂) ialah satu gas iklim yang penting dan mempunyai variasi temporal dan geografi yang signifikan disebabkan oleh sumber dan penyerapannya yang pelbagai. Oleh itu, kami mengkaji lokasi sumber dan penyerapan karbon di satu kawasan pantai tropikal. Kajian ini memberi tumpuan kepada pembolehubah yang mempengaruhi input dan output aliran karbon di lautan pantai. Parameter persekitaran yang diukur ialah fluks karbon dioksida (F_{CO_2}), kelajuan angin (U), halaju geseran (u_*), suhu permukaan laut (SST), kepekatan klorofil- α ($Chl-a$), dan Radiasi Tersedia untuk Fotosintesis (PAR). Kami menggunakan strategi yang menggabungkan kaedah pengukuran in-situ dan pengesan jauh. Penyelidikan ini bertujuan untuk menentukan variasi aliran CO₂ dan faktor-faktor yang mempengaruhinya menggunakan kaedah kovarian eddy dan menilai kesan “upwelling” dan “downwelling” pada CO₂ dari laut ke atmosfera. Hasil kajian menunjukkan hubungan antara proses karbon dan faktor-faktor persekitaran. Hasil kajian menunjukkan sifat kitaran aliran yang dipengaruhi oleh kawalan biologi yang kuat, khususnya klorofil- α dan radiasi aktif fotosintetik atau PAR . Parameter persekitaran lain, seperti suhu atmosfera atau suhu permukaan laut, tidak mempengaruhi fluks. Kawalan biologi pada aliran CO₂ lebih ketara daripada kawalan fizikal pada skala bulanan dan sebaliknya pada skala tahunan. “Upwelling” dan “downwelling” mengawal proses biologi yang meningkatkan dan mengurangkan klorofil- α di kawasan pantai. Analisis “wavelet” menunjukkan bahawa aliran CO₂

dikawal oleh klorofil- α dan radiasi aktif fotosintetik, di mana radiasi membataskan tahap penyerapan CO₂ oleh pantai tropika.

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ABSTRACT

Owing to its numerous sources and sinks, carbon dioxide (CO₂) is one of the best-known climatically important gases that exhibits significant temporal and geographical variations. Therefore, we investigated sources and sinks of carbon in a tropical coastal area. This study focuses on the variables influencing the coastal input and output of carbon flux of the sea. The environment parameters measured are carbon dioxide flux (F_{CO_2}), wind speed (U), friction velocity (u_*), sea surface temperature (SST), chlorophyll- α concentration $Chl-\alpha$, and Photosynthetically Available Radiation (PAR). We used a strategy incorporating methods of in-situ measurement and remote sensing. This research aims to determine the variation of CO₂ flux and its influencing factors using the eddy covariance method and to evaluate the upwelling and downwelling effect on CO₂ from the ocean to the atmosphere. The results showed the relationship between carbon processes and environmental factors. The results indicate the cyclical nature of the flux that is affected by strong biological controls, specifically $Chl-\alpha$ and photosynthetic active radiation or PAR . Other environmental parameters, such as atmospheric or sea surface temperature, did not modulate the flux. Biological controls on CO₂ flux are more prominent than physical controls on the monthly scale and vice versa for the yearly scale. The upwelling and downwelling controlled the biological process, which increased and decreased $Chl-\alpha$ in the coastal area. Wavelet analysis shows that the CO₂ flux is regulated by $Chl-\alpha$ and photosynthetic active

radiation, in which the radiation limits the degree to which the tropical coast absorbs CO₂.

CHAPTER 1

INTRODUCTION

1.1 Carbon Dioxide Flux and the Coastal Ecosystem

The global ocean and sea contain approximately 50 times more carbon than the atmosphere and are among the most important carbon dioxide (CO₂) sinks (Sohma et al., 2018). Coastal systems are even referred to as “blue carbon” (Siikamäki et al., 2013) because they fix a considerable amount of carbon. Coastal ecosystems are pivotal reservoirs for carbon sequestration, recognized as "blue carbon," acting as significant players in mitigating atmospheric carbon levels. Carbon dioxide (CO₂) exchange between the atmosphere and sea, termed CO₂ flux, occurs within these systems. Marine macroalgae drive the most substantial globally fixed CO₂ flux among marine macrophytes. Despite this significance, there is a notable absence of comprehensive field measurements to verify the potential net sequestration of macroalgae-derived biomass in marine sediments. The lack of empirical data significantly constrains the inclusion of macroalgae in global Blue Carbon initiatives to foster oceanic carbon sequestration (Queirós et al., 2019).

Notably, high-latitude fjords and continental shelves have been identified as atmospheric CO₂ sinks. However, our understanding of their contributions to atmospheric carbon regulation faces challenges due to significant spatial and temporal variability, particularly concerning the limited availability of sea-air CO₂ flux data. This scarcity is particularly evident in fjord systems, which impedes their ability to scale up knowledge and accurately assess their roles in the global carbon cycle (Aalto et al., 2021).

The coastal ocean serves as a reservoir that absorbs carbon dioxide (CO₂) and is primarily influenced by seasonal fluctuations in the CO₂ flux originating from the disparity between the air and sea partial pressure of CO₂ ($p\text{CO}_2$). However, wind speed and sea surface temperature alterations also have considerable regional significance in shaping these variations (Roobaert et al., 2019).

