Ocean-atmosphere analysis of Super Typhoon Songda 2011 over Western North Pacific Ocean

[1]Yopi Ilhamsyah, [2]Ahmad Bey, [3]Edvin Aldrian, [1]Junaidi M. Affan

[1]Department of Marine Sciences, Syiah Kuala University, Banda Aceh 23111, Indonesia;
[2]Department of Geophysics and Meteorology, Bogor Agricultural University Indonesia;
[3]Center for Climate Change and Air Quality, BMKG Indonesia. Corresponding author: Yopi Ilhamsyah, y.ilhamsyah@gmail.com

Abstract. The purpose of the research is to understand the influences of ocean and atmosphere to the formation of Super Typhoon Songda 2011. Daily SST from NOAA AVHRR with spatial resolution of 0.5° in latitude and longitude was used to study upper oceanic response to the formation of Typhoon Songda. Meanwhile, 3-hourly meteorological data from ARP model with spatial coverage of 0.5° Latitude x 0.5° Longitude cover 201 x 101 points from 25° N - 20° S and 70.0° E – 170.0° E as well as 13 levels of atmospheric columns was also used in the study. The study was also supported by MT-SAT satellite images. The result showed that from early disturbances until reaching mature stage of Typhoon Songda, SST over WNP reached averages temperature of 30°C. Warm ocean waters continuously produce heat and moisture to the air that are necessary to fuel the genesis, development, formation and intensification of Typhoon Songda. The study also proved that light vertical wind shear (850 – 200 hPa) at about 0 – 5 knot was observed in the early development of Songda at 1800 UTC on May 19th. For the time being, weak vertical wind shear extended to the northwestern of Pacific Ocean. Thus, it made the system to moved toward northwest and reached category Super Typhoon few days later on May 26th. The study also showed the present of Monsoon trough. Monsoon trough occurred where easterly wind met the reversal southerly wind. The region was stretched from southeast to northwest part of WNP Ocean and designated by an extended low pressure area at the surface as well as extended bands of thunderstorms as observed by satellite imagery. On the other hand, potential vorticity shown in the present paper is useful to obtain an understanding of atmospheric motions and development of the upper-level disturbance. Potential vorticity maximum characterize strong vorticity and upward motion. Conversely, weak vorticity with downward motion is demonstrated by mininum potential vorticity.

Key words: monsoon trough, SST, vorticity, wind shear.

Introduction

Western North Pacific (WNP) Ocean is well-known for the most dynamical basin to Tropical Cyclone (TC) occurrences (Lin et al. 2008). The frequent occasion of TC lies from 10°N to 26°N and 121°E to 170°E (Holliday & Thompson, 1979). Principally, extensive periods of warm Sea Surface Temperature (SST) over WNP play a major role in driving the frequencies and intensities of TC throughout the year. Warmer SST lead to higher rates of energy transfer from the ocean and therefore increases the intensification of TC. Various climatological studies showed the evidences of upper-ocean warming to the TC events (e.g., Zhou & Cui, 2011). Early study conducted by Gray (1968, 1975) showed SST exceeding 26.5°C was a favorable environment for genesis of TCs. Meanwhile, Dare and McBride (2011) demonstrated a statistical study regarding to a strong relationship between SST above 25.5°C and early phase of TCs activities in every middle ocean basin. Besides early genesis indicator, SST distribution was also chosen to designate the transition phase into extratropical cyclone (e.g., Bond et al. 2010).

The understanding of air-sea interaction is, however, a principal explanation to describe the development of TC and its life cycle. Warm SST releases latent heat during condensation processes. The moisture sources are subsequently concentrated in the boundary layer which in turn drives to preserve the intensification of TC over the ocean (Ming et al. 2012). On the other hand, weak vertical wind shear is one of atmospheric factors that lead to the development of TC (Chen & Fang, 2012). The influence of vertical wind shear particularly between 850-200 hPa in controlling TC intensity is based on climatological study by Gray (1968). Furthermore, the inner and outer structures as well as dynamics of TCs can be illustrated by pressure and temperature distribution and kinematics of vortex spin-up, i.e., tangential, radial, and vertical velocity. They can also indicate the changes in intensity of TCs.

