Upper ocean response to typhoons in the Northwest Pacific from ARGO floats

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Abstract: Statistical characteristics of the mixed layer responses to typhoons in the North Pacific and their causes are examined using ARGO profiling float data for 4 years from 2000 to 2003. 395 match-up profiles before and after typhoon passage are paired to estimate changes in mixed layer temperature (MLT) and mixed layer depth (MLD). Histogram of MLT and MLD changes show the largest peak of MLD cooling at around 1.0°C and ML deepening of about 5.6 m after typhoon passage. Changes in MLT and MLD are inversely correlated due to their dependence on the initial oceanic status. The ML responses are of remarkable meridional dependence. Maximum cooling and deepening appear at mid-latitudes of 20~30°N and mainly caused by relatively strong wind, slow translation speed of typhoon, and shallow background oceanic ML.

1. INTRODUCTION

Typhoon is the most extreme of atmospheric phenomenon and a distinct product by air-sea interaction. Strong wind by typhoon transfers the heat of the oceanic mixed layer to the atmosphere and diffuses it below the oceanic thermocline through turbulent mixing process [Price 1981]. In overall, this induces surface cooling and decrease of mixed layer temperature. In the North Atlantic, during hurricane event, the oceanic mixed layer depth (hereafter MLD) has been found to deepen by 30 ~ 35 m and its deepening signal was more clear on the right of the hurricane track [Shay et al., 1992]. These upper ocean changes, in turn, affect on the change of typhoon strength through the air-sea feedback mechanism [Emanuel, 1991]. Many of satellite observations and some observational data obtained from moored instruments have showed the cooling with a broad range of 1~6°C at the sea surface as well as in the mixed layer after typhoon passed [Withee and Johnson, 1976; Price, 1981; Cornillon et al., 1987; and many others].

To understand air-sea interaction during the typhoon events, subsurface measurements following the typhoon are of significance. Despite of the importance, most of the previous observational results have been confined to a local area for a single storm. Argo (http://www.argo.net) is a global array of drifting profiling floats that can measure the temperature and salinity of the upper 2000 m of the ocean in or near real-time, even under extreme atmospheric and oceanic conditions during typhoon events [Roemmich and Owen, 2000]. Moored measurements have presented that upper ocean response during hurricane event cannot be directly restored to the marine environment at pre-storm stage, but maintained for more than 20 days [Withee and Johnson, 1976]. The slow restoring characteristics of ocean response enable us to use ARGO float data during typhoon period even though the float data have a relatively sparse profiling interval of about 10 days. Kwon and Riser [2005] showed that Argo float data could give us useful information on the upper ocean response to hurricane in the North Atlantic for the first time.

Here, we present the methodology of the ARGO float data processing for typhoon studies and show statistical characteristics of upper ocean response in terms of MLT and MLD changes in the western part of the North Pacific during typhoon events.

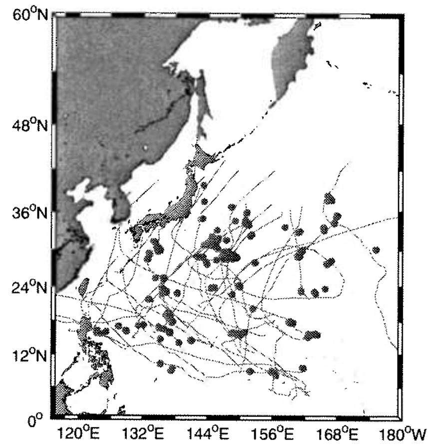

Figure 1. Distribution of profile pairs and corresponding typhoon tracks.

2. DATA PROCESSING

The ARGO floats have been intensively deployed worldwide since 2000. In this study, we utilize all the available profile data, from the Argo Global Data Assembly Centres, in the North Pacific for recent 4 years of 2000~2003. In order to pickup accurate data, real-time and delayed mode quality controls are performed for the profile data [Wong et al., 2003]. Information on typhoon characteristics such as track, wind gust speed, translation speed, and air pressure at the center of the storm is obtained from Joint Typhoon Warning Center (http://www.npmoc.navy.mil /jtwc.html).

