COASTAL UPWELLING UNDER THE INFLUENCE OF WESTERLY WIND BURST IN THE NORTH OF PAPUA CONTINENT, WESTERN PACIFIC

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Abstract. Coastal upwelling play an important role in biological productivity and the carbon cycle in the ocean. This research aimed to examine the phenomenon of coastal upwelling that occur in the coastal waters north of Papua continent under the influence of Westerly Wind Burst(WWB) prior to the development of El Nino in the Pacific. Data consisted of sea surface temperature, vertical oceanic temperature, ocean color satellite image, wind stress and vector wind speed image, sea surface high, and Nino 3.4 index. Coastal upwelling events in the northern coastal waters of Papua continent occurred in response to westerly winds and westerly wind burst (WWBs) during December to March characterizing by low sea surface temperature (SST) (25 - 28°C), negative sea surface high deviation and phytoplankton blooming, except during pre-development of the El Nino 2006/2007 where weak upwelling followed by positive sea surface high deviation. Strong coastal upwelling occurred during two WWBs in December and March1996/1997 with maximum wind speed in March produced a strong El Nino 1997/1998. Upwelling generally occurred along coastal waters of Jayapura to Papua New Guinea with more intensive in coastal waters north of Papua New Guinea indicated by Ekman transport and Ekman layer depth maximum.

Keywords: *Coastal upwelling, wind burst, El Nino, Ekman transport, Ekman layer Depth.*

1 INTRODUCTION

Upwelling is an event of raising water from the deeper water column to the surface waters that is mainly caused by the wind blowing at a certain period. The ecological effects of upwelling are quite diverse, but two impacts are especially noteworthy. First, upwelling brings up cold, nutrient-rich waters to the surface, which encourage seaweed growth and support blooms of phytoplankton. Second, the phytoplankton blooms form the ultimate energy base for larger animal populations in higher food chain, including fish, marine mammals, and seabirds (Mann and Lazier, 2006).

Upwelling that occurs in coastal waters or coastal upwelling play an important role in biological productivity, the carbon cycle in the ocean, and associated with productive fishing areas. Although its regions account for only one percent of the ocean surface, they contribute roughly 50 percent of the world's fisheries landings (Vargas and Gonzalez, 2004; Mann and Lazier, 2006). This role is shown by the ability of warm pool (oligotropic) as the main area of the world tuna catch particularly both Skipjack and Yellowfin tuna. This capability is powered by contribution of north equatorial cunter current (NECC) carrying water upwelling rich in nutrients and chlorophyll-a from Halmahera, Banda, Seram, and Sulu Seas (Messie and Radenac, 2006 ; Christian *et al*., 2004), eddys mechanism (Ganachaud *et al*.,2011), high primary productivity from coastal waters in Papua continent through the mechanism of seasonal current (NGCC and NGCUC), and Ekman transport caused by westerly wind burst (WWBs) (Kuroda, 2000; Ueki *et al*., 2003; Lehodey *et al*., 2011).

WWBs is a synoptic scale disturbances represented by strong westerly winds near the equator with a speed of more than 4 ms^{-1} at a certain period and usually occurs during the period from December to March. WWBs formed some mechanisms including intense tropical cyclone to jump in the cold of mid-latitude and Madden - Julian oscillation

(MJO) or their combination (Seiki and Takayabu, 2006; Tziperman and Yu, 2006). WWBs has been known to cause a shift warm pool to the east that is manifested in the form of equatorial Kelvin waves produced thermocline depression, strengthen ENSO in the eastern Pacific, activate the Rossby waves propagate westward, and generate shallowing thermocline (new upwelling) in western Pacific (Tomczak and Godfrey, 2003; McPhaden and Yu, 2012; McPhaden *et al.*, 2011).

Coastal upwelling research in northern Papua Continent was published by Hasegawa *et al*. (2009) and Hasegawa *et al*. (2010) which focused on the waters around Papua New Guinea using hind cast experiment with a high-resolution ocean general circulation models. However, with the advances of remote sensing technology and the availability of satellite and *in situ* oceanographic data (TAO and ARGO Drifter), the study of coastal upwelling events can be done in an unlimited time and covers a broad region. This research aims to examine the phenomenon of coastal upwelling events that occur in the coastal waters north of Papua continent under the influence of WWBs prior to the development of El Nino in the Pacific.

2 MATERIALS AND METHODS

The research was conducted in the coastal waters northern of Papua continent region with coverage area limited to 10°S - 10°N; 125°E - 155° E on March-September 2012 (Figure 1). Data used in this study include SST in situ data collected by Triton Buoy Mooring and accessed via http://www.pmel.noaa.gov/tao/; vertical temperature in situ data recorded by ARGO drifter; monthly data sets of SST images in 1996/1997, 2001/2002, 2005/2006 (Pathfinder version day and night 4 Km spatial resolution); SST G1SST Ultra - High Resolution 1 Km (accuracy 0.001°C/1 Km) (only Year 2013); ocean color satellite image; wind stress (zonal component) and vector wind speed QuicSCAT satellite image; sea surface high deviation merge satellite ERS-2; Topex/Poseidon and GFO image; data sets Nino 3.4 index (region 5S-5N; 170W-120W) and zonal wind velocity components of the cross-calibrated multi-platform ocean surface wind vector L3.5 a monthly first-look analyses data sets.

SST derived from satellite image was validated using SST insitu recorded by ten mooring station (TAO) in western Pasific ocean at the same time to the date coverage of the image.