These discoveries underscore the intricate interplay of physical and biological factors governing the exchange of CO₂ between the atmosphere and the coastal sea. They emphasized the substantial contribution of coastal systems to the broader global carbon cycle, highlighting their pivotal role in regulating atmospheric CO₂ levels (Ikawa, 2013).

Before the Industrial Revolution and the burning of fossil fuels, the net global ocean CO₂ flux was positive, offsetting the absorption of CO₂ by green plants in the biosphere. Today, humans have reversed this trend, so the seas absorb more CO₂ than they release (Zhang et al., 2022).

Although coastal regions account for only 7% of the global oceans, their contribution to the global ocean CO₂ exchange is high (Lansø et al., 2019). Coastal ecosystems undergo dynamic carbon elemental cycling, which results in rapid carbon loss to the atmosphere.

Furthermore, Bianchi (2011) stated that the total flux of dissolved organic carbon is largely unknown because data on chemical biomarkers and stable isotopes indicate that very little organic carbon in the global sea is terrestrially derived. Moreover, in recent decades, the expansion of organic and inorganic carbon in coastal seas has been observed (Bauer et al., 2013), which warrants further study because little is known about the source of this growth.

Biogeochemically, coastal seas are more dynamic and vulnerable to environmental changes, such as climate change, than the open oceans (Borges, 2011). Previous studies have claimed that large uncertainties exist in the decomposition rates of carbon (Houghton et al., 2012; Prentice et al., 2015) from coastal ranges to the open ocean (Cai, 2011). Additionally, Tang et al. (2011) evaluated sea CO₂ fluxes to determine whether the primary production of CO₂ in coastal seas is exported or recycled. They contended that assessing air-sea CO₂ fluxes entails the absorption of atmospheric CO₂ and determining whether CO₂ primary production in coastal seas is exported or recycled. The ocean plays a pivotal role in the global carbon cycle and harbors over 90% of the Earth's actively cycling carbon pools within pelagic and coastal regions. The equilibrium of carbon exchange between the atmosphere and the ocean is crucial for sustaining a habitable environment (Eglinton, 2011).

Carbon exports can be quantified based on carbon flux. Flux can be defined as the net amount of mass, such as CO₂ (mol), that moves upward or downwards through an area (m²) perpendicular to the surface in a certain amount of time (s); its SI unit is mol m⁻² s⁻¹. Additionally, the flux value directly enumerates the net ecosystem exchange (NEE) of a system, that is, the amount of carbon absorbed or released by the system. The transfer of CO₂ from the sea into the atmosphere is referred to as a positive flux, whereas a negative flux means that the ocean absorbs CO₂.

Coastal and global seas exhibit intricate CO₂ flux patterns influenced by diverse environmental factors. Flux measurements revealed trends in CO₂ exchange linked to these factors. The key influences of coastal CO₂ exchange include seasonal cycles of CO₂ flux and surface seawater *p*CO₂ (*p*CO₂, SW), which are affected by temperature fluctuations, nutrient availability, and primary productivity (Lerner et al., 2021). The spatial variability in CO₂ exchange stems from diverse water mass

distributions, nutrient levels, and primary productivity variations. For instance, a study in the northern Gulf of Mexico estimated an annual CO₂ flux of $-4.3 \pm 1.1 \text{ Tg C y}^{-1}$, with an average annual flux between -0.8 to $-1.5 \text{ mol C m}^{-2} \text{ y}^{-1}$ over 2006–2010, indicative of net ocean uptake (Caib et al., 2018). Environmental drivers such as temperature, wind speed, and salinity sensitivity affect the seasonal amplitudes of the CO₂ flux and $p\text{CO}_2, \text{sw}$ (Lerner et al., 2021). Ocean acidification resulting from anthropogenic CO₂ input alters the seawater carbonate balance, affecting its physical and chemical properties. This change significantly influences the physiology of surface-dwelling planktonic algae in oceans (Xue et al., 2020).

In general, coastal seas exhibit complex patterns of positive and negative fluxes (Dai et al., 2022). Thus, through flux measurements, trends in CO₂ exchange and their association with environmental factors can be discerned. In addition, if the measurement frequency is high, the important timescales of the driving conditions can be understood. Nicholson et al. (2018) stated that to better understand carbon cycling across heterogeneous environments, it is necessary to characterize its temporal and spatial variability.

Although the biological properties (e.g., primary productivity, organic matter decomposition, and bacterial respiration) and physical properties (e.g., temperature, salinity, and water mixing) of seawater play crucial roles in coastal carbon exchange (Xue et al., 2020), it is essential to note that CO₂ fluxes are also influenced by overlying atmospheric factors (e.g., wind, temperature and pressure, humidity, and air composition) (Lerner et al., 2021).

Furthermore, the behaviour of the CO₂ flux varied with the timescale under study. Previous research indicates that factors such as wind speed, sea surface

temperatures, or *Chl- α* govern CO₂ flux on differing timescales: yearly, monthly, daily, or sub-daily. The CO₂ fluxes in coastal waters are also linked to changes in the solubility of aqueous CO₂ (Woolf et al., 2016), which results in changes in the NEE and the water carbonate system (Longhini et al., 2015). Moreover, further investigations are required to comprehend the impact of monsoons on CO₂ flux in the coastal regions (Aalto et al., 2021; Wallmann et al., 2022).

