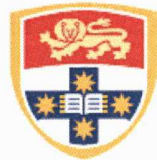


Explaining chlorophyll concentration in the Sulu Sea with the aid of a numerical model



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Abstract

The Sulu Sea is almost an enclosed basin, characterised by a strong seasonally reversing monsoon which induces a complex circulation. Physical features significantly influence phytoplankton biomass which is an engine for the marine food chain that supports fish production. A high proportion of Philippinoes and Malaysians rely on fishing in the Sulu Sea to provide them with animal protein. Nutrients that support the production of marine protein are supplied to the photic zone either through upwelling or by horizontal transport.

A high resolution $1/10^\circ$ eddy resolving global Ocean General Circulation Model (OGCM) was used to determine the upwelling events and surface circulation in the Sulu Sea from 2003 to 2006. Based on the ocean colour data from MERIS, spatial patterns and time evolution of chlorophyll concentration were analysed to examine the dynamic effects on phytoplankton populations in the Sulu Sea.

High chlorophyll concentrations were observed during winter on the eastern boundary of the Sulu Sea when upwelling was active (Correlation between upwelling and Chl-a shows $R^2=0.3303$). The upwelling, on the western boundary of Sulu Sea and central Sulu Sea were weak for the whole year and they only explained a very small part of the reason for local chlorophyll fluctuations ($R^2=0.085$; $R^2=0.056$, respectively). However, the Chl-a concentration in the central Sulu Sea shows high correlation with the upwelling on the eastern boundary of the Sulu Sea ($R^2=0.5061$), higher than local upwelling. The reason for this high association of chlorophyll is the prevailing westward current during winter advecting upwelled waters from the eastern Sulu Sea to the central Sulu Sea. During summer, the whole Sulu Sea has quite low level of chlorophyll concentration and the reversing current brings low nutrient waters to the central region that do not induce high chlorophyll concentrations.

Key words: upwelling, phytoplankton, horizontal advection, numerical model, fish

1. Introduction

1.1 Background

Over the last 50 years, human activities have accelerated global climate changes by increasing carbon dioxide concentrations in the atmosphere, which in turn affects human health, animal lives and all kinds of ecosystems. The ocean, as an important part of energy and material exchange in the climate system, has also responded to climate changes during the last few decades. There is strong evidence observed over the global oceans that marked changes in sea temperature, sea salinity, ocean heat content, pH and sea levels are taking place. These changes in the ocean have the potential to alter the wind patterns and ocean currents which may impact the oceanic biology.

This study focuses on the upwelling system which encompasses only 1% of the ocean area and provides 11% of the estimated 7.2 Gt of annual organic carbon export and more than 50% of the world's fish catch (Chavez and Toggweiler, 1995; Pauly and Christensen, 1995). Much of the global fisheries protein, eaten by humans as food is supported by the nutrients upwelled from the deep ocean into the photic regions. Accumulating evidence has shown that the major upwelling regions of the world likely to increase in intensity as the global warming progresses (Reid et al., 2009). Intensified upwellings will lead to a rise of phytoplankton production and feedbacks from phytoplankton are mainly through its influences on the fish production and carbon sequestration. These insights into the physical and biogeochemical cycles in the upwelling systems provide guidance for the growing need to assess the extent to which ocean processes will respond to climate changes. With numerical simulations and remote sensing observation becoming important tools for analysing ocean dynamic processes, a great resource of information has been created to better understand the ocean's dynamical systems.

With an eddy-resolving (0.1°) ocean general circulation model for Earth Simulator (OFES) coupled with an ecosystem model, it is possible to observe the interaction between marine biology and oceanic physics at the meso-scale (Sasaki et al., 2006). It is possible to determine the upwelling velocity anywhere in the ocean and evaluate the biological

influence it has brought. By using QSCAT wind force for driving the model, small structures of oceanic fields responding to small scale winds patterns can be realistically reproduced (Sasaki et al., 2006).

This study concentrates on the Sulu Sea because a high proportion of the people living around its shore rely on fishing for much of their daily protein. Fish resources rely on the biological environment in the ocean which is greatly influenced by oceanic physics. The Sulu Sea is an almost enclosed marginal basin and this makes small-scale physical processes play an important role in the basin's circulation and biological environment. The MERIS satellite chlorophyll-a measuring system and an ocean model to determine upwelling have been chosen to study the biological response due to the upwelling in the Sulu Sea. Increased understanding of the biological environment in the Sulu Sea can help us to better manage the fish resource in the Sulu Sea while the process of climate change occurs.

1.2 Overview of the Sulu Sea

The Sulu Sea, which has a total area of $250,000\text{km}^2$, is a deep Mediterranean Sea located in the western Pacific Ocean along the western coast of the Philippines. It is isolated from the surrounding seas by a chain of islands and shallow sills no deeper than 420m, extending from 5°N to 11°N and from 117°E to 123°E , as shown in Fig 1.1. The Sulu Sea is a deep ocean basin since it has an average depth over 4400m and a maximum depth of nearly 5600m, compared with the adjacent South China Sea which has an average depth of over 2000m.

The Sulu Sea is separated from the South China Sea by Palawan Island to the northwest. The island of Palawan stretches from the Mindoro Strait to the Balabac Strait located off the southern tip of Palawan Island, which forms the south-western boundary of the Sulu Sea. The Balabac Strait is narrow and only 10m deep. In the southeast, the Sulu Sea is separated from the Celebes Sea by a shallow, partly emerged ridge called the Sulu Archipelago. The Sibutu Passage, located between Borneo and the Sulu Archipelago, serves as a deep channel connecting the Sulu Sea with the Celebes Sea. Dipolog Strait and

Panay Strait are another two important channels that connect the Sulu Sea to the western Pacific Ocean. The Philippines are found to the northeast of the Sulu Sea. Thus, the circular island chains and sills have shaped the Sulu Sea so that it is almost enclosed from upper layer waters and fully enclosed for deep water (Wang et al., 2006).

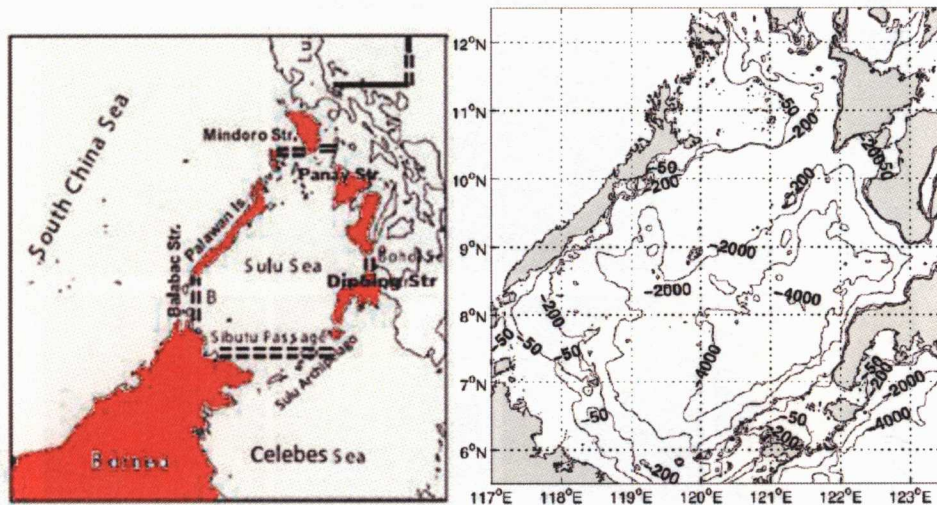


Fig 1.1 The Sulu Sea's location and topography. In the left picture, open boundaries have been marked by Double-dashed lines (Cai et al., 2009).

The Sulu Sea is located in the equatorial region influenced by the North Pacific Trade Winds and the Asian monsoon. The local climate is greatly influenced by two seasonal monsoons - northeast monsoon (winter) and southwest (summer) monsoon (Wang et al., 2006). From December to April the whole Sulu Sea region is under the influence of the northeast trade winds. In January they are fully developed at an average wind speed of around 8m/s (see Fig 1.2). The highest wind speed is located in the North Sulu Sea near Mindoro Strait, then it changes to the reversing wind and continues to weaken into an unsteady state by June. In July and August the southwest wind system becomes a little stronger and has an average wind speed around 5m/s. By September or October the southwest prevailing wind loses strength and gradually changes back to the northeast wind (Wyrтки, 1961).

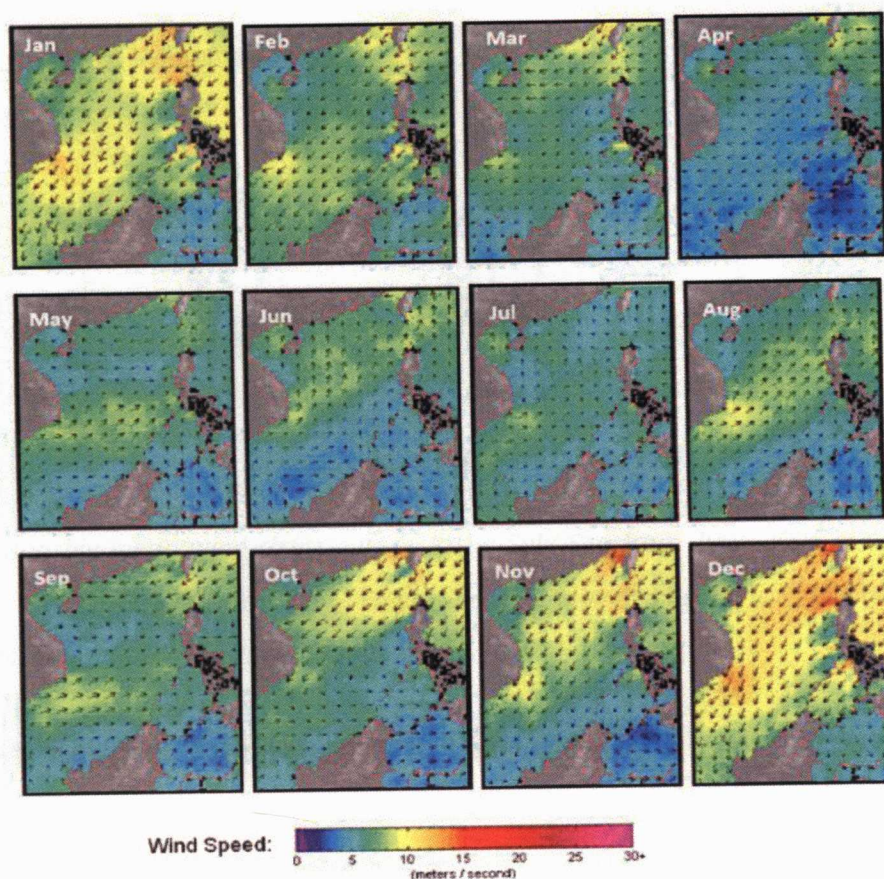


Fig 1.2 Monthly average QuikSCAT wind vectors in 2003 (Wang et al., 2006).

The wind stress curl which is caused by the gradients of wind stress has been described by Han et al. (2009) in a 3-year time series over the Sulu Sea. Both QuikSCAT data and Navy Operational Global Atmospheric Prediction System (NOGAPS) wind datasets have shown similar trend of wind stress curl and this is shown in Fig 1.3. During the winter monsoon significant positive wind stress curl, which is associated with the wind jets, occurs mainly along the Panay strait and Dipolog Strait according to Han et al. (2009). Negative values can be observed during summer monsoon.

The summer monsoon winds from June to August bring more precipitation into the Sulu Sea basin than the winter monsoon winds during December to February. Both seasons can experience intense rainfall influenced by disturbances of air even in the weak winter monsoon. Strong disturbances and irregular cycles bring tropical cyclones into the northern part which causes extreme rains and winds.

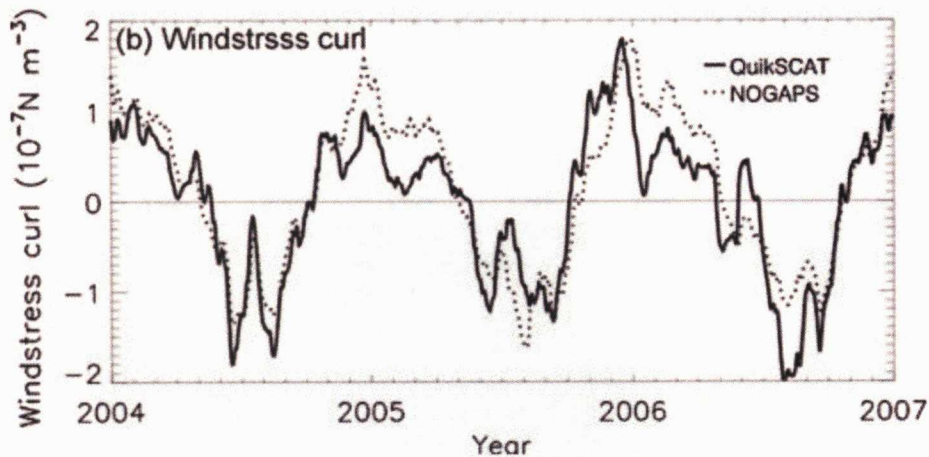


Fig 1.3 Monthly mean wind stress curl over the Sulu Sea from 2004-2006 in comparison between QuikSCAT data and Navy Operational Global Atmospheric Prediction System (NOGAPS) wind data (Han et al., 2009).

1.3 The dynamic mechanisms in the Sulu Sea

1.3.1 General circulation in the basin

The Sulu Sea is part of the southeastern Asian waters (Wyrski, 1961) between the western Pacific and the Indian Oceans and is connected to the South China Sea and the Celebes Sea. It is one of the least studied regions of the world's oceans with complex topography and dynamic factors. There is little observational data available to study of the area, however, high-resolution modelling studies on the Sulu Sea have been continuously conducted to understand the circulation patterns in the Sulu Sea.

The upper circulation in the Sulu Sea is mainly driven by the local wind force and two main channels for transporting water - Mindoro Strait and Sibutu Passage (Wyrski, 1961; Metzger and Hurlburt, 1996; Metzger and Hurlburt, 2001; Qu et al., 2009; Cai et al., 2010). Based on Empirical Orthogonal Function (EOF) analysis using 8 years of Absolute Dynamic Topography (ADT) from satellite altimetry data, Cai et al. (2009) showed that the wind stress curl is the dominant force in inducing the weak anti-cyclonic circulation in summer and strong cyclonic circulation in winter at the centre of the Sulu Sea. Han et al. (2009)

estimated the dynamics mechanism of the seasonal circulation in the Sulu Sea. They used high resolution $1/12^\circ$ of Regional Ocean Modelling System (ROMS) to simulate the mean

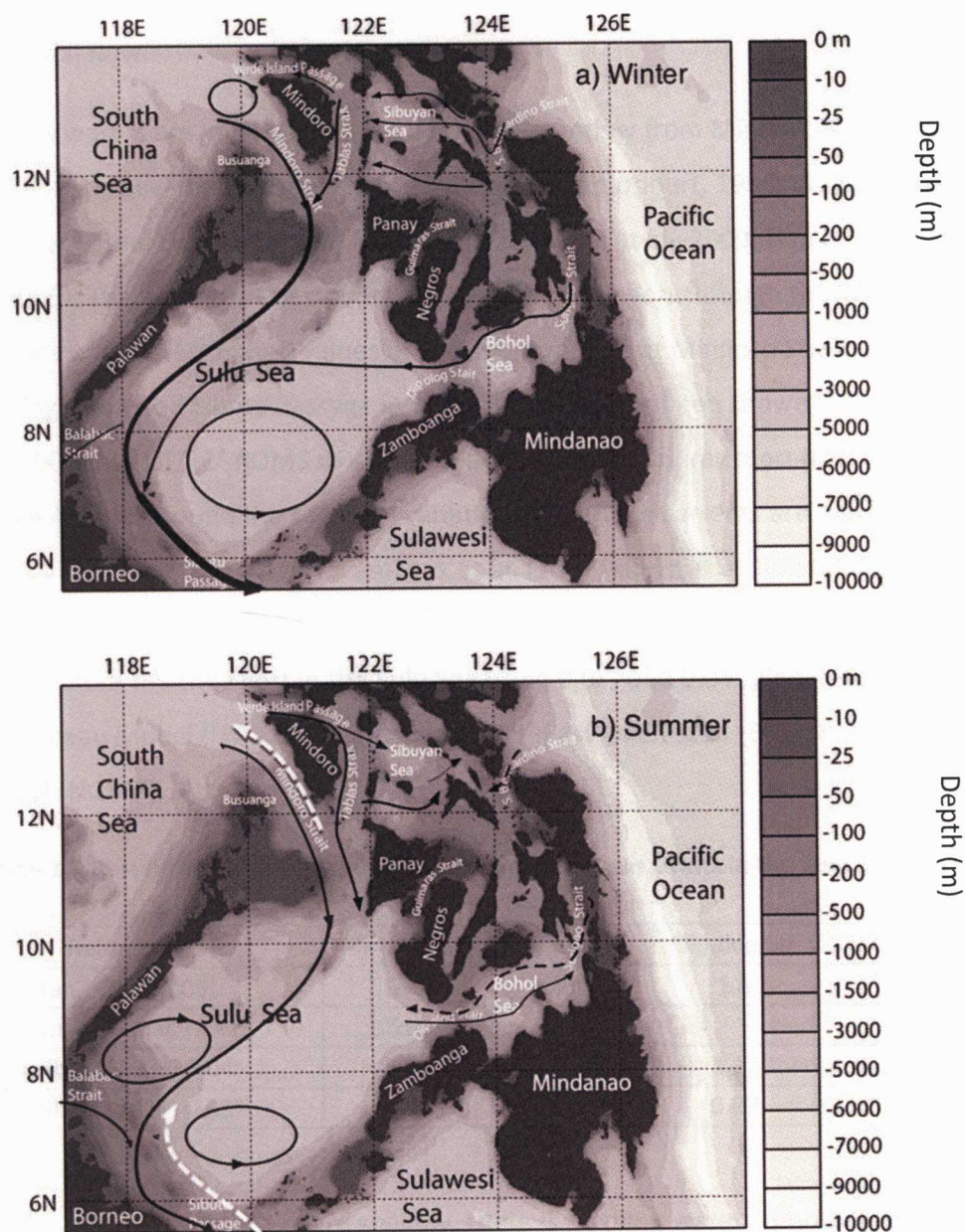


Fig 1.4 Monthly mean surface currents from ROMS over the Sulu Sea during a) winter (November and January) and b) summer (June to August) (Han et al., 2009).

surface circulation during summer and winter for 3 years which shows an annually similar distribution as depicted in Fig 1.4. Water inflows from the South China Sea into the Sulu

Sea through Mindoro Strait and converges with the eastward flow from the Balabac Strait. A large proportion of water exits into the Celebes Sea through Sibutu Passage and the rest merges with the cyclonic circulation in the Sulu Sea. One feature is the strong westward current through Dipolog Strait into the Sulu Sea influenced by the remote forcing and tidal flow.

The Sulu Sea’s waters are mostly balanced by the deep inflow from Mindoro Strait and surface outflow through the Sibutu Passage (Metzger and Hurlburt, 1996; Wajsowicz et al.,1999; Metzger and Hurlburt, 2001; Fang et al., 2003; Cai et al., 2009; Han et al., 2009; Qu et al., 2009). There are a lot of studies on the mean transport through the key straits in the Sulu Sea and the estimated values of transport volume at Mindoro Strait, Balabac Strait, Dipolog Strait and Sibutu Passage in Sv ($Sv=10^6m^3/s$) has been shown in Table 1.1. Han et al. (2009) used 1/12° ROMS to estimate the annual mean transport through the straits above 40m and found the seasonal variations of surface currents are mainly dominated by the remote forcing. Yaremchuk et al. (2009) shows the climatological mean flow through Mindoro Strait simulated by the OFES model. Hurlburt and Metzger (2009) investigated the transport in the Sulu Sea using 0.08° and 0.04° global Hybrid Coordinate Ocean Model (HYCOM) nested with .088° East Asian Seas (EAS) Navy Coastal Ocean Model (NCOM).

Table 1.1 Results of mean transport (Sv) through the main straits in the Sulu Sea

Reference	Mindoro Str	Balabac Str	Dipolog Str	Sibutu Str
Han et al. (2009)	2.3	2.6	1.5	
Yaremchuk et al. (2009)	1.5±0.4			
Hurlburt (2009) 0.04°	3.88		1.17	5.59
Hurlburt (2009) 0.08°	0.92		0.97	2.11

Since the sills around the Sulu Sea are shallow, there is no deep water communications between the Sulu Sea and its surrounding seas. By water mass tracing, it has been demonstrated that the primary sources of the Sulu Sea’s deep waters are from Northern Pacific intermediate waters flowing into the South China Sea and lateral transport passing through the Mindoro Strait into the Sulu Sea (Chen et al., 2006; Yamada et al., 2006). From the OFES model, Yaremchuk et al. (2009) showed the bottom-intensified vertical

profile across Mindoro Strait (Fig 1.5 (a)) and Qu et al. (2006) used the output to confirm the water flow from the adjacent South China Sea is fresher. The currents from Mindoro Strait produce downward overflow into the North Sulu Sea and ventilate the deep waters from North to South (Quadfasel et al., 1990). Gamo et al (2007) conducted a CTD experiment to observe deep convection of the Sulu Sea and suggested that there is geothermal heating which causes vertical overturning in the bottom layer of the Sulu Sea, as shown in Fig 1.5 (b).