In order to examine the change of the MLT and MLD, first of all, we made match-up database of the float profile pairs near typhoon track. Two temperature/salinity profiles before and after a typhoon passage are paired off, if they meet three criteria: (1) both profiles of the pair are within 200 km apart from the typhoon center, (2) the distance between the two profiles should be within 200 km, and (3) both profiles (7-10 days apart in time) should be within a time window defined as ±10 days before and after the typhoon passage. The total number of the profile pairs is 751, but 356 pairs, produced by a particular float with measurement every 24 hours, are eliminated from the following statistical analysis. In determining the MLD, we have used a criterion by temperature only instead of density because some floats have serious error in salinity data or measure temperature only. The MLD is defined as a depth at which the temperature differs from the sea surface temperature by 0.3°C [Monterey and Levitus, 1997]

Using the match-up database, the ML responses during typhoon passage are examined by analyzing differences of MLT and MLD before and after typhoon. In order to distinguish the oceanic response to typhoon from background variability of the ocean, we also searched the profile pairs, from June to October, within the same spatial and temporal windows, but regardless of the presence of typhoon. Statistics of these pairs are regarded as background variation of ocean during non-typhoon period.

3. Statistics of MLT and MLD changes by Typhoon

As denoted with blue line in Fig. 2, oceanic variations irrespective of typhoon events are close to normal distribution both in MLT and MLD changes. During the typhoon events, however they become shifted toward cooling evidently within 99% of confidence level. It is notable that there is the relatively poor correspondence between the histogram and the fitted normal distribution curve in case of the typhoon. That is, Histogram seems to be fitted better using a skew distribution than a normal distribution in case of the typhoon events. This kind of skewed distribution might be caused by the fact that the upper ocean mostly has cooling response to tropical storm. About 89% of the 356 pairs reveal the cooling of 0~4°C. The frequency density peaks at cooling of 1~1.5°C. The range of MLT changes shows good agreement with the previously-reported MLT cooling of 1~6°C [Fedorov et al., 1979; Price, 1981; Pudov, 1978; Shay, 1992]. Gallacher et al. [1989] suggested that the cooling of only 2.5°C in MLT would bring about complete suppression of tropical cyclone. So, the present MLT decrease of 1°C seems to be significant enough to control or weaken the strength of typhoons.

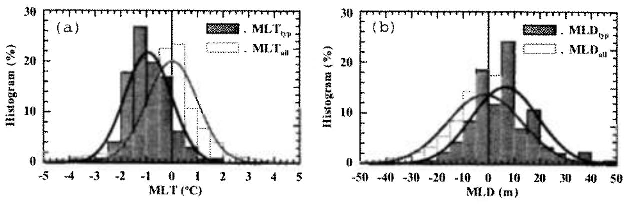

Figure 2. Histogram of difference of temperature in the mixed layer (a) and difference of the mixed layer depth (b) in the North Pacific (AFTER – BEFORE). Open boxes denote histogram of differences of MLT and MLD regardless of typhoon events. Solid curves denote gaussian fits to histograms.

As already pointed out, ML cooling is the most common response to the typhoon [Price, 1981]. Although it is minor, there are still a few points with ML warming in the histogram of the Fig. 2. Those warming samples might not be direct local response to typhoon but some higher frequency noises which could not be resolved in ARGO data with the criteria in section 2. The noises might be related to horizontal Ekman advection, movement of the subtropical or subpolar fronts, or others. Thus, even though typhoon mostly induces the cooling of the upper ocean, the warming tail in Fig. 2 can be due to natural background variability which cannot be distinguished in the float data. The details on background variability will be discussed in section 4.