1.2 Problem Statement

The changes to coastal carbon sources and sink capabilities due to environmental shifts, for example, increased atmospheric CO₂, seasonal perturbations, and climate change, remain unknown. Nevertheless, research has shed light on how these alterations affect the dynamics of carbon emissions in coastal regions. For instance, an investigation of CO₂ exchange between the atmosphere and tropical coastal seas revealed the site's status as a moderate CO₂ absorber, with seasonal variations influenced by monsoonal changes affecting its capacity to either absorb or emit carbon. This study highlights a consistent shift in the role of the coastal sea, transitioning from a carbon-absorbing state at night to a less effective carbon absorber during the day. This shift is believed to result from the combined effects of wind speed and seawater temperature (Yusup et al., 2023).

Although studies conducted in the open ocean have addressed this lack of knowledge, limited coverage and analysis of coastal CO₂ exchange have reduced our understanding of how coastal systems respond to environmental variations (Christiansen et al., 2016). To enhance our understanding of carbon cycling in an ever-changing coastal environment, it is evident that there is a need to broaden spatially

detailed datasets using extensive, direct measurement methodologies on a large scale (Bouskill et al., 2021) .

1.3 Research Questions and Objectives

Based on the issues discussed, the research questions addressed in this study are as follows:

1. How do CO₂ flux and its factors vary in a coastal sea?
2. How does upwelling-downwelling affect CO₂ flux?

The first question aimed to explore the spatial and temporal variations in the CO₂ flux within tropical coastal ecosystems, shedding light on the underlying mechanisms and drivers. The second question investigated the impact of upwelling and downwelling on the CO₂ flux, which could provide insight into the nature of carbon export and cycling in the region.

Based on the research questions, the objectives of the study are:

1. To determine the variation in CO₂ flux and its factors from the atmosphere to the coastal sea and vice versa.
2. To evaluate the upwelling-downwelling effect on CO₂ flux from the sea to the atmosphere using *in-situ* eddy covariance and remote sensing data.

The first objective was to quantify and understand the variation in CO₂ flux between the atmosphere and coastal sea. The eddy covariance method aims to identify the key factors influencing these fluxes, including both biophysical characteristics and atmospheric conditions. The second objective was to assess the impact of upwelling and downwelling on CO₂ flux using a combination of *in-situ* eddy covariance

measurements and remote sensing data. By analyzing these processes, we aim to provide insights into how they affect carbon exchange between the sea and atmosphere.

In summary, this study represents a comprehensive effort to advance our understanding of carbon dynamics in tropical coastal seas. By addressing these research questions and objectives, this study provides insight into the critical processes that shape carbon fluxes in these environments.

1.4 Research Significance and Novelty of the research

This study has substantial significance in the geoscience field for various reasons. First, it enhances our comprehension of carbon dynamics within coastal ecosystems, often recognized as "blue carbon" systems due to their pivotal role in the global carbon cycle. Precise carbon dioxide (CO₂) flux estimation within these ecosystems is indispensable for multiple scientific domains, including oceanography and marine ecology. Such knowledge enables us to understand the impact of coastal ecosystems on the overall carbon budget and the well-being of marine life.

Moreover, this study investigated the effects of CO₂ flux on the characteristics of coastal waters. Factors such as air and seawater temperatures have been studied because they influence the photosynthetic processes in these waters. These variables, in turn, hold direct implications for the vitality and abundance of marine ecosystems, including crucial elements like coral reefs and fisheries. This research also delves into the intricate patterns of CO₂ fluxes between the sea and the atmosphere, a vital component for improving climate models and projecting future carbon budgets.

Through this investigation, we aim to contribute to the body of knowledge surrounding the temporal dynamics of CO₂ flux in coastal regions. By elucidating these climatological trends, we can provide valuable information to inform climate models and enhance their ability to predict and mitigate the impacts of climate change. This research represents a significant step towards comprehending the intricate relationship between oceanic processes, such as upwelling and downwelling, and their role in modulating the Earth's carbon balance.

It seeks to characterize the temporal and spatial variations in carbon cycling within dynamic coastal environments, thereby aiming to reduce uncertainties in estimating carbon flux, particularly regarding organic carbon decomposition.

1.5 Thesis Outline

This thesis is comprised of five chapters, each serving a specific purpose within the overarching research framework.

Chapter 1: Introduction

This chapter provides an overview of the research, contextualizing it within a broader scholarly landscape. It emphasizes the significance of the study, articulates the problem statement, delineates research questions, outlines aims and objectives, and underscores the novelty and importance of the research.

Chapter 2: Literature Review

Following a thorough literature review, this chapter explores the dynamics of CO₂ flux within coastal environments, including the impact of monsoons. It delves into monsoonal patterns, factors such as chlorophyll, and broader environmental considerations. Special attention was given to wavelet analysis to assess the CO₂ flux

and associated environmental parameters. This review includes a detailed analysis of environmental drivers such as seawater temperature, chlorophyll levels, and wind speed while scrutinizing intricate mechanisms such as upwelling and downwelling processes.

Chapter 3: Methodology and Method

This section presents the site description, eddy covariance system structure, and instruments used in this study. It details the methodology for parameter measurements and the data collection method from both *in-situ* stations and remote sensing.

