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A Review of Coastal Upwelling Research in the South China Sea: Challenges, Limitations and Prospects

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Abstract

Since it was first observed in the 1950s a number of coastal upwelling systems have been identified and rigorously studied in the continental shelf of the South China Sea (SCS). Northern SCS in particular has been the predominant focal region while Southern Vietnam and Luzon Strait Upwelling Zones have been the locations that have received disproportionately greater attention from the international research community. Most studies of the phenomenon find it to be predominantly a seasonal occurrence, driven by alongshore wind stress, wind stress curl, bottom topography, coastline orientation, shelf circulation, eddies, islands and capes, and the shape of the coastline. However, the present review finds that since focus has generally been on localized areas, usually at seasonal scale and based largely on proxy indicators such as anomalies of sea surface temperature (SST), sea surface salinity (SSS), nutrients and Chlorophyll-a, it is extremely difficult to directly quantify upwelling. Consequently, long time-series of the phenomenon are inexistent in the SCS and most other marginal seas, rendering analysis of long term dynamics impossible. Moreover, despite the significance of the opposite process of downwelling, this phenomenon has been largely neglected. Finally, this study recommends the development of a time-series of upwelling indices which directly represent the phenomenon, based on method adopted NOAA's Pacific Fisheries Environmental Lab (NOAA PFEG/PFEL).

Keywords: Coastal Upwelling, Dynamics, Review, Challenges, Limitations and Prospects**,** South China Sea.