Super Typhoon Songda (STS), the fourth named TC of the 2011 NH tropical season, was the most devastating storm to strike WNP Ocean for the period of 2011. It lasted from May 18th to 30th, 2011 and strengthened to boost peak activity of powerful Super Typhoon stage between May 24th and 27th. Long curving track and the exhibition of all sequences of TC life cycle, STS was then considered as an ideal case of TC. Its development and intensification still remained questions. The fact that STS is not a subject of exploration yet soon motivates the present study. The purpose of the study with case of STS presented herein is to understand the influences of air-sea interaction to the formation of STS. It is considered that changes of ocean and atmosphere condition also influence the changes of STS intensity. The primary points of emphasis are ocean and atmospheric factors as already mentioned earlier.

Materials and Methods

Model and data

The lifecycle of STS was examined by using 3-hourly and 6-hourly data derived from ARP model. Spatial coverage of 3-hourly ARP model is 0.5° Latitude x 0.5° Longitude cover 201 x 101 points from 25°N - 20°S and 70.0°E – 170.0°E with 13 levels of atmospheric columns (hPa), i.e., 1000, 950, 925, 900, 850, 800, 700, 600, 500, 400, 300, 250, and 200. Meanwhile, 6-hourly ARP model has spatial coverage of 1.5°Latitude x 1.5°Longitude that cover 240 x 121 points from 90°N - 90°S and 0°E – 358.5°E with 15 levels of atmospheric columns (hPa), i.e., 1000, 950, 925, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150, and 100.

Furthermore, from early disturbances, tropical depression, tropical storm, until reaching super typhoon development, this study focuses on 3-hourly data. Meanwhile, from extratropical transition to decay phase in middle latitude, 6-hourly data is implemented in the study. The description of pressure level and surface data are as follows: Air temperature (°C), Web-bulb temperature (°C), Geopotential height (Gpdm), Relative humidity (%), Vertical velocity ($10^{-2}.s^{-1}$), Zonal wind (U) (knots), Meridional wind (V) (knots), Mean Sea-Level Pressure (SLP) (hPa).

On the other hand, daily SST dataset from ftp://eclipse.ncdc.noaa.gov/pub/OI-daily-v2/NetCDF/2012/AVHRR/ was employed to study upper oceanic response to the formation of Typhoon. The spatial resolution of the data covers a latitude and longitude of 0.25°. SYNERGIE was used to display meteorological variables derived from ARP model. The present study was also supported by MT-SAT satellite images.

Radial and tangential velocity

Basic equations used in the present research are equations of motion in *x*, *y*, and *z* direction (Montgomery and Smith, 2011):

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv + F_u \qquad (1)$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu + F_v \qquad (2)$$

$$\frac{\partial w}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + F_w \cdot \qquad (3)$$

By deriving eq. (1), (2), and (3), radial and tangential velocity can be written as :

$$\frac{Du}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + fv + \frac{v^2}{r} \quad \text{and} \quad \frac{Dv}{Dt} = -fu - \frac{uv}{r}$$

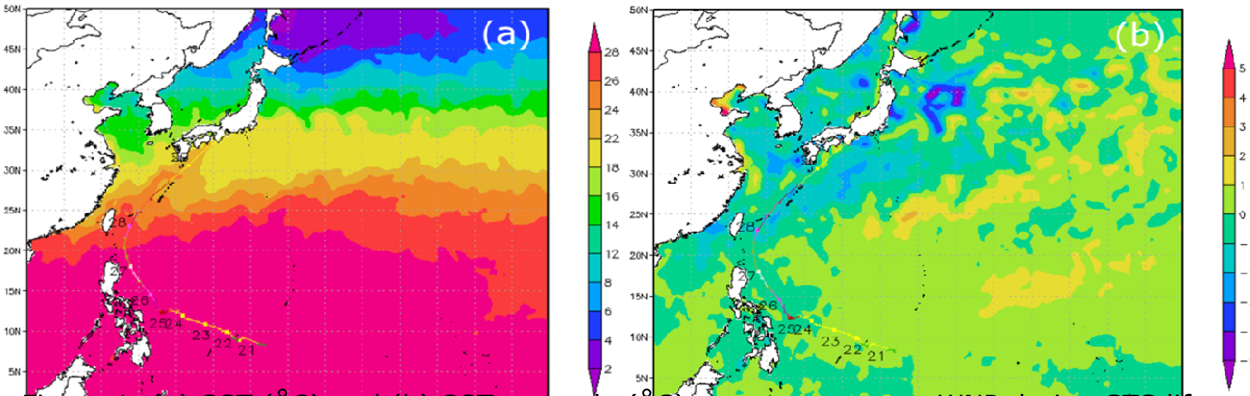


Figure 1. (a) SST (°C) and (b) SST anomaly (°C) on averages over WNP during STS life cycle from May 18th to 30th.