Chapter 4: Results and Discussion

This chapter uses the eddy covariance method to explore the variation in CO₂ flux at the atmospheric–coastal sea interface. It examines factors influencing bidirectional flux, including the impact of monsoons on F_{CO_2} and relationships among monsoons, *Chl- α* , and environmental parameters over annual timescales. Wavelet analysis uncovers dynamic monthly and annual oscillations in F_{CO_2} and environmental parameters. The chapter scrutinizes environmental drivers affecting and ending subscriptions on monthly and annual scales, emphasizing seawater temperature, chlorophyll levels, and wind speed. It integrates *in-situ* eddy covariance and remote sensing data to explore the upwelling–downwelling effect on CO₂ flux, including daily averaged seawater temperature, *Chl- α* , and wind trends in upwelling–downwelling conditions.

Further exploration includes the effects of the upwelling–downwelling (NEM-SWM) phenomenon on CO₂ flux, revealing the intricacies in F_{CO_2} dynamics.

Climatological hourly trends in CO₂ flux during the NEM-SWM period provide insights into temporal aspects, contributing to a comprehensive understanding of CO₂ flux dynamics.

Chapter 5: Conclusion and Future Recommendations

The final section summarizes the main conclusions and offers recommendations based on the findings of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Study

The significant role of the sea as a carbon dioxide (CO₂) reservoir is widely acknowledged in the scientific literature (Canadell et al., 2007). It functions as a crucial CO₂ sink, absorbing a substantial portion of emissions from natural sources and human activities, collectively representing approximately one-quarter of human-generated CO₂ (Wieder et al., 2021). Covering more than 70.8% of the Earth's surface, the sea is a complex ecosystem inhabited by diverse life forms that exert significant control over the release and uptake of CO₂ (Colossi Brustolin et al., 2019). This intricate process of CO₂ absorption by the sea plays a pivotal role in mitigating the impact of climate change (Wang et al., 2021).

Furthermore, the sea serves as a substantial buffer for approximately 30% of the CO₂ emissions resulting from the combustion of fossil fuels, similar to the capacity observed on land. In contrast, the remaining portion remains in the Earth's atmosphere (Friedlingstein et al., 2022). Elaborate global evaluations utilizing sophisticated models and remote sensing data have provided comprehensive estimates of the net primary production of the sea. These assessments revealed a considerable range, ranging from 35 to 70 Pg C y⁻¹, as reported by Carr et al.(2006). Consequently, the sea is a monumental carbon sink that actively influences the global carbon cycle dynamics by facilitating the exchange of CO₂ between the atmosphere and sea (Bates & Mathis, 2009). This profound interaction between the sea and carbon underscores the critical need to understand the mechanisms governing CO₂ flux.

Carbon dioxide significantly influences oceanic biological production and diversity (Zhu et al., 2009). Although CO₂ primarily originates from the processes of living organisms and fossil fuel combustion, aquatic and terrestrial carbon sinks play crucial roles in reducing atmospheric CO₂ levels and act as bulwarks against climate change (Wang et al., 2021). With more than 70.8% of the Earth's surface covered by water, the sea represents a complex ecosystem inhabited by various organisms that affect the release and uptake of CO₂ (Colossi Brustolin et al., 2019). These ecosystems account for approximately 25% of total anthropogenic CO₂ emissions (Wieder et al., 2021). Researchers have found that approximately half of the emitted CO₂ remains in the atmosphere, whereas the oceans absorb the remaining half, making it the dominant CO₂ sink (Le Quéré et al., 2010).

As global warming progresses and sea ice melts, open-water areas in the world's oceans expand, leading to an increased uptake of atmospheric CO₂ (Yasunaka et al., 2018). However, several factors can hinder this process, including water temperature, vertical mixing at the surface, reduced buffering capacity owing to sea ice melting, and increased river runoff (Else et al., 2013; Fransson et al., 2017).

Carbon dioxide plays a vital role in global warming and acidification. Several studies have suggested that continental shelves and coastal regions capture CO₂ and transport carbon to the open ocean (Chen et al., 2004; Kahl et al., 2017). Despite covering only 0.5% of the total ocean volume, the coastal sea contributes significantly to over 30% of the entire air-sea CO₂ exchange and accounts for 80% of oceanic organic matter burial (Chen & Borges, 2009). This is due to high sedimentation rates, upwelling, and runoff of carbon-rich water from river systems and carbon export to the seabed at the shelf edge, making the coastal sea a net carbon sink (Ye et al., 2021).

The ability of the sea to serve as a CO₂ sink is influenced by factors such as temperature, salinity, solubility, biological pumps, and phytoplankton mass (Yang et al., 2021). The transfer velocity of CO₂ is another critical factor affecting the exchange of CO₂ between the atmosphere and sea. Additionally, relative humidity, wind speed, and precipitation play a role in this process.

Phytoplankton, often referred to as the "oceanic carbon pump," drive CO₂ uptake by fixing it into oxygen and organic carbon through photosynthesis. Phytoplankton, including algae and cyanobacteria, fix dissolved inorganic carbon into oxygen and organic nutrients in their chlorophyll via photosynthesis (Birch et al., 2021). Particulate organic carbon is another essential parameter that regulates CO₂ flux and contributes 10% to oceanic carbon emissions; it originates from surface runoff and river systems. Higher concentrations of particulate organic carbon lead to lower atmospheric CO₂ levels (Gloege et al., 2017). This type of carbon is a crucial source for phytoplankton and other marine organisms along the coast. Surface phytoplankton promote CO₂ absorption into the sea and sink particulate organic carbon deeper into the sea.

