Tropical cyclone turbulent mixing as observed by autonomous oceanic profilers with the high repetition rate.

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Abstract. Changes in the ocean mixed layer caused by passage of two consecutive typhoons in the Western Pacific are presented. Ocean profiles were measured by a unique Argo float sampling the upper ocean in high repetition cycle with a period of about one day. It is shown that the typhoon passage coincides with cooling of the mixed layer and variations of its salinity. Independent data from satellite measurements of surface winds were used to set-up an and idealized numerical simulation of mixed layer evolution. Results, compared to Argo profiles, confirm known effect that cooling is a result of increased entrainment from the thermocline due to enhancement of turbulence in the upper ocean by the wind stress. Observed pattern of salinity changes in the mixed layer suggest important role of typhoon precipitation. Fast changes of the mixed layer in course of typhoon passage show that fast profiling (at least once a day) is crucial to study response of the upper ocean to tropical cyclone.

1. Introduction

Tropical cyclone (TC) impact on the upper ocean is manifested by decrease of the sea surface temperature and is known as the "cold wake" (Fisher, 1958). Enhanced surface wind stress forces turbulence and downward momentum transport, leading to increased shear at the bottom of the mixed layer. In effect increased entrainment of cold water from the thermocline results in decrease of the mean temperature across the whole mixed layer. Typically, the ocean response is stronger on one side of the TC track (Price, 1981) which is explained by coupling of the wind stress curl with inertial oscillations. In the northern hemisphere this occurs on the right side of the TC track.

Extreme weather observed in tropical cyclones prevent manned measurements of the cold wakes. Arrays of mooring buoys, such as TAO, are sparse and rarely capture the TC passage (McPhaden et. al., 1998). However, autonomous profiling buoys such as ARGO (Argo Science Team, 2008) enable direct measurements of the oceanic mixing underneath a tropical cyclone as well as analysis of the ocean mixed layer relaxation after the tropical cyclone passage. The purpose of this research is to study data from such autonomous profiler collected during the tropical cyclone passage.
2. Methods and Data

Typical Argo profiler spends most of its time parked at depth of about 1500m. It ascends every 10 days measuring vertical profile of temperature and salinity. Some floats operate in a cycle shorter than three days, but their number is very limited. Such short timescale is necessary to investigate tropical cyclone wake, since transitional speed of tropical cyclone is typically 4 to 8 m/s and post hurricane ocean recovery happens within days. In our analysis data from a non-standard autonomous float, operated in a 1 day cycle instead of a typical 10 days is used. Finding suitable measurement data was achieved by comparing databases of cyclone tracks with information on the position of Argo profilers. We identified that the Argo float WMO ID 5901579 (18N, 127E) coincided, between September 9th and October 5th (Day of the year 253-279, 2008), with two typhoons - TY Hagupit and TY Jangmi. Hagupit passed 80km south west from the buoy leaving it on its right side; Jangmi passed 60km north east from the float leaving it on the left side of the track.

Additionally we used satellite data from QuikScat scatterometer and Tropical Rainfall Measurement Mission (TRMM) radar in order to estimate wind speeds (compare Fig. 1) and precipitation (Fig. 2) at the location of the profiler. Both remote sensing data are averaged over area 17-18N, 126-127E that fits location of the Float ID 5901579 and provides the best information of the atmospheric conditions during typhoons passage. The first peak of the wind speed (09/21st in Fig. 1) represents TY Hagupit, the second one on 09/25th corresponds to TY Jangmi. Maximum value of the wind speed was about 25 m/s for each of the typhoons. It can be seen that maxima in the wind speed are associated with peaks in the precipitation (Fig. 2). An idealized, 3 dimensional, primitive equations, hydrostatic numerical ocean model (3D PWP) (Price et.al., 1994) was used to obtain further insight into the oceanic mixing processes. Model has 5 km horizontal resolution and 5 m vertical resolution, and uses radiative boundary conditions. The model was initiated with the ocean state based on data from the Argo profiler collected before passage of typhoons. Surface forcing was taken from the International Best Tracks Archive for Climate Stewardship (IBTrACS) and other telemetric data.

Figure 1. Wind speed in m/s from QuikScat. Figure 2. Precipitation rate from TRMM.