The relationship between the incidence of westerly winds and anomalies to the development of El Nino in the Pacific established using the compilation graphs zonal westerly wind component with Nino 3.4 index using the microsoft Excel. El Nino events indicated by the distribution of index values greater than the threshold ± 0.4 °C (http://www.cgd.ucar.edu/cas/catalog).

Distribution of SST, chlorophyll-a, sea surface high deviation were compiled by using the interactive "Live Access Server" via the website http://coastwatch.pfel.noaa.gov/coastwatch/ and http://thredds.jpl.nasa.gov/welding/getUI.do.

Upwelling events identified in the SST image (both Pathfinder and G1SST) tested by making vertical transects perpendicular coastline to latitude 1°N, the vertical distribution of temperature at position 138° E (1.5°S - 1°N) and 142° E (2.5°S - 1°N) using recording data ARGO Drifter, and analyzed using Global software Argo Marine Atlas. Upwelling velocity was determined by the movement of isotherm 28°C and 26°C with simple equation:

$$V_{up} = \frac{\Delta x}{\Delta t} \quad \text{(1)}$$

where:
V_{up}= upwelling velocity (m.s^{-1})
Δx = isotherm depth changes (m)
Δt = change of time (s)

Suitability analysis of the upwelling location also tested using the calculation of the Ekman transport and Ekman layer depth utilizing the wind component parallel to the coast from the QuikSCAT satellite image grid 2°x2°. Calculation Ekman transport and Ekman depth refers to the Pond and Pickard (1983) with the form of the equation:

$$M_{yE} = -\frac{\tau_x}{2\Omega Sin\ \theta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where:

M_{yE}= Ekman transport ($kg.s^{-1}.m^{-1}$)

τ_x = wind stress component parallel to the coast (Pa)

f = Coriolis parameter ($rad.s^{-1}$)

Ω = speed of earth's rotation axis (7.29 x 10^{-5} $rad.s^{-1}$)

θ = latitude

Ekman transport calculation results converted into Svedrup units where 1 Sv = 108 m^3s^{-1}

$$D_E = \frac{4.3W}{\sqrt{Sin\,|\,\phi\,|}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3)$$

where:

D_E= Ekman layer depth (m)

W = wind modulus ($m\cdot s^{-1}$) obtained from wind strees image (QuickSCAT satellite)

ϕ = latitude

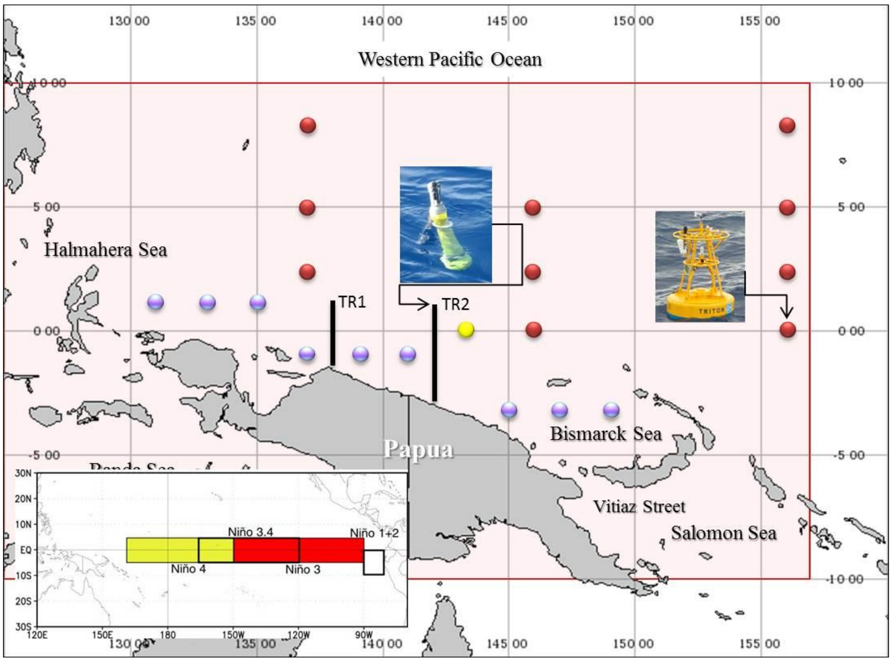

Figure 1. Research location map (discription = TRITON , = Cross-Calibrated Multi-Platform Ocean Surface Wind ;TR = Transect (ARGO Drifter data) = Grid 2° x 2°, = Nino 3.4 Region

3 RESULTS AND DISCUSSION

3.1 SST Validation

SST validation was performed on 50 samples of SST data from satellite image (Pathfinder algorithm) with SST *in situ* records of Triton Mooring Buoy. The results showed that the detection of SST from both measurement systems have a similar pattern although there were variations in the value of the generated SST. These variations may occur depending on the physical oceanographic conditions that control the structure of the temperature at the depth measurement (Figure 2).

T-test at the 95% confidence interval using a 2-tailed test at significance value of 0.173 was obtained $t_{cal}<t_{tab}$ (t_{cal} = -1.383 <t_{tab} = 2.010). The error average and standard deviation were 0.07° C and 0.5°C respectively (Table 1). Base on this test, there was no significant difference between the measurements of SST from satellite and SST from insitu measurement , indicated by $t_{cal}<t_{tab}$ or significance values greater than 0.05. Therefore, the SST image data sets can be used for the analysis of coastal upwelling or other oceanographic phenomena derived through the SST.