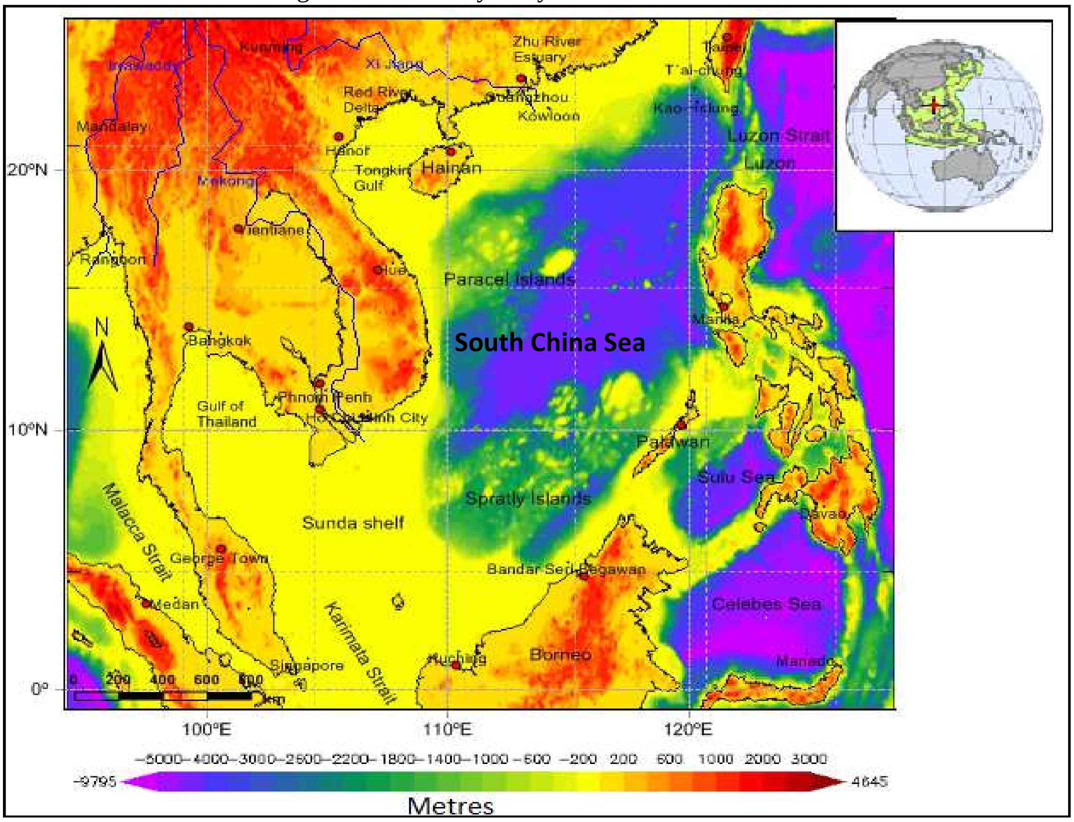
1. Introduction

Upwelling is one of the most important features of sea surface circulation studied since the 1930s (Sverdrup, 1938) which has long been known to result when sea water surface deforms under the action of wind or other forces, but the mechanics of the interaction between wind and water is increasingly complex (Bakun *et al.*, 2015; Schwing *et al.*, 1996). Two major types have been identified: wind-driven and geostrophic upwelling. Wind-driven upwelling is an important component of surface ocean circulation, inducing a vertical circulation when colder deeper ocean waters rise up from beneath to the surface in the open ocean and along coastlines (Schwing *et al.*, 1996; Picket and Paduan, 2003). Contributing factors to the variability of source waters in upwelling zones are therefore said to depend on the properties of local surface waters which are driven by the surface winds, and changes in properties of deep and/or remote source waters that are eventually up-welled from below the pycnocline (Bakun *et al.*, 2015). One of the major reasons why upwelling is one of the most important components of sea circulation is its significant implications for regional biogeochemistry, primary productivity and potentially local meteorology and climate. Most studies of upwelling have focused on determining recruitment and production characteristics of fisheries (e.g. Rivera *et al.*, 2013; O'Toole, 1980; Cushing, 1969; Nielsen and Jensen, 1957) as well as for the analysis of temperature anomalies (Hu *et al.*, 2001). Upwelling has been observed to largely contribute to the transport and vertical displacement of nutrients and phytoplankton to the photic zone where phytoplankton blooms may occur (Wang *et al.*, 2010; Tang *et al.*, 2004; 1999). It also modulates the horizontal and vertical redistribution of temperature and salinity (Dragesund, 1971; Cushing, 1969) and biogeochemical tracers such as the rates of nutrient supply to the euphotic zone which determine phytoplankton composition, concentrations and productivity (Bolton *et al.,* 2016; Sasai, 2013; Lin *et al.,* 2011). Some up-welled waters are also found to have sub-ducted below the euphotic zone for decades during which they accumulated re-mineralized nutrients and carbon dioxide while oxygen was consumed by respiration (Rykaczewski and Dunne, 2010). The South China Sea (SCS), one of the largest marginal seas in the world, with variable bathymetric and complex oceanographic structures (Selvaraja *et al.*, 2015; IHO, 1954) (Fig 1), featuring distinct spatial oceanographic variations in the western tropical Pacific Ocean (Ndah *et al.*, 2015; Li *et al.,* 2014; Hu *et al.*, 2000; Huang *et al.,* 1994), has also long been recognized as a prominent upwelling system (e.g. Wang *et al.,* 2012; Jing *et al.,* 2011; Chen *et al.,* 2006; Ying, 2006; Yuan, 2004; Xie *et al*., 2003; Tang *et al.*, 2002; Hu *et al.,* 2001; 2000; Chu, 1999; Shaw *et al.*, 1996; Huang *et al*., 1994; Chu *et al*., 1999; Cai and Lennon, 1988; Cushing, 1969; Wyrtki, 1961) where research on the phenomenon spans several decades. The intense interest in upwelling in the SCS is largely driven by the effects of the phenomenon on the biogeochemical properties of water (Sasai 2013, Lin *et al.,* 2011). Consequently, it has been observed globally that 50% of all the protein from sea-food is supplied by coastal upwelling regions (Summerhayes, 1996). Upwelling zones in the SCS (e.g. Off Guangzhou Bay popularly known as Qiongdong Upwelling Zone), Taiwan Strait upwelling zones generally characterized by elevated Chl-a (Tang *et al.,* 2002), have therefore historically been fertile fishing grounds and noted for their high fisheries production especially during peak upwelling season. Upwelling off Guangdong (Qiongdong upwelling zone) for example has been found to result in surface nutrient advection and plankton blooms which promote a rich natural fishery in summer, especially in the thriving Qinglan traditional fishing grounds, the dominant species being horse mackerel and chub mackerel caught in large numbers during peak upwelling. Taiwan Strait upwelling zones have been noted for their high fisheries production (Pan *et al.*, 2015; Tang *et al.*, 2002). Zamboanga upwelling zone located on northwest coast of the island of Mindanao has long been noted to support a thriving sardine fishery in southern Philippines (Villanoy *et al.,* 2011), further attesting to the biological significance of upwelling in the SCS. Upwelling has also been found to affect the migration pattern of organisms including fish across an entire basin (Rivera *et al.,* 2013), with serious implications for fishing operations and output (Cushing, 1969). With regards to CO_2, previous studies predict that an increase in atmospheric CO_2 in the coming decades may result in intensification in the eastern boundary upwelling system, which could enhance upwelling of CO_2-rich deep water thus exacerbating the impact of acidification in these productive zones (Liu *et al.,* 2013) with potential adverse consequences on climate.

