

## Impacts of 2009 Typhoons on Seawater Properties and Top Layer Ocean's Structure in the Northwest Pacific Ocean

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### ABSTRACT

*Passing over the ocean surface, typhoon absorbs heat from the sea water as it needs the heat as its 'fuel'. The process is via evaporation of water. Subsequently, the sea surface temperature (SST) in that area will significantly decrease. Due to strong typhoon wind water is evaporated from the surface layer of the ocean, the amount of water mass in that area is lost, but the same amount of salt will remain, causing sea surface salinity (SSS) to increase. Strong winds induced by typhoons will also cause turbulence in the water, causing entrainment, where cold deeper water is brought up to the surface layer of the ocean, which will consequently increase its SSS and change the isothermal layer and mixed layer depth (MLD). Here, isothermal layer means the ocean layer where temperature is almost constant and MLD is the depth where salinity is almost constant. This paper focuses on the effect of typhoons on SST, SSS, isothermal layer and MLD by taking 15 typhoons in the Northwest Pacific throughout 2009 typhoon season (typhoons Lupit and Ketsana are used as examples in results) into consideration. Temperature and salinity data from selected Array of Regional Geostrophic Oceanography (ARGO) floats close to the individual typhoon's track are used in this study. The results showed that SST decreased up to 2.97°C; SSS increased up to 0.44 pss and majority of the typhoons showed deepening of isothermal layer (between 39.8 m and 4.6 m) and MLD (between 69.6 and 4.6 m) after the passage of typhoons. Passing of each individual typhoon also removed significant amount of heat energy from the affected area. The highest amount of heat of 841 MJ m<sup>2</sup> to the lowest of 30 MJ m<sup>2</sup> was calculated during the study period. For comparison purpose, an equivalent amount of electrical energy in kWh is also calculated using the amount of heat removed by the typhoons.*

*Keywords: Isothermal layer; MLD; SSS; SST; typhoon; western North Pacific Ocean*

### ABSTRAK

*Semasa merentasi permukaan lautan, taufan menyerap haba daripada air laut kerana ia perlu kepanasan sebagai bahan 'bakar'. Proses ini dilakukan melalui penyejatan air. Oleh itu, suhu permukaan laut (SST) di kawasan berkenaan akan menurun. Apabila air tersejat daripada lapisan permukaan laut akibat daripada laluan taufan, jumlah jisim air di kawasan berkenaan akan berkurang, tetapi jumlah garam akan kekal sama, menyebabkan kemasinan permukaan laut (SSS) meningkat. Angin kencang dicituskan oleh taufan juga akan menyebabkan pergolakan dalam air di kawasan itu yang menyebabkan percampuran dengan air sejuk dibawa dari kawasan lebih dalam ke lapisan permukaan lautan yang meningkatkan SSTnya dan juga mengubah lapisan suhu dan lapisan campur kedalaman (MLD). Kertas ini memfokuskan kepada kesan taufan terhadap SST, SSS, lapisan suhu dan MLD dengan mengambil 15 taufan di Barat Laut Lautan Pasifik sepanjang 2009 (taufan Lupit and Ketsana digunakan sebagai contoh dalam keputusan) untuk kajian. Data suhu dan kemasinan daripada tatasusunan oseanografi geostropik serantau (ARGO) terapung paling hampir dengan trek taufan masing-masing digunakan dalam kajian ini. Keputusan menunjukkan bahawa SST menurun sehingga 2.97°C; SSS meningkat sehingga 0.44 pss dan majoriti taufan menunjukkan pendalaman lapisan suhu (antara 39.8 dan 4.6 m) dan MLD (antara 69.6 dan 4.6 m) selepas laluan taufan. Laluan setiap taufan juga menyingkirkan jumlah kepanasan yang ketara dari kawasan terlibat. Nilai kepanasan tertinggi ialah 841 MJ m<sup>2</sup> dan yang terendah ialah 30 MJ m<sup>2</sup> semasa tempoh kajian. Bagi tujuan perbandingan, nilai setara tenaga elektrik dalam kWh juga dikira menggunakan amaun kepanasan yang disingkirkan oleh taufan.*

*Kata kunci: Barat Laut Lautan Pasifik; lapisan suhu; MLD; SSS; SST; taufan*

### INTRODUCTION

The terms hurricane and typhoons are specific names for a strong tropical cyclone, based on the region it occurs. Large tropical cyclones are called hurricanes in the North Atlantic and eastern Pacific, typhoons in the western Pacific

and tropical cyclones in the Indian Ocean and south Pacific (Garrison 2005). In short, typhoons (as it is known in areas west of the dateline), are also known as hurricanes (if it occurs east of the dateline) and tropical cyclones (if it occurs on the dateline).