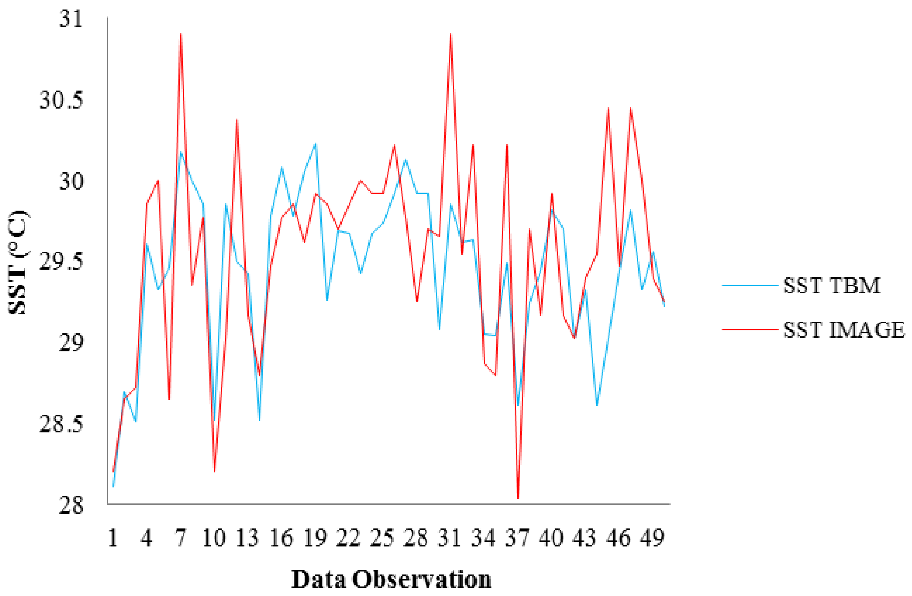

Figure 2 Relationship between SST derived from image and measured by Triton Bouy Mooring (TBM).

Table 1. The results of statistical test (t-test) NOAA-AVHRR SST image with SST recordings by Triton Bouy Mooring in Western Pacific ocean.

	Paired differences					T	df	Sig (2 tailled)
	Mean	Std. dev	Std. error	95% conf. interval diff.				
				lower	upper			
Pair SSTTBM vs SST CST	-0.098	0.505	0.071	-0.242	0.044	-1.383	49	0.173

3.1 Westerly wind burst (WWBs) and El Nino

The time series distribution of zonal wind component and Nino 3.4 index in Figure 3 proved that the variability of WWBs influence the duration and intensity of El Nino events. The development of El Nino in 1997/1998 due to WWBs that occurred in December and March 1996/1997. Wind speeds ranged from 2.84 - 5.72 ms^{-1} with a maximum speed occurred during the month of March. Meanwhile, El Nino in 2002/2003 produced by WWBs that occurred in December and March 2001/2002 with wind speeds ranging between 2.84 – 5.34 ms^{-1} where the maximum speed WWBs occurred in December. El Nino in 2006/2007 produced without the presence of WWBs at speeds ranging from 1.1 - 2.7 ms^{-1} where the peak maximum velocity occurred during December.

WWBs is defined as the event winds with speeds greater than 4 ms^{-1} and lasted at least a few days (5-40 days) and occurs in response to some external force such as Madden - Julian ocillator (MJO) or tropical cyclone intense (Seiki and Takabayu, 2006; Tziperman and Yu, 2006). El Nino events which took place in the East Pacific and coastal upwelling in the north coast of Papua New Guinea variability was significantly associated with the incidence of variability

WWBs (Helber and Weisberg, 2001; McPhaden, 2004; Hasegawa *et al*., 2010).

The influence of WWBs to the development of El Nino in the Pacific also shown clearly on the distribution of index Nino 3.4 (Figure 3). By using a threshold of ± 0.4 °C, the threshold value Nino 3.4 SST index then can be found the influence of WWBs during the 1996/1997. El Nino took place for 14 months (April 1997 - May 1998) with maximum intensity during October-November 1997. WWBs during 2001/2002 induce El Nino events over the past12 months (April 2002 - March 2003) with a maximum intensity occurred during November-December, while the west wind events without the presence WWBs 2005/2006 El Nino lasted for 8 months (June 2006 - January 2007) with maximum intensity also occurred during November - December but its strength was weaker than the previous two years of El Nino.

Based on criteria of Oceanic Nino Index refers to the third years, El Nino are classified into stronger intensity in 1997/1998, moderate intensity in 2002/2003, and the weak intensity 2006/2007. This criterion is identical to the pattern of events which WWBs strong El Nino events are characterized by two peaks WWBs with maximum speed on the latest event (March), with a moderate El Nino events WWBs two peaks but the peak incidence of both lower speeds (March), while the weak El Nino is not followed by events WWBs but zonal westerly wind maximum speed greater than 2 ms^{-1}. From these results, the distribution of the zonal wind component at speeds greater than 2 ms^{-1} was used as a speed preference west monsoon that will trigger El Nino with weak intensity, while WWBs presence at speeds greather than 4 ms^{-1} was significantly generate events El Nino with a moderate to strong intensity, depends on wind speed and duration of events as described by the distribution index Nino 3.4 (Figure 3).