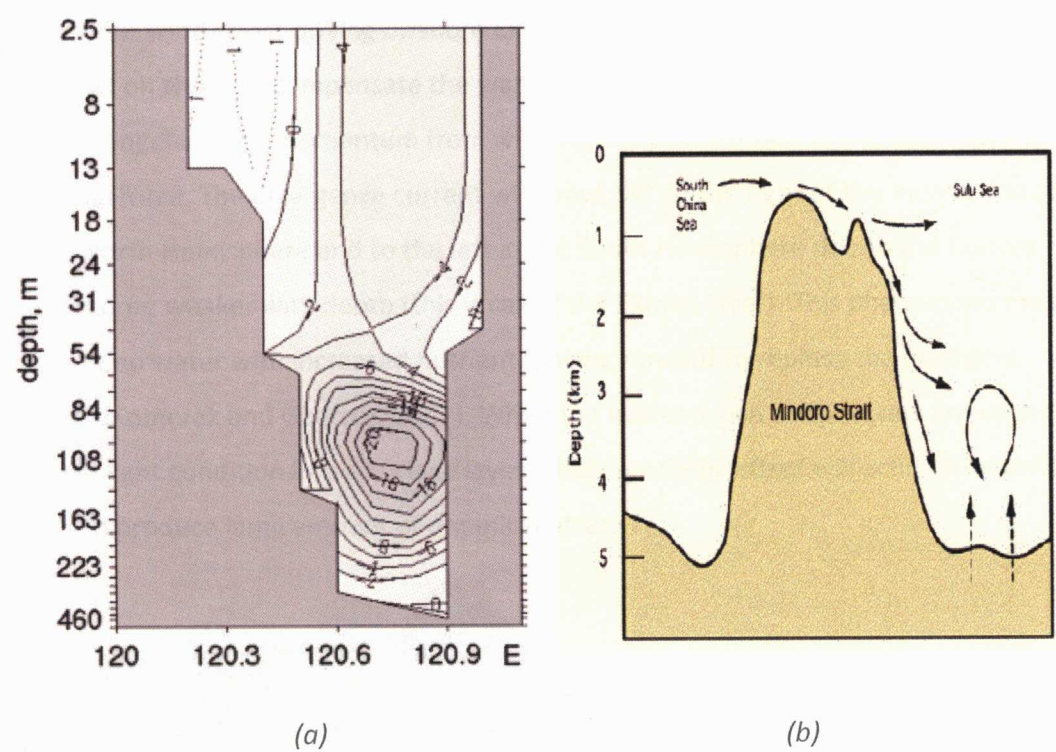


Fig 1.5 (a) The vertical structure of throughflow from OFES across Mindoro Strait (Yaremchuk et al., 2009). (b) The Sulu Sea's deep convection components: water from the South China Sea into the Sulu Sea through Mindoro Strait and the vertical convection in the bottom layer of the Sulu Sea (Gamo et al., 2007).

1.3.2 Upwelling

1.3.2.1. Upwelling mechanism

The upwelling process plays an important role in transporting deep, cold and nutrient-rich waters to the euphotic zone of the surface to activate the photosynthetic processes

and enhance primary production, which in turn supplies food for the fish. The nutrients supplied by the upwelling will be maintained in the surface layer and recycled by phytoplankton rather than being lost (Bakun and Weeks, 2004). Typically, upwelling areas can be identified by the characteristics of cold temperature, low oxygen and high chlorophyll concentrations (Barber, 2003).

There are a wide range of physical mechanisms inducing the upwelling in both the open oceans and coastal areas. The main mechanism to induce coastal upwelling is the alongshore wind stress driving offshore Ekman transport and associated deep water upwelled on shore to compensate the water lost. As depicted in Fig 1.6, when the wind blows alongshore the momentum from wind field is transformed to the ocean by frictional force. The divergence current will move 90° to the right of the mean wind stress in the North Hemisphere and to the left in the South Hemisphere due to the Coriolis force and become weaker with depth (this is called the Ekman layer). This phenomenon results in the deep water with increased nutrient flowing upward to replace the divergent current (Tomczak and Godfrey, 2001). When the nutrient-rich deep waters are under optimal light condition in the surface layer, photosynthetic effect will achieve maximum levels to produce large amount of organic matter.

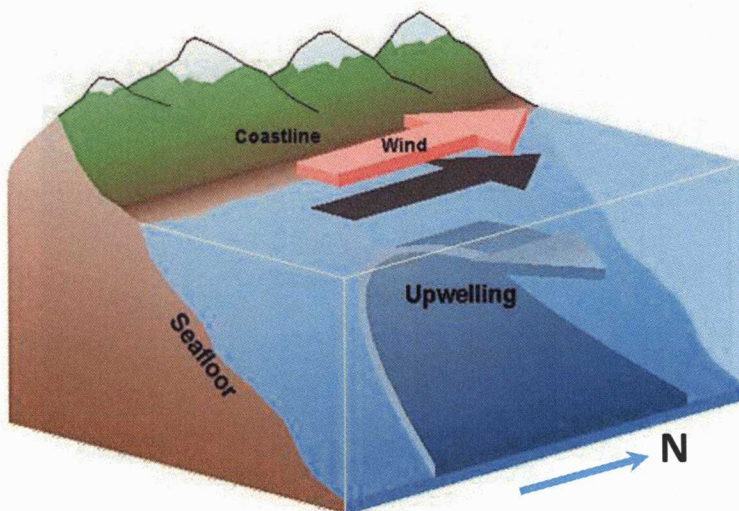


Fig 1.6 Upwelling occurs near the coast due to alongshore wind stress induced Ekman transport perpendicular to the wind in the Northern Hemisphere.

The wind stress curl is another important and dominant force to induce regional upwelling (Jing et al., 2009). The wind stress curl (made up by three components: $curl_x, curl_y, curl_z$) is a vector and tends to induce the rotational flow caused by variations in the wind stress. The wind stress induced by Ekman transport converges in some regions and diverges in others. A vertical-rotational force ($curl_z$) under the surface layer forms to remove the piled water to generate Ekman pumping (negative Ekman pumping is upwelling or “Ekman suction”) (Tomczak and Godfrey, 2001). The wind stress curl is not applicable for near equator:

$$-\rho_o w = curl(\tau / f) = \partial(\tau_y / f) / \partial x - \partial(\tau_x / f) / \partial y$$

where τ_x and τ_y are the x and y components of wind stress τ ; f is the Coriolis parameter; and the vertical velocity w caused by the Ekman pumping is defined by the wind stress curl. As illustrated by Tomczak and Godfrey (2001) in Fig 1.7, the wind stress curl is significant in the region of the Sulu Sea and may contribute to the generation of upwelling in the Sulu Sea.

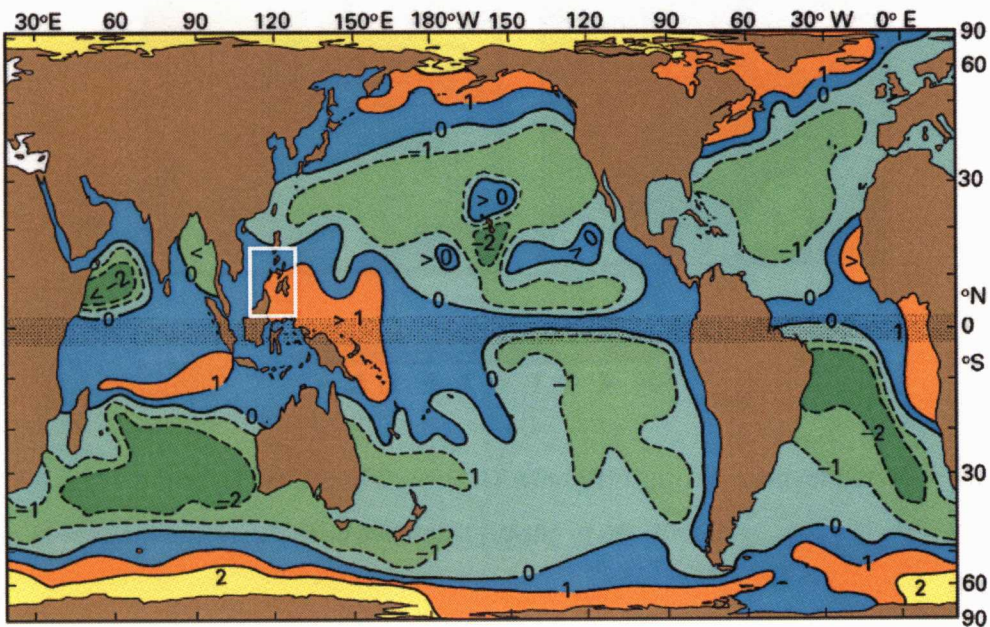


Fig 1.7 The annual mean wind stress curl distribution in the world. The Sulu Sea has been labelled in the white box. Positive values indicate upwelling regions. The region near the equator has been excluded (Tomczak and Godfrey, 2001).

1.3.2.2. Upwelling in the Sulu Sea

The presence of upwelling is not well known in the Sulu Sea since there are no obvious manifestations to indicate upwelling before Wyrтки (1961) pointed out the existence of upwelling regions in the Sulu Sea according to a few hydrographic features. Wang et al. (2006) analysed climatologically prevailing wind fields and Ekman pumping velocities derived from QuickSCAT data in the Sulu Sea. The reversal monsoon in the Sulu Sea is north-easterly and strong in winter and south-westerly and weak in summer. Fig 1.8 (a) shows that the winter monsoon reaches its maximum strength in January and causes wind jets in the lee of island gaps around the north Sulu Sea. In August, a seasonal transition occurs from northeast to southwest with low wind speeds and a wind jet forms along the island of Borneo. The wind stress curl around the wind jets have caused obvious positive Ekman pumping velocities (upwelling) and negative Ekman pumping velocities (downwelling) along the north boundary of the Sulu Sea in Fig 1.8 (b). The central Sulu Sea has strong downwelling in the winter monsoon and weak downwelling in the summer monsoon.

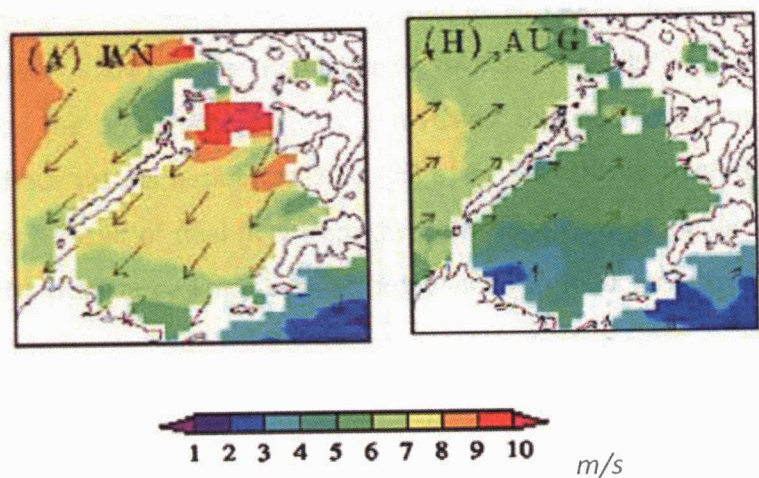


Fig 1.8 (a) Climatological data of QuickSCAT wind fields (m/s): wind jet between the islands in January and weak wind in August (Wang et al., 2006).

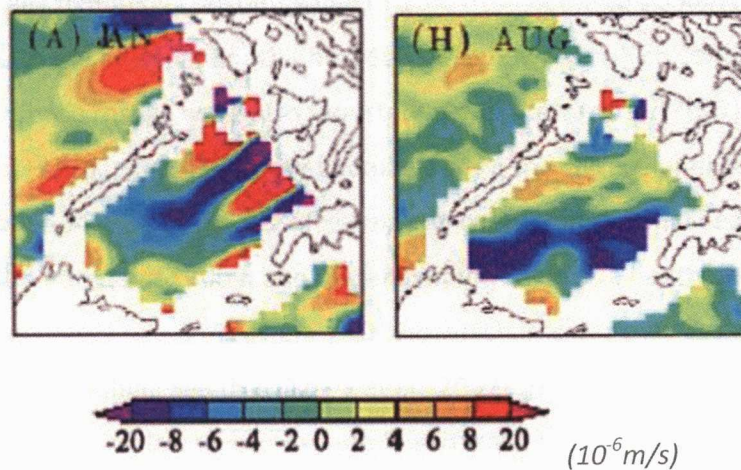


Fig 1.8 (b) Corresponding climatological Ekman pumping velocities (10^{-6} m/s): upwelling and downwelling regions (Wang et al., 2006).

The upwelling occurring occasionally on the western boundary is complex which maybe remotely induced by the cyclonic eddy rather than corresponding to the monsoon (Pietrafesa et al., 1985). From an investigation of the Sulu-Celebes Sea connection where the Sulu Archipelago has complex topography, Han et al. (2009) suggest that the wind driven Ekman layer is thin in the Archipelago. Takeda et al. (2007) conducted field observation near the Sulu Archipelago and revealed that the low-temperature and nutrient-rich surface waters beside the Sulu Ridge are brought up by entrainment and vertical mixing as a result of tidal flow from the Sulu Ridge to the Celebes Sea. Lin et al (2003) noted that tropical cyclones with strong winds can induce occasional upwelling and entrainment in tropical and subtropical oceans. However, tropical cyclones are rare in the central Sulu Sea.

1.4 Bio-chemical environment in the Sulu Sea

1.4.1 Temperature, salinity, dissolved oxygen and sediment

The Sulu Sea was surveyed in December 2002 during the KH-02-4 Cruise by the R/V Hakuho Maru of the Ocean Research Institute, the University of Tokyo (Nishida and Gamo, 2004; Gamo et al., 2007). Fig 1.9 shows homogenous properties below 400m in the Sulu Sea, which corresponds to the Mindoro Strait depth of 420m. The temperature

decreases gradually to a fairly constant value of 10°C from 600m to 5000m deep. It is in sharp contrast with the adjacent South China Sea bottom water which continues to decrease to 4°C. These results were also reported by Nishikawa et al. (2007) during the KH-00-1 Cruise in February 2000. Salinity fluctuates from the surface until 1000m then remains constant at 34.4-34.5. The dissolved oxygen content in the Sulu Sea has minimum value at a depth of ~300m and mid-maximum value at a depth of ~500-600m then gradually decreases to 1.5 ml/L below 1000m which is lower than the adjacent Celebes Sea and South China Sea (Nishikawa et al., 2007). The deep sea water of the Sulu Sea is high in temperature, low in salinity, and low in oxygen features compared with the South China Sea.

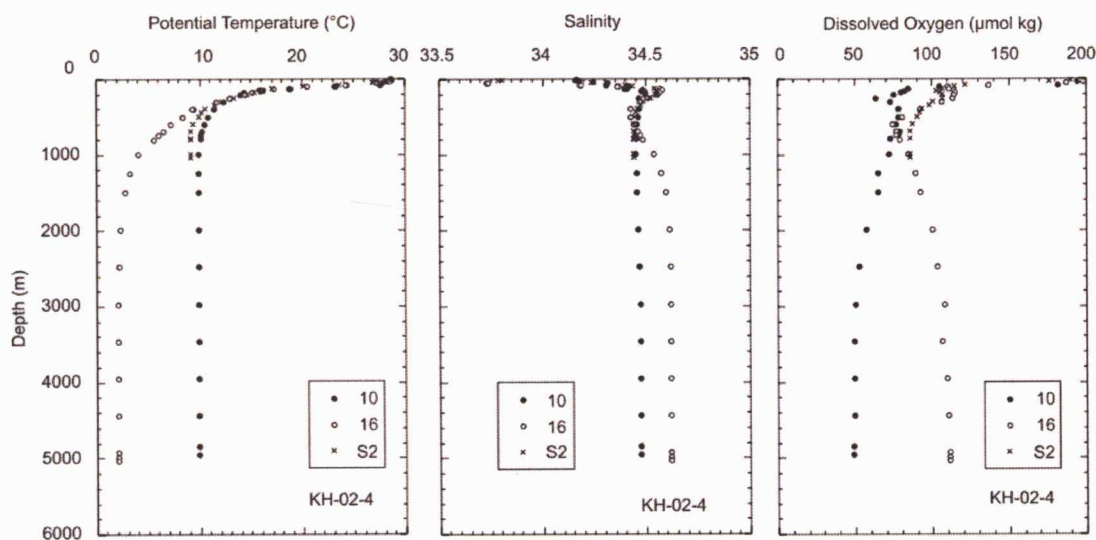


Fig 1.9 Vertical profiles of temperature, salinity and dissolved oxygen sampled during the KH-02-4 Cruise in December 2002. The location: Station 10 (8°50.00'N, 121°47.68'E) in the northern Sulu Sea; Station 16 (13°30.25'N, 119°29.75'E) in the eastern South China Sea; Station S2 (11°27.60'N, 121°49.16'E) in the Mindoro Strait (Gamo et al., 2007).

The Sulu Sea has been recognised as a huge carbon sink since its bottom sediment appear rich in CaCO₃ and low in N and S (Calvert et al., 1993; Chen et al., 2006). The seabed ¹⁴C profiles detect a high organic carbon accumulation rate in the Sulu Sea which is 2-3 times higher than the South China Sea at any depth (Kuehl et al., 1993). This is attributed to a high sedimentation rate in a high temperature environment and deficient oxygen

concentration in deep water which reduces the oxidation responsible for organic matter degradation. Additionally the Sulu Sea is surrounded by many small islands and the runoff from the surrounding islands may further input the heavy organic carbon load into the surface water.

1.4.2 Nutrients

The intermediate waters from the South China Sea compensate the intermediate and bottom waters of the Sulu Sea and create the uniform behaviour of nutrients below 400m in the Sulu Sea, which corresponds to the Mindoro Strait depth of 420m (Lourdes et al., 1999). Lourdes et al. (1999) measured nutrient characteristics in the western Sulu Sea near Palawan Island and showed NO_3 (0-28.4 μM), PO_4 (0-2.15 μM) and SiO_4 (0.36-56.3 μM) concentrations which deplete at the surface and increase with depth. They observed that the adjacent South China Sea has apparent nutrient gradients and a larger nutrient maximum. Gamo et al. (2007) compared the nitrate and phosphate vertical distribution at station 10 (8°50.00'N, 121°47.68'E) in the deepest area of the northern Sulu Sea. They observed respectively in KH-96-5 Cruise (December 1996) and KH-02-4 Cruise (December 2002), as seen in Fig 1.10. The range of nutrient concentrations is similar to the results in Lourdes et al. (1999) and a sharp change occurs at about 400m. Kondo et al. (2007) pointed out that the water of Sulu Sea has an excess of dissolved Fe which maybe caused by rain or riverine input.

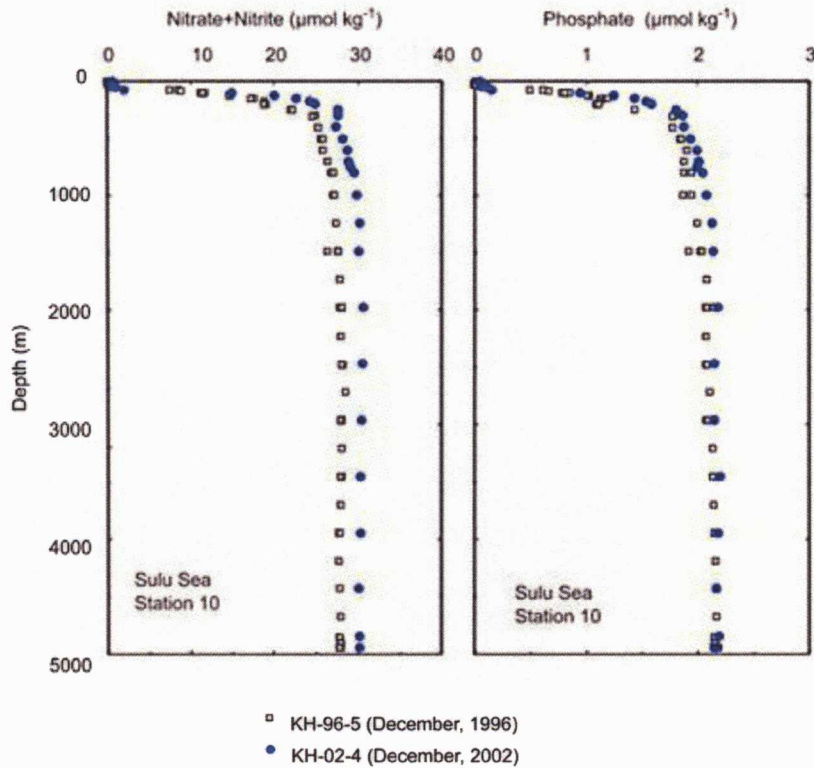


Fig 1.10 Comparisons between the vertical profiles of nitrate+nitrite and phosphate measured at station 10 (8°50.00'N, 121°47.68'E) in the deepest area of the northern Sulu Sea in 1996 and 2002 (Gamo et al., 2007).

1.4.3 Phytoplankton

1.4.3.1. Biological pump

Phytoplankton is important in the global carbon cycle as it plays a vital role in the biological pump, transferring carbon from the upper ocean to deep waters and causing a correspondent decrease of carbon partial pressure in the surface water which will drive the atmospheric CO₂ into the ocean. The biological pump involves photosynthesis conducted by phytoplankton to incorporate dissolved inorganic carbon and inorganic nutrients into organic materials using the energy of the sun and finally exporting organic carbon to the deep ocean as sinking detritus as shown in Fig 1.11. This process removes the excess CO₂ from the atmosphere into the ocean.

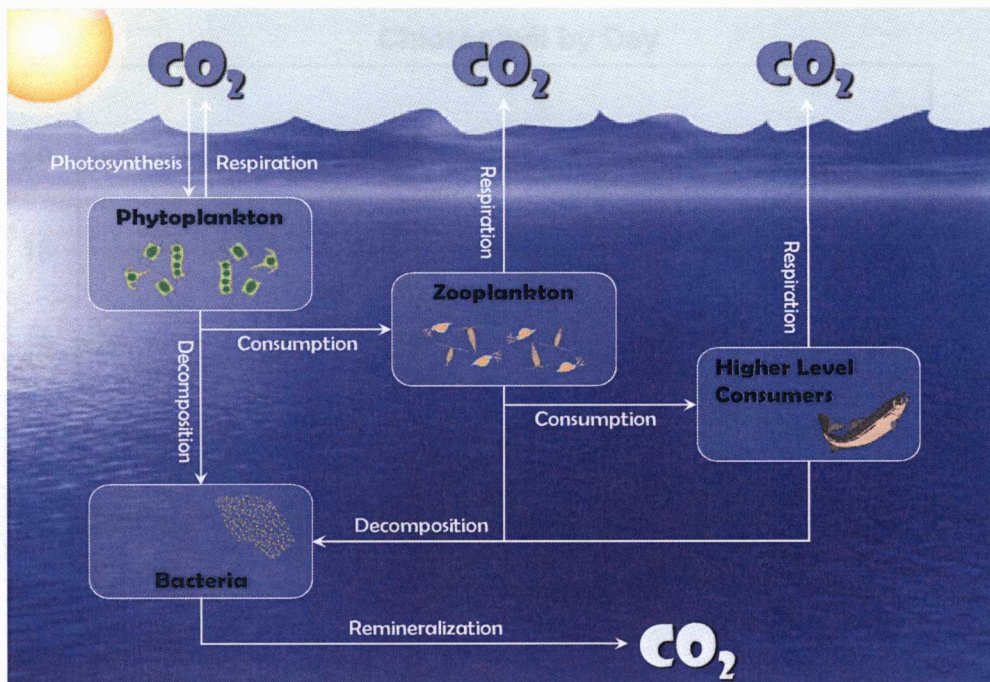


Fig 1.11 Simplified model of the biological pump: CO_2 is fixed in the organic materials through photosynthesis conducted by phytoplankton using sunlight and inorganic nutrients. Phytoplankton, zooplankton and the higher level consumers consume the carbon and the bacteria assimilate their waste which sinks to the deep sea (Ducklow et al., 2001).