Typhoons give rise to two different kinds of MLD responses, deepening and shoaling. The deepening is caused by entrainment due to energetic turbulent mixing from strong wind of typhoon, whereas the shoaling response is caused by Ekman divergence at the surface under anti-clockwise rotating wind field [Shay et al., 1992]. In contrast to the MLT cases, a systematic shift of the probability distribution of the MLD changes in response to the typhoon is less apparent (Fig. 2b). It is partly because the deepening occupies a relatively small fraction of about 60% of total match-ups, while rest of them show shoaling. Another noticeable difference between the histograms of MLD and MLT changes is that the histogram of the MLD change does not look like a single skewed normal distribution or normal distribution. At least, it seems to have two-or three peaks, which could be caused by the MLD response to typhoon in two different ways, the deepening by the mixing and the shoaling by the Ekman divergence.

Figure 3a presents the relation between MLD change and MLT change. Even though the existence of the shoaling responses, the dominant response is deepening of the ML accompanied by cooling, which is consistent with previous studies [e.g. Price, 1981].

On average, the deepening of the MLD is about 56 m and the cooling is about 1°C in the North Pacific. Our observational results manifest that the MLT and MLD responses to tropical cyclone in the North Pacific occur cooler and deeper than those in the North Atlantic by 15~20% when compared with the result of Kwon and Riser [2005]. The two populations of MLT response in the North Pacific and the North Atlantic have statistically different mean with confidence level of 97% by student's t-test. Magnitude of the ocean response is dependent on many factors, such as the initial MLD, intensity of the storm, translation speed of the storm, etc. [Price, 1981]. The MLD in the North Pacific is relatively shallower than that in the North Atlantic [Kara

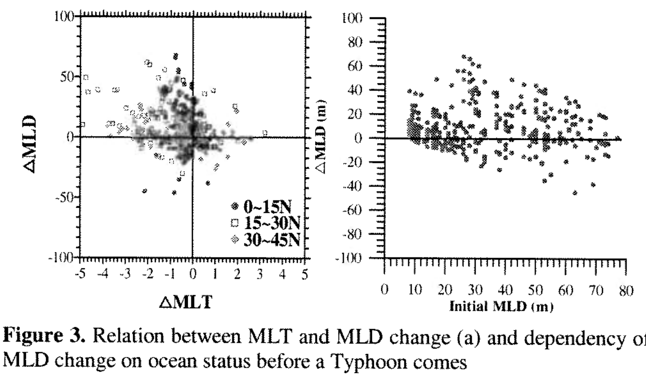

Figure 3. Relation between MLT and MLD change (a) and dependency of MLD change on ocean status before a Typhoon comes

et al., 2003], even though the difference of MLD between both basins varies with season. Thus, relatively shallow MLD in the North Pacific may be one of important contributors on large ocean response to typhoons.

4. Meridional Characteristics of Mixed Layer Response

Magnitude of the ocean response during typhoon event would vary regionally within the North Pacific as well as between the North Pacific and the North Atlantic, due to the spatial variations in the factors affecting the ocean response. Most of these factors related to the background oceanic and atmospheric conditions have zonally coherent spatial distributions. Thus, we will examine the meridional dependence of the ocean response in zonal average sense, in terms of its relations to the meridional variations of the factors affecting them.

The MLT and MLD changes during typhoon event have latitudinal dependency as expected (Fig. 4). The largest cooling with a mean of 1°C appear at 25~30°N latitude band. At higher latitudes (>35°N), relatively weak cooling of less than 0.3°C is present (Fig. 4a). Note that the lower latitude region (<10°N) shows relatively large cooling of about 0.7°C. By contrast, the MLD changes tend to have both positive and negative values (Fig. 4b). Zonally-averaged MLD changes show the maximum deepening at the mid-latitude region of 20~25°N, with 5-degree difference from the maximum cooling region (25~30°N). At higher latitudes from 30°N to 40°N, the MLD change during typhoon event gets smaller. There is strong shoaling at region of lower latitudes (<15 m) (Fig. 4b).