Typhoons occur only in certain regions of the ocean. According to Hidore and Oliver (1993), typhoon usually originates in tropical oceans between latitudes of 5° and 20° and generally forms over the western sides of the ocean. Areas or countries along the equator are safe from typhoons as there is lack of Coriolis force that is needed for the formation of the typhoon. Major typhoons originating grounds includes: The western tropical North Pacific, South Indian Ocean east of Madagascar, North Indian Ocean including Arabian Sea and the Bay of Bengal, tropical waters adjacent to Australia, the Pacific Ocean, west of Mexico and finally the tropical North Atlantic west of Africa including the Caribbean Sea and Gulf of Mexico (Moran et al. 1994). Central and west of the Pacific Ocean experiences an average of 20 typhoons each year, with most occurring from June to October (JTWC 2009).

Typhoons play an important role in maintaining global energy balance by distributing excess heat energy from low latitudes areas to higher latitudes, as an element of the tropical atmosphere-ocean system. Typhoon requires warm, moist air as its fuel. Latent heat provides the typhoons with energy, driving the typhoons' circulation. During this process, water is evaporated as water vapour (which will later condense into water droplets, releasing back the latent heat which originally evaporated the water). When water is evaporated, mass of water in that area will be reduced, but the quantity of salt in the seawater will remain unchanged. This unchanged amount of salt in the water with less mass will increase the salinity of that water (Gierach et al. 2009). Sea surface salinity will also increase due to the mixing of colder deeper water with the surface water of the ocean (thus changing the structure of the ocean).

In this study for 2009 typhoon season in the northwest Pacific Ocean, maximum SST drop of 2.97°C and the highest SSS increase of 0.44 pss were found. The calculated extreme amount of heat removed by a typhoon during the study period was 841 MJ m<sup>-2</sup> and if the whole typhoon affected area was considered, the total amount of heat removed from the ocean surface would be enormous. These findings are fully in line with what the theory predicted.

#### AIMS

Major aims of this study can be itemised as follows:

To evaluate the changes of sea surface temperature (SST) and sea surface salinity (SSS) after passage of typhoons that occurred in Northwest Pacific in 2009; To estimate the amount of heat energy removed from the study area after a typhoon passing; and To calculate the changes on isothermal layer and mixed layer depth (MLD) after passage of each individual typhoon.

#### METHODS

To obtain the changes of SST, SSS, isothermal layer, MLD and the amount of heat energy removed after passage

of each typhoon, ARGO floats data was used (before and after each typhoon's passage) through the salinity and temperature profiles from the Global Oceanography Data Assimilation Experiment (GODAE). These data are available from different ARGO floats that can be found in the Northwest Pacific Ocean, near the typhoons' tracks. An ARGO float measures salinity, temperature and pressure from the surface of the sea to 2000 m depth every ten days. Therefore, an ARGO float data are available every ten days since they only complete one cycle of measurement and transmission within this time frame. The depth is calculated from pressure readings since one decibar is equivalent to one meter.

The temperatures in the ARGO profiles are accurate up to  $\pm 0.005^\circ\text{C}$  and the accuracy of depths is  $\pm 5$  m (ARGO 2010). For salinity, the sensor drift may sometimes affect the real time data. However, this drift is small in most of the floats. Therefore, the uncorrected salinity data are accurate to  $\pm 0.01$  pss (ARGO 2010). Temperature and salinity data accuracy of ARGO are much better than many available oceanography gadgets. Accuracy of depth is not questionable since variation of tides in the ocean is unavoidable.

