

Upwelling in Marginal Seas and Its Association with Climate Change Scenario—A Comparative Review

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Abstract: After Bakun proposed his hypothesis in 1990 regarding upwelling under climate change, researchers conducted intensive studies to obtain the trends, current status, and future predictions of upwelling. Numerous studies have mainly focused on four major upwelling areas, which are part of the Eastern Boundary Upwelling System (EBUS). However, despite its importance, little attention has been given to the marginal seas upwelling areas such as the South China Sea (SCS), Arabian Sea, Baltic Sea, and other small-scale upwelling locations. Here, we combined several published studies to develop a new synthesis describing climate change impacts on these areas. There had been uncertainty regarding the intensification of upwelling, depending on the locations, data type, and method used. For the SCS, Vietnam and the northern SCS showed intensifying upwelling trends, while the Taiwan Strait showed a decreasing trend. Separate studies in eastern Hainan and the Arabian Sea (Somali and Oman) showed contrasting results, where both increasing and decreasing trends of upwelling had been recorded. Like the SCS, the Baltic Sea showed different results for different areas as they found negative trends along the Polish, Latvian and Estonian, and positive trends along the Swedish coast of the Baltic Sea and the Finnish coast of the Gulf of Finland. While small scales upwelling in La Guajira and southern Java showed increasing and decreasing trends, respectively. All of these limited studies suggest that researchers need to conduct a lot more studies, including the future projection of upwelling, by using climate models to develop a new understanding of how the upwelling in the SCS responds to climate change.

Keywords: upwelling; climate change; marginal seas; South China Sea; Arabian Sea; Baltic Sea; review



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1. Introduction

Upwelling refers to the upward movement of deep nutrient-rich and low-temperature waters to the surface, resulting in colder surface or near-surface waters with low dissolved oxygen, high density, and high salinity [1–3]. Upwelling is economically and ecologically significant in the coastal marine system, making it high-priority research. Although representing <1% of the total surface area of the ocean, upwelling regions provide approximately 8% of the global marine primary production and more than 20% of the world's capture fisheries [4–7]. With an increase in offshore transport, strong upwelling usually transports phytoplankton and zooplankton towards the convergence offshore frontal system rapidly [8], relative to a weaker upwelling that limits the nutrient enrichment in the photic zone [9]. Apart from boosting primary productivity and fishery production, upwelling is also crucial for the atmosphere-ocean carbon dioxide exchange and carbon recycling processes [10].

Globally, there are several types of upwelling (i.e., coastal upwelling, large-scale wind-driven upwelling in the ocean, upwelling associated with eddies, topographically induced upwelling, and broad-diffusive upwelling in the ocean interior) [11]. Among them,

wind-driven upwelling is the best-known type of upwelling. Since wind-driven upwelling is primarily induced by winds, different warming trends between land and oceans might affect its formation [12]. There is a large amount of research dealing with the upwelling and climate change topic; however, most of the papers were focused on large-scale upwelling systems such as the California, Iberian/Canary, Humboldt, and Benguela upwellings, which are also known as Eastern Boundary Upwelling System (EBUS). So far, there is very little information available on the influence of climate change on the upwelling in marginal seas such as the South China Sea (SCS), Arabian Sea, and Baltic Sea. Therefore, this paper attempts to provide a review on the upwelling studies under climate change scenarios for both the EBUS and marginal seas. However, detailed reviews will focus on the marginal seas since the information in this area is limited. Furthermore, this paper will also highlight the various methods used to determine the upwelling intensity under the climate change scenario.

2. Characteristics of Wind-Driven Upwelling

Wind-driven upwelling is mostly driven by the local wind stress, which generates currents in the frictional Ekman layer [13]. An alongshore wind interacts with Earth's rotation, causing Ekman transport and Ekman pumping to take place (Figure 1). The Ekman pumping creates surface divergence in the coastal current causing an upward movement of water, which generates an upwelling [14]. In general, the time taken for the water to be uplifted varies from several days to several weeks over a distance of nearly 100 m or more [15].