The meridional dependence of MLT change is rather less clear than that of MLD change. A dotted line in Fig. 4a shows MLT change by turbulent mixing which is decomposed by the following equation,

$$\Delta MLT_{mix} = \frac{1}{MLD_{post}} \int_{0}^{MLD_{post}} T_{pre}(z)dz - MLT_{pre}, \quad (1a)$$

$$\Delta MLT_{nomix} = \Delta MLT - \Delta MLT_{mix}, \quad (1b)$$

where where ΔMLT is total MLT change (MLT before typhoon event minus that after typhoon event), and ΔMLT_{nomix} and ΔMLT_{mix} stand for MLT change by the other effects (Ekman pumping or air-sea heat exchange) and entrainment. MLT_{pre} and MLT_{post} are MLT from a profile before and after typhoon passage, respectively. $T_{pre}(z)$ is temperature profile in pre-typhoon and MLD_{post} is the mixed layer depth in post-typhoon. The MLT change associated with entrainment due to MLD deepening is consistent with MLD change in terms of meridional variation even though the total MLT change is not. That might be because MLT cooling occurs by not only entrainment but also by MLD shoaling (by Ekman pumping) and air-sea heat exchange (by latent heat flux), although air-sea heat exchange is partly related to entrainment.

These meridional characteristics of the MLD and MLT responses are likely associated with characteristics of typhoon itself and initial MLD prior to the arrival of tropical storm. Fig. 5a shows zonally-averaged variations of wind strength, the translation speed of typhoon, and background MLD as a function of latitude. Maximum response of MLT cooling prefers conditions of the strongest wind gust and slow translation of typhoon [Price, 1981]. At the latitude of 25-30°N, the wind gust speed reaches the maximum of about 37 m/s and translation speed is still small to around 5 m/s (= ~18 km/h). Additionally background oceanic MLD getting shallower makes MLD easy to deepen by turbulent mixing. So this oceanic and atmospheric condition induces the maximum of MLT change and MLD deepening at this latitude band. In the higher latitudes (35~40°N), however, weak wind gust speed of about 22 m/s and the fastest typhoon movement of about 13 m/s could have results in relatively small MLT cooling of about 0.5 °C (Fig. 4a). The relatively large cooling at lower latitudes (5~10°N) in spite of weak wind gust of 20m/s seems to be caused by the slowest movement of typhoon by 6 m/s. It is notable that the MLT change by mixing is the smallest in the latitude band shown in Fig. 4a. Slow movement of typhoon and deep background ML lead to condition of shoaling rather than deepening at the lower latitude band. This dominant shoaling might be a key factor to determine degree of MLT cooling, although the cooling by deepening and shoaling can be hardly decomposed quantitatively using the only profile data that were available in this study.

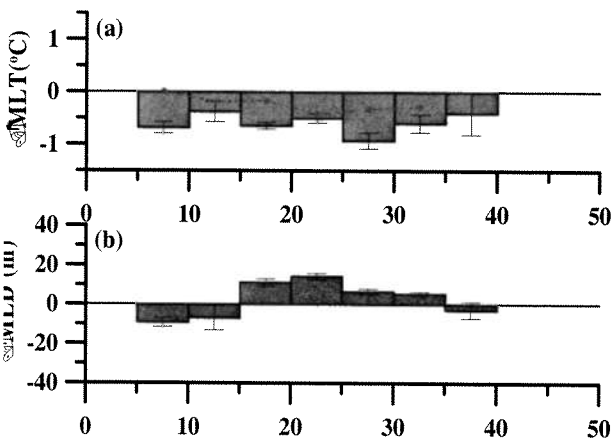

Figure 4. Zonal averaged MLT (a) and MLD (b) change during Typhoon event. A dotted line shows MLT change by turbulent mixing. Error bars present mean standard error in each 5° band.