Once all the data have been gathered, T and S profiles will be plotted and calculations will be made to estimate the changes on SST, SSS, isothermal layer and MLD after passage of the typhoons. The amount of heat energy removed after passage of each individual typhoon was also estimated using a simple formula based on basic Physics. Figure 1 shows the study area of the Northwest Pacific Ocean. In this study a special focus was made on 2009 typhoon season in the Northwest Pacific Ocean and 15 typhoons were taken into consideration. The tricky part was picking the appropriate ARGO floats for data analysis such as location and time. For example, a particular typhoon passed over a huge amount of ocean surface area and temperature and salinity data for the strongest time of the typhoon was chosen for analysis. Individual ARGO floats have their own cycles and the closest dates before and after a typhoon and a location nearest to the typhoon path were used in this study.

#### RESULTS

Having obtained the temperature and salinity data from the appropriate ARGO floats close to the typhoon paths, to observe the change in SST and SSS after the passage of a typhoon, temperature and salinity profiles for before and after the passage of each typhoon were plotted. Each plot shows the temperature and salinity profiles of the water in that area before the typhoon pass under normal condition and also temperature and salinity profiles after the typhoon passage, to evaluate the changes of temperature and salinity. For each typhoon, profiles were plotted using temperature and salinity data from the respective ARGO floats. From the 15 typhoons that occurred in 2009, typhoons *Lupit* and *Ketsana* were picked as examples (to show in details the changes before and after the typhoon).

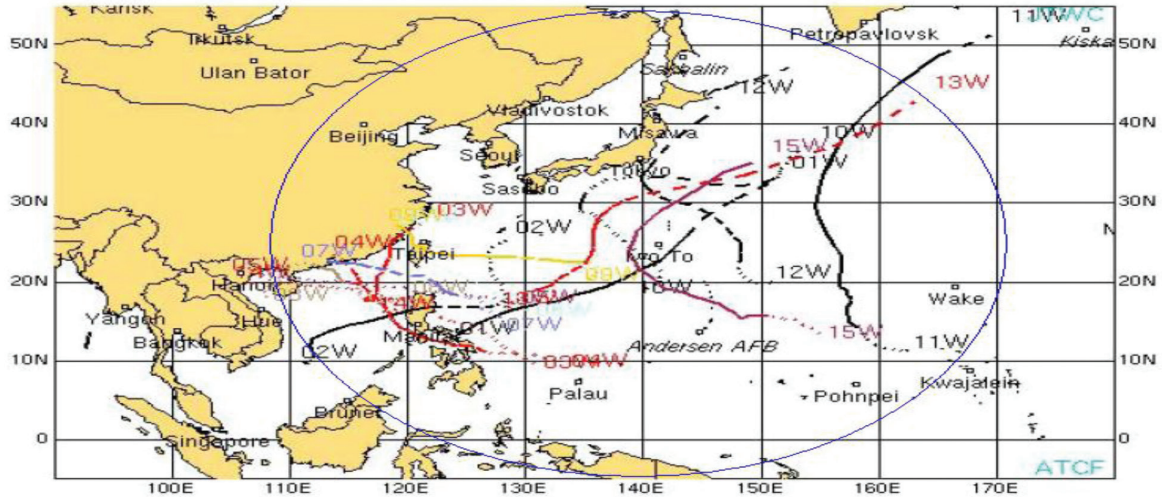


FIGURE 1. Map showing the study area and some of the typhoons' tracks (Source: JTWC 2009)

Having the most significant changes out of all typhoon analysed, *Lupit* and *Ketsana* were therefore chosen as outstanding examples. Typhoon *Lupit* occurred between 14th and 26th October 2009 and reached maximum wind speed of 259 km/h, and was categorized as a super typhoon. Typhoon *Ketsana* occurred between 25th and 29th September 2009, reaching maximum wind speed of 167 km/h. For each of the typhoons analysed, two floats were selected and temperature and salinity profiles were plotted for each typhoon. Each plot shows the temperature and salinity profiles in the area before the occurrence of the typhoon and after the typhoon had passed (Figure 2 for typhoon *Lupit* and Figure 3 for typhoon *Ketsana*). The results for the other 13 remaining typhoons that occurred in the study area in 2009 were also calculated.

Temperature and salinity profiles for typhoon *Lupit* are shown in Figure 2(a) and 2(b) for Float 1, and Figure 2(c) and 2(d) for Float 2.