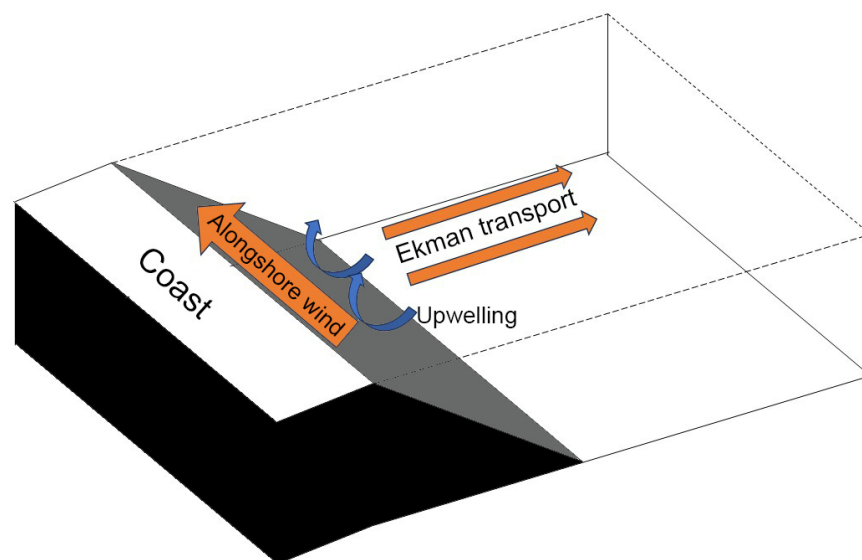


Figure 1. Schematic diagram on coastal upwelling mechanisms.

In EBUS, which is located in the tropics and sub-tropics, the upwelling is generated by equatorward alongshore trade winds (Figure 2). The trade winds blow equatorward, parallel to the eastern borders of the ocean basins, and induce an Ekman transport from the coast to the open ocean, perpendicular to the wind stress forcing. This creates a transport divergence and thereby leads to an upwelling at the coast [7]. Meanwhile, in the marginal sea, the upwelling is usually seasonal and depends on the monsoonal winds that blow parallel to the coastline (Table 1). For example, in the southwest of Luzon Strait and northwest Sabah, strong northeast monsoonal wind (December to February) generates and strengthens the Ekman transport, which in turn induces the upwelling in the subsurface layer [16–21]. Apart from the Ekman transport, the presence of positive wind stress curl also generated Ekman pumping, which contributes to the upwelling formation. Meanwhile, on the east coast of Peninsular Malaysia, the southwesterly wind (June to August) is the responsible factor that creates positive Ekman transport and also Ekman

pumping [22–24]. A similar mechanism was observed in southern Vietnam, however, with a stronger upwelling intensity [25,26].

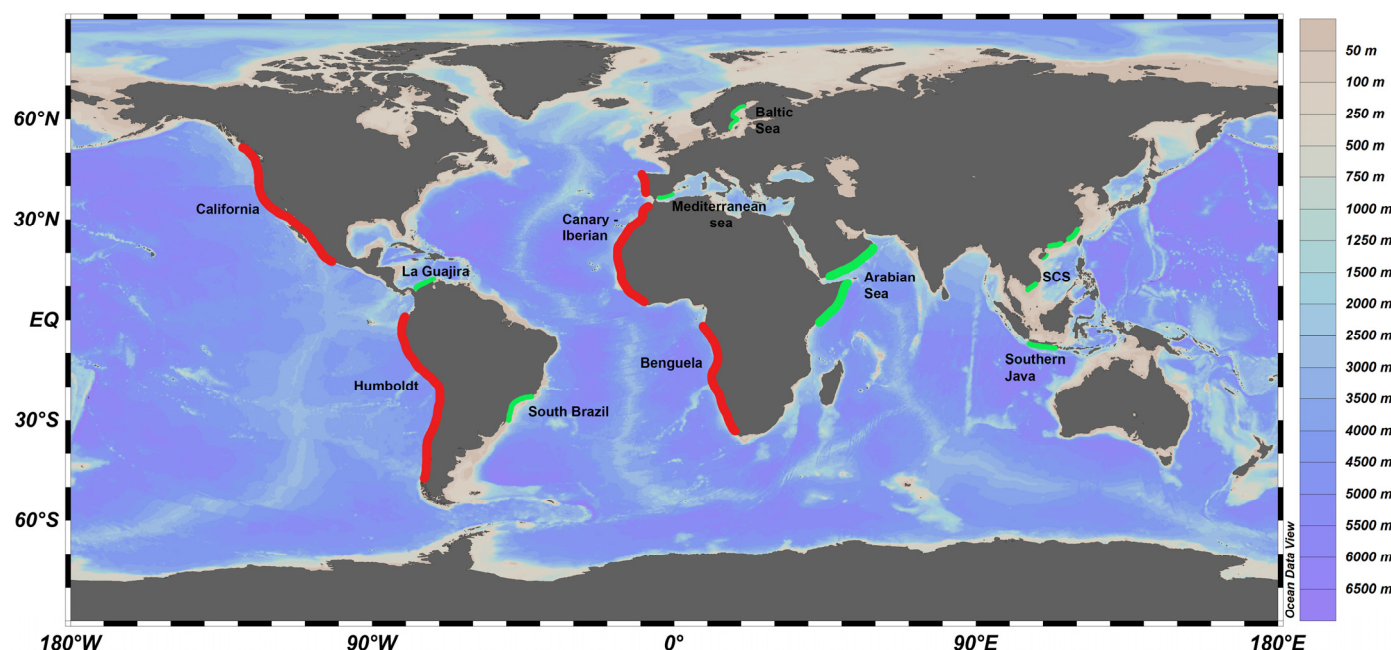


Figure 2. All the upwelling locations analyzed in this paper. The red line indicates the upwelling in EBUS areas, and the green line indicates all the other upwelling in marginal seas/small scale upwelling areas.