5. Summary and Discussion

The data obtained from ARGO floats clearly confirm biased responses of MLT and MLD to typhoons and shows the profile data are useful to investigate the upper ocean response during typhoon events. The mean MLT and MLD change in the North Pacific reach -1.0°C and 5.6 m which is larger by 15~20% than that in the North Atlantic presented by Kwon and Riser [2005]. The relatively large response in the North Pacific might be attributable to relatively shallow MLD in the North Pacific as well as stronger wind of typhoon. Emanuel [1991] pointed out that MLT cooling could cause the negative feedback of atmosphere and ocean. Indeed, the MLT cooling and weakening tendency wind gust have positive correlation (not shown).

The mean MLT and MLD change peak around 20~30°N where the wind gust of typhoon hits a maximum and the translation speed of storms is still relatively small. The MLT change presents relatively weak dependence on latitude, which could be attributed to the fact that MLT cooling is produced by various mechanisms, such as turbulent mixing, Ekman pumping, and air-sea heat flux.

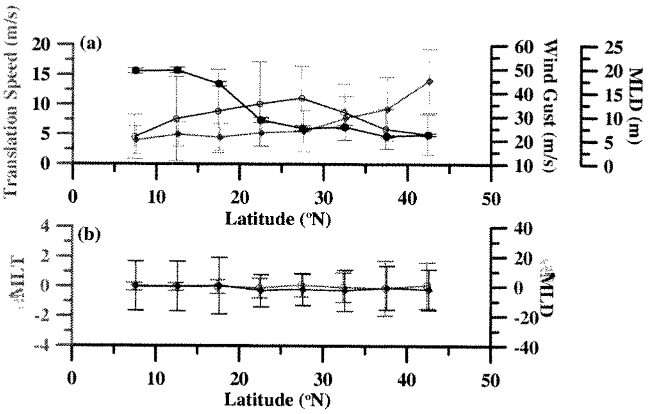

Figure 5. (a) Zonal averaged translation speed (Red) and maximum wind gust (Blue). Error bar shows one standard deviation in each 5° band. Zonally averaged MLD from all float data collected within 115°E~180°E in summertime (Jun.~Oct.) (Black). Error bar presents mean error. (b) Zonal averaged MLT difference (Red) and MLD difference (Blue) obtained from profile pairs with non-typhoon event. The error bars denote the standard deviations of each latitude band.

The present statistical approach may contain some limitations, which mainly come from sampling errors, various characteristics of typhoons themselves, and statistical characteristics of background ocean regardless of typhoon. We would like to have a close look especially on possible contribution from the variance of background MLT and MLD. Since the number of sampling is enough to evaluate the statistics (more than 30) and does not have significant dependence on latitude, the sampling is likely not the source of the difference in variances among latitude bins. The variance of MLT gets larger as it goes to the high latitude (Fig. 5b). This suggests that the chance for the temperature of the mixed layer at 30~40°N to vary within 200 km and ±10 days just due to background variability is relatively higher compare to the lower latitude. Indeed, this region contains the Kuroshio extension which has high mesoscale variability with less than 100 km. One of other potential contributors to the large meridional variations in variance may be meridional change of Rossby deformation radius. In fact, our rough estimation shows the baroclinic Rossby deformation radius at 40°N is 4 times smaller than that at 10°N. It is interesting to note that the meridional variation of the variance of the MLT change due to the typhoon is almost proportional to that of the background MLT change (Fig. 5b). Contrast to the MLT case, but variance of MLD does not show remarkable dependence on latitude.

It gives some idea about those spatial and temporal criteria to obtain upper ocean change by typhoon should be varied with latitude in the North Pacific. However, since the statistical analysis in this study focuses on the variation of mean value, the constant criteria in time and space are reasonable for the analysis and spatio-temporal varying criteria do not provide significantly different results.

The Argo floats deployed in the North Pacific also measure salinity profiles so that the freshwater exchange in the upper ocean during typhoon event will be analyzed as a further study.

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