Crucially, the exchange of CO₂ between the atmosphere and ocean and the transport of organic carbon into the deep sea is intricately regulated by phytoplankton and zooplankton. Zooplankton serve as trophic links between primary producers and higher trophic levels and also function as recyclers of particulate carbon and nutrients into dissolved forms (Mitra et al., 2014; Steinberg & Landry, 2017). Maznah et al. (2021) reported the influence of water quality parameters on the abundance and diversity of zooplankton in coastal waters. They revealed a direct connection between the zooplankton community, water quality, and sediment variables.

In this ecosystem, phytoplankton are the primary producers and infuse vital energy into the food chain. Phytoplankton composition, abundance, and biomass offer insights into the overall health of ecosystems (Zanuri et al., 2020). Notable species within this phytoplankton community include *Skeletonema* sp. 1, *Skeletonema* sp. 2, *Gyrodinium* sp. 1, *Prorocentrum* sp. 1, *Protoperidinium* sp. 1, *Protoperidinium* sp. 2, *Karenia* sp., and *Thalassiosira* spp., which encompass *Thalassiosira nanolineata*, *Thalassiosira densannula*, and *Thalassiosira gravida* (Javeed et al., 2018; Zanuri et al., 2020). These phytoplankton species significantly influence factors such as water turbidity and dissolved oxygen concentration.

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al., 2020). These phytoplankton species significantly influence factors such as water turbidity and dissolved oxygen concentration.

Zooplankton assume the role of secondary producers in aquatic ecology and hold significance as bioindicators of aquatic ecosystem health. They play an integral role in the marine food chain (Steinberg & Landry, 2017). Notably, marine zooplankton species tend to be larger than their freshwater counterparts and encompass a wide array of animal phyla (Davies et al., 2009; Maznah et al., 2021). The zooplankton community is highly sensitive to various environmental factors, including nutrient levels, temperature, food availability, pollution, light intensity, predation, pH, and heavy metal concentrations. Within the study area, an extensive array of 49 taxa of zooplankton species thrives, representing diverse phyla, such as *Arthropoda*, *Chordata*, *Coelenterata*, *Protochordata*, *Mollusca*, *Polychaeta*, *Hydrozoa*, and *Echinodermata* (Wan Maznah et al., 2014).

The tropical coastal sea, a subset of the global ocean, is known for its rich biodiversity and connections to various biomes, including estuaries, rivers, tidal wetlands, and continental shelves (Ward et al., 2020; Yusup, Kayode, et al., 2018b). Jyothibabu et al. (2015) suggested that the highest chlorophyll concentration is found in shallow ocean areas compared to deeper ocean regions. Consequently, the carbon cycle in tropical coastal oceans is recognized as a key element of the global carbon cycle and budget.

The total carbon content of the sea consists of dissolved organic carbon, dissolved inorganic carbon, dissolved methane, and particulate organic carbon (POC) (Fiedler et al., 2008). Particulate organic carbon is significantly associated with microbial degradation, photochemical oxidation, and detritus (Bauer et al., 2013). CO₂

in dissolved organic carbon continuously undergoes processes in the atmospheric surface layer that are affected by turbulent mixing in the ocean (Mari, 2008; Riebesell et al., 2007; Smetacek, 1999). The equilibrium of CO₂ in the atmospheric surface layer occurs on timescales ranging from weeks to months and is driven by wind. When CO₂ dissolves in the ocean surface, it reacts with seawater to form carbonic acid, which subsequently dissociates into bicarbonate ions.

Biological processes are pivotal in influencing CO₂ exchange on the spatial and temporal scales through two central mechanisms. The first involves the conversion of inorganic carbon into particulate organic carbon via photosynthesis, which removes CO₂ from the atmosphere. The second process involves forming calcium carbonate shell materials through calcification (Sailley et al., 2013). The latter process was significantly slower than the former. Inorganic carbon is absorbed and fixed by marine phytoplankton in the euphotic zone of the ocean via photosynthesis and respiration. Photosynthesis contributes half of the net synthesis of organic matter on the ocean surface. Particulate organic carbon is a critical component for the growth of marine phytoplankton. Its degradation contributes to the formation of dissolved organic carbon, which is the foundation for developing marine phytoplankton (Yamaguchi et al., 2003). Circulation processes transport particulates and dissolved organic carbon back to the water surface via the respiration of marine organisms.

2.2 Carbon Dioxide Fluxes in Coastal Environments

Carbon dioxide flux was systematically measured on a global scale. These studies aimed to characterize its variability and identify the factors that influence it. Researchers have employed various methods, including the eddy covariance method, water and air sampling, and remote sensing techniques (Harmon, 2020). One study

concluded that the eddy covariance method is reliable for quantifying air-sea exchanges of CO₂ and CH₄ along the coast (Gutiérrez-Loza et al., 2019). Deemer et al. (2016) described the application of micrometeorological methods, such as eddy covariance, in monitoring CO₂ fluxes, which can address many monitoring challenges by providing continuous, long-term, spatially integrated flux measurements. Other studies have reported that spatially integrated eddy covariance or acoustic monitoring yields higher flux measurements than methods with limited spatial and temporal coverage, such as floating chamber and thin-boundary layer measurements. This aligns with the finding that a low sampling coverage in stochastic systems leads to underestimating fluxes (Wik et al., 2016).