Specifically, in the South China Sea, earlier findings of upwelling are only based on direct measurements or in-situ data, as in the study by Wrytki [27]. But later, with the rapid development of science and technology, especially in remote sensing and hydrodynamic models, researchers are able to access the image data easily, which allows new qualitative insights and understanding of this phenomenon [28,29].

Table 1. Several locations of upwelling based on seasonality.

Marginal Sea	Location of Upwelling	Time Occurring	Author
South China Sea	Taiwan Strait	Southwest Monsoon (June to August)	[30,31]
	Southern Vietnam	Southwest Monsoon (June to August)	[25,26]
	Hainan Island	Southwest Monsoon (June to August)	[32,33]
	East Coast of Peninsular Malaysia	Southwest Monsoon (June to August)	[22–24]
	Northwest Luzon	Northeast Monsoon (December to March)	[16–18]
	Northwest Sabah	Northeast Monsoon (December to March)	[19–21]
Andaman Sea	Andaman Sea	Northeast Monsoon (December to March)	[34]
Arabian Sea	Somali and Oman	Southwest Monsoon (June to September)	[35–38]
	Southwest India	Southwest Monsoon (May to September)	[39,40]
Indian Ocean	Southern Java	Southeast Monsoon (June to October)	[41–43]
Baltic Sea	Gulf of Finland	Summer (June to September)	[28,44]

3. Upwelling and Climate/Atmosphere Variability

As upwelling is largely influenced by winds, the amplitude and timing of upwelling-favorable winds are sensitive to climate variability [45]. Large-scale climate phenomena such as El Niño Southern Oscillation (ENSO) will affect the upwelling event depending on the upwelling location. ENSO is a periodic fluctuation in sea surface temperature (SST; El Niño) and the air pressure of the overlying atmosphere (Southern Oscillation) across the equatorial Pacific Ocean. The warm ENSO (El Niño) occurs when the surface in the central and eastern tropical Pacific Ocean is warming or above the average SST, and the convection shifts to the central or eastern Pacific [46]. In contrast, the cool ENSO is called La Niña, which is the opposite phase of El Niño.

Upwelling can be influenced by ENSO as this event impacts the wind intensity. For example, the upwelling in Peru usually weakens during El Niño and strengthens during La Niña. This might be due to the occurrence of the El Niño event weakening the trade winds, thus reducing equatorial upwelling and causing an anomalous increase in the coastal SST and an anomalous deepening of the thermocline off the Peruvian coast as well as a decrease in nutrients [47]. This weakened upwelling event was also documented in California as its equatorward wind decreased due to the expansion of the Aleutian low-/contraction of the North Pacific high-pressure systems [48]. Nevertheless, some areas experienced an intensified upwelling, such as in the north SCS (NSCS) and northwest Sabah [21,49]. This occurred due to the presence of an anticyclonic atmospheric circulation anomaly, which intensifies the monsoonal wind during El Niño.

The Indian Ocean Dipole (IOD) is another climate phenomenon that can alter the upwelling intensity. The IOD is a phenomenon coupled between the atmosphere and the ocean with varied anomaly bi-polar temperature sea surface in the tropical Indian Ocean [50]. The irregular oscillation of SST causes the western Indian Ocean to become alternately cooler while the eastern part of the ocean becomes warmer, which is called the 'negative IOD phase.' As for the positive IOD phase, the water in the east of the Indian Ocean is cooler but warmer in the west. During the developing phase of a positive IOD, the upwelling of the subsurface cold water along the coasts of Sumatra and Java expands westward and produces a large zonal SST gradient in the central-eastern tropical Indian Ocean. The resultant atmospheric pressure gradient intensifies southeasterly wind anomalies along the coasts. The wind anomalies further strengthen the SST gradient through the enhancement of the upwelling [43].