2. Spatial and Temporal Variability of Upwelling in the South China Sea

Results of a phylogenetic study of bacterial community structures in surface seawater of northern South China Sea (NSCS) revealed that the bacterial communities exhibited heterogeneity within zones of upwelling and anticyclonic eddies, suggesting a two-level pattern of spatial distribution of surface bacterial communities of which upwelling plays an important role (Li *et al.,* 2014). Prominent upwelling regions in the SCS have been found to be mostly located in Northern SCS, and include: inshore areas from the Shantou Coast to the Nanri Islands, off southern Fujian Province, referred to as the Yuedong Upwelling Zone; east of Hainan Island, east of the Leizhou Peninsula and the southeast of the Zhanjiang/Guangzhou Bay, coastal Guangdong province, referred to as the Qiongdong Upwelling Zone, south of Lingshui, north to the east side of Qiongzhou Strait (Jing *et al.,* 2008), and the Taiwan Strait Upwelling (TSU) near the Taiwan Shoal (Jing *et al.,* 2007; 2008). Tang *et al.* (2002) investigated upwelling in the Taiwan Strait and uncover the presence of five upwelling zones: (1) coastal upwelling near Pingtan Island (2) coastal upwelling between Meizhou and Xiamen; (3) intense coastal upwelling near Dongshan Island, sometimes extending offshore, (4) small occasional upwelling near the Penghu Island (PHU) and (5) an intensive upwelling in the Taiwan Bank. Hu *et al.* (2001) used a combination of the hydrographic indicators and Sea Surface Temperature (SST) to establish evidence for the existence of four upwelling zones in the Taiwan Strait during the summer-time, including: along the southwestern coast of the Taiwan Strait, along the northwestern coast of the Taiwan Strait, near the Taiwan Bank and around the Penghu Islands, respectively. S.W. Taiwan upwelling zone is characterized by important geological systems such as Gaoping Submarine Canyon and numerous other deep sea canyons which have been the subject of numerous geological surveys (Selvaraj *et al.,* 2015). In Northern SCS which has generally been the focal point for upwelling research, the phenomenon is said to be one of the most outstanding features (Jing *et al.,* 2006; 2007; 2008; Hong and Li, 1991; Li 1990, 1993). On the continental shelf of South China in particular, numerous upwelling zones have been identified and studied over the past decades, including: off the coast of Hong kong by Wyrtki (1961), the east coast of –

Fig 1: General bathymetry of the South China Sea

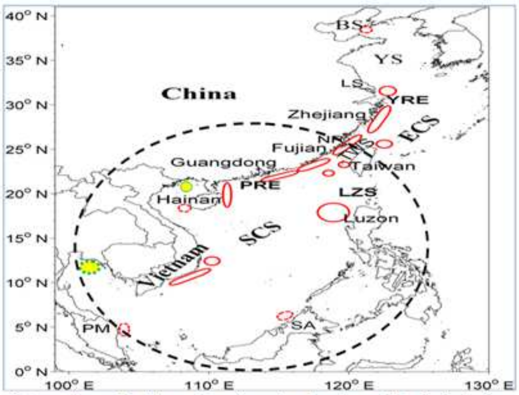


Source: This map is based on Satellite data and in situ measurements combined to form a global data set of the earth's surface relief (v 9.0) by Smith and Sandwell (1999); data provider: APDRC-SOEST, URL: http://apdrc.soest.hawaii.edu/datadoc/smith.php; Image produced with MeteoInfo v.1.1.0.0.

Table 1: Summary of upwelling zones and studies in the South China Sea (SCS)

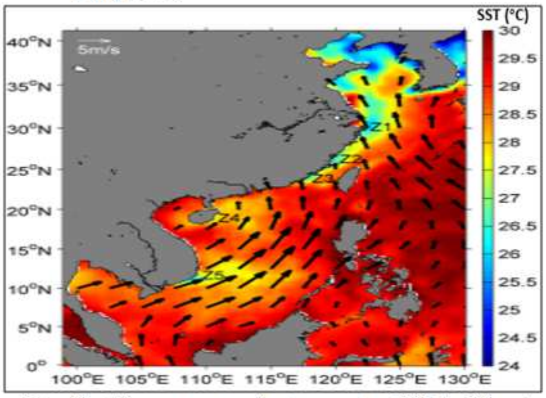
Name of upwelling zone	Location
Off Luzon (e.g. Martin and Villanoy 2008; Liu *et al.*, 2002; Qu, 2000; Shaw *et al.*, 1996; Nitani, 1970) and Zamboanga Peninsular, northwest coast of the island of Mindanao (Villanoy *et al.*, 2011)	East / Southeast SCS
South Vietnam (e.g. Bolton *et al.*, 2016; Sadatzki *et al.*, 2016; Zheng *et al.*, 2016; Jing *et al.*, 2011; 2008; Hein, 2007; Liu *et al.*, 2002; 2007; Xie, *et al.*, 2003; Yuan, 2004; Wang *et al.*, 2003; 2006; 2008; Kuo *et al.*, 2000; 2004; Cushing, 1969; Wyrtki, 1961)	West SCS
North Vietnam off Hanoi (e.g. Ndah, 2016)	North SCS
Taiwan Strait (e.g. Ndah, 2016; Hong *et al.*, 2008; Jing *et al.*, 2007; 2008; Tang *et al.*, 2002; Hu *et al.*, 2000, 2001; Peng and Wang, 1999).	Northeast SCS
Off Guangdong including off Hongkong (e.g. Ndah, 2016; Jing *et al.*, 2007; 2008; Wyrtki, 1961)	North SCS
Off Hainan (e.g. Ying, 2006; Niino and Emery, 1961)	North SCS
Off Fujian (e.g. Jing *et al.*, 2007; 2008)	North SCS
Off West coast of Malaysia (e.g. Akhir, 2015)	Southwest SCS
Gulf of Thailand (e.g. Cushing, 1969; Wyrtki, 1961)	Northwest SCS
Off Borneo (e.g. Yan and Chen, 2015; Wang *et al.*, 2012; Xiu and Chai, 2011; Yuan, 2004; Xie *et al.*, 2003; Wang *et al.*, 2012; Xiu and Chai, 2011; Yuan, 2004; Xie *et al.*, 2003).	South SCS

Fig 2: Prominent upwelling zones in the South China Seas adapted from Hu and Wang, 2016



Note: the red ellipses locations in the large black-dashed ellipse mark the major upwelling regions in the China seas. The dashed yellow-filled ellipse represents the least documented upwelling zone while the yellow-filed circle off the coast of Northern Vietnam is being documented for the first time by Ndah (2016).