Similarly, temperature and salinity profiles for typhoon *Ketsana* were also plotted and are shown in Figure 3(a) and 3(b) for Float 1, and Figure 3(c) and 3(d) for Float 2.

All profiles show changes when compared between before and after the passing of each typhoon: Sea surface temperature decreased and sea surface salinity increased. The highest SST drop after a typhoon was as much as 2.97°C and the lowest was found to be 0.1°C. It is to be noted that the accuracy of ARGO float data for temperature is up to  $\pm 0.005^\circ\text{C}$ . Similarly, SSS increase was found to be between 0.44 and 0.1 pss while the accuracy of salinity measurement via ARGO float was  $\pm 0.01$  pss.

Temperature drop after a typhoon had passed indicates that some amount of heat in that area is removed by the typhoon. The change of heat energy can be calculated using the equation as follows. According to basic Physics, sensible heat exchange, is equal to where is the mass of seawater considered, is the specific heat capacity of seawater and is the temperature change. Therefore, the amount of heat removed from a unit area for all typhoons

that were analyzed in this study can be calculated using the following equation:

$$(\Delta Q/A) = \rho z c \Delta T,$$

where  $(\Delta Q/A)$  is the Change of energy per unit area ( $\text{J m}^{-2}$ );  $\rho$  is the average density of seawater in the area ( $1022 \text{ kg m}^{-3}$ );  $z$  is the depth of the isothermal layer (m);  $c$  is the specific heat capacity of seawater ( $3993 \text{ J }^\circ\text{C}^{-1} \text{ kg}^{-1}$  at  $20^\circ\text{C}$ );  $\Delta T$  is the change in temperature ( $^\circ\text{C}$ ) before and after a typhoon; and  $A$  is the typhoon affected area on the sea surface.

For example, the amount of heat removed after the passage of typhoon *Lupit* (Float 1) is as follows:

The average density of seawater in the area,  $\rho$  is  $1022 \text{ kg m}^{-3}$ ; the depth of the isothermal layer,  $z$  is 69.4 m; the specific heat capacity of seawater,  $c$  is  $3993 \text{ J }^\circ\text{C}^{-1} \text{ kg}^{-1}$ ; and the change in temperature,  $\Delta T$  is  $2.97^\circ\text{C}$ .

Putting all the values stated in the equation as follows:

$$\begin{aligned} (\Delta Q/A) &= 1022 \times 69.4 \times 3993 \times 2.97 \\ (\Delta E/A) &= 841,135,815.8 \text{ J m}^{-2} \\ &\approx 841 \text{ MJ m}^{-2}. \end{aligned}$$

From an area of  $1 \text{ m}^2$  of the sea, 841 MJ of energy was removed by typhoon *Lupit*. When looking at the electrical energy point of view:

$$\begin{aligned} \text{Energy} &\approx 841 \times 10^6 \times (1 \text{ h}/3600 \text{ s}) \\ &\approx 233,611.111 \text{ Wh} \\ &\approx 233.61 \text{ kWh}. \end{aligned}$$

Approximately 233.61 kWh of electrical energy was removed by *Lupit* from just  $1 \text{ m}^2$  of area. It simply means that a 100 W light bulb can be lit for 2336.1 h or almost 100 days by using this energy. If the total sea surface area