Figure 3. Wind Shear (850 – 200 hPa) in knots of (a) Tropical Depression at 1800 UTC on May 19th and (b) Extratropical cyclone at 1800 UTC on May 29th.

Results and Discussion

From early disturbances until reaching mature stages of STS, SST over WNP reached temperature averages of 30°C as shown in figure 1a. Warm ocean waters continuously produce heat and moisture to the air that are necessary to fuel the genesis, development, and intensification of STS. Figure 1b showed that the temperature anomalies from Tropical Depression to category Tropical Storm on May 20th – 24th were about 1 °C. It indicated that the temperatures were high on the period of STS development. In the meantime, on the period of STS intensification from May 24th to 27th, the anomalies decreased at about 0°C lead to cool ocean waters. Shay (2010) explained that the decrease of temperature on the period of TC passage is due to mixing of cooler thermocline with warmer ocean mixing layer as thermocline depth increase about 20 – 40 m. Additionally, the cooling SST pointed out the cold wake in the upper layer. However, it still remains question since warm SST is needed to keep sustaining TC development.

On May 28th – 30th, SST slowly decreased while entering middle latitude. The condition further impacted in reducing STS intensity. On May 28th, it is shown that SST was about 28°C which still exceed the threshold of TC development. Thus, the intensification of

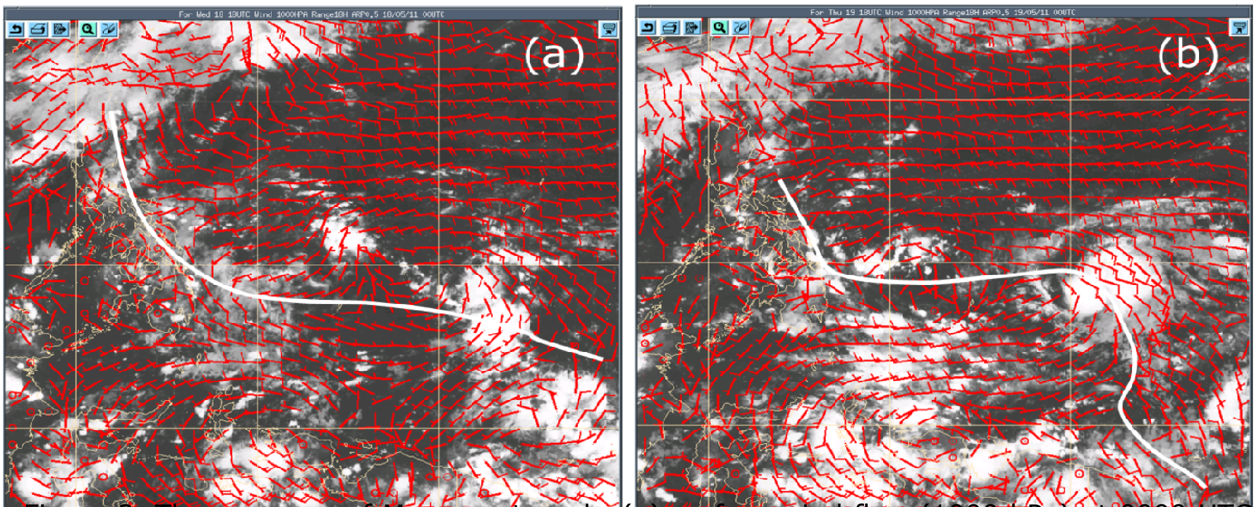
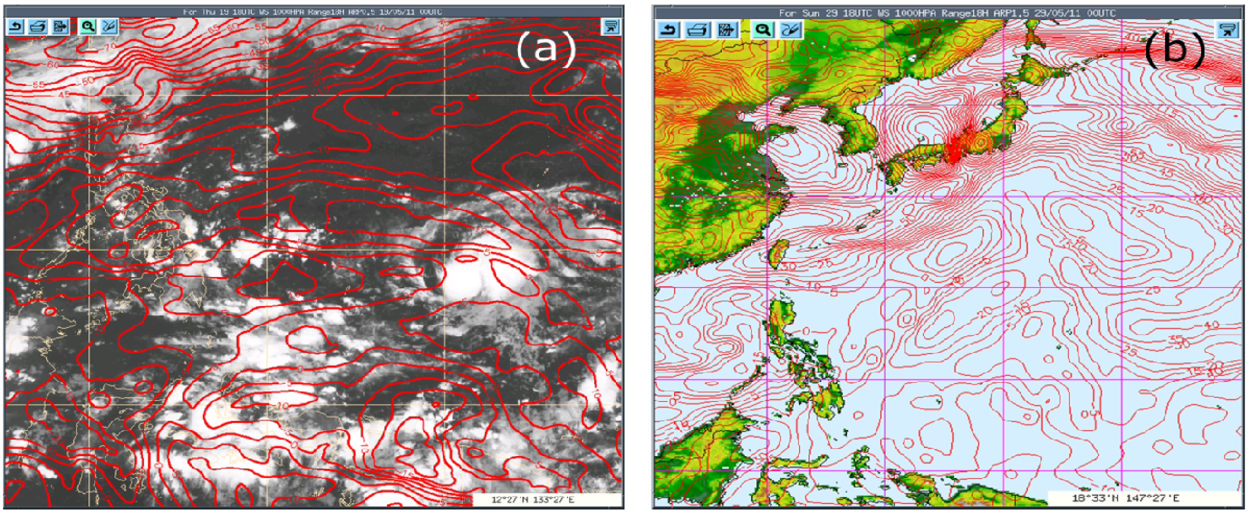