Van Dam et al. (2021) studied air-water CO₂ exchange in coastal seagrass meadows, finding it comparable to carbon burial rates. Key drivers include tidal forcing, temperature, wind, and light. Surface drag coefficients in seagrass meadows were higher than in the open ocean, indicating enhanced gas transfer. Near Bob Allen Keys, Florida, they observed significant diurnal CO₂ variability, with daytime rates 36% higher than nighttime, identifying the site as a net CO₂ source. Temperature changes significantly influenced CO₂ flux, and evaporation rates were ten times greater than precipitation, increasing salinity and affecting seagrass health. These findings highlight the importance of temperature in CO₂ and evaporation dynamics in seagrass ecosystems.

In the investigation conducted by Long et al. (2021), they explored the air-sea CO₂ fluxes in the Southern Ocean. This study employed atmospheric transport models and measurements of atmospheric CO₂ gradients obtained from aircraft observations to establish reliable constraints. The research outcomes indicated an annual average carbon flux of approximately $-0.53 \pm 0.23 \text{ Pg C yr}^{-1}$ (indicating net CO₂ uptake) below

the latitude of 45°S during the period spanning from 2009 to 2018. These results are consistent with previously established estimates but point to a more substantial CO₂ uptake when compared to recent observations using profiling floats.

Table 2.1 shows that some studies have reported the open-ocean CO₂ flux of the Southeast Asia region. However, the net flux on the tropical coast is either unknown or under-represented. Decadal studies suggest that the tropics should be a net-positive CO₂ flux area due to warmer water temperatures. However, the flux may depend on other sub-decadal timescale factors, such as phytoplankton mass. The tropical coast is known to have large concentrations of *Chl- α* -containing organisms (Yusup, Alkarkhi, et al., 2018), suggesting competing factors in the flux that could depend on the season and modulate the decadal pattern.

Table 2.1 Literature values of the net CO₂ flux in the South China Sea and Southeast Asia oceans. The Chukchi Sea is included for comparison. The primary method used to estimate the flux is the bulk transfer method using the sea–air difference.

Location	Latitude	Longitude	Net CO ₂ Flux (mmol m ⁻² d ⁻¹)	Reference
Northern South China Sea	18°–21°N	112°–118°E	1.26	(Zhai et al., 2013)
Central/Southern South China Sea	7°–18°N	110°–117°E	3.75	(Zhai et al., 2013)
West of the Luzon Strait	18°–22°N	118°–121°E	3.32	(Zhai et al., 2013)
Indonesian Water	10°N–10°S	90°–145°E	7.81	(Ekayanti & Rahman as- syakur, 2011)
Northern South China Sea	16.9°–24.0°N	109.5°–119.0°E	–2.3	(Li et al., 2020)
South China Sea	10.8°–20.2°N	114°–119.3°E	1.2	(Li et al., 2020)
East China Sea	26.02°–32.02°N	121.46°–125.52°E	–6.39	(Qu et al., 2013)
East China Sea	24.47°N	123.02°E	–4.30	(Chou et al., 2009)
Chukchi Sea	65°–75°N	150°–170°W	–14.6	(Bates, 2006)
Indian Ocean	14°N–14°S	20°–146°E	0.77	(Takahashi et al., 2002)

2.3 Influence of Monsoons on CO₂ Flux

Investigating the influence of monsoon systems on the CO₂ flux is critical because of the potential impact of monsoons on the global carbon cycle. A pivotal study Sabine et al. (2004) centered on the Indian Ocean Basin, unveiled insights into this intricate relationship. Their findings emphasized pronounced seasonal and regional variations in surface seawater CO₂ levels within the Indian Ocean. In another region, the Southwest Monsoon was identified as a key event that elevated partial pressure of CO₂, $p\text{CO}_2$, values in the Arabian Sea coastal, an upwelling region.

Building on this foundation (Yusup, Kayode, et al., 2018b), this study extends the exploration to the southern South China Sea, further elucidating the effect of monsoonal cycles on CO₂ flux dynamics. Their study revealed that the tropical coastal ocean in the southern South China Sea functioned as a net carbon dioxide sink. However, during the Southwest Monsoon and Fall Transitional Monsoon phases, this CO₂ uptake diminished by 60% owing to increased precipitation, underscoring the significant role of monsoonal precipitation in regulating the CO₂ flux in this region. Collectively, this body of research suggests the critical role of monsoons as drivers of fluctuations in the CO₂ flux, thereby enhancing our understanding of their broader implications for the global carbon budget.

Monsoons in the northern Indian Ocean induce seasonal upwelling in the Arabian Sea, leading to increased productivity. Pronounced fluctuations in particle flux have been observed in sediment traps, particularly during monsoon periods. The principal determinant contributing to this variability is heightened productivity stemming from wind-driven mixing and nutrient infusion, which is significant for CO₂ absorption during periods of intensified wind speed, as indicated in prior research (Nair et al., 1989).