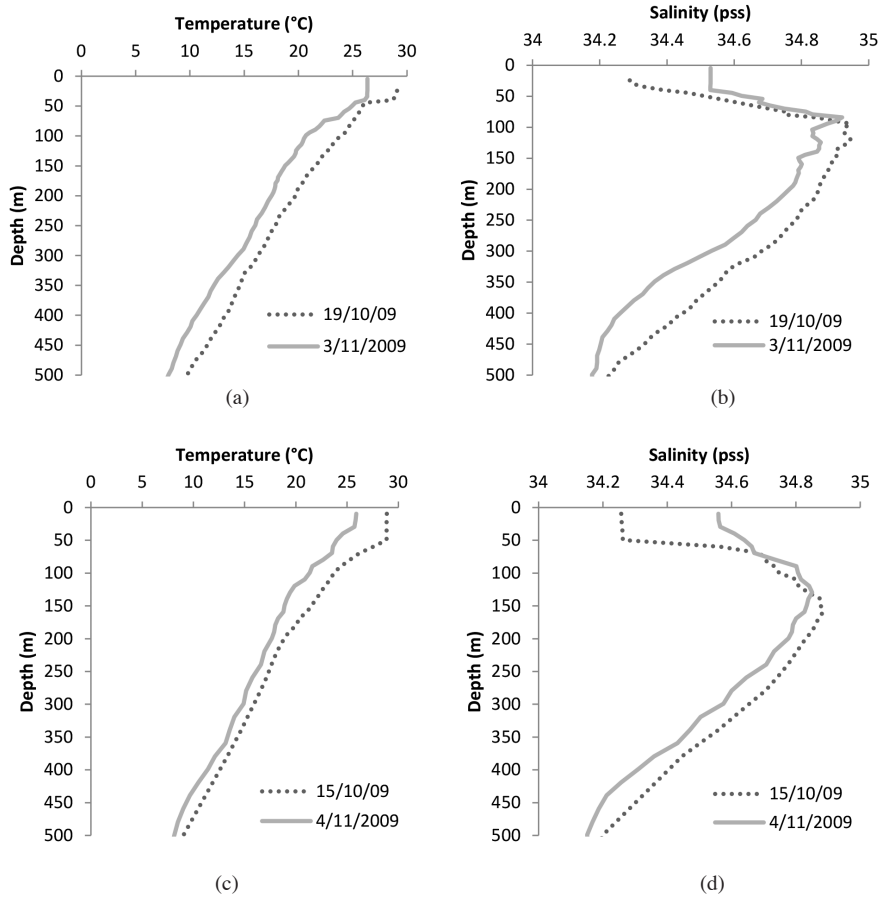


FIGURE 2. Temperature and salinity profiles for Typhoon *Lupit* (a) and (b): Float 1; and (c) and (d): Float 2

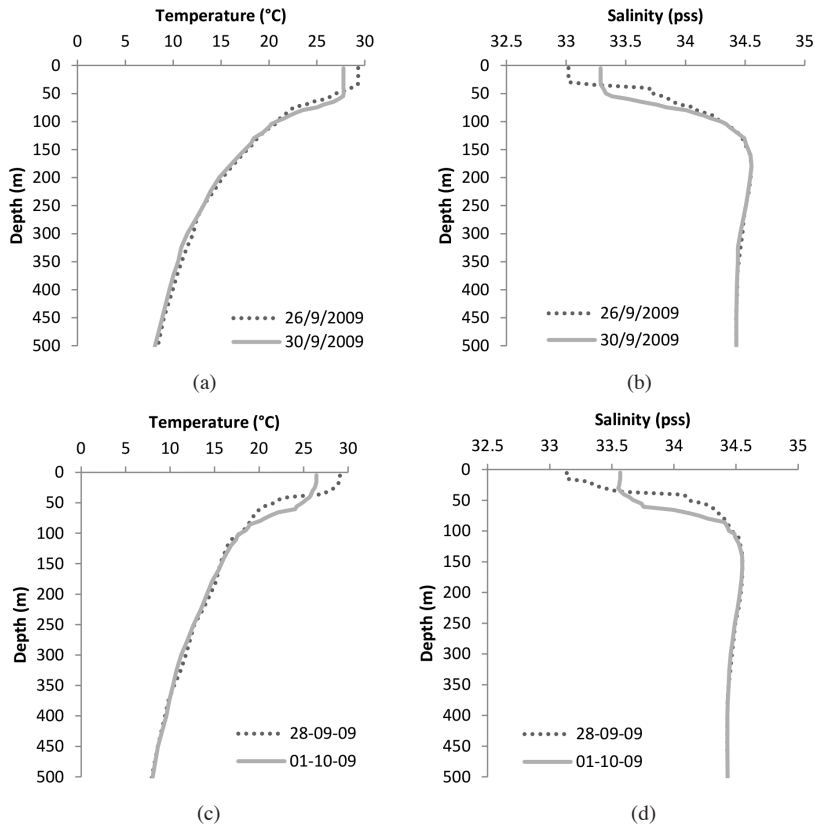


FIGURE 3. Temperature and salinity profiles for Typhoon *Ketsana* (a) and (b): Float 1; and (c) and (d): Float 2

near the typhoon's track (area in contact with the typhoon) is considered, the total amount of energy (an equivalent electrical energy) removed is extremely large. During this study, the calculated amount of energy, removed from sea surface area (of 1 m<sup>2</sup>) ranged from 841 to 30 MJ m<sup>-2</sup> depending on the strength of a typhoon.