Figure 2. The presence of Monsoon trough, (a) surface wind flow (1000 hPa) at 0000 UTC, (b) 1800 UTC on May 19th. Monsoon trough is illustrated by area of convergence barb (White thick line).



STS was still noticeable even though the status was downgraded to become Typhoon 4 in stages. Meanwhile, on May 29th – 30th, SST was monitored below 26°C and the remnants of Songda had undergone into Extratropical transition and tropical depression which was confirmed by low SST anomaly below -1°C at the time of the decaying stages as shown in figure 1b.

Figure 2a and b showed the convergence zone of the wind pattern in the tropics known as Monsoon trough in the period of STS genesis on May 19th. It was demonstrated that Monsoon trough occurred when easterly wind met the reversal southerly wind. The region was stretched from southeast to northwest part of WNP Ocean and indicated by an extended low pressure area at the surface as well as extended bands of convective clouds. In addition, Monsoon trough also revealed the existence of Inter Tropical Convergence Zone (ITCZ) in the tropics. Monsoon trough provide sufficient condition for TC development. This is because significant low-level spin from vorticity prior to surface disturbance could drive the possibly rotating motion on TC.

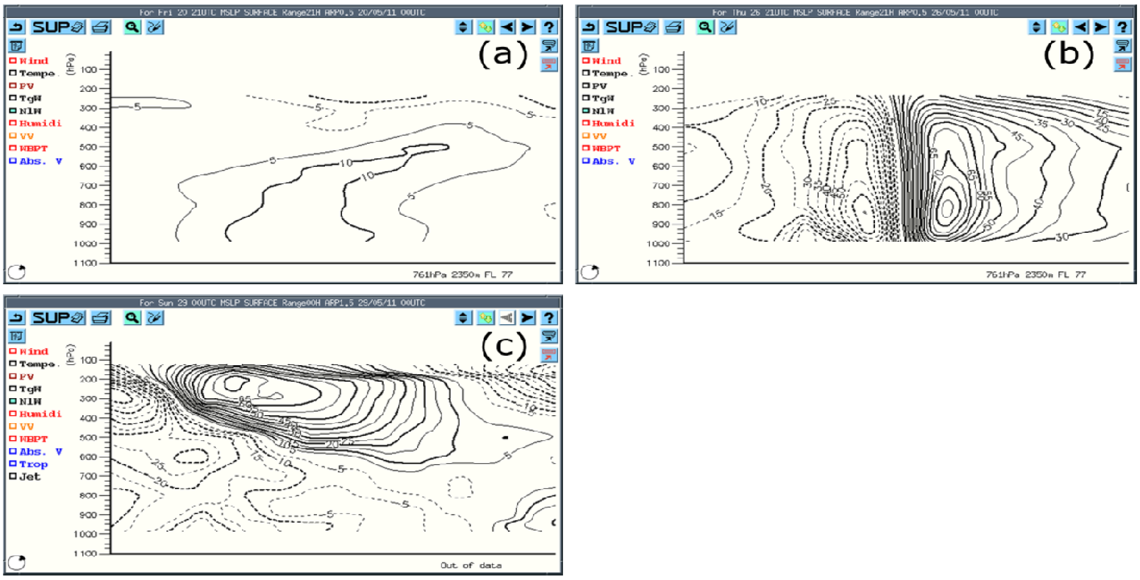


Figure 4. West-East vertical cross-sections of tangential velocity in knots of (a) Tropical Storm, (b) Super Typhoon, and (c) Extratropical cyclone.