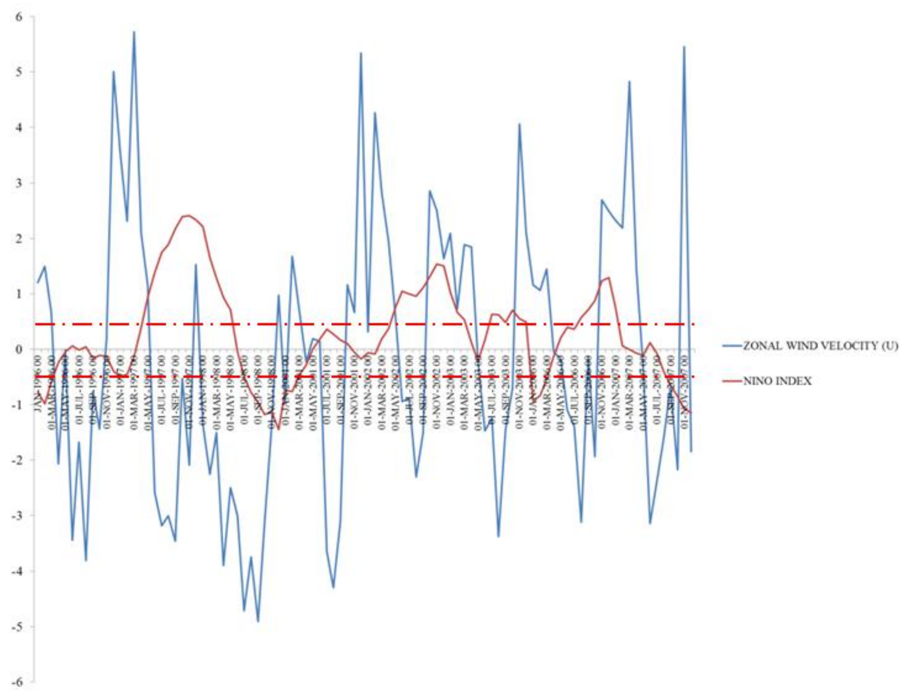

Figure 3. Zonal wind component and Nino 3.4 index during El Nino years (1997/1998, 2002/2003,2006/2007)positive = westerly wind , negative = easterly wind. Index Nino 3.4 positive = El Nino.negative = La Nina, dashed line is the threshold ± 0.4°C

3.2 Coastal upwelling

Coastal upwelling in the year of 1996/1997 was preceded by the presence of WWBs (December and March). Coastal upwelling beginning to grow in December, was characterized by low sea surface temperatures in the eastern of Mindanao and northern of Halmahera Island. Along with the intensification of the WWBs, SST was lower than normal conditions in the north of Waigeo Island, Manokwari and Biak Island surrounding waters to the east ofcontinent. Strong coastal upwelling clearly visible during March where SST ranges 26 – 27°C was concentrated in the coastal waters between Jayapura - Papua New Guinea (138°E - 149°E) and corresponding to the wind speed greater than 5 ms^{-1} parallel to the coastline. The location of the coastline forming an angle (θ) 22.5° (Hasegawa *et al.*, 2010) and the influence of the wind strees adn Coriolis force, produced Ekman transport move surface water away from the coast and piled up on the equator. In the year of 2001/2002, WWBs produce coastal upwelling with sea surface temperature range similar but the intensity was not as strong as 1996/1997 period. In the year of 2005/2006, there was no presence of WWBs, and weak coastal upwelling characterized by sea surface temperatures range 27 - 28°C at north of Papua New Guinea coastal waters (Figure 4, 5, and 6).

During the WWBs, coastal upwelling occurred in coastal waters northern of Papua continent and triggered El Nino events in the Pacific (Ueki *et al.*, 2003; Hasegawa *et al.*, 2009; Hasegawa *et al.*, 2010). This statement supported by the results of previous analyses of the zonal wind component (U) and the Nino 4.3 index suggesting that the variability WWBs in the western Pacific significantly affect the strength of El Nino events that occurred in the eastern Pacific in three events with different intensity. This indication signaled that the incidence of coastal upwelling in coastal waters northern of Papua continent will be comparable with the intensity of El Nino which to be generated.

Coastal upwelling due to Ekman transport of surface water moving away from the coast while the void surface water was replaced by water from deeper layers with lower temperatures. When the wind was parallel to the coastline in the surface, Ekman transport directed 90° to the right (left) of the wind direction in south (north) of the equator, resulting in movement of surface water off the coast in the direction of

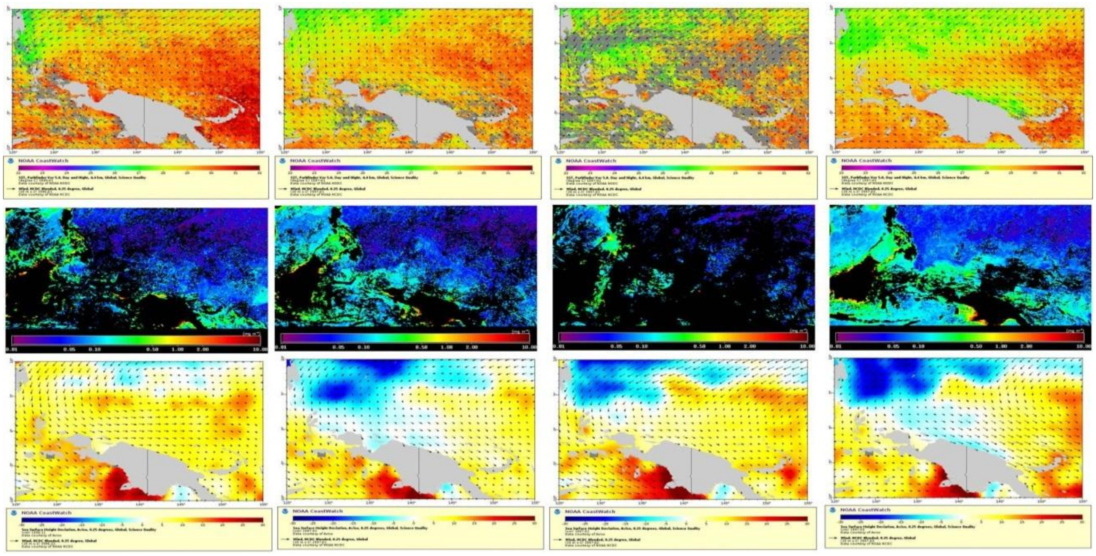

Figure 4 Satellite image of SST , chlorophyll-a and sea surface high deviation during period of westerly wind and WWBs (December – March)