Passing of a typhoon, apart from causing changes in temperature and salinity in the affected area, will also cause changes in the top layer ocean's structure. From the temperature profiles of individual ARGO floats for 15 typhoons in 2009, changes of the affected isothermal layer were also identified in this study. Isothermal layer of the ocean is the depth between the starting point of thermocline and the surface, where temperature is almost constant. Similar to what was done for isothermal layer changes based on temperature profiles, changes of mixed layer depth based on salinity profiles were also calculated. Mixed layer depth of the ocean is the depth of the starting point of halocline from the surface, where salinity is almost constant. The range of isothermal layer deepening is between 39.8 to 4.6 m. It is noteworthy that the accuracy of depth measurement via ARGO floats is  $\pm 5$  m and the findings less than 5 m is not taken into consideration as significant. Similarly, the MLD also changed (deepened) from 4.6 to 69.6 m due to the effect of typhoons. Biologically, the impacts of these changes in ocean top layer play a major role on the sustainability of marine ecosystem although it is not the main thrust of this study.

## DISCUSSION

There are at least three types of exchange (or flux) between air and sea, such as heat, water and momentum flux. Among them, we focus on heat flux: Movement of energy by two kinds of radiation, short wave (light) and long wave (heat); direct contact between ocean and air as sensible heat and evaporation (or condensation) as latent heat. Even for the concept of heat flux our thought is only on the last two processes (sensible heat and latent heat) only. Latent heat released during any kind of storm increases instability in the atmosphere causing severe weather. The concept is the key point of wind induced surface heat exchange (WISHE) proposed by Emanuel (1986).

After a typhoon or hurricane or a tropical cyclone passes over a certain area of sea surface along the cyclone track, the temperature of mixed layer (SST) drastically drops and the salinity at the surface layer (SSS) increases. The amount of heat loss to reduce the temperature is simply used as WISHE to evaporate some amount of water from the surface layer and the salinity in that area increases subsequently (Emanuel 1986).

As evidenced from the results we have achieved in this study, sea surface temperature decreased (up to  $\sim 3^\circ\text{C}$  in one particular case of typhoon *Lupit*) and sea surface salinity increased (as much as 0.44 pss for a strong typhoon, *Ketsana*) after the passage of each typhoon. Decrease in SST after a passage of a typhoon is in agreement with

several previous studies. For example, studies by Babin et al. (2004), Chen et al. (2003), Dickey et al. (1998), Lin et al. (2003), Mueller-Karger et al. (2000), Price (1981) and Son et al. (2007) have all recorded cooling of SST after the passing of a typhoon. Other than that, Xiaoping et al. (2008) also showed that SST in the South China Sea dropped by  $5.5^\circ\text{C}$  in response to the passing of typhoon *Krovanh*. Walker et al. (2005) also found that SST cooled by approximately 3 to  $7^\circ\text{C}$  after passage of *Hurricane Ivan* in the Gulf of Mexico. Study done by Wang et al. (2011) also explained that based on both ARGO floats data and satellite SST data, there was significant cooling of SST in the Northwest Pacific after passage of typhoons *Kaemi* and *Cimaron*.

Typhoons can be likened to an engine that requires moist, warm air for its fuel. Therefore, it is also known as a natural heat removing mechanisms, which is beneficial as its transport and moves heat away from the tropic regions (where it usually originates) to the subtropic regions. In other words, typhoons plays an important role in maintaining global energy balance by distributing excess energy from low latitudes areas to higher latitudes as an element of the tropical atmosphere-ocean system (Garrison 2005). The results in this study agree and are consistent with this concept, as it was calculated that typhoon *Lupit* removed approximately 841 MJ of heat energy from an area of 1 m<sup>2</sup> during its course. If the whole area affected by *Lupit* is considered, the amount of heat energy removed is enormous.