Fig 3: Popular upwelling zones in the SCS associated with seasonal advection of cold waters *courtesy of Hu and Wang (2016)*



Note: Monthly mean sea surface temperature (SST, in °C) and wind (vector, in m/s) in August 2013. Z1, Z2, Z3, Z4, and Z5 in the figure represent five relatively low SST zones associated with the coastal upwelling in the China seas

Island, southern coast of Shantou (Niino and Emery, 1961). In subsequent years, especially since 1986, prominent upwelling zones on the coast of South china have been named as follows: inshore areas from the Shantou Coast to the Nanri Islands, generally off southern Fujian Province, referred to as the Yuedong Upwelling Zone and the east of Hainan Island, east of the Leizhou Peninsula and the southeast of the Zhanjiang Bay generally off Guangdong province, referred to as the Qiongdong Upwelling Zone (Jing *et al.*, 2008). Another significant upwelling zone in NSCS is located in the Taiwan Strait on the northeast coast of the SCS. Taiwan Strait Upwelling (TSU) has attracted significant attention since the 1980s based on hydrological, chemical, biological and satellite observations (Jing *et al.*, 2008).

3. Temporal Variability of Upwelling in the SCS

The phenomenon has been observed to occur at various temporal scales: seasonal and at finer scale and longer scales.

3.1 Seasonal Variability of Upwelling

Seasonal variability is a dominant feature of upwelling in the SCS. Cushing mentioned that upwelling occurs slightly all year round at 12°N and 101°W, on the west coast, in the shallow Gulf of Thailand in August (S.W Monsoon), and on the northeast coast in October and January (N.E Monsoon) (Cushing 1969). In Northern SCS, summer upwelling off the central South Vietnamese coast at Nhatrang extending some hundreds of miles up the coast (Cushing, 1969; Wyrtki, 1961) has especially received great attention. Recent studies have documented the evolution, mechanisms of the South Vietnam Upwelling (e.g. Yuan, 2004; Xie *et al.*, 2003). Contrary to what is generally reported, this upwelling zone was first observed and reported by Dale who documented a cold SST anomaly off the central Vietnam coast in summer, as early as 1956 (Akhir *et al.*, 2015). Another important upwelling zone in the SCS which has received great attention in the scientific community is located off Luzon, Northern Philippines. Nitani (1970) made the first observation of a cold pool northeast of the SCS off Luzon Island during winter. More recent investigations by Jing *et al.* (2011), Martin and Villanoy (2008) confirm previous findings of strong winter upwelling events off the northwest tip of Luzon in the South China Sea during the northeast monsoon. Another study by Chu *et al.* (1997a, b) using SST measurements observed that the mesoscale cold pool off Luzon is a warm pool during boreal spring, indicative of a seasonal alternation between upwelling and down-welling. Off the coast of Zamboanga Peninsula, northwest coast of the island of Mindanao, S.W. Philippines, Villanoy *et al.* (2011) found, in agreement with numerous studies that cooler temperatures and elevated chlorophyll a were indicative of upwelling.

Summer upwelling is a regular phenomenon on the northern continental shelf of southern China, from June-September based on observations of proxies such as surface and subsurface water characteristics, lower temperature, higher salinity and higher potential density especially on the coasts of Shantou and Xiamen off Guangdong and Fujian Provinces respectively (Jing *et al.,* 2007). Large and strong upwelling has also been found to occur within 150~200 km from the coast, east and northeast of the Hainan Island, the east of Leizhou Peninsula and the southeast of the Zhanjiang Bay, south of Sanya to the west of Qizhou Archipelagoes mostly occurring at depths of less than 100 m within 130 km off the coast, and at 100 m depth within 100 km off the coast, where the SST was found to be generally lower than offshore waters during the summer of 1998 (Jing *et al.,* 2007). In Qiongdong upwelling zone (off Guangdong province), characterized by two hundred kilometers long coastline and an average width of 100 kilometers wide, and about 130 kilometers to the North and about 90 km to the south, coastal upwelling is a common occurrence in summer, that is from April-September, but peaks from June to July (Jing *et al.,* 2008). Further east, upwelling has been widely studied in the Taiwan Shoal, west of Penghu Archipelagoes (Jing *et al.,* 2007) and Taiwan Strait in general (Hong *et al.,* 2008). Hu *et al.* (2001), using hydrographic data (salinity as an indicator) in August of 1997-1999 and a four-year satellite-derived Sea Surface Temperature (AVHRR SST) dataset to establish evidence for the existence of four summer upwelling zones in the Taiwan Strait consistently observed high salinity and low temperature anomalies in the four zones, indicating the occurrence of summer upwelling in the Taiwan Strait. Another satellite remote sensing-based study aimed at studying the intensity of upwelling on the Taiwan Bank Upwelling Region in 1998 found that upwelling intensifies on its southeastern edge, measuring about an average of 2796 km^2 with a mean temperature anomaly of about 2.3°C in the summer, July to October (25-26 °C) coupled with high mean Chl-a concentrations (up to 0.8-2 mg m^{-3}) consistent with field measurements of water temperature, salinity, and Chl-a (Tang *et al.,* 2002). Upwelling has also been studied on the west coast of the SCS, off east Peninsular Malaysia during the southwest and inter-monsoons (June to September) using cruise and satellite remote sensing data and established that southwesterly wind that blowing along coast are important drivers of Ekman dynamics and upwelling (Akhir, 2015). In Southern SCS, winter coastal upwelling has been studied off northwest Borneo using satellite data, climatological temperature, salinity fields and reanalysis data and established that upwelling forms and strengthens between December and March induced by the alongshore N.E monsoon wind which drives Ekman transport and Ekman pumping, modulated orographic wind stress curl and amplified by ENSO-induced anomalies (Yan and Chen, 2015).