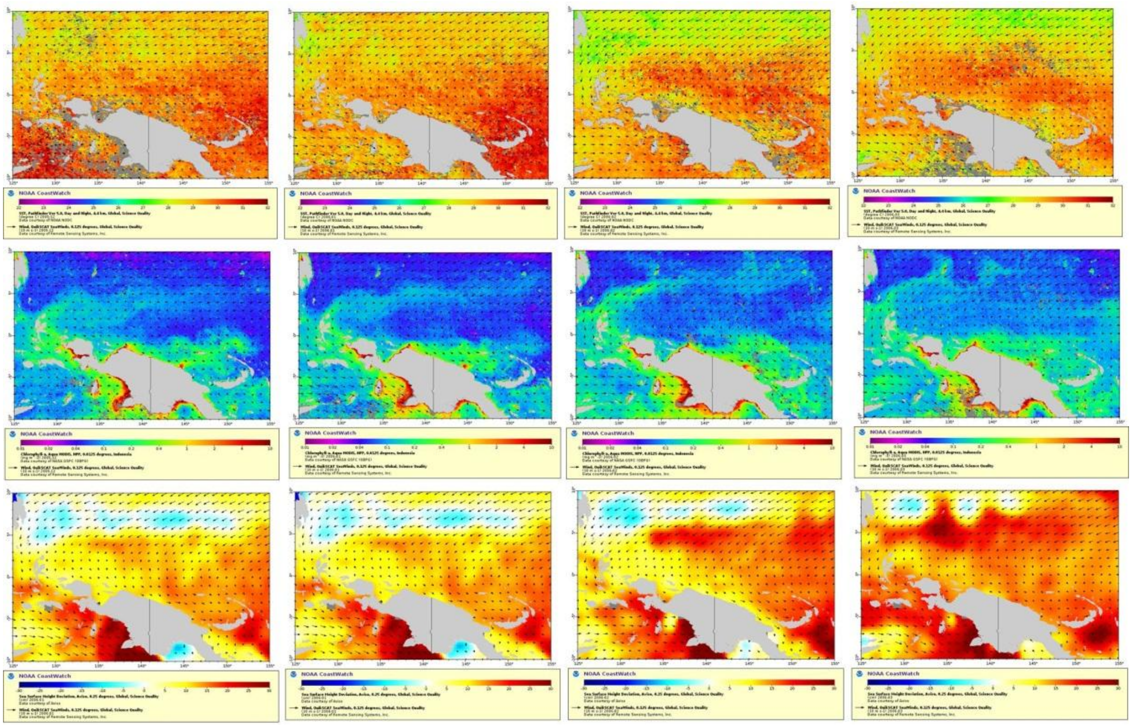

Figure 6. Satellite image of SST, chlorophyl-aandSea surface high deviation during period of westerly wind and WWBs (December – March) 2005/2006.

the two parts of the hemisphere. Consequently, coastal upwelling decrease sea level near the coast. The consequence was a pressure gradient normal to the coast, which encourages geostrophic currents along

the the coast with the same direction of movement by the wind. Net movement of water was the result of Ekman flow generated by wind and geostrophic current flow. It was directed away from the beach near the surface, parallel to the coast at mid-depth and at an angle that leads to the coast in the bottom waters (Tomzcak and Godfrey, 2001).

SST as the main indicator of upwelling events was also detected using SST imagery G1SST ultra - high resolution over a period of westerly winds and WWBs in 2012/2013 (December-March). The analysis showed similarities of the of upwelling events in coastal water of Manokwari - Biak to about longitude 138° E during January-February (SST 24- 27°C) while in March, upwelling dominates the coastal waters around Jayapura - Papua New Guinea (SST 25 - 27°C). Based on the result of image detection both Pathfinder and G1SST ultra - high resolution, coastal upwelling events in the coastal waters north of Papua continent was characterized by sea surface temperature preference 25-28°C under the influence of westerly winds and WWBs (Figure 7).

Coastal upwelling is also characterized by low sea surface high deviation and blooming phytoplankton which is marked by increased concentrations of chlorophyll-a in the waters. It can be understood because these three parameters interact each other where the thermocline shallowing indicated by the low dynamic height associated with negative value of sea surface high deviation. Simultaneously, nutrient-rich cold water from the thermocline can reach surface waters due to barrier layer disappears triggering phytoplankton blooming. During the westerly wind burst period (1996/1997 & 2001/2002) upwellling was characterized by negative value of sea surface high deviation with the distribution pattern of curving northwest towards coastal waters north of Papua continent, especially in the waters of the main central upwelling events. Moreover, this pattern also had similarities with the pattern of distribution shown by the distribution of wind speed and wind direction vector. This indicated that a strong wind strees during WWBs able to move the surface water masses and the vacuum is replaced by water from the layer below it so that decreasing surface temperature and sea level. Another factor contributing to decrease of sea level during this period coincideed with the arrival of partly phase of Rossby waves on north branching of latitudes 5 - 7°N which hit the east coast of Mindanao island on Phillipina and reflection following the distribution pattern of the wind to the coastal waters north of continent. The presence of equatorial Rossby wave on the waters part as a response to a shift Warm Pool to the east that occurred during the WWBs. These waves caused disturbances in the thermocline and Sea Level (Tomczak and Godfrey, 2003). Different condition was shown during an episode in 2005/2006 years where the weak upwelling followed positive value of sea surface high deviation. This was due to the absence of WWBs so the shoaling Warm Pool to the east was weak. As a result the equatorial Rossby wave generated very weak compared to the conditions pre strong and moderate El Nino.