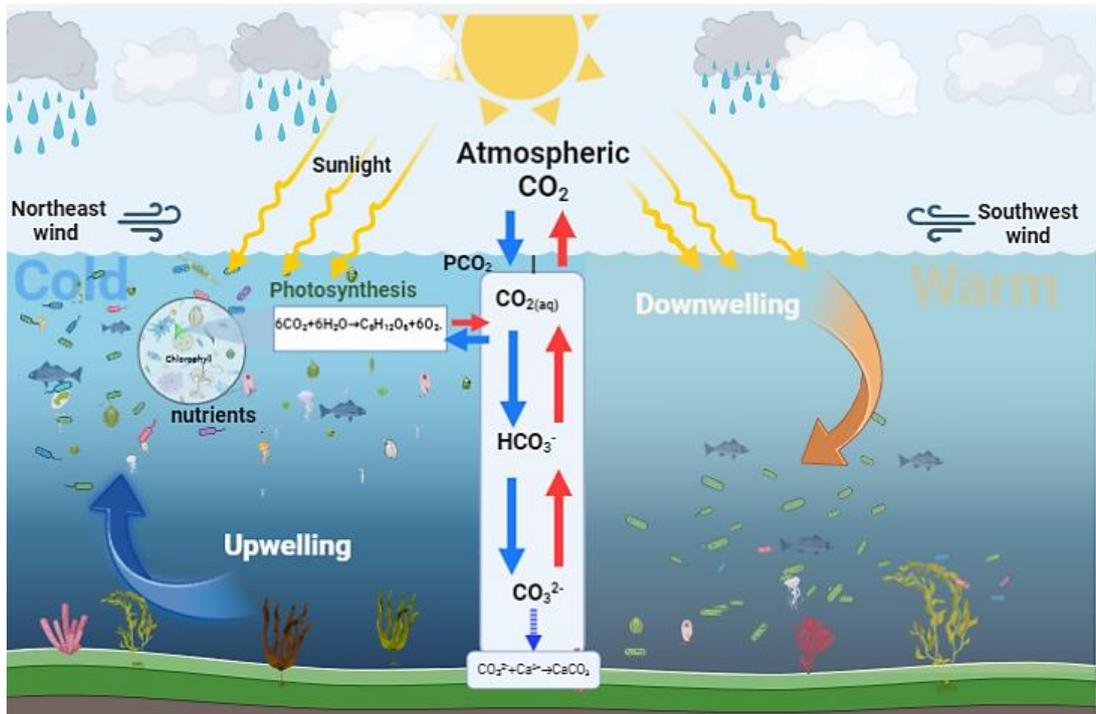


Figure 2.1 Conceptual framework of air-sea CO₂ exchange in the coastal region.

One study investigated $p\text{CO}_2$ in the Amazon River plume and the western tropical North Atlantic Ocean during expeditions in 2010-2012. This revealed strong connections between sea surface $p\text{CO}_2$, air-sea CO₂ exchange, and sea-surface salinity. The Amazon River plume acted as a variable CO₂ sink with significant fluctuations, including a pronounced CO₂ reduction during the spring flood in June 2010 and a moderate reduction during the declining river discharge in September and October 2011. In July 2012, the region briefly became a minor CO₂ source due to complex CO₂ interactions. This study demonstrates the need to account for biological processes, exports, and air-sea gas exchange when estimating regional CO₂ fluxes beyond relying solely on salinity data. (Mu et al., 2021).

Takahashi et al. (2002) investigated the interplay among $p\text{CO}_2$ levels in surface ocean waters, wind speed, and CO₂ transfer velocity in the Indian Ocean. It particularly focused on the influence of wind speed on gas exchange between the ocean and

atmosphere, highlighting the significance of the chosen wind speed dependence in estimating the CO₂ flux. Notably, using wind speed to the power-of-three (U^3) dependence led to a substantial increase in annual oceanic CO₂ uptake, coupled with heightened sensitivity to wind speed variations. This research revealed a significant CO₂ sink for atmospheric CO₂ between latitudes of 40° and 60° in both hemispheres. This zone results from the mixing arm and cold nutrient-rich subpolar waters, causing a noticeable reduction in surface water $p\text{CO}_2$ levels. Additionally, the study emphasized the seasonality of surface water $p\text{CO}_2$, attributing it to the interplay between biological CO₂ utilization and seasonal temperature fluctuations. Interestingly, these factors exhibited phase differences across regions, creating areas with minimal seasonal $p\text{CO}_2$ variation.

This shifting source-sink surface may have been caused by variations in the wind. Estuarine $p\text{CO}_2$ depends on various factors, including mixing with low- $p\text{CO}_2$ shelf water, water temperature, residence time, and biogeochemistry. Recent global estuarine CO₂ estimates have been revised to 0.10 Pg C yr⁻¹, considering unreported Asian and Arctic data showing lower sea-to-air CO₂ fluxes due to higher $p\text{CO}_2$ ($p\text{CO}_2$ in the water) and weaker Asian winds. In comparison, Europe and North America have higher fluxes. Polar estuaries tend to absorb CO₂. Globally, continental shelves primarily act as CO₂ sinks influenced by water temperature, river plumes, upwelling, and biology. Stronger winds at high latitudes result in higher air-to-sea CO₂ fluxes. Low-latitude areas experience smaller sea-to-air fluxes due to weaker winds. To summarize, global estuaries release 0.094 Pg C yr⁻¹, primarily due to lower Asian wind speeds, whereas polar estuaries may absorb more CO₂. Continental shelves consistently absorb 0.4 Pg C yr⁻¹, in line with prior findings (Chen et al., 2013; Laruelle et al., 2014).