4. Climate Change versus Upwelling

One of the major concerns on upwelling nowadays is how the upwelling responds to climate change or global warming. According to Bakun [12], upwelling will intensify under a climate change scenario as the sun radiates more heat, causing the land to be heated faster and stronger. This condition steepens the temperature difference between ocean and land, resulting in a stronger alongshore wind (Figure 3). This hypothesis is supported by Wang et al. [51], who found a robust relationship between the increase of land-sea temperature differences and the upwelling intensity in the twenty-first century. They also added that the changes are also latitude-dependent, where upwelling intensity and duration increased at higher latitudes. However, an alternative hypothesis was proposed by Rykaczewski et al. [52], where changes in the magnitude, timing, or location of upwelling winds could be associated with the poleward migration and intensification of major atmospheric high-pressure cells in response to the increased greenhouse gas concentrations (Figure 4).

Understanding the trends of upwelling under climate change scenarios is essential. Stronger upwelling may increase the nutrient input and offshore transport, potentially leading to rapid transportation of phytoplankton and zooplankton toward the convergence offshore frontal system [8]. On the other hand, weaker upwelling may potentially decrease the primary production as it limits the nutrient enrichment of the photic zone [9]. Improvement can be made for fisheries management and other marine resources in all

upwelling areas by understanding the relationship between the upwelling and the nutrient inputs and how they are likely to change in the future.

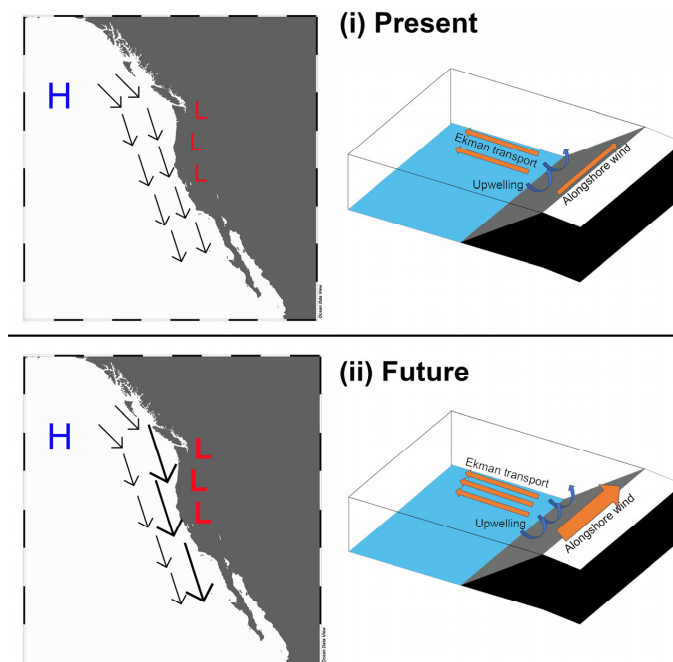


Figure 3. Illustration diagram of anticipated climate change impacts on upwelling in EBUS based on Bakun Hypothesis. (i) current state of coastal upwelling zones. (ii) Potential future state of upwelling zones. Continental thermal lows (L) are expected to deepen in the future, thus intensifying upwelling-favourable winds.

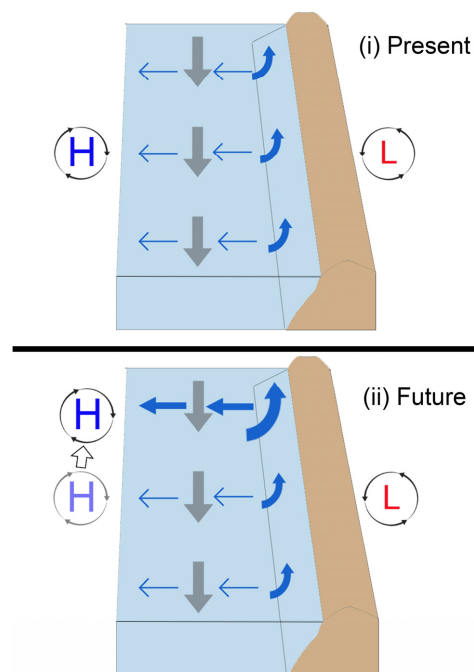


Figure 4. Expected change of upwelling from climate change based on the alternative hypothesis. (i) Present condition of upwelling as the difference between high- and low-pressure systems drive upwelling-favourable winds (grey arrows) and cause the upwelling to occur (blue arrows). (ii) Poleward migration of high-pressure systems, leading to enhanced wind and upwelling in the poleward region.

5. Eastern Boundary Upwelling System (EBUS)

As stated, rigorous studies have been made in the EBUS area regarding the climate change impacts on upwelling. One of them is a meta-analysis by Sydeman et al. [53], which synthesized 22 studies, each with more than 20 years of observational or model-derived data published between 1990 to 2012. The results indicated consistent observations, where the wind intensified in California, Benguela, and Humboldt upwelling systems and weakened in the Iberian, suggesting the possibility of wind intensification at higher latitudes. In the meantime, equivocal wind change was found in the Canary region.