Light and nutrients are the primary factors controlling the growth of phytoplankton. Usually light can penetrate roughly 200m and phytoplankton can grow with nutrients in the Redfield ratio (C: N: P = 106: 16: 1 in molar ratio). The sources of nutrients include upwelling of deep nutrient-rich waters to the surface euphotic zone, riverine input, atmospheric deposition and nitrogen fixation by diazotrophs (a type of bacteria that fixes nitrogen from the atmosphere to a usable form). By providing the necessary nutrients, photosynthesis will enhance to ensure the biological uptake by phytoplankton. From culture bottle experiments carried out in the Sulu Sea by Harrison (2007), phytoplankton takes about 6 days to peak in response to a new supply of nutrients, as seen in Fig 1.12 (a). A similar iron nourishment experiment was carried out in the eastern equatorial Pacific between May and June 1995 (IronEx II) by Cochlan (2001). The results show a high correlation with the culture bottle results with that phytoplankton peaking approximately 6-8 days after the iron fertilization in the open ocean, as shown in Fig 1.12 (b).

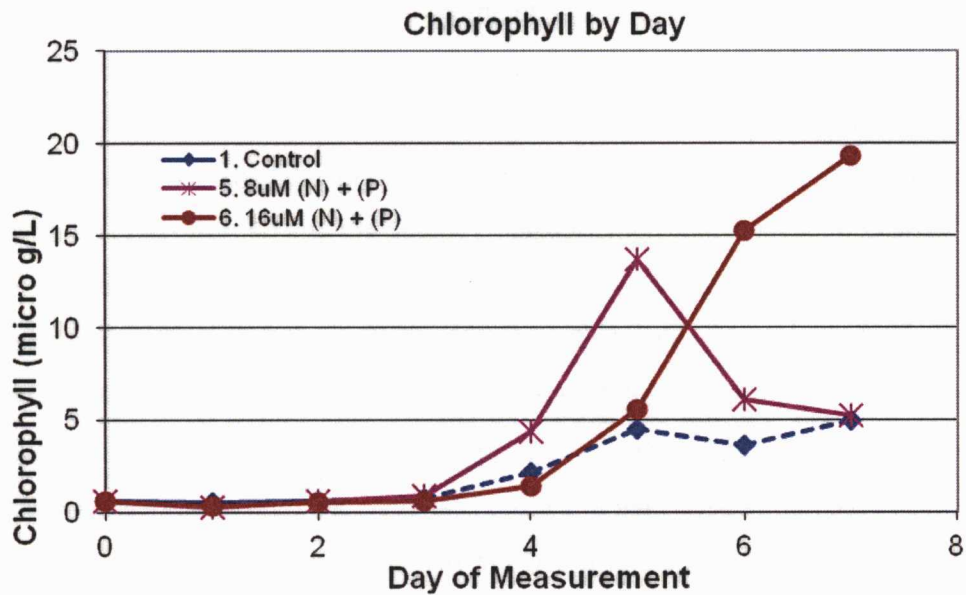


Fig 1.12 (a) Comparison of the chlorophyll-a concentrations between the control sample and the nourished samples (N+P) (Harrison, 2007).

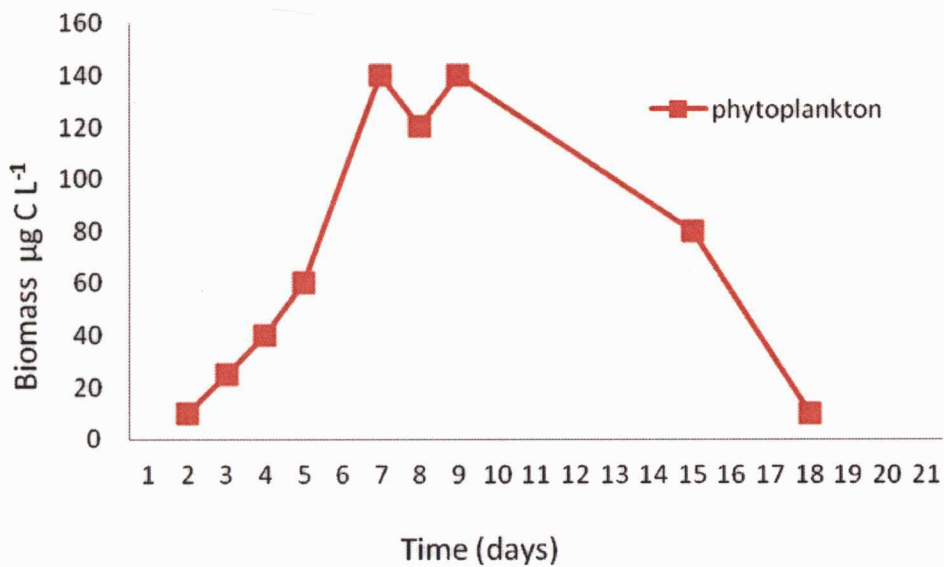


Fig 1.12 (b) Phytoplankton biomasses respond to Fe fertilisation at the depth of 15m in the open ocean. (Cochlan, 2001)

1.4.3.2. Chlorophyll concentration in the Sulu Sea

With the development of remote sensing technology, the phytoplankton concentration in the surface ocean (usually in top 10m) can be estimated by using ocean colour satellite

images of chlorophyll concentration. Wang et al. (2006) compared the monthly mean chlorophyll concentrations at a resolution of 9×9km from SeaWiFS during the period from 1997 to 2004. They found that high chlorophyll concentration patterns occur in the northern regions of the Sulu Sea where wind jets are located during the winter monsoon season. But near Borneo and the Sulu Archipelago, high chlorophyll ($>0.5\text{mg/m}^3$) last year-round. The central basin of the Sulu Sea is a desert usually with quite low chlorophyll concentration levels (0.15mg/m^3), but there are high values (0.35mg/m^3) in winter, as shown in Fig 1.13. The chlorophyll concentration of the central Sulu Sea from SeaWiFS shows a satisfactory agreement with a short period OCTS (Ocean Colour Temperature Scanner) observation reported by Jones (2002) and field observation data from Hakuho Maru Cruise KH-96-5 (Gamo, 1997). The above authors provide no explanation for the seasonal nature of the chlorophyll concentration in the central Sulu Sea. The Ekman pumping velocities as shown in Fig 1.8 (b), cannot explain the high chlorophyll concentration in winter, especially since downwelling that occurs for the whole year will not supply nutrients to support high chlorophyll concentrations.

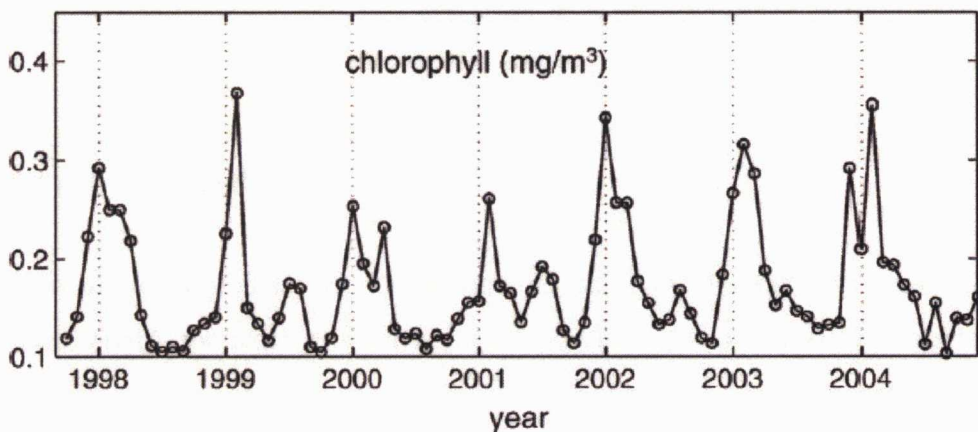


Fig1.13 Monthly averaged chlorophyll concentration in central Sulu Sea from 1998 to 2004 (Wang et al., 2006).

Field observations along Palawan Island in the Sulu Sea from RPS Explorer from 9th to 22nd May 1998 were carried out by Lourdes et al. (1999). The deep chlorophyll maximum in the Sulu Sea was found between 50 to 80m near the nutricline coinciding with the location of the maximum dissolved oxygen concentration. The maximum depth of chlorophyll concentration in the Sulu Sea is 10m deeper than in the South China Sea and

the peak value is almost twice that in the South China Sea. The results of the RPS Explorer agree well with the measurements taken during the KH-00-1 cruise (February 2000) and the KH-02-4 cruise (November–December 2002). Fig 1.14 compares the vertical profiles of chlorophyll-a concentration between the Sulu Sea, the adjacent Celebes Sea and the South China Sea (Nishida et al., 2007).

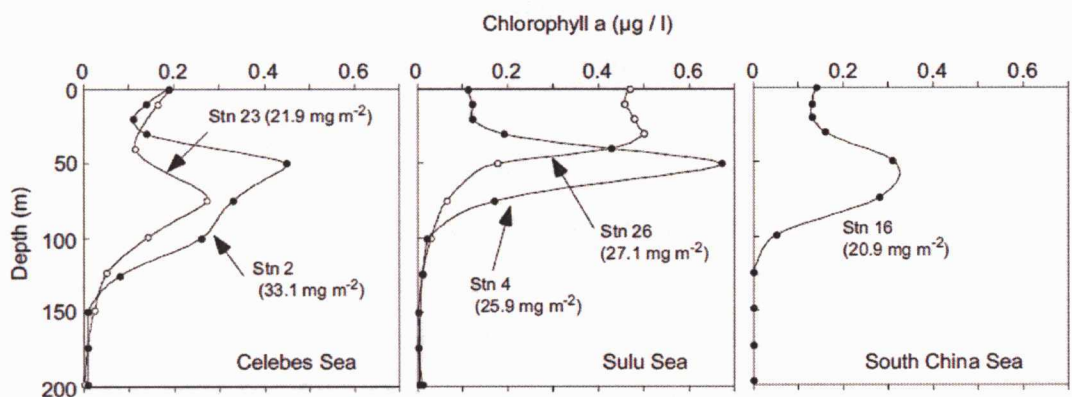


Fig 1.14 Depth-integrated chlorophyll values (0-200m) in the Sulu Sea, Celebes Sea and the South China Sea during KH-00-1 (stn23 ,stn26) and KH-02-4 (stn2, stn4, stn16).

Stn23/Stn2: in Celebes Sea; Stn4/Stn26: in Sulu Sea; Stn16: in South China Sea (Nishida et al., 2007).

1.4.4 Primary production

Primary production, as the organic compounds necessary for most marine life, is always a desired variable for ocean productivity studies. Primary production data was obtained during the RPS explorer field observation by using the 24-h¹⁴C method. Lourdes et al. (1999) found that primary production follows a similar trend to that of chlorophyll concentrations and 30-70% of water column production is contributed from the top layer between the surface (30m-70m). By analysing depth integrated values (top 70m), higher primary production was found in the oceanic part of the Sulu Sea (195 g C×m⁻²yr⁻¹) compared to that in the South China Sea (147 g C×m⁻²yr⁻¹). This is most likely the reason why the sediment in the Sulu Sea is 2-3 times richer in CaCO₃ than that found in the South China Sea. The fisheries in the Sulu Sea rely on the high rate of primary production to provide animal protein to the people in the Philippines and Malaysia, but this is still not a satisfactory level for local fishermen (Jones, 2002).

1.4.5 Fish resources

The fisheries in the Sulu Sea provides about 60-70% of animal protein for the people of the Philippines, Indonesia and Malaysia (UNEP, 2005). Although the Sulu Sea is a rich source of animal protein which supports the economies of the surrounding countries and the daily sustenance of artisanal fishermen, there are more and more people suffering from malnourishment due to decreasing fish resources. From the assessment of fish yields in the Sulu Sea, more than 20% of fish production declined during mid-1980s which was mainly caused by illegal and destructive fishing practices (Alcala et al., 2003). The Philippines for example, reduced the total fish catch from 1,389,000MT in 1987 to 804,000MT in 1995. Overfishing has threatened the food security of the people surrounding the Sulu Sea and has damaged the marine ecosystem's ability to replenish itself.

2. Model description and Satellite data

2.1 Physical-biological model from *OFES*

2.1.1 Model configuration

We have results from the OFES (Ocean general circulation model For the Earth Simulator) which is based on the Modular Ocean Model (MOM3) (Pacanowski and Griffies, 2000). OFES was developed by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC, <http://www.jamstec.go.jp/esc/ofes/eng/>) and is recognised as one of the highest-resolution global Ocean General Circulation Model (OGCM) which solves the Navier-stokes equation. It has performed an eddy-resolving ($1/10^\circ$) quasi-global ocean simulation with a time step of 200 seconds coupled with a simple NPZD (nitrate-phytoplankton-zooplankton-detritus) ecosystem model from 1999 to 2007. Output was every 3 days (Sasaki et al., 2006). The domain of this model covers from 75°S to 75°N in a horizontal resolution of 0.1° and 54 vertical levels with vertical resolutions from 5m near the surface to 330m at the maximum depth of 6065m. The model topography is built on the 1/30 bathymetry dataset supplied by the OCCAM project at the Southampton Oceanography Centre. By using daily mean of NCEP/NCAR reanalysis data, the surface heat flux is calculated by the Rosati and Miyakoda (1988) bulk formulae. The salinity flux is obtained from the fresh water flux which combines the precipitation rate from the same reanalysis data and evaporation from bulk formula. In addition to the surface salinity flux, the monthly mean sea surface salinity of the World Ocean Atlas 1998 (WOA98) was used. A biharmonic operator is employed for horizontal mixing of momentum, tracers and noise control. K-profile Parameterization (KPP) boundary layer mixing scheme is used for vertical mixing. The model contains no tidal forcing and this introduces uncertainty in the realism of the flows in shallow water.

The wind force for the hindcast simulation is from the daily mean surface wind stress observed by the QSCAT satellite in Japanese Ocean Flux data sets with Use of Remote sensing Observations (J-OFURO) (Kubota et al., 2002). The wind stress with a horizontal resolution of 1° can represent well the small scale wind field effect on ocean physical

processes which is important to the marine biological environment (Kutsuwada, 1998). The embedded simple four component (NPZD) ecosystem model is governed by an advective-diffusive equation for any biological tracer concentration C_i :

$$\frac{\partial C_i}{\partial t} = -\nabla \cdot (u C_i) + \nabla \cdot (A \nabla C) + sms(C_i)$$

Where the first item stands for advection, the second item represents diffusion and the last one is the source minus sink through biological activities (Sasai et al., 2006). The initial nitrate field is from the climatological data (WOA98) and initial phytoplankton is set to $0.14 \text{ mmol N m}^{-3}$.

This model has a good computational performance for the Earth Simulator at maximum work output. 100 years integration is expected to be finished in 17 days CPU time with 1500 processors which for each has peak performance of 8Gflops on the Earth Simulator (Masumoto et al., 2004).

2.1.2 Model accuracy

The OFES model has improved the horizontal resolution in a meso-scale simulation to show us the ocean circulation and its variation in details. With $1/10^\circ$ eddy resolving resolution, OFES can capture realistic meso-scale eddies, upwelling events, fronts and boundary currents. (Masumoto et al., 2004) By the use of QSCAT daily surface wind stresses, small scale wind effect such as orographic effects, air-sea surface interactions, and coastlines effects have been included in the model to allow us to see small scale oceanic responses (Sasaki et al., 2006). Du et al. (2005) has suggested that the circulation from OFES is one of the best simulations available from a model. Nonaka et al. (2006) compared the simulated Sea Surface Temperature (SST) with observational datasets and confirmed that the OFES model can reproduce the physical variables. The simple ecosystem model embedded in the OFES has reproduced seasonal pattern of chlorophyll concentrations in the North Pacific compared with SeaWiFS observational data (Sasai et al., 2007). The simulated numerical range of chlorophyll concentration however shows a discrepancy with SeaWiFS images. This suggests that the simulated nitrate distribution

may not correspond to reality. To examine the reliability of the model, we will use the MERIS satellite measured chlorophyll concentrations to investigate the marine biological fields influenced by simulated physical processes.

2.2. Remotely sensed chlorophyll-a data from *MERIS*

2.2.1 MERIS sensors work processes

The Medium Resolution Imaging Spectrometer (MERIS) is one of the main instruments constructed by European Space Agency (ESA) for the Envisat platform to measure solar radiation reflected by the Earth. MERIS runs a five-camera side-by-side instrument equipped with 68.5° field-of-view push-broom spectrometer for each camera to collect radiances in 15 spectral bands (390nm to 1040nm) (MERIS Product Handbook, 2006). MERIS can cover the earth in a continuous way from pole to pole in 3 days. The Full Resolution (FR) product provides estimations in a spatial resolution of 300m at the Earth surface but the commonly used resolution which has been applied in our research is the Reduced Resolution (RR) reprocessed product in a resolution of 1200m.

MERIS's main ocean observational variables include chlorophyll, yellow substance (dissolved organic materials) and suspended particulate matter together with plankton blooms. They are determined by the spectral information contained in the water-leaving radiances in the visible and near chlorophyll concentration infrared channels of the spectrum which are converted to reflectance (ρ_w) at the top of the atmosphere after removing the atmospheric effect, which is given as

$$\rho_w(\lambda) = \frac{\pi L_w(\lambda)}{E_d(\lambda)}$$

where $L_w(\lambda)$ is upward water-leaving radiance and $E_d(\lambda)$ is downward radiance above the water surface (MERIS Product Handbook, 2006).

MERIS Level 2 products contain both algal-1 (for Case I waters essentially the open ocean) and algal-2 (for Case II waters essentially coastal ocean). Algal-1 is simply estimated from blue-to-green reflectance ratio to obtain chlorophyll-a concentration. This band ratio

algorithm fails in Case II waters since coastal water color is usually influenced by sediments and yellow substance.

Algal-2 is the remotely retrieval of chlorophyll concentration, suspended matter (non-absorbing scattering particles) and gelbstoff (also called yellow substance) from model inversion by use of a neural network for Case I and Case II waters on the base of perfect atmospheric correction. The neural network is a multiple non-linear regression method which applies the feed-forward back-propagation optimization technique to derive its coefficients of reflectance, angle and correspondent concentration. The detailed algorithms for atmospheric correction and the retrieval of algal-1 and algal-2 products can be consulted to MERIS Product Handbook (2006).

2.2.2 MERIS product accuracy

MERIS can measure 9 visible bands (410nm-705nm) for the retrieval of marine parameters and 3 infrared channels which greatly enhance the radiometric accuracy and provide details of spectral information. Compared with SeaWiFS, MERIS has improved the quantification of the concentrations of phytoplankton, mineral particles and yellow substances in Case II water. The availability of infrared channels allows the estimation on aerosol thickness to perform accurate atmospheric correction (Bricaud, 1999).

MERIS has performed accurate band-to-band calibration activities to achieve the accuracy requirement of 1nm for the spectral bands characterization (Delwart et al., 2007). MERIS Level 2 reduced resolution products (second reprocessing) control the errors in predicting chlorophyll concentrations within 15% and yellow substances within 30% (MERIS Product Handbook, 2006).

Antoine et al (2008) conducted match-up analysis with in situ observations in the “BOUSSOLE” project (French named translated as “buoy for the acquisition of a long-term optical time series”), as shown in Fig 2.1. They suggested that enhanced calibration and validation should be introduced to MERIS and the atmospheric correction do not meet the specifications. Similar comparison was conducted by Folkestad et al. (2007) and it is found that MARIS algal_1 data had shown less variability of Chl-a within neighbouring

pixels as compared to both MODIS and SeaWiFS which is good for small area observation and had a good performance in evaluating the spatial distribution patterns.

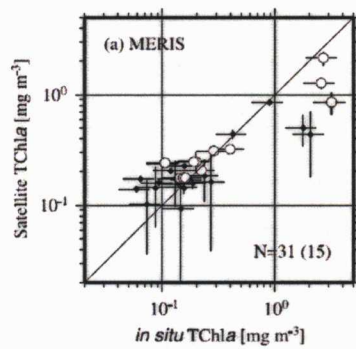


Fig 2.1 Satellite-to-in situ match up analysis on chlorophyll-a concentration MERIS. The open circles are the subset from the full possible match-ups to which certain criteria were applied. N is in situ data numbers and the bracketed numbers are match-up numbers (Antoine et al., 2008).

3. Method

For our use of the OFES model, the domain of our focus covers the whole of the Sulu Sea (105.05°E-125.05°E, 0.05°N-30.05°N) with a horizontal resolution of 0.1×0.1 degree and 56 levels in the vertical (where the bathymetry allows it). A total of 3,360,000 stations were extracted from the OFES dataset. We have chosen a latitude of ~8.6°N across the Sulu Sea basin and selected 3 stations along this line to gain some understanding of the nature of upwelling. Fig 3.1 displays the chosen location of the three stations in the Sulu Sea while the longitude/latitude, distance from the shore and the water depth of the three stations is shown in Table 3.1. Station 2 is in the region where Wang et al. (2006) made a time series of chlorophyll concentration.

Table 3.1 The geographic information of the three observed stations.

station	Longitude/latitude	Water depth (model) meters	Distance from shore (km)	Typical mixed layer depth meters (m)*
1 (west)	119.0°E,8.7°N	1600	35	40
2 (central)	120.1°E,8.6°N	3500	-	40
3 (east)	122.2°E,8.2°N	1400	21	40

**see Fig 4.1(b) & 4.2(b).*

We conducted a preliminary investigation on the interplay of surface chlorophyll-concentrations and physical processes in the Sulu Sea based on one-year time series data in 2003. Key results were obtained from the preliminary investigation and three more years data (2004-2006) were extracted for analysis to determine the result confidence.