3.2 Long Term Variability of Upwelling in the SCS

In comparison with seasonal observations, studies of long term variability of upwelling are limited in the SCS and largely based on the use of proxy indicators such as anomalies of temperature, salinity, chlorophyll-a, and even nutrients, from which Ekman Transport and pumping are extrapolated (Sasai *et al.,* 2013; Liu *et al.,* 2007; 2002; Xie *et al.,* 2003). Using a multivariate statistical analysis, Lin *et al.* (2011) have demonstrated that analysis of surface nutrient anomalies (silicate) in the SCS can be a viable indicator or proxy for identifying and measuring the occurrence of upwelling based on the observation of a strong correlation between upwelling and silicate concentrations across multiple zones in Northern SCS. In their attempt to analyze upwelling over inter-annual time scales using a time series of SST, Villanoy *et al.* (2011) observed that La Niña and El Nino were the primary sources of inter-annual variability of upwelling off Zamboanga Peninsular. Hong *et al.* (2008) also studied inter-annual variability of summer coastal upwelling in the Taiwan Strait, based on empirical orthogonal function (EOF) analysis using NOAA Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature dataset from 1985 to 2005; hydrographic records at two coastal stations from 1970 to 2001; cruise measurements in 1988 and 2004 and alongshore wind component, derived from 17 years of the European remote sensing (ERS) satellite and QuickScat wind dataset from 1992 to 2005. In another study, a 20-year historical water temperature, salinity and dissolved oxygen data has been used to extrapolate summer upwelling in the NSCS (Hong and Li, 1991; Li, 1990, 1993). Moreover, using multi-proxy records of two sediment cores from the north-eastern South China Sea in comparison with sediment records of summer monsoon-driven upwelling east of South Vietnam, to determine millennial-scale changes in the intensity of winter monsoon upwelling over glacial-interglacial cycles, Sadatzki *et al.* (2016) found seasonal upwelling in the SCS to be in response to orbital-scale changes in the East Asian Monsoon. Another study based on radiocarbon-based techniques, Poriteslutea coral collected from Hon Tre Island, Vietnam, South China Sea (SCS) was analyzed over a ~ 100-yr-long period from AD 1900 to 1986, Bolton *et al.* (2016) confirm the historical occurrence of upwelled water depleted in 14C from the deeper SCS basin. This study suggests that the South Vietnam upwelling region occupies a unique oceanographic position, reflecting the seasonal influence of older, deeper SCS waters that upwell periodically in this area and modify local surface waters over the last 100 year (Bolton *et al.*, 2016). In brief, the study of upwelling dynamics in the SCS, both in short and long timescales is based on proxy indicators which may or may not be perfect representations of upwelling.