Overall, out of the 15 typhoons studied in this current study, the amount of heat removed ranged from 30 MJ m<sup>-2</sup> (from passing of typhoon *Chan Hom*) to 841 MJ m<sup>-2</sup> (from passing of typhoon *Lupit*). The amount of temperature change in that area (influenced by wind intensity) during passage of the typhoon greatly affects the consequent amount of heat removed. The removal of heat by typhoon can be calculated from rain and wind speed as well (Emanuel 1986) using other formulae.

This massive heat loss after course of a typhoon can be beneficial not only to marine life, but also to us as human. Most marine life can only tolerate very little increase in temperature. For example, corals, which reefs are one of the most important marine ecosystem. Increase in global air temperature over the past decades has caused massive bleaching of corals. The phenomenon called coral bleaching is caused by stressor such as high temperature and oxygen deficiency, among others. When these conditions present themselves, zooxanthellae that are found in the corals will expulse themselves from the corals' polyps, often resulting in the coral's death (Sorokin 1995). Therefore, heat removal from the ocean caused by a typhoon can prevent these corals from stressing due to increase in water temperature and provide a healthier environment for coral reefs' growth.

Similarly with this present study, increase in SSS after an event of a typhoon has been recorded in previous studies such as in the study done by Chen et al. (2003). It was found that there was more saline water in areas where the

temperature has dropped by 4°C after a typhoon. Mueller-Karger et al. (2000) also recorded an increase in SSS after passage of a typhoon due to upwelling. Simulation studies have also been carried out to further study the impact of typhoon on SSS. Robertson and Ginis (1998) also endorsed that there was a 0.20 pss increase in salinity of seawater to the right of the typhoon's track.

Change in SSS can affect the livelihood of marine organisms that can be found in the surface water. This is mainly due to salinity of water having significant influence on the species composition, as different species can tolerate different level of salinity. Therefore, changes in SSS even in small amount, could affect certain species.

Significant changes on isothermal layer and MLD of the ocean were also observed in this study, as passage of the typhoons caused mixing and turbulence of the ocean water, hence changing the structure of the ocean (deepening of the isothermal layer up to ~40 m and MLD up to ~70 m). These modifications of the ocean properties and structure influences marine organisms in the affected area, not only generally, but also the behavior of marine organisms that perform vertical motion in the ocean due

to changes of food source and predator stress. These elements are important in maintaining growth of marine organisms, as well as for the growth of phytoplankton in the ocean (Garrison 2005). When a typhoon passes an area of the ocean, the subsequent increase in salinity and nutrients in the surface layer of the ocean will influence the primary production through phytoplankton bloom in that area.

To demonstrate the changes in estimate of net primary production from chlorophyll in the water after passage of typhoon *Ketsana*, satellite images from MODIS are used as an example (Figure 4). Different colours on the figures indicate different level of net primary production level, based on MODIS chlorophyll and temperature data (MODIS 2012). Data are available for an 8-day cycle as it takes that long for the satellite to complete one mission around the globe.

It can clearly be seen that net primary production in the areas affected by *Ketsana* (areas between northern Philippines and Vietnam) increased, as can be seen in Figure 4(b) when compared with the net primary production before the passage of *Ketsana*, as in Figure 4(a).