The simulated temperature and three components of velocity were extracted by Matlab for every 3 days at a depth of 41 m. The time-series variability of chlorophyll-a concentration from MERIS data sets are processed with BEAM Version 3.2 (Basic ERS & ENVISAT AATSR and MERIS Toolbox). BEAM is an application programming interface (API) which has been developed to facilitate the visualisation,

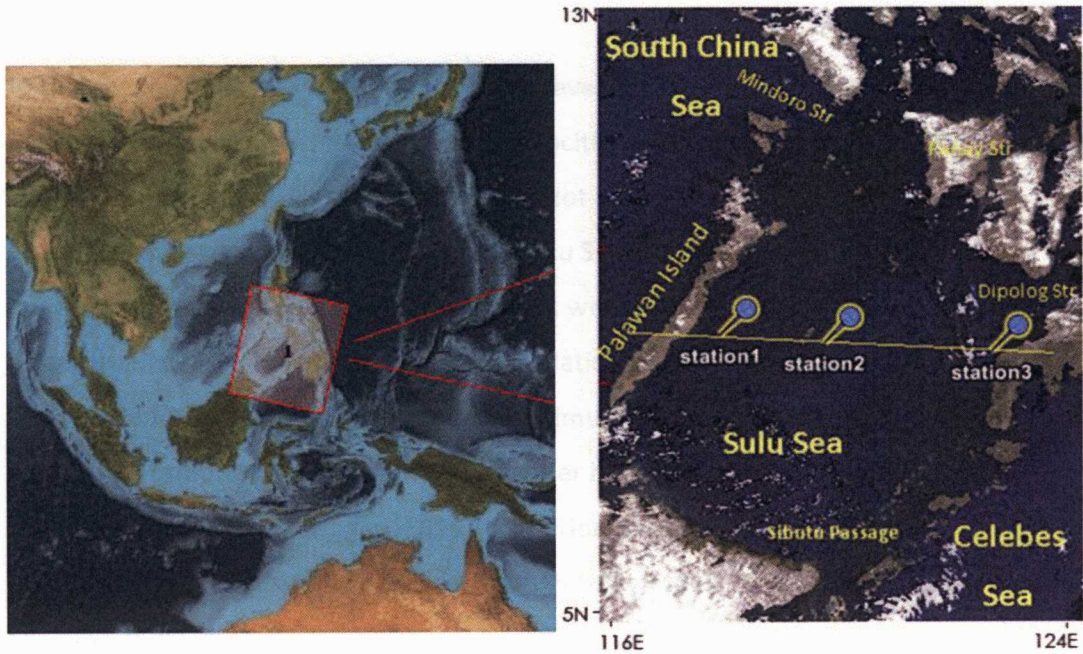


Fig 3.1 The Sulu Sea extracted from the world map and three observation stations distributed along $\sim 8.6^{\circ}\text{N}$ latitude line.

viewing and programming of MERIS data (MERIS Product Handbook, 2006). We need to resample MERIS data from 1.2km spatial resolution to 11km spatial resolution so that it can match with the ocean model horizontal resolution of 0.1 degree. BEAM loops over 10×10 points in the target grid and looks up the nearest neighbour pixel in the input product that contains the geographical centre coordinate of the current output pixel. We assume the simulated values from OFES represent the centre of the pixel.

4. Results and Discussions

In this section, we first look at the features revealed by the OFES model. We concentrated on the meso-scale vertical velocities and temperature over 3 stations in the Sulu Sea and the monthly changes in 2003. Not limited to the three stations, we expanded the range of view to the whole Sulu Sea to expose the monthly variations of large-scale upwelling distribution patterns as well as the yearly accumulation of upwelling velocities in every pixel. We have used correlation analysis to link upwelling events in temporal and spatial scales. Moreover, the simulated sea surface temperature (SST) which is an important parameter for sea water has been compared with the satellite observed 10-year climatological SSTs. In addition to observing the vertical dynamics, the contributions of horizontal advection through key straits to the circulations in the Sulu Sea have been estimated.

Then we look at the chlorophyll-a concentration as the indicator of phytoplankton production in surface water. The temporal and spatial variability of chlorophyll concentration was investigated using MERIS data. And the correlation analysis method has been used to analysis the temporal and spatial scale of chlorophyll events.

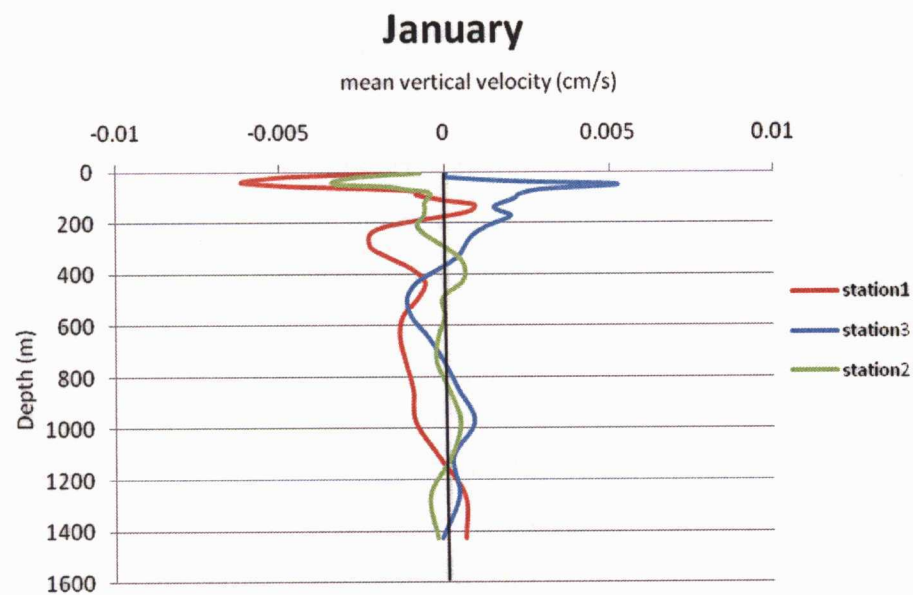
Finally we try to synthesis the two data sets to observe the oceanic physics influences on biological production. Whether or not the upwelling acts positively on the biological production mainly depends on the quantity of nutrients that are upwelled. Judging from the ocean transport and mixing process, we can identify the nutrient sources of high biological production areas.

4.1 Numerical Results

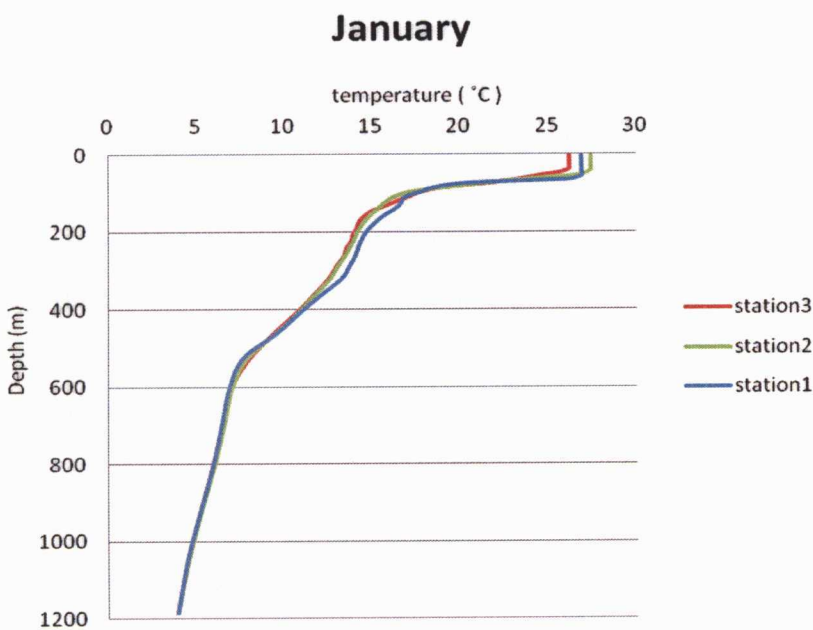
4.1.1. Meso-scale variations of vertical velocity and temperature

The Sulu Sea is dominated by strong northeast (to the southwest) wind in winter (Dec-Mar) and weak southwest wind in summer (Jun-Sep). We have selected January and July as typical months to represent winter and summer monsoon seasons. According to the

upwelling mechanism, winter's northeast wind in Northern Hemisphere triggers coastal



(a)



(b)

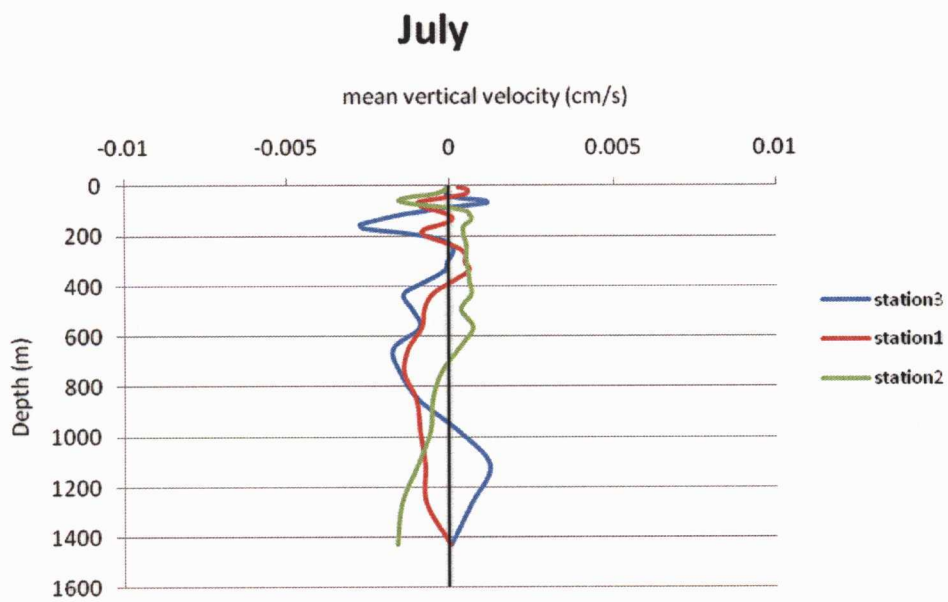
Fig 4.1 Monthly mean (a) vertical velocity w and (b) temperature observed for three stations at depths from 5 m to 1400 m in January (winter) of 2003. (Station1 - west, Station 2 – central, Station 3 - east)

upwelling on the eastern boundary (station 3 location) of the ocean and coastal upwelling occurs on the western boundary (station 1 location) during summer's southwest wind. A clear contrast between the profiles of vertical velocities in the three stations across the Sulu Sea can be seen in Fig 4.1(a) where station 1 has downward velocities (defined as negative velocity) while upward velocities occur at station 3. The coastal upwelling at station 3 has been confirmed to happen during winter following the wind. The centre of the Sulu Sea is almost stationary below the surface layer as indicated by a straight line near zero in Fig 4.1(a).

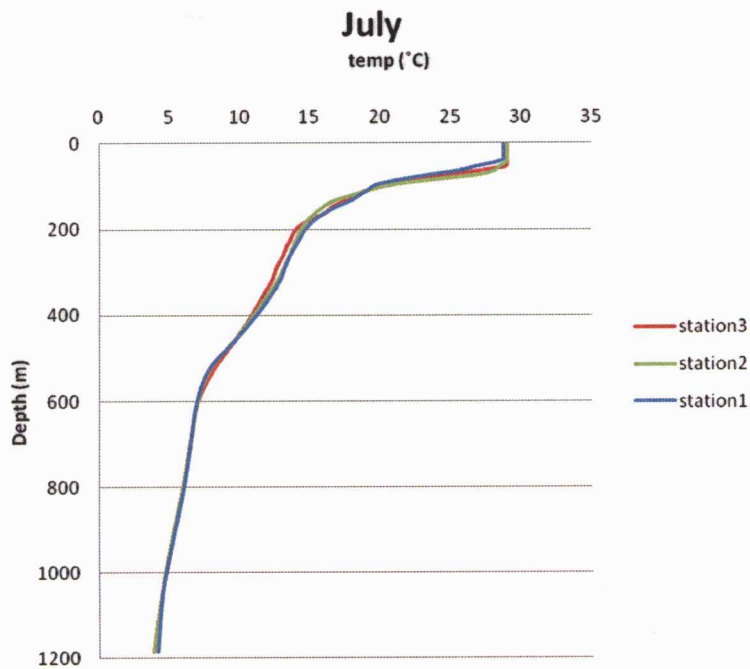
During the weak southwest summer monsoon, the vertical dynamics strength has been weakened both at station 1 and station 3 as shown in Fig 4.2 (a). Station 2 in the centre of the Sulu Sea has maintained a quiet signal except for the surface downwelling velocities. It should be noted that, the surface maximum upwelling or downwelling depth suggested from vertical velocity profiles during summer and winter is near 50 m.

Temperature fields in Fig 4.1(b) and 4.2(b) revealed that vertical temperature profiles are quite similar during summer and winter. Constant temperature was maintained in the mixed layer until about 40 m and then a steep decline occurs. We can identify that the mixed layer depth is around 40 m and it varies little along latitude $\sim 8.6^{\circ}\text{N}$ across the Sulu Sea both in summer and winter. Chu et al. (2002) used the conductivity–temperature–depth (CTD) data from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS) and certain gradient criterion to determine the monthly mixed layer depth in the Sulu Sea. Results show the simulated mixed layer in the Sulu Sea is deeper in winter than in summer. Below the mixed layer, temperature decreases gradually and becomes fairly constant at 6°C in deep water. Referring to Fig 1.9, a vertical temperature profile from KH-02-4 Cruise field measurement was 10°C at depth, so the simulated temperature from the OFES model is 4°C lower than this observation.

The instantaneous vertical velocity and temperature for one year series of 2003 at the three stations exhibits variations of temperature and vertical velocity for every three days

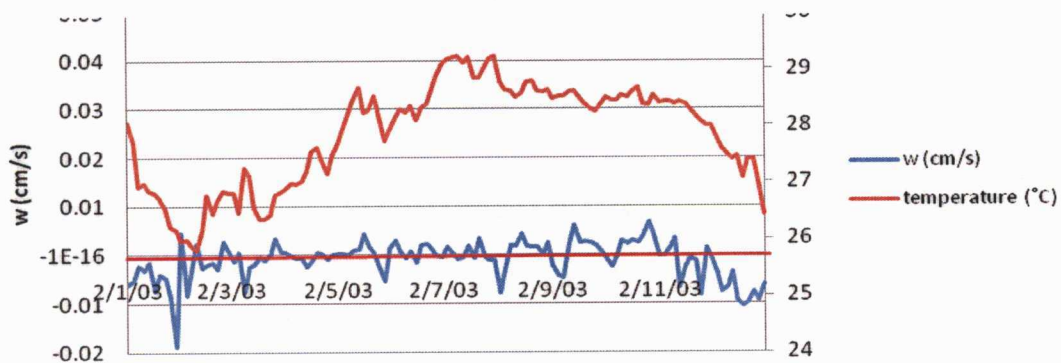


(a)

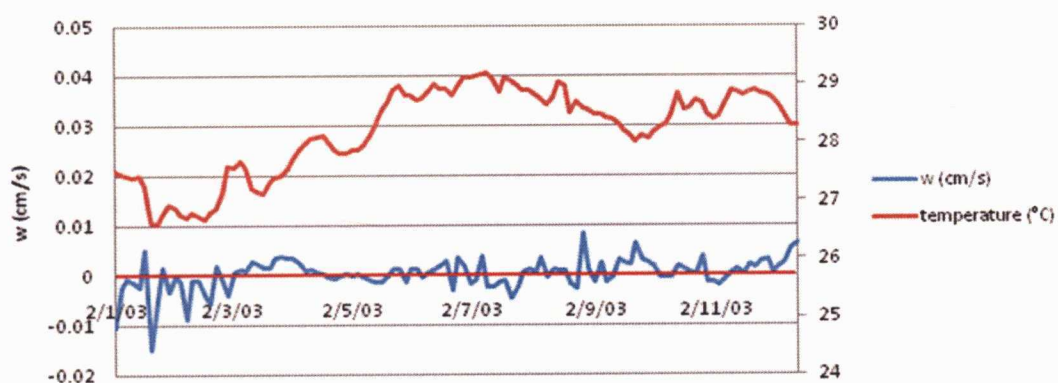


(b)

Fig 4.2 Monthly mean (a) vertical velocities w and (b) temperature observed from 3 stations at depths from 5m to 1200m in July (summer) of 2003. (Station1 - west, Station 2 – central, Station 3 - east)



Station 2



Station 3

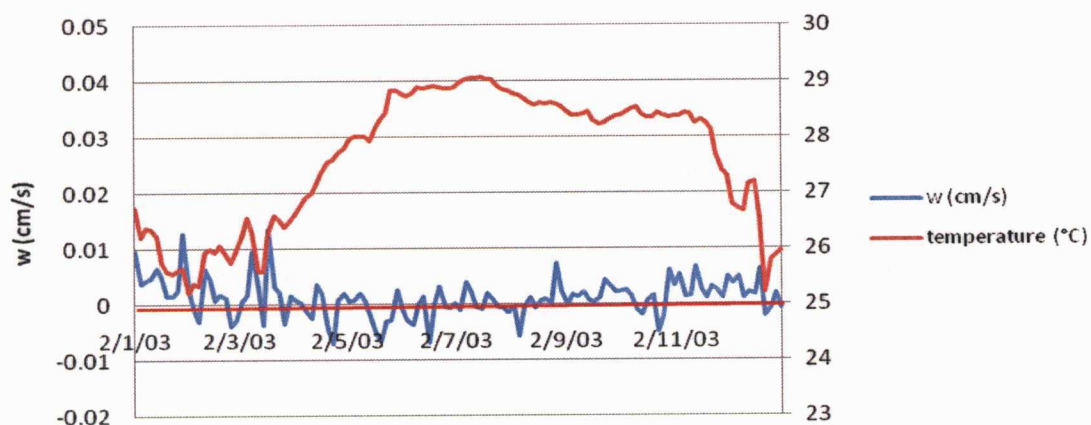


Fig 4.3 A time series of vertical velocity (cm/s) and temperature ($^{\circ}\text{C}$) in 2003 sampled every three days from three stations at depth of 41 m. (Station1 - west, Station 2 – central, Station 3 - east)

at a depth of 41 m and indicates the timing of upwelling or downwelling events, as shown in Fig 4.3. From December to February, downwelling prevailed at station 1 as well as upwelling prevailed at station 3 and the yearly mean vertical velocity is -0.001 cm/s (equal to -0.8 m/day) at station 1 and 0.001 cm/s (equal to 0.8 m/day) at station 3 respectively. The maximum upwelling event at station 3 happens in January which exceeds 0.015 cm/s (equal to 12.9 m/day) and the lowest temperature occurs at the same time. Both station 1 and station 2 separated by $\sim 110\text{ km}$ have strong downwelling in January and December. We can say January is an active month since both upwelling and downwelling have achieved extreme values. Seasonal variations at station 2 are small except for two significant downwelling events during winter. Surface temperature is a sensitive indicator of upwelling because deep cold waters are then brought to the surface and lead to regionally low temperature. We can find that temperature decline corresponds to the presence of upwelling during the winter season.

4.1.2. Spatial variations of upwelling patterns each month

The monthly average vertical velocity distributions at 41 m can help us to identify and characterize the monthly potential upwelling areas in the Sulu Sea. As seen in Fig 4.4, there is a strong upwelling ribbon along Panay Strait, Dipolog Strait, Sulu Archepalog and western side of Palawan Island in the South China Sea (see Fig 3.1 for locations) in January and December. In these upwelling areas, the maximum upward velocity is over 0.1 cm/s (equal to 86.4 m/day). When the winter monsoon ceases, strong upwelling is almost gone but downwelling is also small. Weak upwelling is found along the western boundary of the Sulu Sea under reversing monsoon in August and September. It should be noted that the adjacent Celebes Sea shows persistent signals of strong upwelling and downwelling for most of the year.

Compared with the predicted upwelling and downwelling areas in Fig 1.8 (b) from the climatological Ekman pumping velocities by Wang et al. (2006), the wind jet formed upwelling and downwelling intersection along Panay Strait in January doesn't appear in our model simulation. However the expected strong upwelling ribbon is found by our model along the western side of Palawan Island and Sulu Archepalog in January.

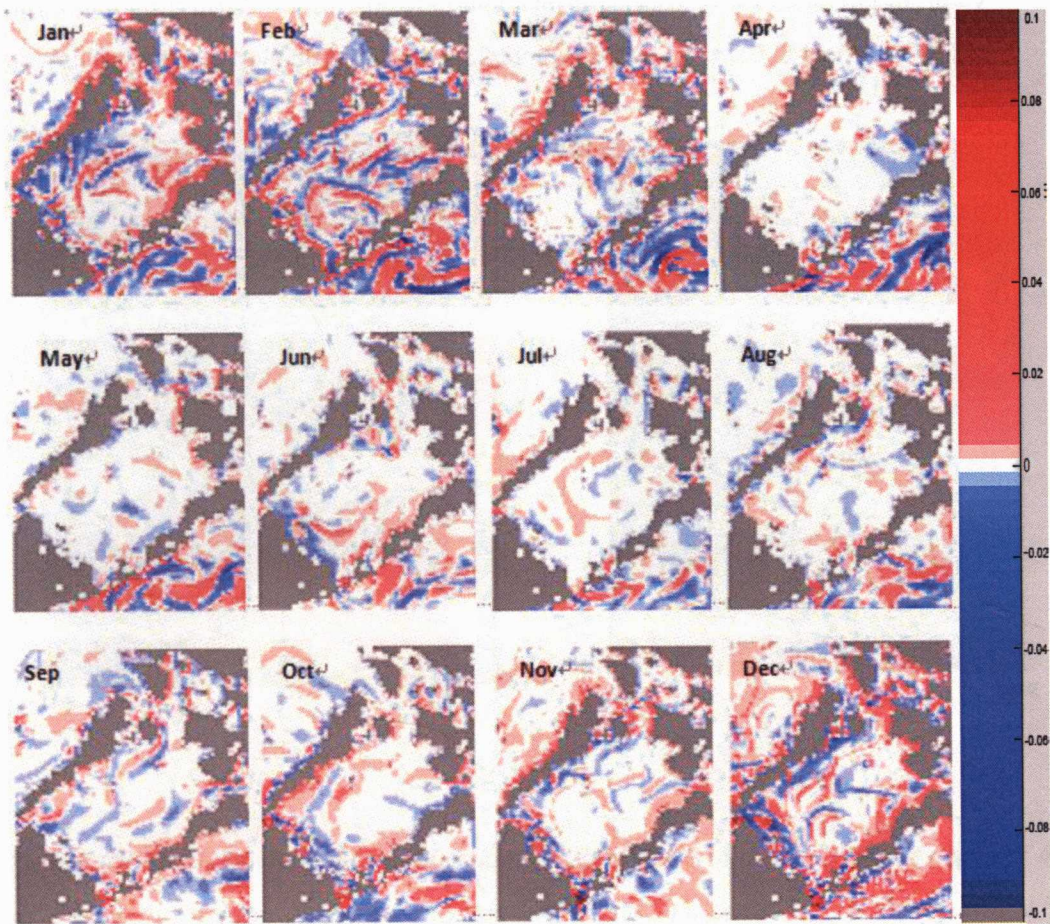


Fig 4.4 The distribution of monthly mean vertical velocities (cm/s) of 2003 in the Sulu Sea at 41 m.