Specifically in the California region, a comparison of mean physical and biological variables between two periods (Period 1 = 1990–2009, Period 2 = 2030–2049) has been made using a high-resolution coupled physical-biological model system, which is the Regional Ocean Modeling System (ROMS) and Carbon, Silicate, and Nitrogen Ecosystem model (CoSiNE-31) [54]. The results showed that the SST slightly increased in the upper 100 m over the entire California Current System (CCS), which led to an increase in ocean stratification and a decrease in the upward transport of nutrients by vertical mixing. However, the concentration of nitrates is enhanced in the study area, especially in the coastal water, and the upwelling is intensified due to a strong alongshore wind.

Later on, a regional ocean model of Geophysical Fluid Dynamics Laboratory (GFDL)-CM3 was used by Arellano and Rivas [55] to explore how primary production in California's upwelling region would react to the future climate change scenarios under the Representative Concentration Pathway 6.5 and 8.5 (RCP6.0 and RCP8.5). The SST projection of RCP6.0 and RCP8.5 showed an increase of SST between 1.0 to 2.5 °C and 1.0 to 4.0 °C that could lead to an increase in stratification. However, the wind also intensified twofold and fourfold during spring and summer, respectively. Further, under the RCP8.5 scenario, a decrease in thermocline depth was observed in the coastal area attributable to the increase in upwelling activities. And with the exception of small regions, these upwelling activities under RCP8.5 were able to counteract the increase in stratification that decreased the chlorophyll-*a* concentration.

In the case of the Canary-Iberian region, Casabella et al. [56] managed to capture the trend of upwelling at the coast of Galicia by using three regional climate models by the European project; ENSEMBLES. There were no trends observed for the upwelling during 1961–1990. However, during 2061–2090, an increasing trend of upwelling was observed in Galicia's middle and west coast between April and October. On the north coast, called the Cantabric coast, the value of upwelling will continue to reduce, and therefore the phenomenon will remain less frequent than on the Atlantic Coast.

Later on, Sousa et al. [57] used the Delft3D-Flow model to observe the historical upwelling status from the year 1976 to 2005 and predict the future upwelling in the years 2070–2099 under the condition of RCP 8.5. Even though the upwelling index showed an increment for both historical and future observations, the stratification also increased, and the thermocline will deepen from 5–15 m historically to 5–25 m in the future. This increment in ocean stratification is said to be the main factor that will decrease the upwelling intensity in the future even though the wind stress is increased based on Bakun Hypothesis.

However, using GCM from the CMIP6 project recently, future SST changes were evaluated for both the coast and the offshore regions under 5–8.5 socioeconomic scenarios in the Canary-Iberian upwelling region [58]. Results showed that the upwelling is intensified in the future for the northern and middle regions of the Canary-Iberian Upwelling system and weaken in the southern region, which implies that upwelling changes depending on the latitudinal displacement as suggested by Rykaczewski et al. [50].

In Senegalo-Mauritanian, located on the southern edge of the North Atlantic Ocean (southern part of the Canary Upwelling System), the upwelling intensity has been analyzed using 47 climate models from the CMIP5 database under the RCP8.5 scenario [7]. Even though each model showed diverse responses to the RCP8.5 scenario in terms of amplitude, the general picture demonstrated a reduction of the upwelling toward the end of the twenty-first century. This was evidenced by decrements in SST and the SST

upwelling index (offshore minus coastal) for most of the models in both the northern and southern parts of the Senegalo-Mauritanian upwelling area. The main cause of this weakening of upwelling is the reduction of the wind forcing linked to a northward shift of the Azores anticyclone and a more regional modulation of the low pressures found over Northwest Africa.

6. Upwelling under Climate Change in Marginal Sea

In this section, we focus on three marginal seas: the SCS, Arabian Sea, and Baltic Sea. Studies on the impact of climate change on upwelling in these marginal, particularly in the SCS, are less focused. Unlike the EBUS, only a few studies used the modeling method to form a future projection on upwelling under climate change scenarios. Most studies only focus on the trend of recent upwelling based on historical data from various sources. These various sources showed an uncertain result on upwelling intensity under climate change.