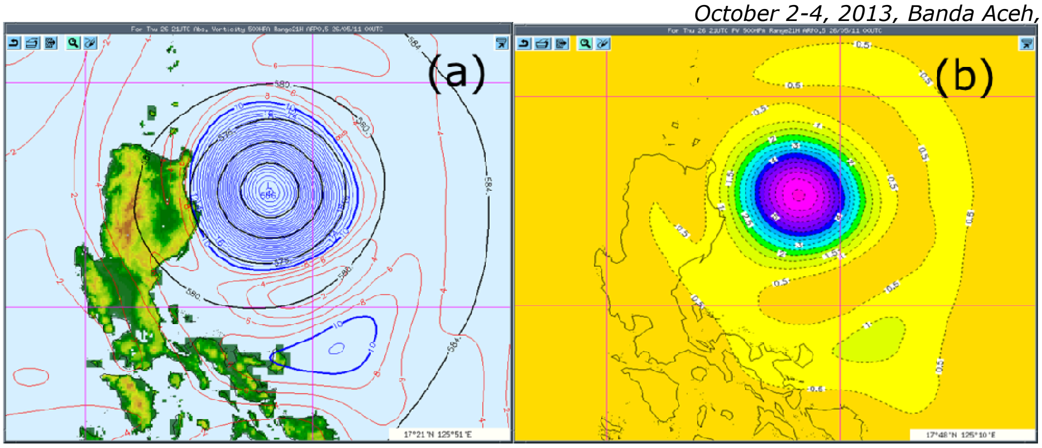


Figure 5. 500 hPa chart of (a) absolute vorticity (blue and red contour) in 10^{-5} s^{-1} and geopotential height (black contour) in gpdm and (b) potential vorticity in PVU of STS at 2100 UTC May 26th.

By examining figure 2, it can be confirmed that Monsoon trough was essential to the early genesis of STS over WNP Ocean. Satellite images portrayed an obvious understanding to the changes of weather condition within 18 hours. Consequently, bands of convective clouds had grown into the whirling clouds and started moving along the convergence zone. From figure 2, it is also noted that Monsoon trough continued to exist without any disturbances for long period of time. This result is consistent with model simulation performed by Wang and Magnusdottir (2005) who found that long-lasting period of Monsoon trough led to not only the genesis but also the development of TC.

Weak to moderate vertical wind shear is one of the prerequisites of TCs formation. According to Gray (1968), WNP Ocean was one of ocean basin that has weak vertical wind shear. Wind shear with speeds of less than 10 knot might deepen TCs formation. Weak wind shear contributes to the growth of TC vertically. Thus, TC can be well-developed since latent heat from condensation is released directly into the air. On the other hand, stronger wind shear is responsible to the dispersion of latent heat release over large area. Consequently, the vertical growth of TC becomes more tilted. Figure 3a proved that light vertical wind shear (850 – 200 hPa) at about 0 – 5 knot was observed in the early development of STS at 1800 UTC on May 19th. For the time being, weak vertical wind shear extended to the northwestern of Pacific Ocean. Thus, it made the system to moved toward northwest and reached category Super Typhoon few days later on May 26th.