4.1.3. Upwelling accumulation

We will use a depth of 41 m, which is close to the near surface maximum upwelling velocity depth, to calculate the extent of upwelling in the Sulu Sea. The method simply adds up the amount of upward velocities day by day to indicate the accumulation of yearly upwelling, defined by

Yearly Upwelling Accumulation = $\sum w$ (for $w > 0$), where w is the vertical velocity.

Downwelling has been excluded from the calculation since we care about the volume of deep water upwelled to the surface. This volume can be used to infer what quantity of

deep nutrients has been brought up to the euphotic layer (and which will then stimulate phytoplankton production). The spatially averaged upward transport volume by upwelling in the whole Sulu Sea was 4.2 Sv ($\text{Sv}=10^6\text{m}^3/\text{s}$) in 2003 from the OFES.

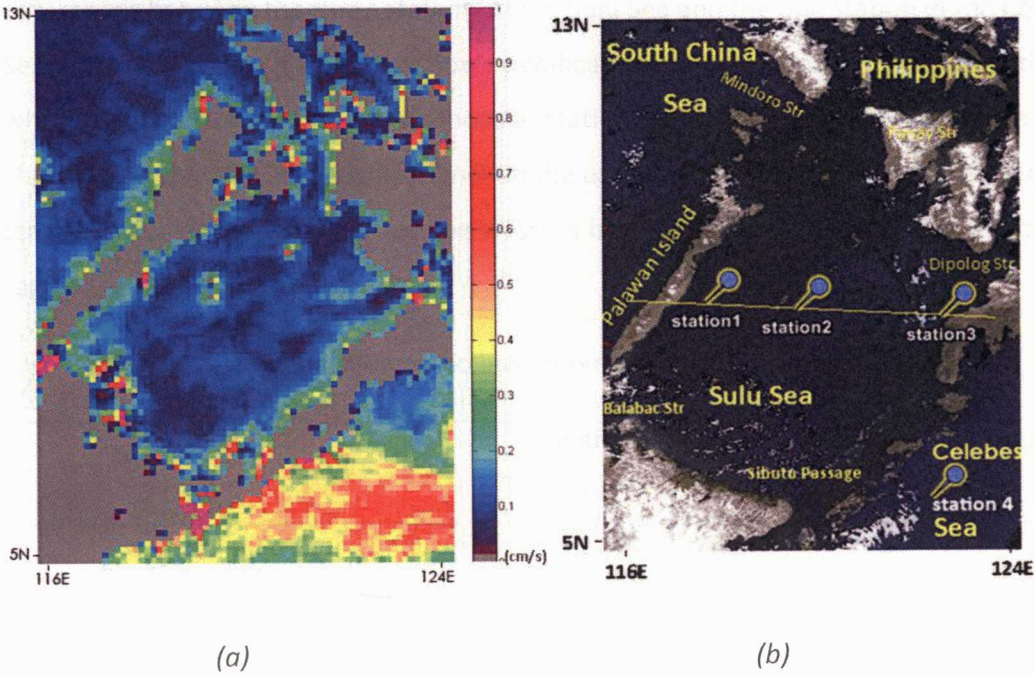


Fig 4.5 (a) Yearly upwelling accumulation (cm/s) of 2003 in the Sulu Sea at depth of 41 m. (b) Three observation stations are distributed in the Sulu Sea along~ 8.6°N latitude line and station 4 is chosen in the Celebes Sea.

Fig 4.5 (a) shows the yearly accumulation of upwelling in the Sulu Sea. The coastal areas along the Dipolog Strait, Sulu Archepalog and western side of Palawan Island show high values of yearly upwelling accumulation. High values were also found around the small islands on the northern boundary of the Sulu Sea. Small islands topography exerts a profound effect on regional vertical mixing and upwelling in the upper ocean which is called “Island Mass Effect” (Takeda et al., 2007). From Fig 4.5 (a), the observed high values at the edge of these small islands can imply frequent entrainment of subsurface water and vertical upwelling. There are two obviously strong upwelling areas where 1cm/s is exceeded, located in the narrow channels of Sibutu Passage and Balabac straight. Such strong upwelling event is widely distributed on the other side of the Sulu Archipelago within the Celebes Sea. We have chosen a station in the Celebes Sea (the

location of station 4 is shown in Fig 4.5 (b)) to compare with the three stations in the Sulu Sea.

A comparison table 4.1 shows the upwelling accumulation and upwelled nutrient differences between the three stations in the Sulu Sea and the one station in the Celebes Sea. Station 4 in the Celebes Sea shows significant high yearly upwelling accumulation which is about 10 times more than those at station1 & 2 and 4 times more than that at station 3. Within the Sulu Sea, station 3 on the eastern boundary of the Sulu Sea shows strong upwelling than station 1 on the western boundary and station 2 in the central region.

Table 4.1 Upwelled distance accumulation and nitrogen for 4 stations in 2003

	station 1 west	station 2 central	station 3 east	station 4
Upwelling accumulation (m/yr)	279	259	780	2767
Flux of nitrogen (g·m ⁻² ·yr ⁻¹)	121	112	338	1200
Flux of nitrogen (mol·m ⁻² ·yr ⁻¹)	8	8	24	85

** Nitrogen content in upwelled water is 30 μmol kg⁻¹ shown in Fig1.10.*

4.1.4. Upwelling persistence

We would like to use the ocean model to estimate the nature of upwelling events. It seems to be a few major events in year 2003 from Fig 4.3. In order to examine large but infrequent events, four year time series (2003-2006) at the three stations were prepared. First kurtosis was calculated, using the formula in Excel :

$$\left\{ \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum \left(\frac{x_i - \bar{x}}{s} \right)^4 \right\} - \frac{3(n-1)^2}{(n-2)(n-3)}$$

where “s” is the sample standard deviation. (Note that this is the form used in Excel)

The kurtosis of the normally distributed variables is 0, but vertical velocity at station 2 has a kurtosis of 5.9. This is typical of a “spiky record” as seen in Fig 4.3, the high kurtosis value being caused by the events such as those in January and December. Station 1 and

station 3 which are near coastal stations have kurtoses of 2.7 and 2.0 respectively. The frequent fluctuations contribute to reduce the overall kurtosis values to be near those for a normal distribution.

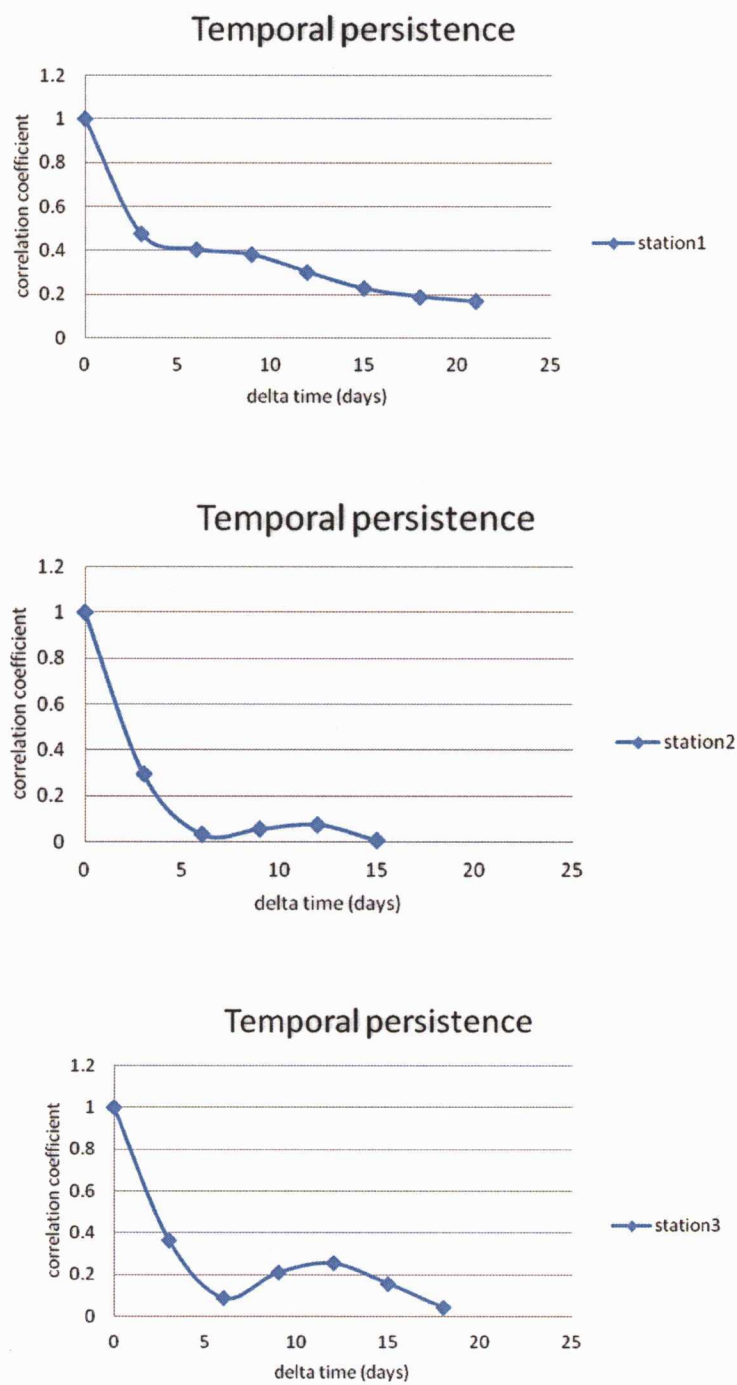


Fig 4.6 The temporal persistence of upwelling in a 4 year time series (2003-2006 year) at station 1, 2 and 3 in the Sulu Sea. (Station1 - west, Station 2 – central, Station 3 - east)

Thus we calculate the auto-correlation of the vertical velocity in a time series of 2003-2006. The auto-correlation of this series is simply the correlation of the series with itself at a temporal distance of 3-day lags of time period. The correlation coefficient is defined as (in Excel):

$$Correl(X, Y, t) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}$$

where $\bar{x}$ and $\bar{y}$ are the sample means. This correlation is an indication of the fluctuation about the mean rather than zero.

When y is x itself over a particular time lag difference, the equation is used for temporal persistence analysis. When y is at a spatial distance from x at the same time, the equation is used for spatial persistence analysis. When x and y are two different time series, the equation is used for cross-correlation analysis.

There is a marked difference between the correlation C at the site of station 1 and those of station 2 and 3, as shown in Fig 4.6. The upwelling correlation at the site of the latter two stations drop to e^{-1} in less than four days. This suggests the correlation was dominated by a few large short duration upwelling events. Station 1 shows where the temporal correlation stays positive for more than 10 days. As will be seen in the next section, the spatial correlations of upwelling at the three sites are different.

4.1.5. Spatial correlation of upwelling

In order to get some feeling for the spatial extent of upwelling, a four year time series (2003-2006) of vertical velocities was constructed around the three stations. Visual inspection of the upwelling from Fig 4.4 shows ribbons along shore rather than across shore, so we choose separations along the shore to do spatial correlation analysis. The spatial correlations shown in Fig 4.7 suggests the spatial scale (distance to correlation of e^{-1}) of a hundred kilometers along shore direction for station 1 and station 3. Station 2 is much shorter, around 10 km.

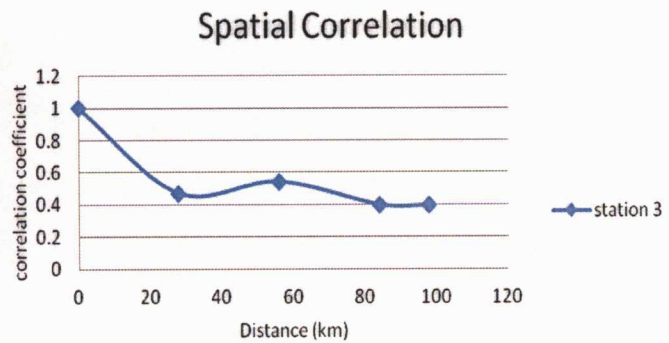
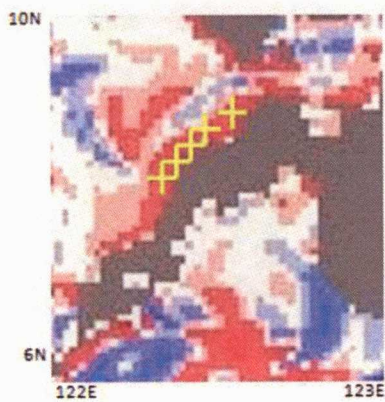
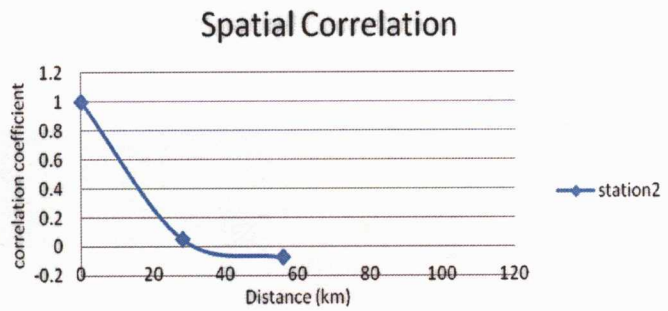
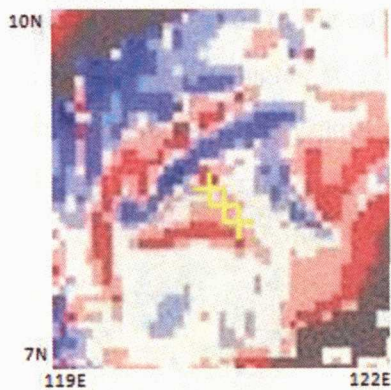
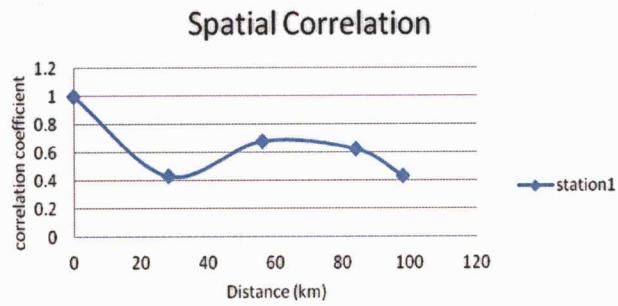
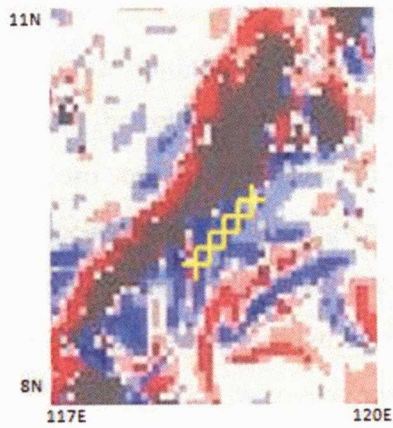


Fig 4.7 The spatial correlation of upwelling at station 1, 2 and 3 in the Sulu Sea in 2003. (Station1 - west, Station 2 – central, Station 3 - east)

4.1.6. Sea Surface Temperature

The sea surface temperature (SST) in the OFES model exhibits obvious seasonality with higher temperatures in summer (Jun-Sep) and lower temperature in winter (Dec-Mar), as

shown in Fig 4.8. The temperature gradient within the Sulu Sea is stronger in winter than in summer, and shows increased temperature close to the Equator. During the winter season, the colder water is located in the north regions of the Sulu Sea and close to the Mindoro Strait (which leads to the South China Sea). This cold water may be attributed to the occurrence of coastal upwelling in the north boundaries of the Sulu Sea in response to north-easterly winds or the intrusion waters from upwelling regions near the islands of the Philippines and through Mindoro Strait from the South China Sea. It should be noted that the anomalously cold temperature is consistent with the upwelling patterns in Fig 4.4. During summer season, the central Sulu Sea warms up faster than the coastal regions and expands to the adjacent Celebes Sea through Sulu Archepalog. Lasting for three months, the higher surface temperature pattern ceases out of the Sulu Sea through Sulu Archepalog to the Celebes Sea.

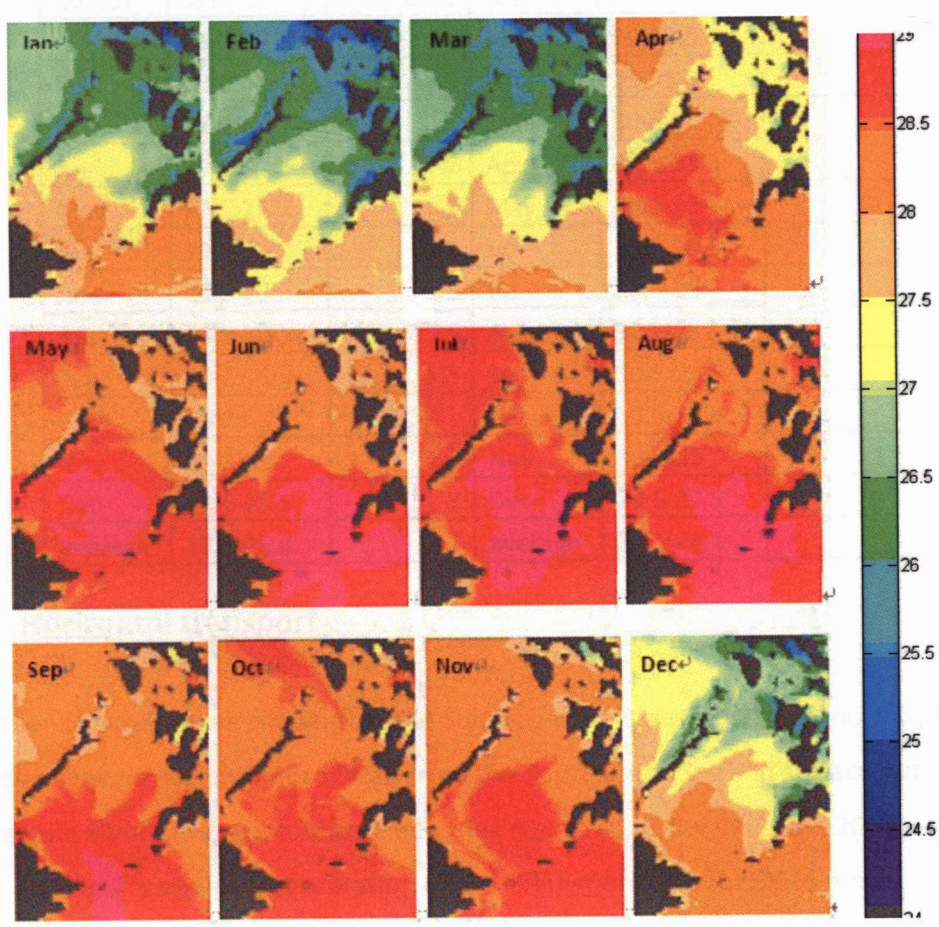


Fig 4.8 The seasonal variations of mean sea surface temperature (SST) in the horizontal distribution in 2003 from the OFES.

Table 4.2 compares the model simulated surface temperature with climatological mean fields of monthly mean SST provided by The National Ocean and Atmosphere Administration (NOAA) satellites measured by Advanced High Resolution Radiometer (AVHRR) in Wang et al. (2006). The temperature range are similar between the satellite observed SST and the model simulated temperature while the averaged simulated temperature is about 1.2 - 1.3°C lower than the satellite observations. It has been pointed out above that simulated temperature in the deep water is 4°C lower than the measured value. The simulated temperature gradient of 2°C from the north to the south in the Sulu Sea agrees well with the observation.

Table 4.2 Temperature verification with 10-year climatologically mean data (Wang et al., 2006)

Model Temperature			Satellite Temperature		
Month	SST (°C)	Difference	Month	SST (°C)	Difference
Jan	28.5-25.5	3	Jan	29-26.5	2.5
Feb	28-25	3	Feb	29-26.5	2.5
Mar	28-25.5	2.5	Mar	30-28	2
Apr	29-27	2	Apr	30.5-28.5	2
May	29.5-27.5	2	May	30.5-29	1.5
Jun	29.5-27.5	2	Jun	30.5-28.5	2
Jul	29.5-28	1.5	Jul	30.5-29	1.5
Aug	29.5-28	1.5	Aug	30.5-28.5	2
Sep	29-27.5	1.5	Sep	30.5-28.5	2
Oct	29-28	1	Oct	30.5-28.5	2
Nov	29-27.5	1.5	Nov	30-28.5	1.5
Dec	28.5-25.5	3	Dec	29.5-27.5	2
average	28.9-26.8	2.1	average	30.1-28.1	2

4.1.7. Horizontal transport

A number of papers have shown that the Sulu Sea waters are mostly balanced by the deep overflow through Mindoro Strait from the South China Sea and surface outflow through the Sibutu Passage to the Celebes Sea (Qu et al., 2009; Cai et al., 2009; Fang et al., 2003). Having a realistic representation of the circulation from the OFES model, we focused on the horizontal transport through the straits and passages in the Sulu Sea. Relatively high horizontal resolution is required to represent the very narrow and complex strait/passage geometry and sill depths.

First, we observed the horizontal transport during the northeast (to southwest) monsoon in winter. In Fig4.9 (a) & (b), horizontal advection velocity components have been separated to be in line with the direction of 45° diagonally from northwest and 45° diagonally from northeast respectively. We can find strong flow from northwest happens when passing through the Mindoro Strait and the Sibutu Passage in Fig 4.9(a). The current component from northeast in Fig 4.9(b) shows conspicuous flow along the eastern coast of Palawan in winter. There is also strong flow through Panay Strait and Dipolog Strait into the Sulu Sea.