For instance, historical data taken from a sediment core in an upwelling area in Vietnam revealed a rapid intensification of upwelling in Vietnam since approximately 1950 [59]. The core provides 3200 years of historical data showing the fluctuation of the selected terrestrial elements concentration, such as aluminum, titanium, and potassium. These fluctuations were then correlated with the upwelling intensity. There was a rapid decrease in selected elements since 1950 as they reached their minimum values, suggesting an abrupt intensification of upwelling from the same period. The record of summer monsoon wind data over the past 1810 year taken by Zhang et al. [60] was also well matched with the data from the sediment core, where the wind showed an intensification during the summer monsoon, which are the primary driver of upwelling in Vietnam.

In the NSCS region, the SST record (1876–1996) obtained from the eastern Hainan Island coral core revealed an upwelling fluctuation [61]. The SST anomaly is divided into three periods based on their trend. The latest (1961–1996) showed a signature weakening in upwelling intensity based on the high SST anomaly during that period. The weakened upwelling is believed to be due to the weakening of the Asian Summer Monsoon (ASM), which is the primary driver of upwelling events in this area. The weakening of ASM is related to the ‘sunlight dimming’ process, which comes from anthropogenic pollution, resulting in dimming and surface cooling. These lingering anthropogenic aerosols can reduce the amount of solar radiation reaching the surface by as much as 20 Wm^{-2} , which is likely to weaken monsoonal circulation and near-surface wind speed [62].

This weakened upwelling has also been discovered by Xie et al. [63], as the Upwelling Index (UI) from 1982–2012 showed a decreasing trend with a rate of $0.01 \text{ }^{\circ}\text{C/a}$. The wind stress curl that has a higher correlation with the UI was also compared to the wind stress. The analysis documented a decreasing trend, suggesting that upwelling in eastern Hainan is affected more by the wind stress curl.

Meanwhile, a study by Su et al. [64] revealed that even though SST anomalies showed a negative trend (increasing) from 1960 to 2006, the alongshore wind stress exhibited an intensification during the upwelling season over the past 20 years (1988–2008). The SST trends are linked with the strong western boundary current that causes strong stratification in the off-eastern Hainan Island, which can mask the upwelling in this region. The SST UI based on the offshore to onshore SST differences showed an intensification of upwelling at the end of the 1990s, and these SST upwelling indices agreed reasonably with the time-series upwelling index.

Later on, by analyzing long-term trends of wind data in the NSCS, Hong and Zhang [65] discovered that the annual mean wind speed demonstrated a decreasing trend in the coastal area of the southeast of Hainan Island due to the weakening of the easterly (zonal) wind. However, in the offshore area, an intensifying trend of wind is recorded due to the strengthening of northerly (meridional) wind. An increasing upwelling trend along the east coast of Hainan Island and Guangdong is observed due to the strengthening of the wind stress curl in the coastal area, especially in the upwelling area.

Later, Zhu et al. [66] analyzed the interannual variation and trend of upwelling around Hainan Island. The SST data obtained from the MODIS-Aqua revealed the SST trend in the Hainan Island region is showing warming trends during 2003–2021. Based on the EOF analysis, the upwelling intensity around Hainan Island showed an increasing trend from 2003–2021, especially in the period after 2013. However, this positive trend could not compete with the overall warming trends of SST in the northwest area of the SCS.

The latest study on long-term SST trends in the SCS was performed by Liu et al. [67] by using SST data from satellite observation and reanalysis during 1982–2020. All three regions that had been focused on (eastern Guangdong, eastern Hainan, and eastern Vietnam) showed increasing trends of upwelling intensity as the intensity reached ~ 0.2 °C per 10 years in the past 40 years or so. The strengthening of wind stress curl is the main factor for the increasing trends of eastern Guangdong and eastern Hainan upwelling intensities. Meanwhile, both alongshore wind stress and wind stress curl contribute to the increasing trend in northern Vietnam but not in southern Vietnam as it is not significantly related to the wind field.

In the Taiwan Strait (TWS), Zhang [68] used a long time series of SST from AVHRR and wind data from the ECMWF-ERA5 throughout 1982–2019 in order to observe the upwelling response in this area under the climate change influence. The results showed that upwelling intensity in TWS after the year 2000 decreased by about 35% compared to the year before 2000, especially in the Pingtan upwelling zone. Similar results were obtained from the cross-shore Ekman transport calculation, which is the dominant mechanism that pumps cold water upward to the surface based on the correlation that has been made. Again, the weakened monsoonal wind decreased the alongshore wind is believed to be the primary cause that weakened the upwelling intensity after 2000.

Meanwhile, in the Arabian Sea, two upwelling locations were focused on: Somalia and Oman. Firstly, a study on the impact of monsoon low-level jet (MLJJ) shift in terms of upwelling and productivity in Omani and Somali coasts under the global warming scenario has been performed using ROMS that is forced with six CMIP5 model outputs [69]. The results indicated an intensifying (weakening) wind stress, zonal mass transport, and vertical transport over Oman (Somali), thus leading to a stronger (weaker) upwelling event due to the poleward shift in MLJJ. Analysis of wind from ECMWF CFSR with a spatial resolution of 0.3° by Varela et al. [70] also found the weakening of the Somalian upwelling system, which supported the findings from Praveen et al. [69].