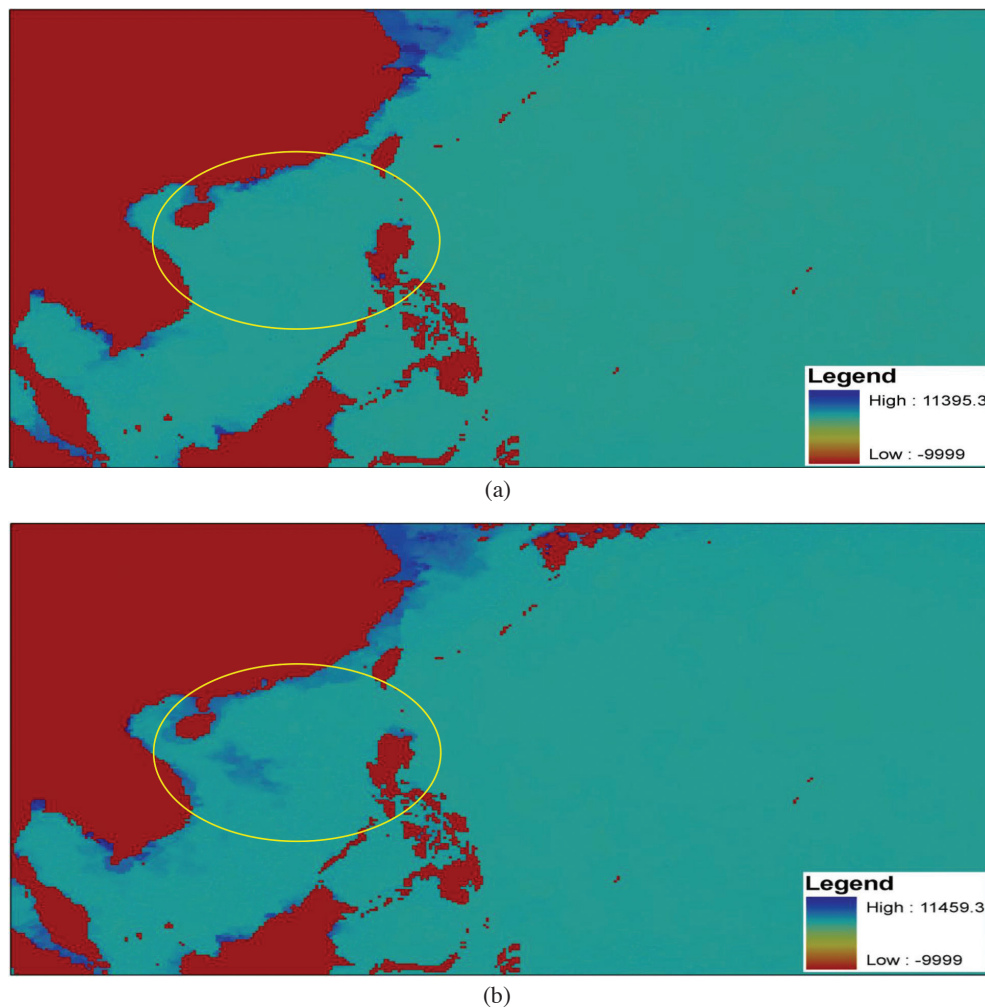


FIGURE 4. Net primary production ( $\text{g C/m}^2/\text{day}$ ) in the study area affected by *Ketsana* (a) 14 September 2009 - 21 September 2009 and (b) 30 September 2009 - 7 October 2009 (Source: MODIS 2012)

If changes in phytoplankton concentration in the affected areas of all remaining typhoons were to be shown as were done for *Ketsana* (Figure 4), similar results can be expected or anticipated: Phytoplankton concentration level will increase during the passage of the typhoon and approximately 10 days after.

#### CONCLUSION

From this study and based on the results, it can be confirmed that SST, SSS, isothermal layer and MLD have significant changes after the passage of a typhoon. In this case, SST decreased up to 2.97°C after passage of typhoon *Lupit* and 2.64°C after the passage of typhoon *Ketsana*. SSS increased up to 0.30 and 0.44 pss after the passage of typhoon *Lupit* and *Ketsana*, respectively. Isothermal depth and MLD also showed changes after passages of the typhoons, where deepening of isothermal depth and MLD are up to 42.3 and 69.6 m, respectively. There were also shallowing of isothermal depth and MLD, but the values are insignificant compared with deepening of the depths and the values are less than the accuracy of depth measurements via ARGO floats,  $\pm 5$  m. Understanding the effect of typhoons on seawater properties and ocean's structure is not only important to the marine organisms and environment, but also to human beings, as it is responsible in cooling the tropics regions and maintaining moderate temperature for life. Without these regular typhoons in our region, our lives together with marine eco-system would have been rather miserable with unbearable heat stress. Although it is undeniable that typhoons have brought so many grieves, damages and deaths over the years, what most of us failed to see or understand is despite all that, they actually have positive impacts, not only to marine environment but also to human beings, especially from the science point of view. As the saying goes: Even the road to hell is paved with good intentions!

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