Phytoplankton blooming that occurred during WWBs had the same general pattern, where high chlorophyll-a concentration corresponding to the low sea surface temperatures as on record by OCTS and SeaWiFS satellite imagery in January-March 1997 & 2002. Blooming concentrated in the waters around Biak island, Jayapura - Papua New Guinea coastal waters and the Bismarck Sea coincided with the low sea surface temperatures. Unlike the previous period, during weak upwelling, phytoplankton bloom also occurred on coastal waters. Besides to coincide with low SST, blooming occurred due to nutrient-rich water from the coastal area on injection to equator through mechanism anomalies new guinea coastal current (NGCC) on surface waters and new guinea coastal under current (NGCUC, in the thermocline) reverse direction to the southeast along coast north of continent and turn direction around longitude 142°E, which seem obvious in the pattern of chlorophyll-a distribution on ocean color imagery, and joining with equatorial under current (EUC) (Kuroda, 2000; Ueki *et al*., 2003). NGCC together

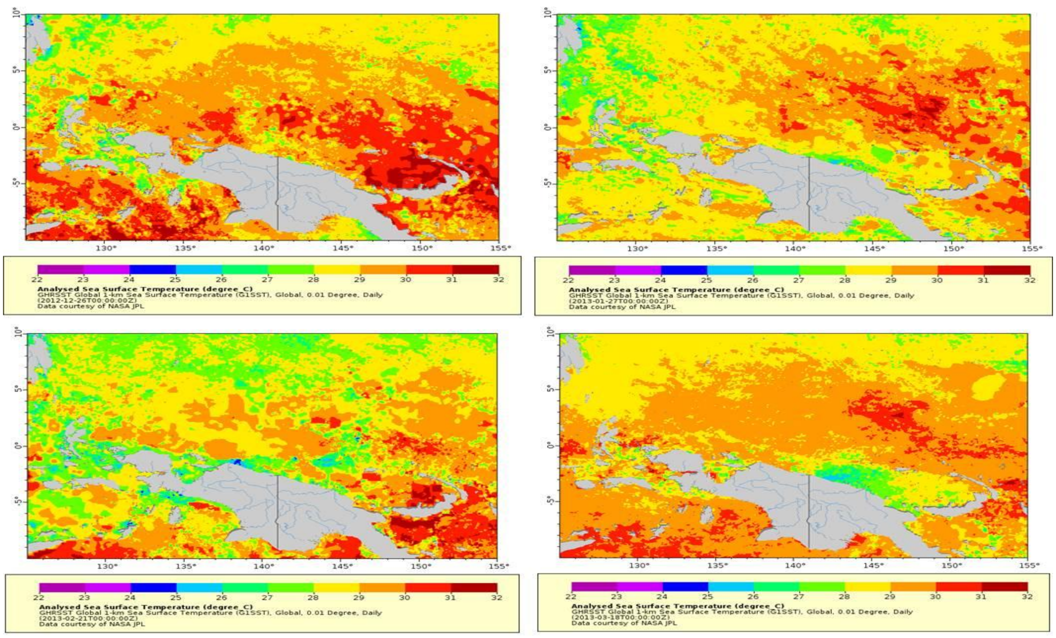

Figure 7 Satellite image of SST (Ultra – High Resolution) coverage of the period December– March 2012/2013.

with cold water mass as the result of Ekman transport mechanism was directed and accumulate at the equator, while NGCU joined the EUC to inject higher concentration of iron (Fe) from Papua New Guinea coastal waters (Sepik river) to limit primary production on the central Pacific (Lehodey *et al*., 2011; Ganachaud *et al*., 2011).

The presence of coastal upwelling and the loss of barrier layer during the period of WWBs increase primary productivity, and warm pool become fishing grounds and spawning ground (high recruitment) of Skipjack tuna. This mechanism was part of the enrichment process of the oligotrophic warm pool besides chlorophyll-a front (Figure 4 and Figure 5) and eddies that existed during the period of development of the westerly wind and WWBs in 1996/1997, 2001/2002, and 2005/2006 in the NECC flows among Phillipina - Indonesia - Papua New Guinea.