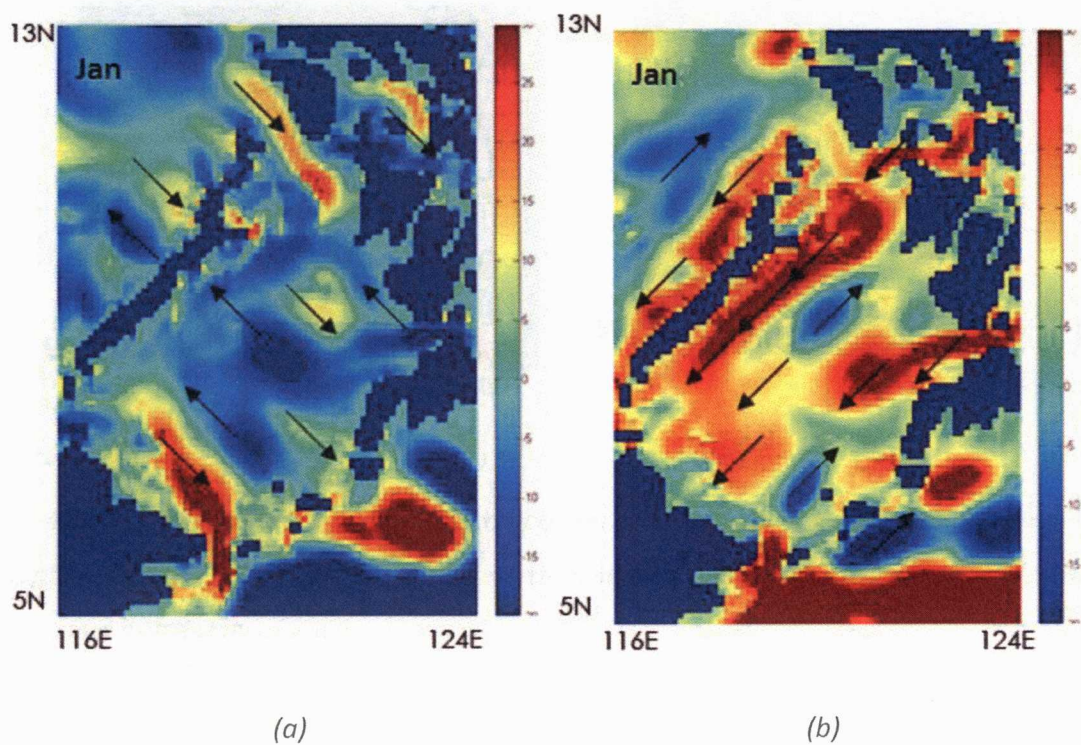


Fig 4.9 (a) A snapshot of north-west component of horizontal velocity (cm/s) at 41 m depth in January of 2003. (b) A snapshot of north-east component of horizontal velocity (cm/s) at 41 m depth in January of 2003.

In summer weak southwest monsoon prevails, the flow along both sides of the Palawan reverses and flows to the northeast, see Fig 4.10 (b). Compared with the currents during winter monsoon in Fig 4.9(a) & (b), the flow through the key straits mentioned above in summer monsoon are weaker. There is relatively strong flow from northwest through Mindoro Strait, Sibutu Passage and strong flow from southwest through Balabac Passage.

The wind changes direction between the monsoons, the monthly average wind may be small as a result of averaging two periods of consistent winds of opposite direction. Such a forcing may give a very different monthly average current to that using the one day averaged wind. Thus the OFES model has the advantage of using daily wind values.

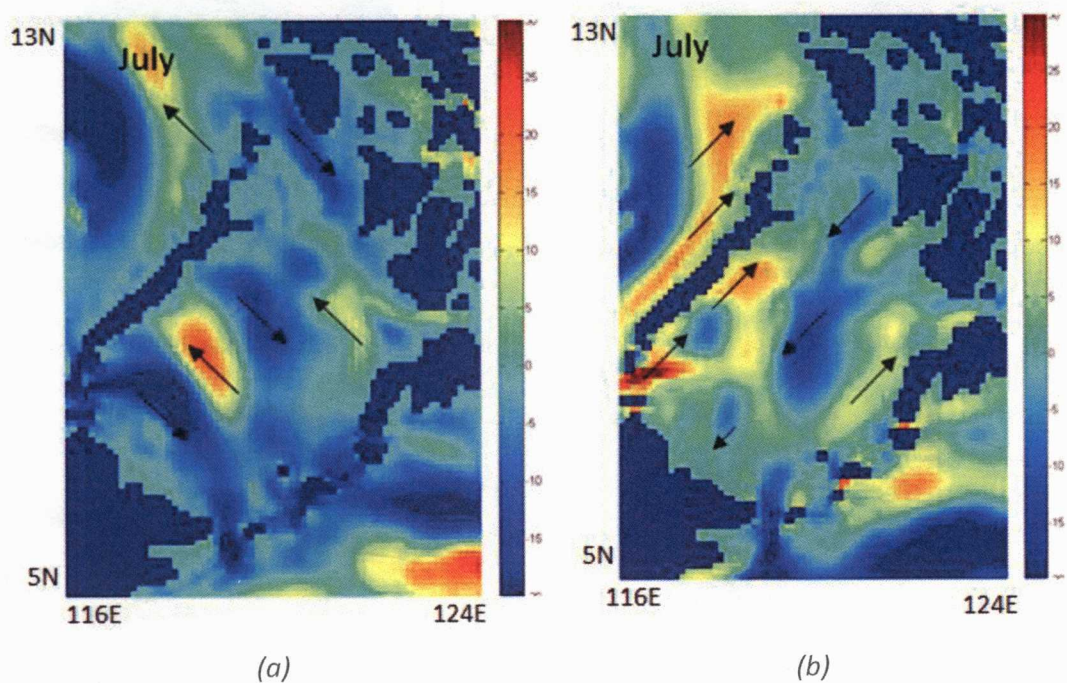
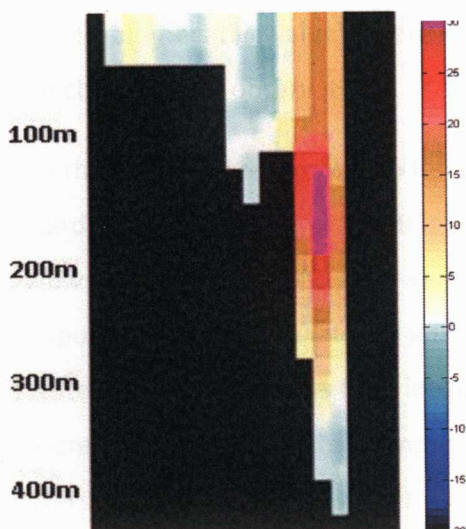
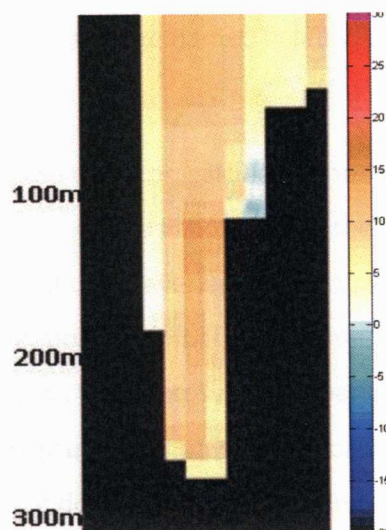


Fig 4.10 (a) A snapshot of north-west component of horizontal velocity (cm/s) at 41m depth in July of 2003. (b) A snapshot of north-east component of horizontal velocity (cm/s) at 41m depth in July of 2003.

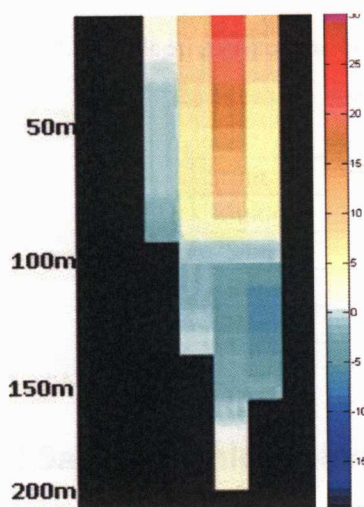
The vertical structures of yearly mean horizontal advection at the key straits in the Sulu Sea are shown in Fig 4.11. We can investigate the topography and sill depths in these key straits and estimate the horizontal transport volume through the four main straits. According to Metzger et al. (2010) by using a $1/12^\circ$ global version of the Hybrid Coordinate Ocean Model (HYCOM), Panay Strait has a sill depth ~ 580 m, Dipolog Strait is ~ 480 m and Sibutu Strait is 241m. Compared with the sill depths used in OFES in Table 4.3, there are differences due to the use of different databases. From Fig 4.11(a), the subsurface inflow through Mindoro strait into the Sulu Sea is significant. Sibutu passage (Fig 4.11 (b)) has shown uniformly outflow transport from surface to deep, Panay strait (Fig 4.11(c)) and Dipolog Strait (Fig 4.11(d)) have shown reversed direction between surface and the deep (the positive values indicate the inflow into the Sulu Sea).



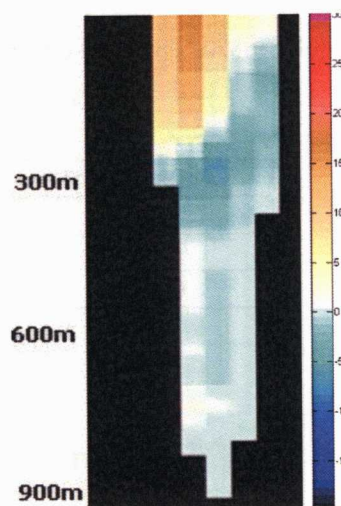
(a)Mindoro Strait



(b)Sibutu Passage



(c)Panay Strait



(d)Dipolog Strait

Fig4.11 Mean horizontal velocities (cm/s) in 2003 from surface to deep through the key straits. In (a) & (b), red/orange colours (positive values) indicate flow from northwest while blue colour indicates flow from southeast. In (c) & (d), red/orange colours (positive) indicate flow from northeast while blue colour indicates flow from southwest.

The water transports (S_v) through the main four straits were computed and shown in Table 4.3. Compared with the previous studies on the transport through those straits in Table 1.1, results from OFES are smaller than the other numerical models. The positive values indicate the inflow into the Sulu Sea is mostly balanced by the outflow through

Sibutu Strait (negative value). There is another outflow passage named Balabac passage not included in the observation.

From the upwelling accumulation for the whole Sulu Sea, we can calculate a notional upward transport for the year 2003. Upwelling accumulation will not include the downward flows which occur between upwelling events. The average rate of upward transport is 4.2Sv as calculated in upwelling accumulation section. If we assume the persistent upwelling events have longer time scale than the photosynthesis period. The nutrients upwelled would have enough time to be consumed by phytoplankton to organic matters in the surface layer rather than being brought down by downward flows. Compared with horizontal transport, more nutrients would be carried by upwelling into the Sulu Sea.

Table 4.3 Sill depths (m) of the key straits and passages and the net transport (Sv) into the Sulu Sea during 2003 according to OFES.

Strait	Model sill depth(m)	Transport(Sv)
Mindoro	460	1.07
Sibutu	287	-0.99
Panay	207	0.20
Dipolog	911	0.37

4.2 Satellite Chlorophyll-a concentration results

4.2.1. Chlorophyll-a distribution patterns

MERIS images from 2003 to 2006 were acquired to detect the distribution of phytoplankton pigment chlorophyll-a (Chl-a) concentration in the Sulu Sea. Satellite sensor data is only intermittently available to observe the phytoplankton variations associated with the upwelling because of the clouds. The images were masked for cloud, land and invalid pixels. The invalid pixels may be caused by invalid reflectance, extremely high phytoplankton concentrations or high yellow substances concentrations.

On the basis of monthly MERIS satellite observations from 2003 to 2006, we focused on the high Chl-a areas as an indicator of the abundance of primary production in the Sulu

Sea. The pattern of strong Chl-a concentration along Mindoro Strait, Panay strait and Dipolog Strait, shown in Fig 4.12, mainly occurs from December to March. Peak values of

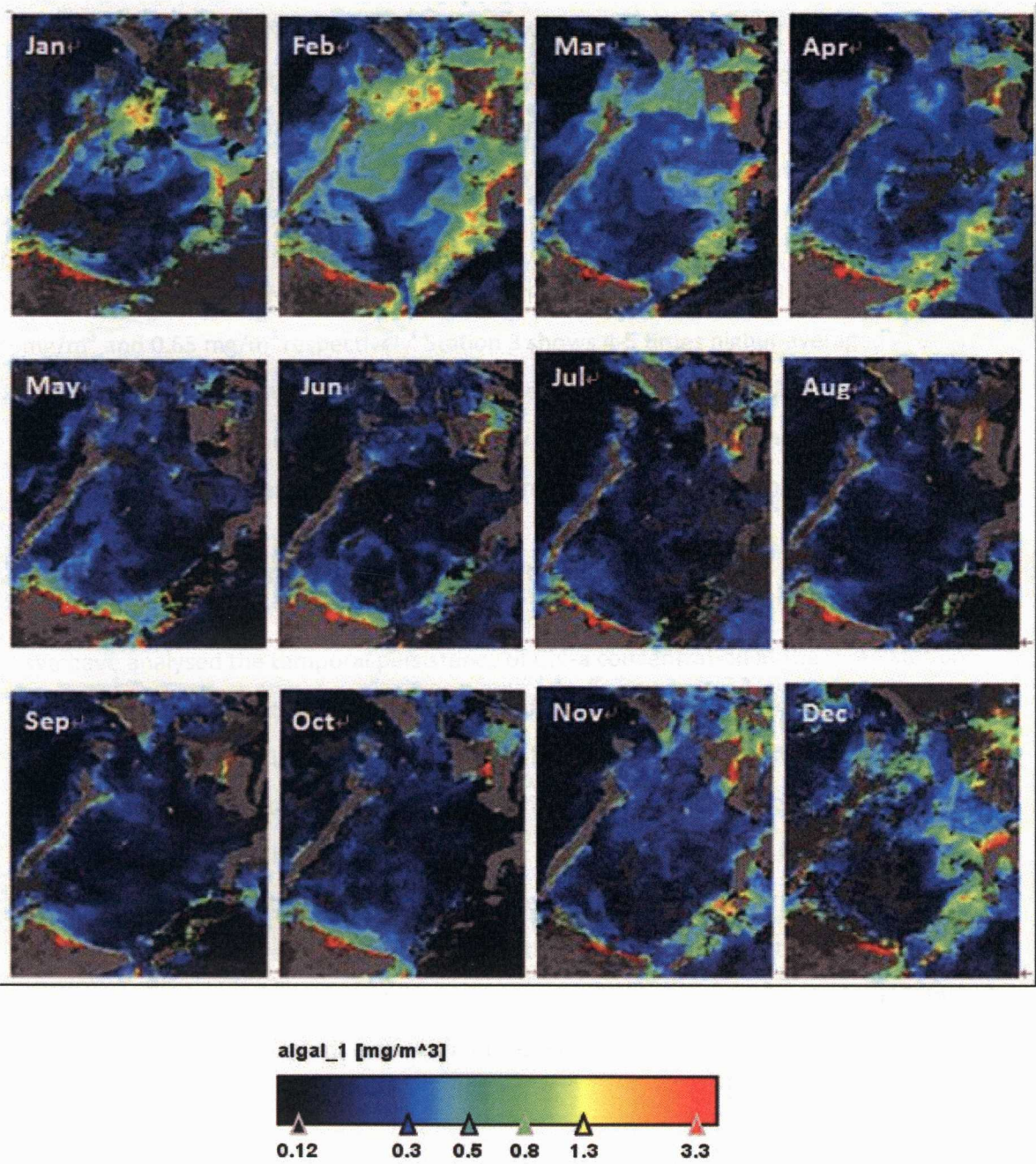


Fig 4.12 Monthly mean distribution of Chl-a concentration (mg/m^3) in the Sulu Sea for 2003. Data obtained from <http://merci-srv.eo.esa.int/merci/>.

Chl-a concentration for these areas exceed $3 \text{ mg}/\text{m}^3$. However, the yellow-red pattern near Mindoro Strait in the north Sulu Sea maybe attributed to sediment mixing on a

topography. The entrainment of subsurface water and enhanced vertical mixing has brought the nutrient-rich water and the sediments on the bottom to the surface to induce phytoplankton bloom. The Low Chl-a value with a range between 0 and 1 mg/m³ happens from April to November. The coastal water along Borneo Island and the Sulu Archipelago shows yearly persistent signs of high Chl-a concentration of more than 3.3mg/m³. The adjacent South China Sea has presented very low Chl-a concentration in the central area and slightly high values along western side of the Palawan Island during winter.

The yearly averaged Chl-a concentrations at the three stations were 0.19 mg/m³, 0.18 mg/m³ and 0.65 mg/m³ respectively. Station 3 shows 4-5 times higher averaged concentration than station 1 and 2. The kurtoses at station 1, station 2 and station 3 are 0.474574, 0.370326 and 2.253998 respectively which suggests that the Chlorophyll-a concentrations are distributed approximately normally at station 1 and station 2.

4.2.2. Temporal persistence of Chl-a concentration

We have analysed the temporal persistence of Chl-a concentration at the three stations. Since the sensor collected no data during cloudy days, we have got a dataset of around 164 values for station 1, 165 for station 2, 135 for station 3 available to calculate the rough temporal persistence. The data are distributed evenly throughout the whole time series. From Fig 4.13, the temporal correlation at the site of station 2 is the most significant which has correlation coefficient greater than e^{-1} for more than 15 days. Station 3 has values greater than e^{-1} for more than 12 days, while station 1 has the shortest events which could last for 6 days. The Chl-a concentration has been maintained at an approximately constant level without frequent variations at the three stations

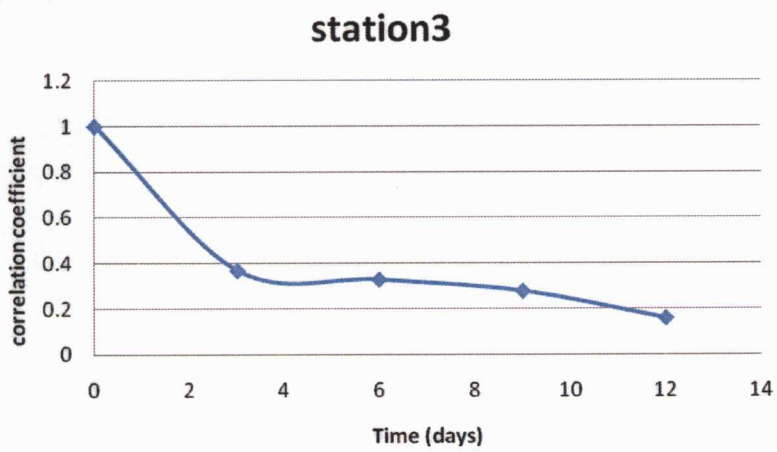
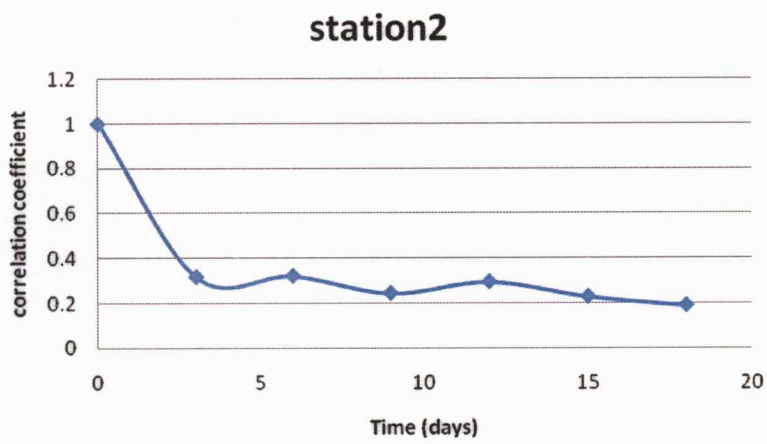
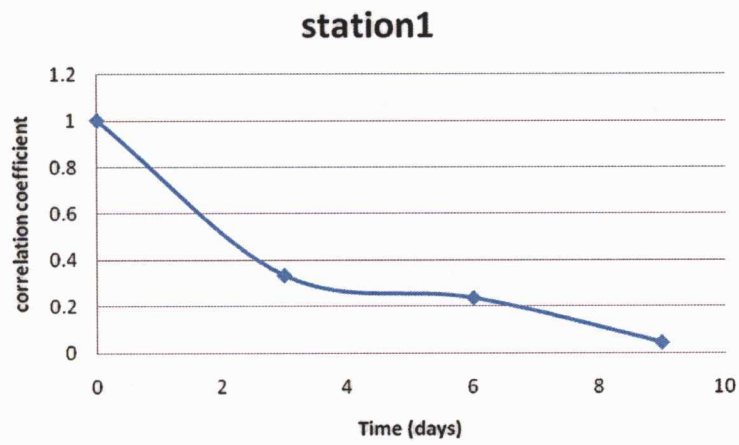
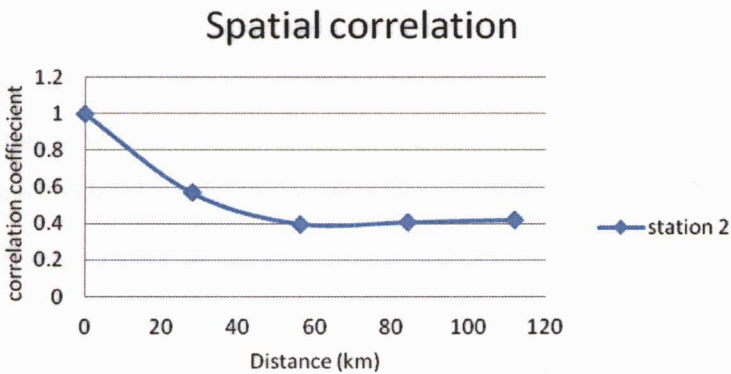
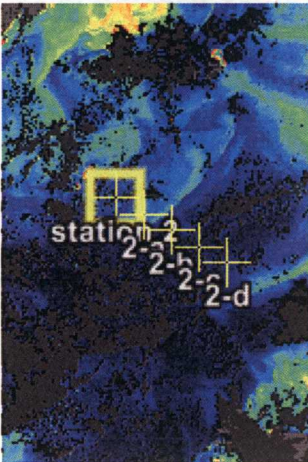
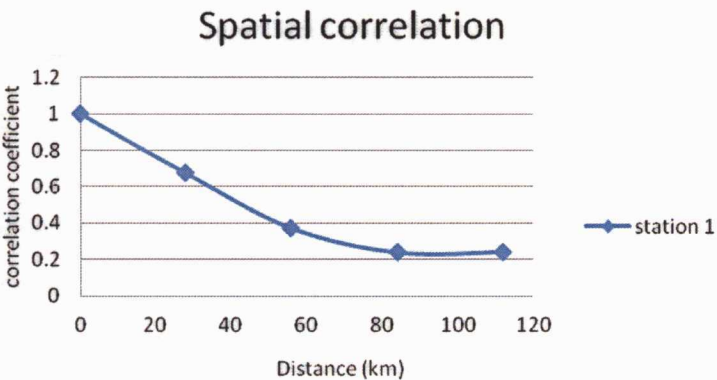
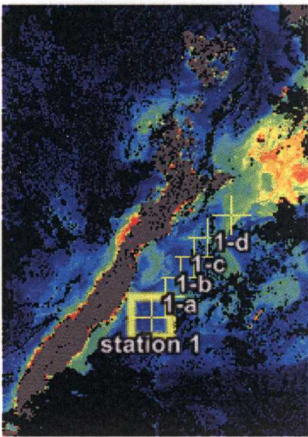


Fig 4.13 The persistence of upwelling in 2003 at station 1, 2 and 3 in the Sulu Sea.
(Station1 - west, Station 2 – central, Station 3 - east)

4.2.3. Spatial correlation of Chl-a concentration

To get some feeling for the spatial extent of Chl-a concentration, a one year series of Chl-a concentrations was constructed around three stations. The spatial correlation shown in Fig 4.14 suggested the Chl-a concentrations are all highly correlated within the neighbouring pixels. A good spatial correlation (i.e. correlation $> e^{-1}$) was found at station 2 and 3 for more than 100km, especially at station 3 where there was a good agreement ($C=0.6$) even 100km away. Station 1 has a shorter correlation with a scale of 70km. It should be noted that the upwelling spatial correlation at station 2 is much shorter than station 1 & 3, only around 10 km which can not explain the high spatial correlation of the chlorophyll-a concentration.