4. Mechanisms and Forcings of Upwelling in the South China Sea

Upwelling, one of the most important features of sea surface circulation studied since the 1930s (Sverdrup, 1938) has long been known to result when sea water surface deforms under the action of wind or other forces (Bakun and Agostini, 2001), but the mechanics of the interaction between wind and water is increasingly complex (Schwing *et al*., 1996). Wind fields over the ocean are important components of many geophysical parameters because the marine wind induces heat and momentum transfers between the ocean and the atmosphere and is a main driving force for surface ocean circulation (Kubota and Yokota, 1998). Air-sea coupling thus generates surface ocean circulation which is responsible for the distribution of variable oceanographic, cyclonic and anti-cyclonic structures (Griffa *et al.*, 2008). Therefore, two major types have been identified: wind-driven and geostrophic upwelling. Wind-driven upwelling is therefore an important component of surface ocean circulation, inducing a vertical circulation when colder deeper ocean waters rise up from beneath to the surface in the open ocean and along coastlines (Schwing *et al.*, 1996; Picket and Paduan, 2003). However, although most coastal upwelling regions are governed by the classical wind-driven Ekman dynamics (Schwing *et al.*, 1996; Bakun *et al.*, 2015; Bakun and Weeks, 2004; Bakun, 1973; 1975; 1990), several possible localized mechanisms have been attributed to upwelling in the SCS. Some of the most important ones include: the nature of the coastlines, the bathymetry, local wind stress and Kuroshio intrusion (Hu and Wang, 2016; Wang *et al.*, 2012; Jing *et al.*, 2011; Yuan, 2004; Xie *et al.*, 2003; Chu *et al.*, 1999). Changes in the upper circulation system in the SCS governed by the alternating monsoons which generate the strong southwesterly/northeasterly winds and drive cyclonic and anticyclonic gyres or mesoscale eddies in the SCS, found to result in localized upwelling (e.g., Chen *et al.*, 2011; Xiu *et al.*, 2010; Zhuang *et al.*, 2010; Liu *et al.*, 2008; Wang *et al.*, 2003; Chi *et al.*, 1998). During the N.E monsoon (winter) the northeasterly winds have been found to force a cyclonic gyre in the SCS and drive the localized upwelling off the western Luzon (Qu, 2000; Liu *et al.*, 2002). These mechanisms have also been found to drive the development of the Borneo Vortex as well as other anti-cyclonic oceanographic structures including gyres and eddies in Southern SCS (Wang *et al.*, 2012; Xiu and Chai, 2011; Yuan 2004; Xie *et al.*, 2003). Ying (2006) has attempted to simulate observed upwelling characteristics in NSCS using a three-dimensional Regional Ocean Model System (ROMS), forced with idealized upwelling favorable winds. The results of this study suggest that upwelling over the shelf of NSCS has a strong alongshore variation occurring with great intensity off Shantou, Hainan Island, Daya Bay - Red Sea Gulf and east of Hong Kong largely driven by the interaction between the coastal upwelling jet and the local shelf topography, coastline orientation and strength of the local wind stress. Jing *et al.* (2007) have investigated summer upwelling systems in the northern continental shelf of the South China Sea (NCSCS) using Pathfinder, Advanced Very High Resolution Radiometer (AVHRR) Sea Surface Temperature (SST) data and a three-dimensional baroclinic nonlinear numerical model (ECOMSED) forced by QuikSCAT winds. In a follow-up study, using QuikSCAT wind data to model upwelling index Jing *et al*. (2008) have confirmed that local alongshore winds and wind stress curl drives offshore Ekman transport and induces Ekman pumping, and play a significant role in forcing summer coastal upwelling in Guangzhou Bay (Qiongdong Upwelling). In contrast, results of numerical modeling experiments reveal that stable alongshore wind stress is a very important dynamic factor which induces upwelling in the Yuedong Upwelling (YDU) zone, while the wind stress curl has little contribution and even unfavorable to upwelling in this zone (Jing *et al.*, 2008). In another study, Kuo *et al.* (2000) observed the evolution of upwelling along the western coast of the South China Sea (SCS) using NOAA satellite AVHRR (Advanced Very High Resolution Radiometer) IR (infrared) data for the summer of 1996-1997 and found that upwelling intensity, defined by the total heat loss in the anomalous low cold water region, is determined by alongshore wind stress which is the dominant factor responsible for the pumping of cold water onto the sea surface. Xie *et al.* (2003) have studied the inter-annual variations of summer upwelling off Vietnam coast and the offshore spread of cold water using a range of satellite measurements and established that southwesterly winds force an anticyclonic ocean eddy to the southeast in July and August, advecting the cold coastal water offshore into the open South China Sea (SCS) in summer, modulated by the effects of topography (Indo-China cordillera mountains east of Saigon) on impinging winds, leading to the development of a strong wind jet curl at the southern edge of this mountain range, inducing upwelling off Vietnam (Yuan, 2004; Xie *et al.*, 2003). During the