Coastal upwelling phenomena detected by satellite imagery verified by Drifter ARGO data analysis during the December to March 2008/2009 (data available from 2004 - 2012), period of the early development of the moderate El Nino 2009/2010. The results showed that along the transect TR1 at longitude 138°E (1.5°S-1°N) during westerly winds and WWB (wind speed 1 - 4 ms^{-1}) upwelling occurred near the southern coast of 1.2° S, indicated by an increasing the isotherm 28°C from depth of 85 m (December), 60 m (February) with upwelling velocity 4.8 $x10^{-4}$ $cm.s^{-1}$. Similarly, the 26 ° C isotherm upward from the depths of 117 - 95 m with velocity 8.5 x 10^{-4} $cm.s^{-1}$. Meanwhile, a similar trend occurred in TR2 transect at longitude 142° E(2.5°S - 1°N) where upwelling occurred in the south longitude 2.5°S indicated by the move-up of 28 °C isotherm near the coast of Papua New Guinea from depth of 85 m (December) - 65 m (February) with the velocity of 3.8 x 10^{-4} $cm.s^{-1}$ while the 26°C isotherm going up from the depth of 115 m (December) - 105 m (January) with velocity 3.5 x 10^{-4} $cm.s^{-1}$. Evidence of coastal upwelling events were also reported by Hasegawa *et al.* (2009) and Hasegawa *et al.* (2010) by using CTD recordings by RV/Kaiyo in September 2000 and December 2001 at the same location (142° E). In normal conditions the isotherm 28°C is found at a depth of 50 - 55 m, in the event of WWBs the isotherm at the depth of 30 - 40 m. Similarly, the 27 °C isotherm at normal conditions ranged between 60 - 70 m, while upwelling events at depth 45-50 m or upwelling intensity stronger than normal conditions (Figure 8).

Characteristics that have been identified as SST, sea surface high deviation and chlorophyll-a concentrations needs to be tested by the Ekman transport and Ekman layer depth calculations extracted from QuikSCAST satellite image data at the same coverage period. The calculation results showed that the westerly wind and WWBs move the water masses on zonal 1°N along the longitude 131°E - 135°E leads to the coast, while at the zonal between 1°S - 3°S along longitude 137° E - 149° E the water mass moved away from the coast as an indication of upwelling events. Areas along the coast between longitude 140°E - 149°E (Jayapura - Papua New Guinea) was a region of potential occurrence of upwelling due to the strategic location to the wind trajectory. This evidence caused the cold water move away from the coast more intensive which indicated by the higher value of the Ekman transport (0.01 – 0.20 Sv) from other parts of the coastal waters (Figure 9).

Similar indication was also shown by the calculation result of the Ekman layer depth. On the most potential coastal upwelling region, Ekman layer depth was relatively deeper (38 – 85 m) generated by WWBs with speed 4.79 – 7.42 ms^{-1}. Meanwhile, on the others coastal upwelling region, Ekman layer depth was relatively shallow (20 – 29 m) generated by WWBs with speed 4.12 – 6.25 ms^{-1} (Figure 10). By comparing depth distribution of normal isoterm 27°C and 28°C during 2000/01 and moderate El Nino 2002/03 with Ekman layer depth calculation result , it can be speculated that wind stress cause by WWBs in the