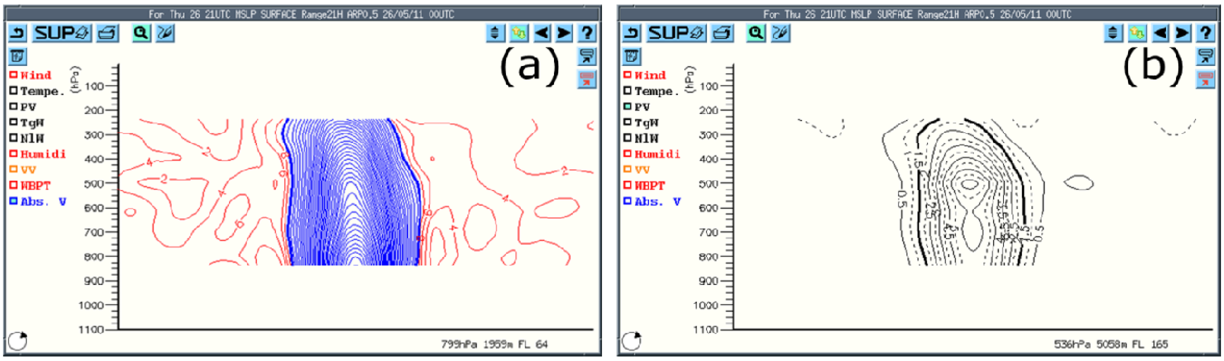


Figure 6. Vertical cross-section in west-east axis of absolute vorticity in 10^{-5} s^{-1}, Upward and downward motion are indicated by blue and red contour, respectively and (b) potential vorticity in PVU of STS at 2100 UTC May 26th, Upward and downward motion are indicated by high and low values, respectively.

Nevertheless, strong wind shear when the system transformed into Extratropical cyclone in middle latitude was due to the presence of Jet Stream in the upper troposphere as shown in figure 3b. Wind shear of more than 20 knot was observed on at 1800 UTC on May 29th. The presence of Jet Stream was responsible to spread out upper-level clouds. Strong shear also disturbed vertical supply of heat and moisture of STS. Thus, it contributed to distort the vertical shape of STS which further affect to the tilted development of the vortex.

Symmetric of STS can be identified by changes in the kinematics motion of the inner structures. Figure 4a, 4b, and 4c showed vertical cross-sections in west-east axis of kinematics changes of STS in every stage, that is, Tropical Storm, Super Typhoon, and Extratropical Cyclone, respectively. Figure 4a showed the asymmetric structure which can be characterized by disproportionally balance of tangential velocity for the western and eastern portion of Tropical Storm inner structure. Tangential velocity of 10 knot are located in the upper and lower of the inner structure. On the contrary, figure 4b depicted a well-defined concept of balance where flows of tangential velocities were precisely circulated in the western and eastern part of the inner structure. In addition, mature STS as demonstrated in figure 4b can be defined as patterned self-similarity of Typhoon. In fact, both patterns have different velocities. Maximum tangential velocities in western and eastern structures were about 65 knot and 85 knot, respectively. Maximum velocities were found close to the eyewall in the spiral rainbands. Moreover, figure 4c illustrated the decay phase of STS when undergo into Extratropical Cyclone in middle latitude. It showed that the structure had turned out to be asymmetric where we can simply find diagonal tilting of the inner structure. Maximum tangential velocities were both found in the upper-level pressure of 200 hPa. The eastern structures had stronger velocity than in the western. Maximum tangential velocity of 70 and 60 knots were found in the eastern and western inner structures of Extratropical cyclone, respectively. The changes of symmetric structures of STS in every succession required thermodynamics and dynamics of favorable environment.

Figure 5a and b showed absolute vorticity overlaid with geopotential height and potential vorticity in 500 hPa chart, respectively. Vertical cross-section in west-east axis of absolute and potential vorticity was exhibited in figure 6a and b. Vorticity represent the spin of air parcels. In this case, it corresponds to the spin of horizontally flowing air about a vertical axis and characterizes with higher vorticity values, called positive vorticity maxima (generally above $16 \times 10^{-5}\ s^{-1}$). High values of vorticity maximum indicate upward motion that assist to strengthen surface central low pressure area as well as bring precipitation. On the contrary, low values of vorticity maximum illustrate the sinking air. High and low vorticity maxima in figure 5a are presented by blue and red contour, respectively. Upward motion occurred in STS vortex presented by blue contour meanwhile sinking air occurred around primary vortex presented by red contour. Potential vorticity in figure 5b and 6b is useful to obtain an understanding of atmospheric motions and development of the upper-level disturbance. Potential vorticity maximum characterize strong vorticity and upward motion. Conversely, weak vorticity with downward motion is demonstrated by mininum potential vorticity.

Conclusions

Averages SST of 30°C were found during STS lifetime. It was also proved by SST anomaly at about 1°C when the system transform into tropical storm on May 24th. Heat transfer from ocean to troposphere during the intensification of Typhoon was also significant to generate warmer surface air layer. Weak vertical wind shear at about 5 knot was found during early development. Weak vertical wind shear was mostly found in the northwestern. It further drives the disturbance system to move toward the region. The identification of weak vertical wind shear region, however, becomes essential to determine the storm motion. Monsoon trough indicates the area of convergence zone where easterly wind meet southerly monsoon wind from Australia. Consequently, the tropical disturbances started to form along this the convergence zone.

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