2.4 Photosynthetic Active Radiation and *Chl- α*

The *Chl- α* and photosynthetically active radiation (*PAR*) parameters serve as critical indicators of the biological processes intricately linked to the ocean's CO₂ flux (F_{CO_2}). *Chl- α* concentration, for instance, provides insights into the primary productivity of the marine ecosystem and exhibits a direct correlation with phytoplankton density (Mauri et al., 2007). Additionally, *PAR* plays a pivotal role in estimating primary productivity, as it collaborates with *Chl- α* to regulate photosynthetic rates within the oceanic environment. Studies have shown a significant correlation between *PAR* and the net ecosystem exchange of CO₂, particularly in regions characterized by low *PAR* values (Burrows et al., 2005).

In the context of tropical oceans, a natural temperature control system exerts its influence, resulting in a modulation of the impact of biological processes on *Chl- α* concentration. This phenomenon manifests as a pronounced seasonal pattern, wherein the ocean experiences a greater influx of CO₂ during winter and subsequently undergoes an outflux during summer. Notably, the Atlantic Ocean emerges as a substantial carbon sink, effectively sequestering carbon at rates ranging from -815 to -1295 mmol C m⁻² y⁻¹. In contrast, the Pacific-equatorial region exhibits a noteworthy carbon source behavior. However, this effect is harmonized by temperate regions within the ocean that act as carbon sinks. Notably, the direction of carbon flux in the global ocean system is intricately influenced by dynamics between various physical and biological factors, further modulated by seasonal variations (Lekshmi et al., 2021).

Chowdhury et al. (2021) highlight the potential influence of several factors on the accuracy of *Chl- α* measurements, notably the contamination of remote sensing images by dissolved organic material or total suspended matter. Similarly, Luang-on et al. (2022) emphasize the impact of factors like atmospheric correction, sensor

calibration, and colored dissolved organic matter on the precision of chlorophyll- α measurements. Shen et al. (2018) further underscore that *Chl- α* measurement accuracy can be affected by factors such as the presence of other pigments, sensor spectral characteristics, and suspended particles. It is imperative to recognize that the relevance of these factors may vary depending on the specific measurement context and location. Moreover, the absence of ground-truth measurements can pose challenges in validating the accuracy of *Chl- α* concentration values (Chowdhury et al., 2021).

The chlorophyll- α (*Chl- α*) and Photosynthetically Active Radiation (*PAR*) in the sea surface can be observed in the context of CO₂ flux. There is a notable strong negative correlation between CO₂ flux and *Chl- α* , signifying that higher *Chl- α* concentrations are associated with increased phytoplankton density, which, in turn, enhances CO₂ uptake due to their photosynthetic activity, as elucidated by Znachor and Nedoma (2010). This higher *Chl- α* concentration often indicates elevated nutrient levels and greater availability of *PAR*, promoting phytoplankton growth. During the Spring Transitional Monsoon, *PAR* peaks after the Northeast Monsoon, a period marked by concurrent peaks in *Chl- α* and CO₂ flux. However, the reasons behind the reduction in *Chl- α* concentration during the Spring Transitional Monsoon are not fully understood. It is hypothesized that this decline may be linked to heightened *PAR* variability or a decrease in essential nutrients required to sustain the phytoplankton community. Further research is needed to elucidate these dynamics (Adams et al., 2021).

A substantial phytoplankton bloom, featuring a ten-fold surge in *Chl- α* concentration, reduces coastal water clarity, a more confined photosynthesis zone, and nearly a 50% decline in average *PAR* within the phytoplankton habitat layer. This

bloom induces variations in the downwelling irradiance spectrum and the specific absorption coefficient, with diatom or dinoflagellate blooms displaying significant alterations, whereas coccolithophore blooms exhibit only minor changes (Churilova et al., 2020).

The decrease in seawater temperature observed during the Fall Transitional Monsoon may indicate a broader cooling trend on the shelf. This trend is similar to what was observed on the Patagonian shelf, where a significant increase in *Chl- α* concentrations occurred after seawater temperatures dropped due to cooling processes (Gregg et al., 2005). This suggests that cooler temperatures may promote the growth of phytoplankton populations, possibly due to enhanced upwelling processes triggered by the declining shelf temperature (Edwards et al., 2016).

Studies have shown that the optimal temperature range for the growth of common phytoplankton species falls between 25-29°C, which is lower than the average temperature during the Southwest Monsoon (Cupp, 1943; Tian et al., 2002; Tomas, 1997). This suggests that conditions during the Northeast Monsoon favored optimal phytoplankton growth rates. In addition, warm waters tend to fix less CO₂ (Camoying & Trimborn, 2023; Weiss, 1974).

Studies have shown that river discharge and precipitation events are crucial for increasing the concentrations of organic materials and nutrients in the sea. These enriched conditions have the potential to stimulate the growth of phytoplankton, leading to elevated *Chl- α* concentrations and increased primary production. During the Northeast Monsoon, the region experiences substantial precipitation, which can lead to sporadic but significant river influxes from the estuaries into the ocean. This heightened precipitation contributes to increased river discharge and surface run-off,