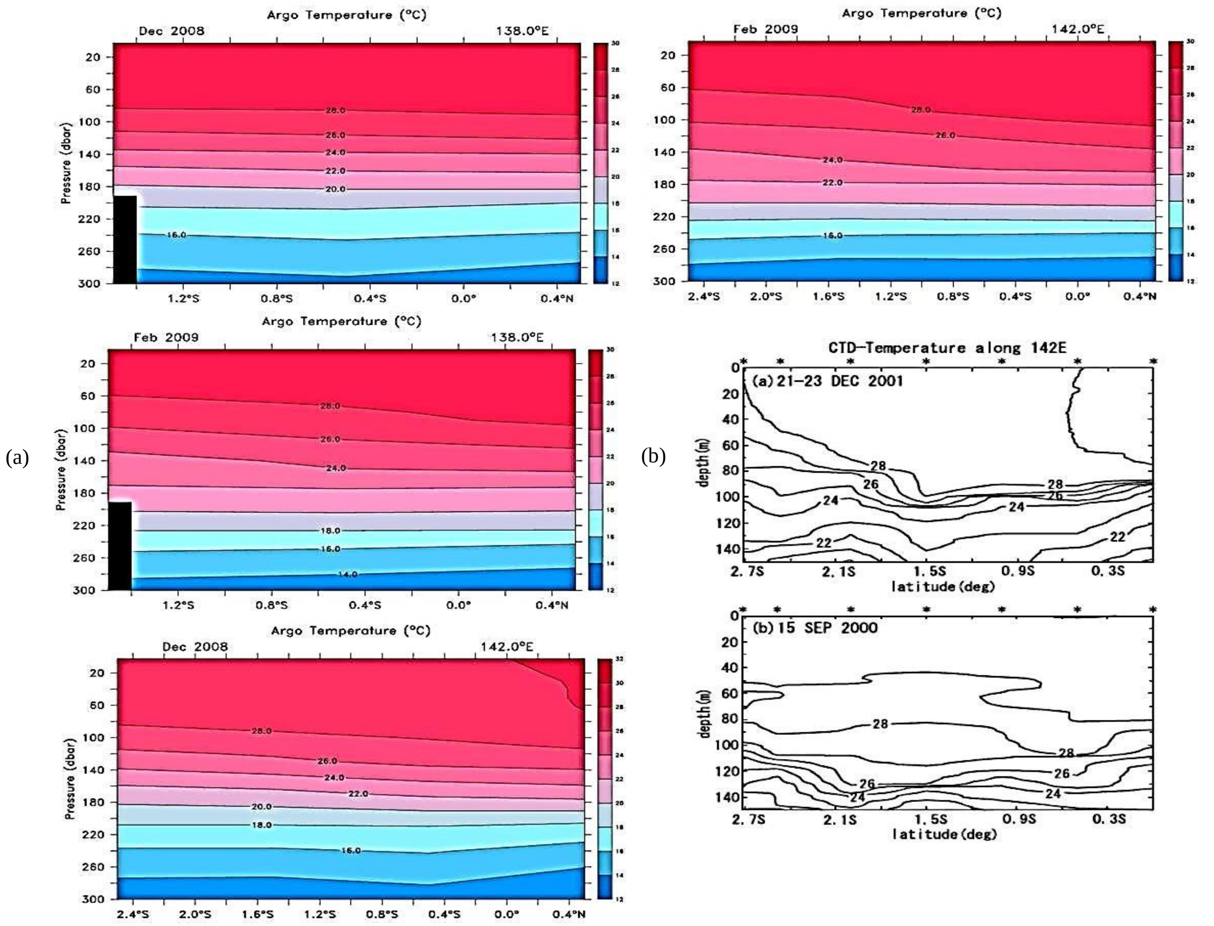

Figure 8. Vertical distribution of temperature (a) ARGO Drifterrecordings along longitude 138°E & 142 °E; (b) CTD RV/Kaiyo recordingalong longitude 142°E (Hasegawa *et al*.,2009 & Hasegawa *et al*.,2010).

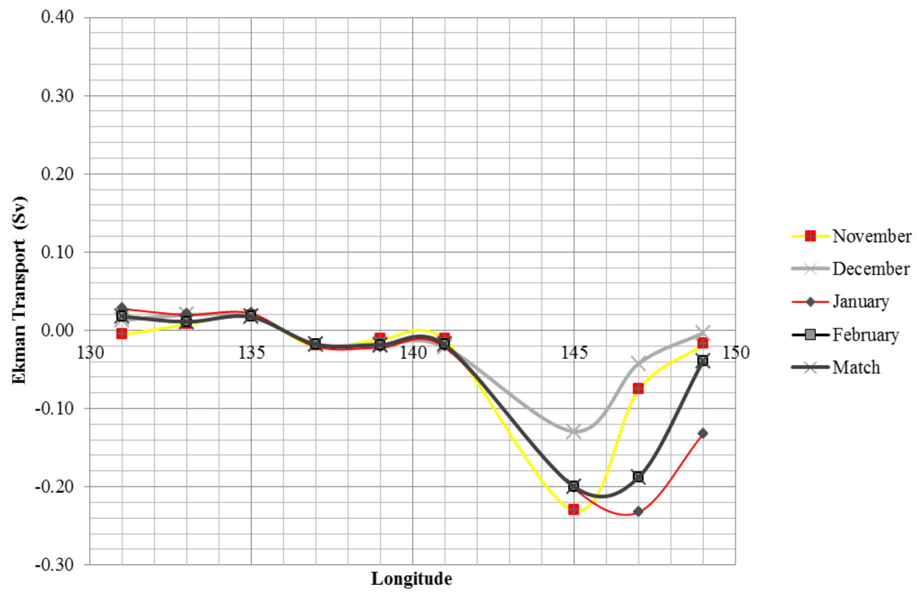

Figure 9. Ekman transport distribution on a grid 2°x 2° in coastal waters north of Papua continent.

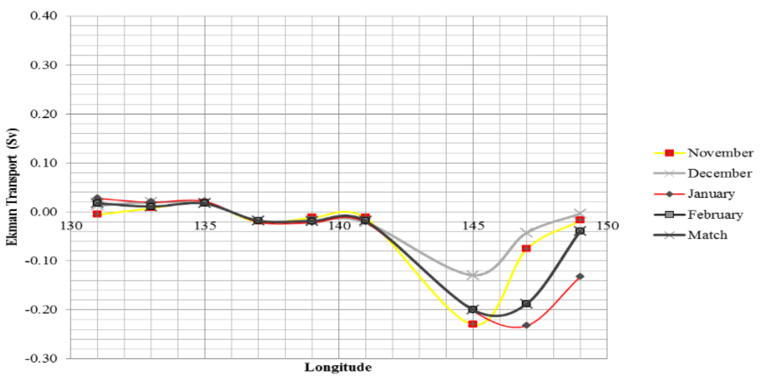

Figure 10. Ekman transport distribution on a grid 2°x 2° in coastal waters north of Papua

region between Jayapura – Papua New Guinea produce coastal upwelling with SST range 27 – 28 °C corresponding to the range of SST found by Hasegawa *et al*.(2009) ; Hasegawa *et al*. (2010) and Leger *et al*. (2010) using NOAA/AVHRR satellite SST image and CTD data during coastal upwelling event in this region. Coastal upwelling with lower SST could be expected to occur during strong El Nino conditions where the wind stress generated by WWBs with speed > 7.5 ms^{-1}.

4 CONCLUSION

Under the influence of westerly winds burst (WWBs), an intensive coastal upwelling (moderate and strong intensity) occurred with winds speed more than 4 ms^{-1}. Meanwhile, weak upwelling occurred without the presence of the westerly wind burst with wind speed greater than 2 ms^{-1}, which took place from December to March and could be used as an indicator of the development of El Nino in Pacific. Coastal upwelling indicted by low SST associated with negative value of sea surface high deviation and phytoplankton blooming, except in 2006/2007 period that weak upwelling accompanied by positive value of sea surface high deviation. The coastal waters north of Jayapura (Irian Jaya) – Papua New Guinea are potential areas of upwelling. However the coastal waters North of Papua New Guinea is the place of occurrence of strong intensity, which characterised by the magnitude of the mass transport of water that moved away from the coast and deeper water column influenced by wind stress. In addition to winds, coastal upwelling caused by advection of equatorial Rossby waves in response to movement of Warm Pool to eastern Pacific and NECC & NGCUC the reverse direction to the southeast at around longitude 142°E (anomalie) together with Ekman transport water mass leads and hoards nutrient-rich water mass and chlorophyll-a at the equator.

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