But, in the same year, the analysis of upwelling by using both the Global Climate Model (GCM) and Regional Climate Model (RCM) found that upwelling in Somali is projected to increase with latitude, even higher than the EBUS under the RCP 4.5 and RCP 8.5 with a robust value at 8.5° N [71]. The intensification of upwelling here is more affected by the Ekman transport relative to Ekman pumping, as the projected Ekman pumping did not show clear trends for most latitudes. A significant decrease in Ekman pumping is found in the southernmost latitudes. Air pressure and temperature variations between land and sea are also projected to increase significantly throughout the 21st century due to global warming. This intensification significantly impacts the coastal upwelling, supporting and strengthening Bakun's theory.

In addition, a recent coral core study revealed that the Arabian Sea upwelling was stable during the last millennium and significantly weakened in the current anthropogenic warming [72]. The weakening of the upwelling is consistent with the weakening trend of the wind stress curl and the Indian monsoon circulation index in the past 50 and 70 years [73]. The weakening of the SW monsoon is due to anthropogenic forcing, where rapid warming on the northern Indian Ocean compared to the Indian subcontinent led to the decline of the land-sea thermal gradient in the recent century [74,75].

As for the Baltic Sea, Lehmann et al. [76] calculated the temporal development of upwelling events along the Baltic Sea from the time series upwelling frequencies from 1990 to 2009. Generally, there is a negative trend along the Polish, Latvian, and Estonian coasts, which is in line with the warming trend of annual mean air temperatures and mean

SST derived from infrared satellite images (1990–2008) presented in Lehmann et al. [77], and a positive trend of upwelling frequencies along the Swedish coast of the Baltic Sea and the Finnish coast of the Gulf of Finland. Adding to that, the trend of upwelling favorable wind results derived from wind station data showed a positive trend of south-westerly and westerly wind conditions along the Swedish coast and the Finnish coast of the Gulf of Finland and a corresponding negative trend along the east coast of the Baltic Proper, the Estonian coast of the Gulf of Finland and the Finnish coast of the Gulf of Bothnia.

In the northwest part of the Alboran Sea (part of the Mediterranean Sea), as upwelling has directly influenced the nutrients input, Mercado et al. [78] evaluate the wind patterns for the period 1992–2006 from Agencia Espanola de Meteorologia (AEMET) to know the variability of the nutrients in the study area. The findings showed that the intensity and frequency of westerly wind decreased from 1992 to 2006, which led to a weaker upwelling event in this region, thus lowering the nutrient input. Meanwhile, Vargas-Yáñez et al. [79] analyzed the variability of oceanographic and meteorological conditions in the Alboran Sea and how it influenced sardine landings. Upwelling is closely related to the number of sardine landings, as upwelling enhances the primary productivity in the area. There is a downward trend of sardine landings, and the empirical orthogonal function (EOF) analysis showed that these downward trends are affected by the warming trend of sea surface temperature and a decrease in upwelling intensity.

Apart from these three marginal seas, several other small-scale upwelling studies related to climate change have been conducted in various locations. For instance, the negative trend of SST retrieved from the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) at 0.25° in La Guajira in the Caribbean Sea from the year 1982 to 2014 plus the increasing trend of UI based on the wind data from National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) suggests that upwelling in La Guajira had been intensified for the past 32 years [80]. However, by using almost similar analysis of SST and UI like La Guajira, upwelling in Southern Java showed a negative trend from 1982–2014 as slight coastal warming was detected during the upwelling season (July to October) along with the moderate decrease of UI [81].

Meanwhile, by downscaling Earth System Models (ESM) using the Hamburg Shelf Ocean Model (HAMSO), de Souza et al. [82] managed to project the future upwelling projection under RCP8.5 in the South Brazil Bight. Even though the Ekman forcing showed an increment trend, the vertical velocities at the bottom of the mixed layer showed a decrement trend at the end of the century. An increase in water column stability due to the surface warming and a slight reduction of the Brazil Current (BC) transport south of 25° latitude tend to decrease the upwelling intensity in this area.

7. Methods for Defining Upwelling under Climate Change

Table 2 shows the methods applied by each study above for both the EBUS and marginal seas areas. Based on the studies that have been conducted, we found that each of the studies used different kinds of methods in determining how upwelling will respond to climate change. A modeling method is a common method used in the EBUS area, where they have simulated a future upwelling projection under the climate change scenario based on the data from the CMIP5 or CMIP6. This method was also used in the Arabian Sea and in the South Brazil Bight.