3. Argo Results

Temporal evolution of the upper ocean temperature interpolated from consecutive Argo profiles is presented in Fig. 3. Arrows indicate intensive cooling events on days 263 and 271; September 19th and 27th, respectively. These dates match the shortest distances of the float from typhoons Hagupit and Jangmi. Cooling is associated with deepening of the mixed layer, which points to the dominant role of entrainment from the thermocline.
The temperature drop after Hagupit passage - 0.65°C - is greater than that after Jangmi passage - 0.23°C. This can be explained by the fact that measurements were taken on the right side of the first typhoon and on the left side of the second one. Another possible effect is that the depth of the mixed layer and stability at the thermocline increased after passage of the first TC. Once well mixed upper ocean would need stronger momentum flux to break stability and to increase entrainment and mixing. Less entrainment and redistribution of heat in the thicker water column would cause snakker temperature drop. One can see in Fig. 1 that wind stress at the ocean surface was comparable in both typhoons. Location of the float wasn’t favourable for momentum flux enhanced by coupling with inertial oscillation. In effect thermal response to typhoon Jangmi was weaker then to typhoon Hagupit even when according to IBTrACS Jangmi was stronger tropical cyclone during transition above float location.

Typhoon passage is associated with remarkable variation in mixed layer salinity (Fig. 4). Initially, after typhoon passage salinity increases, which correlates well with entrainment and mixing of cold and salty water from beneath the mixed layer. In the following days gradual freshening of the mixed layer originating at the ocean surface can be seen. This is effect of high precipitation (Fig. 2) lasting longer than the increased wind forcing. Rainfall water forms a stable layer on top of the mixed layer which slows downward transport of the fresh water. Such a scheme is consistent for both Hagupit and Jangmi. For both typhoons decrease in salinity occurs first at the surface and later propagates down through the mixed layer. Weaker increase of salinity during passage of the second typhoon agrees with weaker entrainment as documented by temperature observations. Presence of a stably stratified layer close to the ocean surface is not reflected in temperature profiles, since intensive mixing before its formation resulted in uniformization of temperature across the mixed layer. This means, that effect of water supply due to rainfall and following stratification changes is visible only on salinity profiles.

4. Modelling Results

3DPWP numerical model was set to simulate ocean response to Jangmi passage. Typhoon was parameterized as a Rankine vortex with the radius of maximum wind and the value of maximum wind speed based on IbTrACS data. When Jagmi was passing by the float location it had 60 km radius, 49 m/s maximum wind speed and was 6 m/s transitional speed. These values were
used to set vortex in the 3DPWP model. Initial vertical profile in the ocean was from Argo observation taken 1.5 day before storm approach. Distribution of temperature and salinity within model the domain was horizontally uniform.

Figure 5 shows 3 successive Argo profiles and corresponding profiles from the simulation. Modeled oceanic response compares reasonably well with the observations, confirming mixing effects of typhoon passage on the upper ocean. Temperature values and tendencies are well reproduced in the simulation. On the other hand modeled mixed layer depth deviates from the observation. This may be explained by internal ocean variability or by inertial oscillations left by tropical cyclone. Since we compare individual Argo profiles there is no way to know the phase of inertial oscillation, which changes the depth of thermocline but does not affect the temperature within the mixed layer.

Figure 5 presents 3 consecutive profiles of temperature taken day after day and can be compared to Figure 3 showing longer period of observations. It can be seen that cooling occurs within first 1-2 days during typhoon passage. After 3 days cooling stops and relaxation begins, ocean warms up to steady state conditions. Therefore daily temporal resolution is required to investigate upper ocean response to tropical cyclone forcing. Even more frequent sampling is needed to observe effects of inertial oscillations and details of freshwater transport from the surface.

5. Summary

Unique observations of the upper ocean response to typhoon passage were presented. Results shown are based on high repetition rate Argo float in situ measurements that coincidentally happened to operate in region close to track of two major typhoons during 2008 typhoon season - typhoons Hagupit and Jangmi. Float ID 5901579 had different from usual operational scheme what made it useful tool for data collection. Measurements show cooling due to both typhoons, but stronger due to the first one. In addition changes in salinity were measured showing high variation in the upper ocean due to typhoon-ocean interaction.
Figure 5. Sequential comparison between Argo profile and 3D PWP model.

Acknowledgments

Dariusz Baranowski was partly supported by Office of Naval Research Visiting Scientist Program Grant. QuikScat data are produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team. Data are available at www.remss.com. Analyses and visualizations used in this study were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

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