N.E. Monsoon part of the southward jet off Saigon is pushed across the Sunda Shelf into the shallow Java Sea by the initiated Ekman transport due to the impact of the wind stress vector but the shallow nature of the shelf (a mean depth of only 43 m) prevents the occurrence of upwelling since only surface water is transported (Jing *et al.,* 2011) while a significant portion turns eastwards in a cyclonic motion, initiating a weak upwelling on the coast of Borneo Island, specifically off northwestern Sarawak around Kuching Bay (Jing *et al.,* 2011; Yuan, 2004; Xie *et al.,* 2003). In Southern SCS, wind-stress and ocean circulation patterns across the SCS during the N.E Monsoon generate conditions for upward Ekman pumping or upwelling, such as the development of the Borneo Vortex as well as other oceanographic structures such as anticyclonic gyres and eddy (Wang *et al.,* 2012; Xiu and Chai, 2011; Yuan, 2004; Xie *et al.,* 2003). Martin and Villanoy (2008) found that winter upwelling events on the east coast of the SCS, off the northwest tip of Luzon in the South China Sea using Empirical Orthogonal Functions based on ocean altimetry data. They found in agreement with numerous other studies that upwelling is associated with positive wind-stress curl initiated by the Northeast monsoon winds as they enter the SCS via Luzon Strait and modulated by topographic effects. Similar mechanisms related offshore Ekman transports forced by northeast monsoon winds have been found to initiate upwelling off the coast of Zamboanga Peninsular (Villanoy *et al.,* 2011). A simulation study forced with observed upwelling favorable winds in the SCS by Ying (2006) reveals that upwelling intensity at the near-shore location is sensitive to the orientation and strength of the local wind stress. In a study by Chu *et al.* (1999), based on simulations using the Princeton Ocean Model (POM), while recognizing that seasonal oceanographic circulation patterns and upwelling are determined and forced by winds, their results also point out the significance of lateral boundary forcing which play a secondary role in limiting the circulation velocities. Overall, Jing *et al.* (2011) suggests that the adjacent basin-scale upwelling in the SCS have different responses and maintaining mechanisms because of the anticyclonic atmospheric circulation anomaly over the SCS and Northwest Pacific. The northern flank of the atmospheric circulation anomaly intensifies the monsoonal winds off the NSCS coast, while the southern flank suppresses the southwesterly winds along the Vietnam coast resulting in strong summer upwelling (Jing *et al.,* 2011). In another simulation model by Wang *et al.* (2003; 2008), the seasonal variation of upwelling between northern and southern SCS has also been addressed. According to the research, the influence of the deep ocean cyclonic gyre on upwelling in the SCS all year is very significant; being more prominent in the northern part in winter, while in summer, the anticyclonic gyre in the southern SCS is pronounced. Because of the strong upwelling of deep water, the cyclonic gyre in northern SCS (NSCS) is weakened, but the anticyclonic gyre in the southern SCS (SSCS) is intensified in summer (S.W. monsoon), while cyclonic gyres in both the southern and northern SCS are weakened in winter (Wang *et al.,* 2012). By including an "upward pumping" component into the simulation model, the study further points out that in all seasons, the dynamic influence of thermohaline circulation on wind-driven circulation is larger in the northern SCS than in the southern SCS, and that the upwelling associated with the thermohaline circulation in the deep ocean plays a crucial role in regulating the wind-driven circulation in the upper ocean (Wang *et al.,* 2012). Finally, Villanoy *et al.* (2011) have established the strong association between ENSO and upwelling, noting that La Niña causes the strengthening of the monsoon-driven upwelling while El Nino induces an opposite effect, suppressing upwelling off Zamboanga Peninsular, Southwestern Philippines. Deep wind-driven ocean circulation patterns have also been identified as playing a significant role in modulating the occurrence and intensity of upwelling over the entire sea basin over much longer timescales. The influence of the strong 'western boundary' Kuroshio current, with velocity of up to 250 cm S-1 generally flowing northward, partially intruding into the SCS via the Luzon strait during the N.E monsoon, is found to be responsible for conditions of weak upwelling in Northern SCS and strong upwelling off the coast of Luzon (Dai *et al.,* 2013; Du *et al.,* 2013; Wang *et al.,* 2012; Jing *et al.,* 2011;Yuan, 2004; Xie *et al,* 2003; Chen *et al.,* 2001; Chu *et al.,* 1999).

In summary, wind stress and ocean circulation patterns across the SCS have thus been found to generate conditions for upward or downward Ekman pumping in the SCS, coupled with topographic effects. Upwelling in the SCS is thus largely driven short term dynamic wind stress patterns which significantly impact on the Ekman layer acting as a major initiator of coastal upwelling over short time scales (hourly, daily, weekly), modulated by the seasonally reversing monsoon winds and the intervening periods (inter-monsoons). The frontal interaction of the two current systems with contrasting origins and thermal characteristics, numerous canyons, the orientation of the coastline and the seasonal monsoon gap winds which force their way through the narrow Taiwan Strait are generally identified to be major contributing factors to upwelling in Taiwan Strait or Taiwan Bank (Jing *et al.,* 2007; 2008; Tang *et al.,* 2002; Hu *et al.,* 2001). These mechanisms impart lateral and vertical motion to the sea surface layers (Dai *et al.,* 2013), resulting in a dynamic exchange with the Western Pacific Ocean via an upper part exchange with the Kuroshio and overflow at depth (Chen *et al.,* 2001; Dai *et al.,* 2013; Du *et al.,* 2013).

5. Challenges and Limitations of Upwelling Research in the South China Sea

It has become increasingly important to understand upwelling regions for the coming decades due to the possible dramatic ecosystem and socioeconomic impacts which may emanate from rapid environmental and climatic changes (Bakun *et al.,* 2010; 2015) especially driven by changes in the carbon cycle, regional climates, primary production and fishery systems. However, despite extensive research and growing understanding of the importance of upwelling and upwelling systems, its occurrence over the continental shelf of the South China Sea (SCS) remains unclear (Ying *et al.,* 2006), and limited to monthly to seasonal observations (e.g. Sasai *et al.,* 2013; Jing *et al.,* 2011; Xiu *et al.,* 2010; Lin *et al.,* 2010; Zhuang *et al.,* 2010; Liu *et al.,* 2007; 2002; Chen *et al.,* 2006; 2011; Ning *et al.,* 2004; Wang *et al.,* 2003; Xie *et al.,* 2003; Liu *et al.,* 2002; Kuo *et al.,* 2000; 2004, Qu, 2000; Chi *et al.,* 1998).