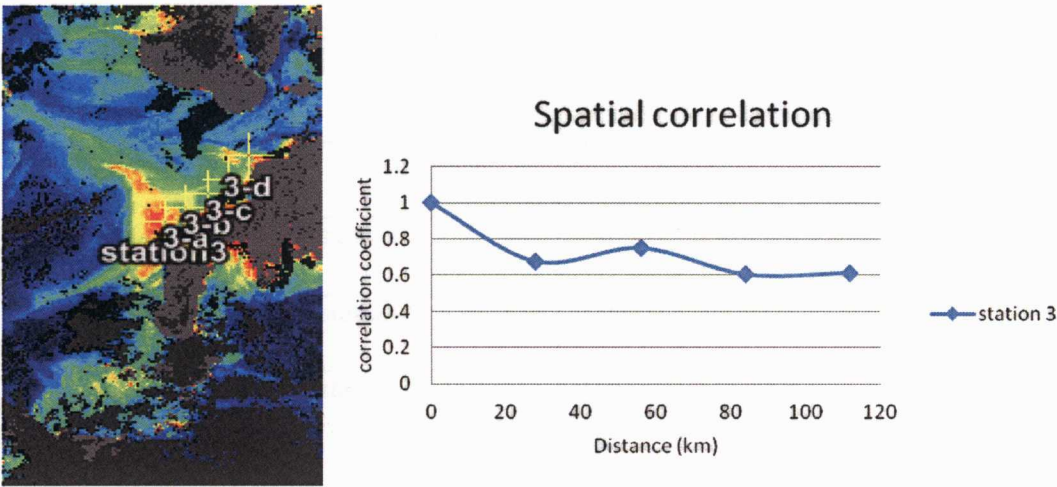


Fig4.14 The spatial correlation of Chl-a concentration in 2003 at station 1, 2 and 3 in the Sulu Sea. (Station1 - west, Station 2 – central, Station 3 - east)

4.3 The comparison between numerical model results and satellite Chl-a results

When deep waters are upwelled, they bring up nutrients which limit the surface phytoplankton growth. In general, phytoplankton can start to subdivide and their concentration increases after a number of days.

4.3.1. Kurtosis comparison

The kurtoses of vertical velocity and Chl-a concentration at the three stations are compared in Table 4.4 and show much larger kurtoses for the vertical velocities. The kurtosis of normally distributed variables is zero. At station 1 and station 2, the kurtoses of vertical velocity were much spikier than the Chl-a record. It suggested that the upwelling at station 1 and station 2 may not have significant effect on the variations of Chl-a concentration. Station 3 has similar kurtosis values between vertical velocity and Chl-a concentration. So Chl-a concentration may follow the fluctuations in upwelling.

Table 4.4 The kurtosis number comparison between vertical velocity and Chl-a concentration at the three stations.

Upwelling		Chl-a	
station1	2.730442	station1	0.474574
station2	5.937422	station2	0.370326
station3	2.013517	station3	2.253998

4.3.2. The relationship between upwelling and Chl-a concentration

First, we have time series data of the upward vertical velocity (by excluding those times when the velocity were downward) that we designate upwelling velocity and Chl-a concentration at the three stations to conduct the correlation analysis. The fluctuations of Chl-a concentration is traditionally explained in terms of the vertical mixing and upwelling of deep nutrients. Ruiz and Navarro (2006) pointed out that the persistent vertical advection for 1 week during the upwelling process will bring significant new production. The estimated period of water volume upwelling into the photic zone until it reached the surface was 1-2 days. During this period, phytoplanktons under enough light condition could make use of the deep-nutrients during different time scales. The whole upwelling process will take 6-10 days for phytoplankton to produce maximum concentration of organic matter (referring to Fig 1.12 (a) & (b)) which can be detected by high chlorophyll concentrations in MERIS images.

Fig 4.15 shows correlation coefficient between the upwelling and the corresponding Chl-a concentrations at the three stations. The three stations all have contemporaneous correlation between upwelling and Chl-a concentration due to the upwelling that brings the subsurface waters, containing higher Chl-a concentrations, to the surface which increases the surface Chl-a concentration (but this surface high Chl-a vanishes quickly). The vertical profile of Chl-a concentration in the Sulu Sea was shown in Fig 1.14 which is a clear evidence for the vertical Chl-a peak value at around 50m. We find the correlation coefficient peaks again 12-15 days after the beginning of the upwelling event at the three stations. It means the Chl-a concentration increases again in the upwelling plume 12- 15

days after the beginning of the upwelling, during which period the phytoplankton grows to the peak value as a response to upwelled nutrients at the three stations. The highest correlation coefficient is 0.6 after 15 days at station 3, higher than the other two stations which are around 0.2.

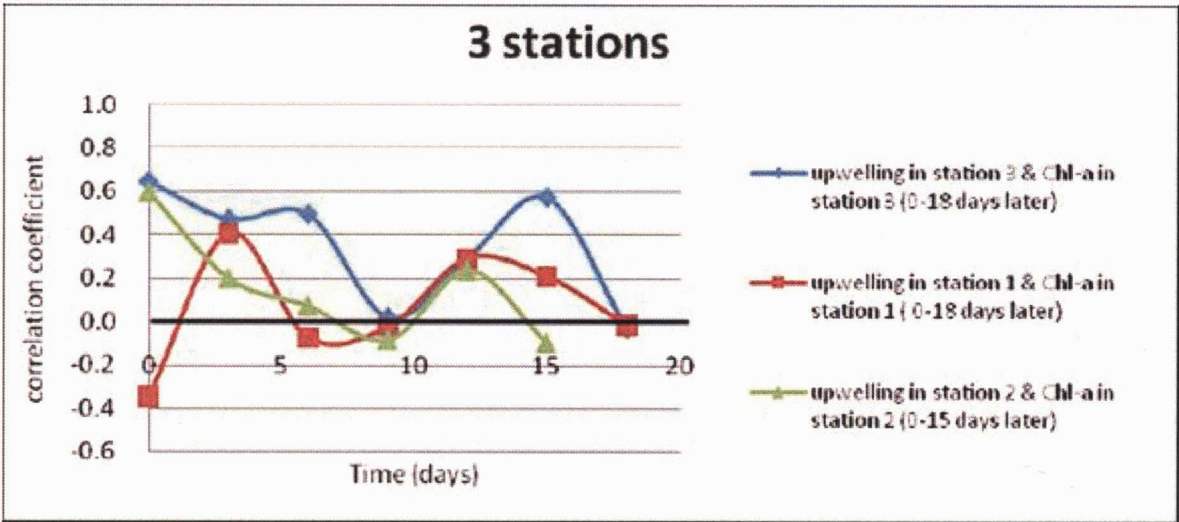


Fig 4.15 The correlation between upwelling velocity and Chl-a concentration in three stations in 2003. The upwelling has caused two peak values of Chl-a concentration. The first peak is caused by the maximum subsurface Chl-a concentration being brought to the surface by the upward flux. The second peak of Chl-a, 12-15 days later, is caused by the upwelled nutrients inducing phytoplankton bloom. (Station1 - west, Station 2 – central, Station 3 - east)

Then, the linear regression analyses between the upwelling velocity and the Chlorophyll-a concentration 12-15 days later were conducted. The R^2 value is interpreted as the proportion of the variance in Chl-a concentration attributable to the variance in upwelling velocity. Fig 4.16 (a) & (b) & (c) show the results. Station 3 shows a good R^2 value of 0.3303 and the regression equation is $y=121.51x+0.1887$ (Fig 4.16(c)). It suggests that the upwelling is the dominant force to supply deep nutrients to the euphotic zone and induce high Chl-a concentration 15 days later. The spatial correlation of both upwelling and Chl-a concentration at station 3 along the eastern boundary of the Sulu Sea has shown a highly correlated relationship as shown in Fig 4.7 & Fig 4.14, so the upwelling is the main factor to dominate the Chl-a concentration in the eastern coastal area of the Sulu Sea. The Chl-a

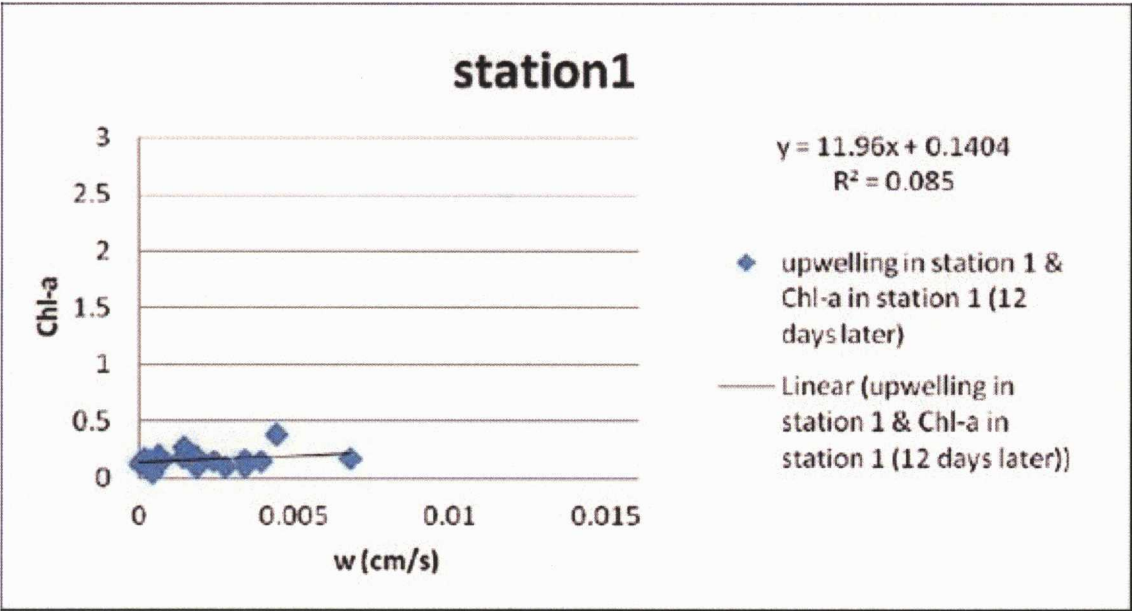


Fig 4.16 (a) The linear regression analysis between the upwelling at station 1 (west station) and the peak Chl-a (12 days later). X-axis is upwelling velocity (cm/s) at station 1, y-axis is Chl-a concentration (mg/m^3) at station 1. The number of data points is 18.

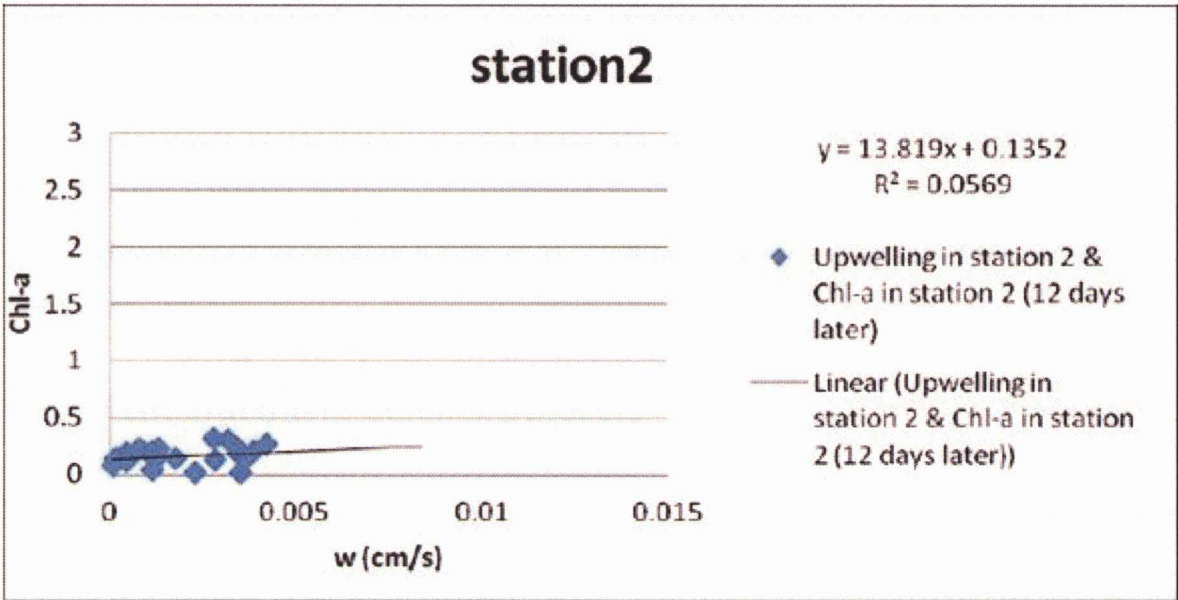


Fig 4.16 (b) The linear regression analysis between the upwelling at station 2 (central station) and the peak Chl-a (12 days later) in 2003. X-axis is upwelling velocity (cm/s) at station 2, y-axis is Chl-a concentration (mg/m^3) at station 2. The number of data points is 22.

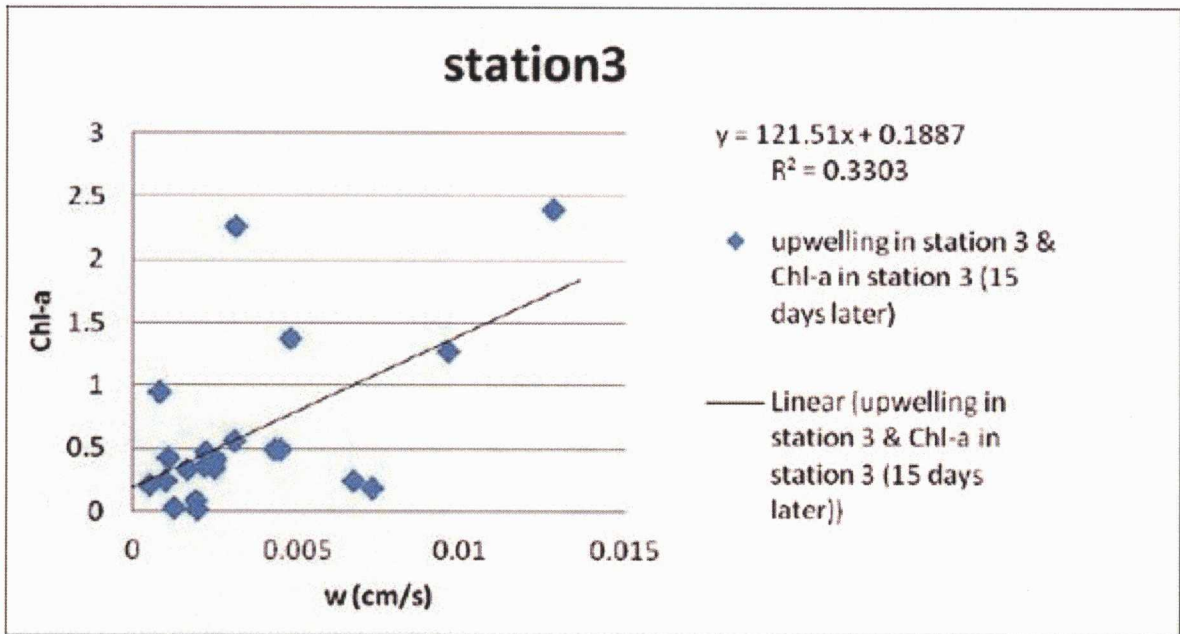
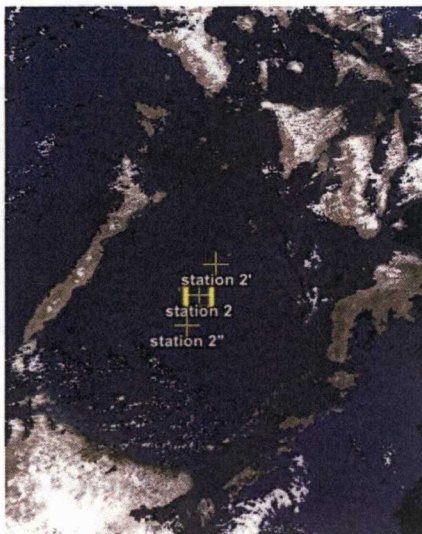


Fig 4.16 (c) The linear regression analysis between the upwelling at station 3 (east station) and the peak Chl-a (15 days later). X-axis is upwelling velocity (cm/s) at station 3, y-axis is Chl-a concentration (mg/m³) at station 3. The number of data points is 21.

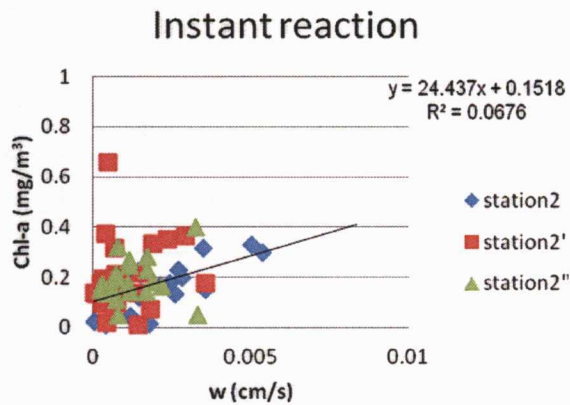
concentrations at stations 1 and station 2 are poorly correlated with the upwelling velocity, as shown in Fig 4.16 (a) & (b), which implies the upwelling process is not determining the chl-a concentration at stations 1 and 2. It is necessary to invoke other dynamical factors to explain Chl-a concentrations at station 1 and station 2. Also, some non-dynamical factors maybe significant such as riverine input (Subramaniam et al., 2008), atmospheric deposition (Duce, et al., 2008) and nitrogen fixation (LaRoche and Breitbarth, 2004).

4.3.3. Central station’s dominant process

We have chosen 0.5 degree north of the station 2 and 0.5 degree south of the station 2, together with station 2 at 8.6° N to represent central region of the Sulu Sea, as shown in Fig 4.17(a). The linear regression analysis between upwelling velocity and Chl-a concentration in central stations (in Fig 4.17(b)) shows low R² suggesting that upwelling at station 2 explains only a very small part of the Chl-a fluctuations. This is consistent with the observation by Wang at al. (2006) that Ekman pumping is downward all year in the central Sulu Sea.



(a)



(b)

Fig 4.17 (a) The central stations located at station 2 and 0.5 degree north and south of station 2. (b) The linear regression between upwelling velocity and contemporaneous Chl-a concentration in central stations.

Williams and Follows (1998) suggested in general that the horizontal transport by the surface Ekman drift or geostrophic eddies may transfer nutrients from the neighbouring upwelling regions and account for the new primary production in its adjacent regions. We can find a patch of high Chl-a concentration stretching from Dipolog Strait to the centre during winter in Fig 4.12 and westward current at station 2 in Fig 4.9(a), which both suggest lateral transfer occurs from the upwelling region at station 3 to the central of the Sulu Sea at station 2. The westward current in Fig 4.9 (a) reaches the speed of about 15 cm/s (13 km/day) at 41 m depth during winter and it will take about 15 days for waters to travel to station 2 over a horizontal scale of 200 km. While the parcel of water containing the upwelled nutrients travel from station 3 to central station 2 photosynthesis can occur if there is enough sunshine and nutrient supply during this 15 days. So we analysed the correlation between the Chl-a concentration at station 2 and the upwelling at station 3 to see if the intensified coastal upwelling region has influenced the

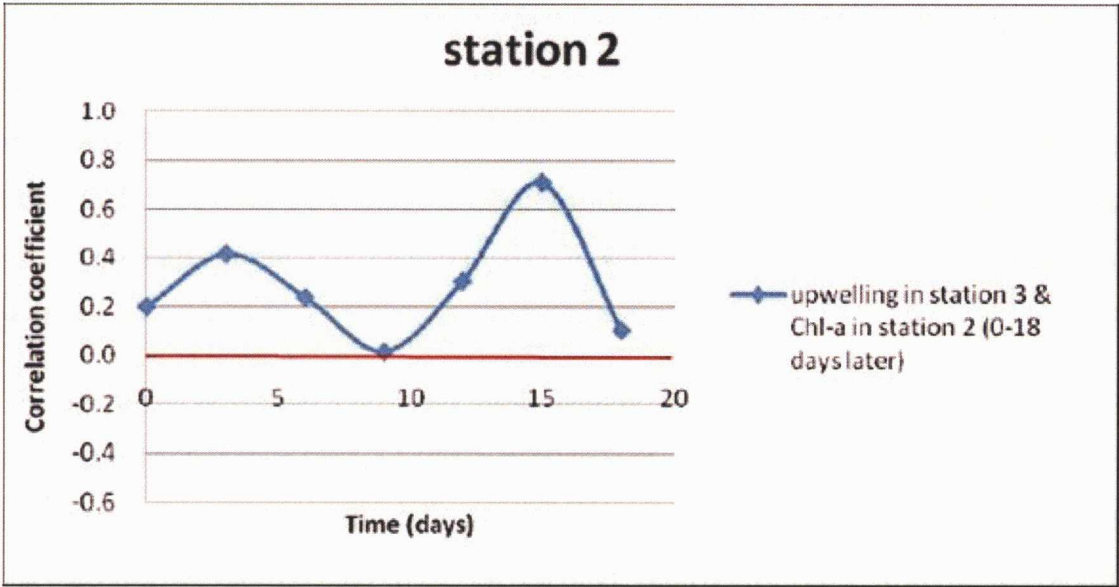


Fig 4.18 (a) The correlation between the upwelling at station 3 and the Chl-a concentration at station 2 in 2003. The peak value of correlation coefficient is 0.75 which suggests the upwelling in station 3 has caused a high Chl-a concentration 15 days later at station 2.