Meanwhile, for the marginal sea area, specifically in the SCS, no modeling approach has been carried out in the studies relating to the upwelling response to climate change. Most of the studies use historical data, which came from various sources such as reanalysis and in-situ data. Thus, no future upwelling projection has been made in the SCS, which left a huge gap in upwelling studies under climate change scenarios. This is the limitation that we found in most of the marginal seas. Even though modeling approaches have been used intensively in the EBUS region, they are still not widely used by researchers in this region.

Table 2. The methods and data sources of each study included in this paper.

EBUS/ Marginal	Area	Method, Data Source	Data Type (Historical/Future)	Results	Author
EBUS	All EBUS	Synthesis of other papers	Historical	Intensifying in California, Benguela, Humbolt.	[53]
EBUS	California	Modeling (ROMS-CoSiNe), CMIP5	Both	Intensifying	[54]
EBUS	California	Modeling (GFDL-CM3), CMIP5	Both	Intensifying	[55]
EBUS	Canary-Iberian	Modeling ENSEMBLES, CMIP5	Both	Intensifying	[56]
EBUS	Canary-Iberian	Modeling (Delft3D-Flow), CMIP5	Both	Weakening	[57]
EBUS	Canary-Iberian	Modeling (GCM), CMIP6	Both	Intensifying	[58]
EBUS	Senegalo-Mauritanian	Modeling (GCM), CMIP5	Both	Weakening	[7]
SCS	Vietnam	Sediment core	Historical	Intensifying	[59]
SCS	Hainan Island	Coral core	Historical	Weakening	[61]
SCS	Hainan Island	Reanalysis wind data	Historical	Weakening	[63]
SCS	Hainan Island	SST and wind data	Historical	Intensifying	[64]
SCS	Hainan Island	Wind data	Historical	Intensifying	[65]
SCS	Hainan Island	SST from MODIS-Aqua and wind data from ECMWF	Historical	Intensifying	[66]
SCS	Eastern Guangdong, Eastern Hainan, Eastern Vietnam	SST from OSTIA, ERA5, and ORAS5, wind data from CCMP, ERA5, and ORA5	Historical	Intensifying	[67]
SCS	Taiwan Strait	SST and wind from AVHRR	Historical	Weakening	[68]
Arabian Sea	Somali and Oman	Modeling (ROMS), CMIP5	Both	Weakening in Somali, intensifying in Oman	[69]
Arabian Sea	Somali	GCM, CMIP5	Both	Intensifying	[71]
Arabian Sea	Oman	Coral core	Historical	Weakening	[72]
Baltic Sea	Whole Baltic Sea	SST (NOAA-AVHRR)	Historical	Weakening in Polish, Latvian and Estonian coasts, intensifying along the Swedish coast of the Baltic Sea and the Finnish coast of the Gulf of Finland	[76]
Mediterranean Sea	Alboran Sea	Wind from AEMET	Historical	Weakening	[78]
Mediterranean Sea	Alboran Sea	SST and Wind data from NOAA/OAR/ESRL, Chl-a from NASA Ocean Color	Historical	Weakening	[79]
Caribbean Sea	La Guajira	SST (NOAA-AVHRR) and wind (NCEP-CFSR)	Historical	Intensifying	[80]
Eastern Indian Ocean	Southern Java	SST (NOAA-AVHRR) and wind (NCEP-CFSR)	Historical	Weakening	[81]
Western Atlantic Ocean	South Brazil Bight	Modeling (HAMSO, CMIP5)	Both	Weakening	[82]

8. Conclusions

Upwelling intensities are changing under the influence of climate change as it can disrupt wind intensity worldwide by causing differential land-sea heating that leads to a deepening of the pressure gradient. Changes in the intensity of alongshore wind that result in stronger wind stress and wind stress curl are the major driving mechanism that contributes to the change in upwelling intensities. Using climate models, most studies are focusing on the EBUS area, which is a large-scale upwelling system, and most of the results showed an intensification of upwelling under climate change. Limited studies are conducted, and uncertain results are obtained in the marginal seas, especially in the SCS, where a change in intensity of upwelling varies according to the location, type of data, and data range. Very few studies on marginal seas and other small-scale upwelling areas under climate change suggest that more studies should be conducted in order to obtain a clearer observation of how upwelling changes under climate change scenarios. We suggest that

the future projection of upwelling be implemented in the marginal sea, especially in the SCS, as we can predict the future upwelling event based on the latest IPCC AR6 future emission scenario.

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