Even where an attempt is made to analyze a time series of upwelling it has been based entirely on different proxy variables, including the observation and/or modeling and extrapolation of water chlorophyll-a, sea surface temperature, salinity, coral records (e.g. Sasai *et al.,* 2013; Jing *et al.,* 2011; Liu *et al.,* 2002, 2007, 2013; Xie *et al.,* 2003; Hong *et al.,* 2000, 1993). Overall, the study of upwelling in the SCS has been largely based on a seasonal timescales associated with seasonal monsoon variability and shorter term intra-seasonal variability often associated with tropical cyclones (Hu *et al.* 2016); a few studies have observed the phenomenon at an inter-annual time scale and associate it with the El Niño Southern Oscillation (e.g. Villanoy *et al.,* 2011; Zhao and Tang, 2007), and an even smaller number of studies have attempted to describe the phenomenon over longer time-scales based on proxy indicators such as point-specific coral records from which centennial SST records are inferred (e.g. Bolton *et al.,* 2016; Liu *et al.,* 2013) and at millennial time-scale, using sediment core records (Sadatzki *et al.,* 2016).

Moreover, previous studies of upwelling occurrence and its mechanisms in the South China Sea (SCS) have been generally point-specific, mostly focusing on single zones with disproportionately greater attention on South Vietnam Upwelling (e.g. Chen *et al.,* 2006; 2011; Xiu *et al.,* 2010; Lin *et al.,* 2010; Zhuang *et al.,* 2010; Ning *et al.,* 2004; Wang *et al.,* 2003; Xie *et al.,* 2003; Liu *et al.,* 2002; Kuo *et al.,* 2000; 2004, Qu, 2000; Chi *et al.,* 1998). Even long term analysis proxy indicators such as coral records are often collected from specific locations e.g off Hainan Island and extrapolated to wider areas of the SCS (in the case of Liu *et al.,* 2013), although such a sample may not be representative of this diverse marginal sea. The study of upwelling is therefore imbued with numerous challenges (McGregor *et al.,* 2007) and climate models have not also proven very effective at generating consistent upwelling results (Wang *et al.,* 2010). The primary reason for the difficulties of directly measuring upwelling is because observed time series of the phenomenon do not exist (Schwing *et al.,* 1996), in stark contrast with other ocean-atmosphere circulation indices such as winds, currents and waves (Ndah *et al.,* 2015; Huang *et al.,* 1994). This is because of the inherent difficulties in estimating, measuring and directly quantifying the process amidst the interaction of various complex mechanisms, coupled with its highly localized occurrence in space. Consequently, understanding the behavior of coastal upwelling in the SCS under contemporary and future global changes remains evasive, poorly understood, documented and appreciated. It is therefore imperative to directly quantify upwelling in the SCS over longer time scales in order to ascertain and forecast the current and potential changes in the pattern and intensity to marine primary productivity, fishery systems and general circulation in the SCS.

6. Conclusion

Studies of upwelling in the SCS find the phenomenon to be largely a seasonal phenomenon, induced by many factors including: alongshore wind stress, wind stress curl, bottom topography, coastline orientation shelf circulation, eddies and islands and capes shape of the coastline. However, very few analyses have been done of inter-annual and longer term variability of the phenomenon. Moreover, upwelling studies in the SCS and around the world have largely ignored the opposite process of down-welling which generally occurs in reverse of upwelling, both of which culminate to produce an upwelling-downwelling cycle forced by opposing mechanisms. Therefore, since down-welling could be the dominant process under conditions of weak or no upwelling, with potentially significant implications for the biogeochemistry of coastal and shelf zones, it is imperative to pay more attention to this process. Overall, upwelling in the SCS has been entirely based on analysis of proxy variables from which upwelling is inferred. In fact, a previous long term study on the subject, based on coral records, suggests that the trend of upwelling in northern South China Sea has been weakening since 1961 (e.g. Liu *et al.*, 2013) and this could have far-reaching implications for marine primary production and carbon flux. A direct measurement and time-series of upwelling could enable researchers to determine the validity of previous findings, and with greater certainty, ascertain the potential for significant changes in marine biogeochemistry and primary productivity in upwelling zones. Based on the observed limitations of upwelling research in the SCS and mindful of the immense significance of the phenomenon, there are therefore numerous and exciting opportunities for the furtherance of upwelling research in this marginal sea. This should however begin with the derivation of a long time series of upwelling indices for the SCS from which the long term pattern can be ascertained, and which can directly be analyzed using multivariate statistical methods to determine the direct implications of upwelling on oceanographic and regional meteorological/climatic patterns, as well as uncover the mechanisms that may have a significant modulating effect on upwelling intensity. An approach to achieve this is already in use by NOAA-Pacific Fisheries Environmental Lab (PFEL) to derive upwelling indices and could be adopted to generate a time series of upwelling indices for the SCS spanning several decades.

Finally, since the major coastal upwelling zones coincide with Major River systems in S.E Asia, fresh water flux may have a significant impact on upwelling strength resulting in changing patterns of nutrient and phytoplankton dynamics. The varying shape of the coastline, the influence of the riverine discharge from the Mekong, Xi, Red, Jiulong Rivers etc., which influence surface water stratification and the depth of the mixed layer, and the seasonal dynamics of the monsoon winds and current patterns culminate to create a complex system of processes that enhance or impede upwelling in the South China Sea. Generally, the complex interaction between stratification, the general circulation of the SCS, should thus be recognized as a major control factor of upwelling intensity and deserves greater attention.

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