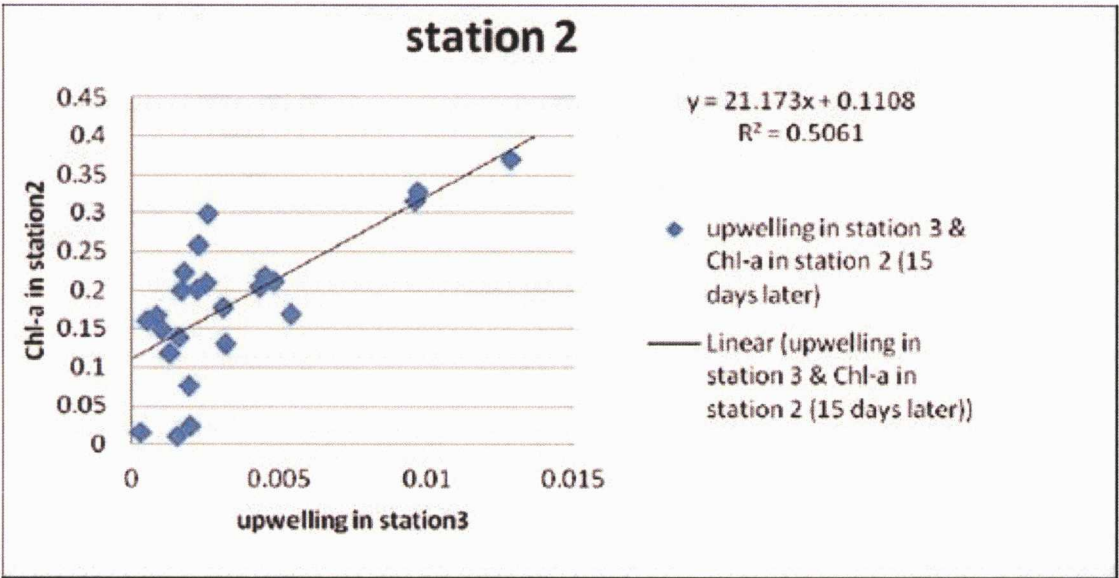


Fig 4.18 (b) The linear regression analysis between the upwelling at station 3 and the peak Chl-a at station 2 (15 days later) in 2003. X-axis is upwelling velocity (cm/s) at station 3, y-axis is Chl-a concentration (mg/m³) at station 2. The number of data points is 24.

central Sulu Sea’s chlorophyll concentration. The correlation between upwelling at station 3 and the Chl-a at station 2 is found to be significant. We obtained a high value of

correlation coefficient between the upwelling at station 3 and Chl-a concentration at station 2 after 15 days, as shown in Fig 4.18(a). Assuming the variables are normally distributed, we are 95% confident that the correlation is greater than 0.55 (Ezekiel and Fox, 1961). The R^2 value of 0.506 is the proportion of the variance in Chl-a concentration at station 2 attributable to the variance in upwelling velocity at station 3, as shown in Fig 4.18(b).

The upwelling at station 3 provides an explanation for the seasonal variations of Chl-a in the central Sulu Sea in Fig 1.13. The vertical velocity at station 3 has from 2003 to 2006 a seasonal nature that have upward velocities peak in late December or early January (in Fig 4.19(a)). We can see that there are also high chlorophyll concentrations at station 3 shown in Fig 4.19 (b) in January and February caused by the upwelling.

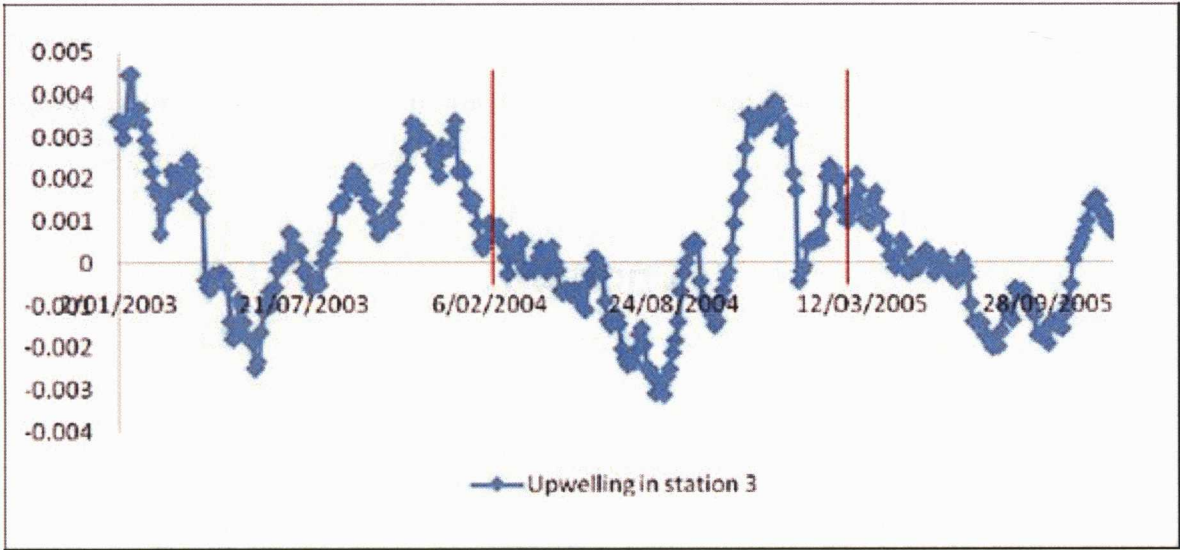


Fig 4.19 (a) Smoothed seasonal vertical velocity at station 3 from 2003 to 2005.

The time lag between upwelling occurrence at station 3 and peak Chl-a at station 2 suggests that it may take about 15 days for the water to travel from station 3 to station 2. During summer, the whole Sulu basin away from Borneo is at quite a low level of chlorophyll concentration. The eastward current at station 2 (see Fig 4.10 (a)) brings low nutrient waters from station 1 to station 2. As analysed above, the yearly accumulated upwelling at station 1 is much less than that at station 3. So the eastward current during summer will not induce high chlorophyll concentration at station 2.

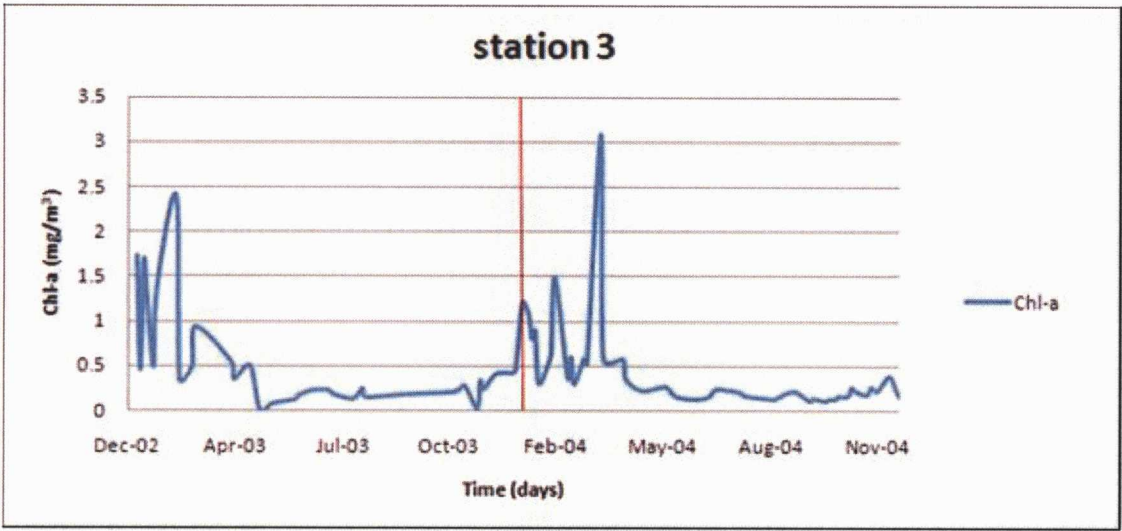


Fig 4.19 (b) The fluctuations of Chl-a concentration at station 3 during 2003-2004.

The speed of the surface current is another important factor in determining the volume flux of nutrients advected to the station 2. The westward current during winter (from station 3 to station 2) has a temporal persistent at station 2 since the correlation decreases to e^{-1} after 15 days.

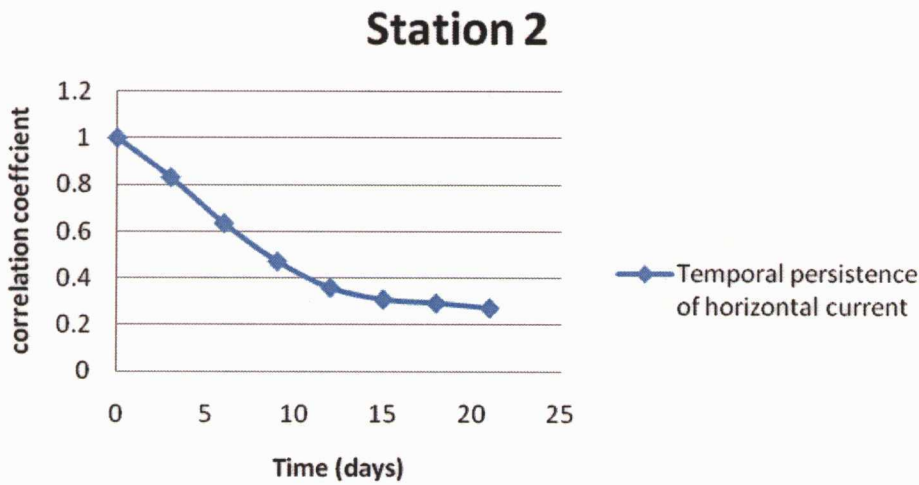


Fig 4.20 The temporal persistence of surface current (at a depth of 41 m) at station 2 in 2003.

The correlation and regression analysis between surface current velocity and Chl-a concentration at station 2 is shown in Fig 4.21 (a) & (b). Nutrients are transferred by horizontal advection to station 2 and during this 15 days nutrients will be maintained in

the surface layer rather than lost. It takes 15 days for phytoplankton to respond to the nutrients.

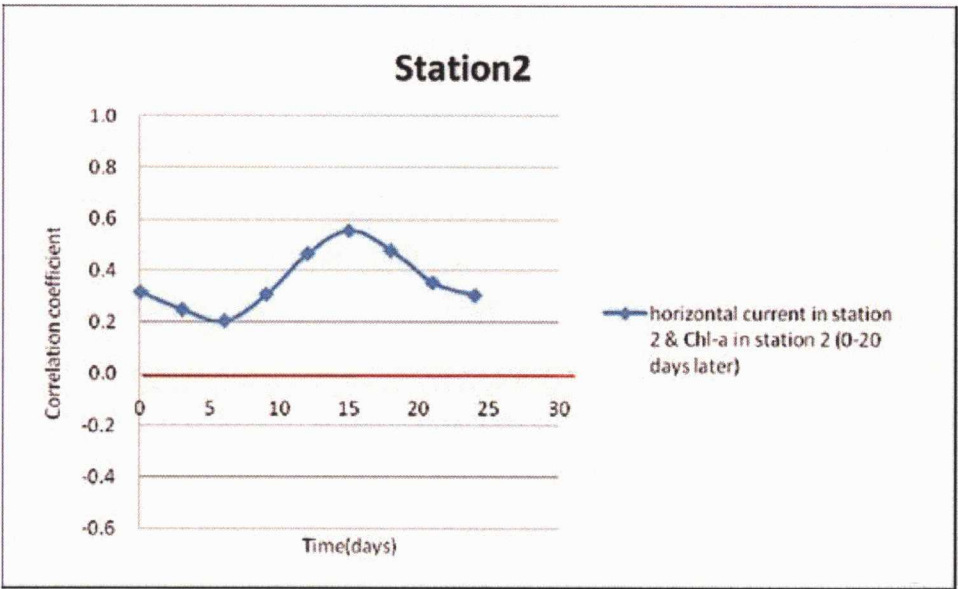


Fig 4.21 (a) The correlation between the horizontal current velocity at 41 m depth at station 2 and the Chl-a concentration at surface at station 2 in 2003. The peak value of correlation coefficient is 0.6 which suggests the surface current at station 2 has induced a high Chl-a concentration 15 days later at station 2.

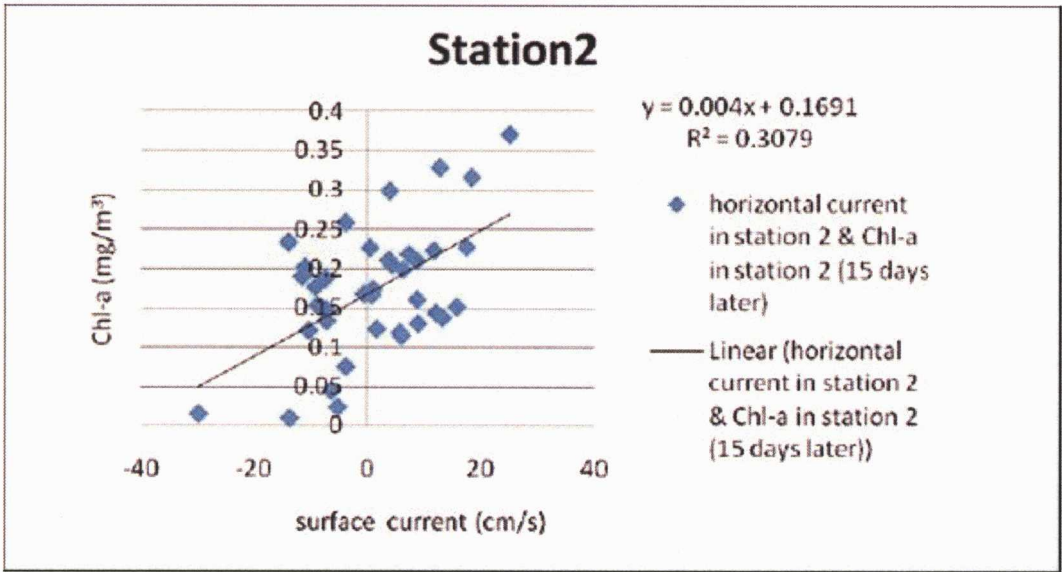


Fig 4.21 (b) The linear regression analysis between the surface current (at 41 m depth) at station 2 and the peak Chl-a in station 2 (15 days later) in 2003. X-axis is current velocity (cm/s) at station 2 where positive is south-easterly current and negative is north-westerly current, y-axis is Chl-a concentration (mg/m³) at station 2. R^2 is 0.3079.

The above preliminary investigation on the relationship between upwelling at the eastern strong evidence that the horizontal advection of boundary upwelled waters would cause the variations of central Sulu Sea’s chlorophyll-a concentration. To increase the reliability of the conclusion we got, we have done correlation analysis for 4 year time series data of chlorophyll-a concentrations at station 2 and vertical velocities at station 3 from 2003 to 2006 shown in Fig 4.22 and null hypothesis test. We found a total number of about 120 data points to calculate correlation coefficient which peaks at 0.45 over a 15-day lag between upwelling at station 3 and chlorophyll-a concentration at station 2. According to correlation coefficients at 5% and 1% levels of significance for 120 degrees of freedom by Emery and Thomson (2001), to achieve 95%-99% correlation confidence, the correlation coefficient should be in the range of 0.174-0.228. The 4 year time series correlation coefficient has higher confidence level than99% and supported the conclusion that horizontal transport from eastern side of the Sulu Sea might cause central Sulu Sea’s chlorophyll-a concentration variation.

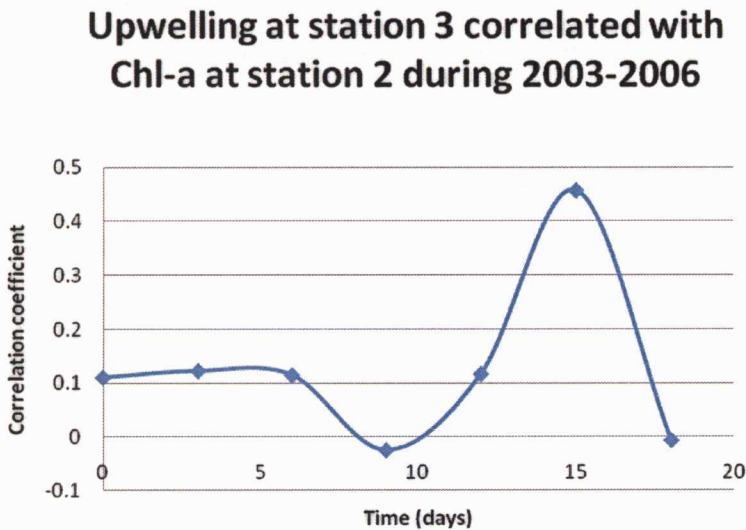


Fig 4.22 The correlation analysis between the upwelling at station 3 and the peak Chl-a at station 2 (15 days later) in 2003. X-axis is upwelling velocity (cm/s) at station 3, y-axis is Chl-a concentration (mg/m³) at station 2. The number of data points is 120.

5. Conclusion

Gaining detailed ocean circulation information from $1/10^\circ$ high eddy resolving Ocean For Earth Simulator (OFES) model, we have determined the vertical and horizontal distributions of vertical velocity which has seldom been available in the past. We mainly concentrated around a latitude 8.6°N in the Sulu Sea. The seasonal variations of upwelling velocities and yearly upwelling accumulation shows significant upwelling on the eastern boundary of the Sulu Sea during winter. The western side of the Sulu Sea and the central region have no strong upwelling. Temporal persistence analysis shows the west side of the Sulu Sea has longer events than the central and the eastern side of the Sulu Sea where upwelling events last no more than 5 days. The spatial scale of upwelling events along eastern and western side of the Sulu Sea is more than 100km which is much larger than that in the central region, which has a magnitude of 20km. The horizontal transport through key straits is lower than the transport estimations of earlier models. Considering only the upward vertical volume transport (upwelling) in the Sulu Sea basin, this transport has brought more (nutrient rich) water to the surface ocean than horizontal transport through the Sulu Sea key straits.

Ocean physics will redistribute the nutrients in the ocean and bring deep nutrients to the surface where sun light supports phytoplankton growth. Phytoplankton is the basis of the marine food chain which will lead to the production of fish. Chlorophyll concentration measured by the satellite sensor is the main tool to indicate the phytoplankton concentration in the ocean over large areas. We obtained chlorophyll concentration data from the MERIS instrument to predict phytoplankton dynamics in the Sulu Sea. We observed obvious seasonal fluctuations of the chlorophyll concentrations occurring on eastern side of the Sulu Sea where frequent upwelling is located. Finally, the correlation analysis between two data sets can help us to find how significant is the oceanic physics to the surface phytoplankton distribution within a closed basin. The fluctuation in chlorophyll concentration in the central Sulu Sea is strongly seasonal as shown by Wang et al. (2006). This can not be explained by the local upwelling. Central region chlorophyll is correlated (0.46 at 15 days lag) with the upwelling along the eastern side of the Sulu Sea because of horizontal transport. The westward current during winter can result in

horizontal transport of high nutrient water from coastal upwelling areas on the eastern side of the Sulu Sea to the central region. During summer, the whole Sulu Sea is at quite a low level of chlorophyll concentration and the current brings low nutrient waters to the central region that do not induce high chlorophyll concentrations. The chlorophyll concentration at the western side's station 1 is not correlated with horizontal advection nor is it correlated with the local lagged upwelling. The eastern side's station 3 is dominated by upwelling in winter where chlorophyll concentration shows a good correlation with local upwelling velocity.

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Appendix

Matlab code for reading OFES binary data and drawing pictures

```
function [C]=test3

dtadata={};
a=dir;
b=struct2cell(a);
c=b(1,:);
[h,1]=size(c);
jj=0;
for ii=1:l
    if strfind(c{ii},'.dta')
        jj=jj+1;
        dtadata{jj}=fopen(c{ii},'r','ieee-be');
        for i=1:6
            [A]=fread(dtadata{jj},201*301,'float32');
            array2=reshape(A,201,301);
            B=rot90(array2);
            left=155;right=155;top=174;bottom=174;
            C(jj)=B(top:bottom,left:right);
            display(C)
            display(jj)
        end
    end
end

%for i=1:1
%    [A]=fread(dtadata{jj},200*300,'float32');
%    array2=reshape(A,200,300);
%    B=rot90(array2);
%    left=121;right=125;top=207;bottom=208;
%    C=B(top:bottom,left:right);
%    display(C)
%[r,c] = size(B)
%figure('Units','Pixels','Position',[100 100 c r])
%image(B,'CDataMapping','scaled')
%set(gca,'Position',[0 0 1 1])
%colormap
%    caxis([-0.1 0.1])
%colorbar
%axis image off
%end
function [array2]=test9
[fid]=fopen('v.12.22.2003.dta','r','ieee-be');

for i=1:54
    [A]=fread(fid,201*301,'float32');
    k=20000;
    array2=A(k);
    display(array2)
    plot(array2,B(i));
    axis([0 30 0 6000]);
end
```