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Process Study of Oceanic Responses to Typhoons Using Arrays of EM-APEX Floats and Moorings

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LONG-TERM GOALS

Our long-term scientific goals are to understand upper ocean dynamics, to understand the coupling between the ocean and atmosphere via air–sea fluxes, and to quantify the mechanisms of air–sea interactions. Our ultimate goal is to help develop improved parameterizations of air–sea fluxes in ocean–atmosphere models and parameterizations of small-scale processes in the upper ocean and the stratified interior.

OBJECTIVES

Tropical cyclones derive energy from the ocean via air–sea fluxes. Oceanic heat content in the mixed layer and the air–sea enthalpy flux play important roles in determining the storm's maximum potential intensity, structure, energy, trajectory, and dynamic evolution. The most energetic oceanic responses to tropical cyclone forcing are surface waves, wind-driven currents, shear and turbulence, and inertial currents. Quantifying the effect of these oceanic processes on air–sea fluxes during tropical cyclone passage will aid understanding of storm dynamics and structure. The ocean's recovery after tropical cyclone passage depends upon small- and meso-scale oceanic processes in the storm's wake region. These processes are the least understood primarily because of the paucity of direct field observations under passing tropical cyclones; as a consequence, there are large uncertainties in air–sea flux parameterizations in extreme wind regimes.

We designed an experiment to make in-situ oceanic observations in the western Pacific Ocean on the paths of tropical cyclones to understand the coupled atmospheric–oceanic dynamics in a wide range of conditions. Our broad focus is on surface waves, inertial waves, shear instability, internal waves and

meso-scale eddies before, during, and after the passage of tropical cyclones. Primary objectives of this project are (1) to provide observations of oceanic responses to a wide range of atmospheric wind forcings including tropical cyclones, (2) to provide observations of the effect of various oceanic conditions on the strength of tropical cyclones, and (3) to help provide better parameterization schemes for air–sea fluxes, especially in the tropical cyclone extreme wind forcing regime and for interior ocean mixing.

APPROACH

Long-term observations of atmospheric forcing and upper oceanic conditions were made by moorings in the western Pacific Ocean on the likely paths of tropical cyclones in 2009 and 2010. During the 2010 typhoon season (intensive observation period of ITOP), subsurface temperature measurements on the moorings were transmitted via Iridium satellite, and one upward-looking 75-kHz Long Ranger ADCP was deployed on each of three subsurface moorings. Two arrays of seven EM-APEX floats each were air-launched in front of typhoons Fanapi and Megi; the floats transmitted near-real time observations of velocity, temperature, salinity, and GPS position via Iridium satellite.

WORK COMPLETED

Four ATLAS surface moorings (A1, A2, A3, and A4) and three subsurface moorings (SA1, SA2, and SA4) were deployed in the western Pacific Ocean before summer 2010 (Fig. 1). The mooring configurations are shows in Fig. 2. In November 2010 two of four surface moorings and all three subsurface moorings were recovered. Two surface buoys (A1 and A3) were broken off from the moorings by Typhoon Megi. All underwater instruments and data were lost.

Seven EM-APEX floats were launched from C130 aircraft on 17 September 2010, one day ahead of Typhoon Fanapi (Fig. 3). Based on the forecast, three floats were launched to the right of the eye of Fanapi, one on the eye, and three to the left, with 25 n mi separation between floats. The forecast of the typhoon track was very accurate and the eye of Fanapi passed the center of the float array as planned. After the deployment, these floats profiled vertically between the surface and 250-m depth taking measurements of temperature, salinity, pressure and horizontal velocity. When at the surface, they transmitted GPS positions and temperature, salinity, pressure and horizontal velocity data via Iridium satellite communications. Unfortunately, strong surface waves forced by the tropical cyclone may have damaged the floats' ballasting system, causing problematic connections between the floats and Iridium satellites. The transmission of GPS fixes was intermittent throughout the mission; the transmission of temperature, salinity, pressure and horizontal velocity data was mostly successful until all floats suddenly stopped transmissions about 10 days after their deployment.

Another array of seven EM-APEX floats was launched on 16 October 2010, one day ahead of Typhoon Megi (Fig. 4). The plan for float placement was similar to that for Typhoon Fanapi, three to the right of eye, one at the eye, and three to the left of eye based on the forecast, with 20 n mi separation between adjacent floats. Unexpectedly, the eye of Megi passed over the southern-most float of the array; therefore six floats sampled the ocean to the right of Typhoon Megi and one at the eye. The floats made vertical profiles between the surface and 250-m depth before and after the passage of Megi. During storm passage, floats profiled between 30 and 250-m depths, staying at least 30 m below the sea surface to avoid possible damage to their ballasting systems, a lesson learned from the Typhoon Fanapi mission. All seven floats were recovered successfully 3–4 days after their deployment.

RESULTS

EM-APEX Floats

Strongest inertial waves were observed by EM-APEX float #4907, which was deployed in the inertial resonance region of Typhoon Fanapi. The horizontal current speed was greater than 1 m s^{-1} (Fig. 5). Strong shear instability was observed below the base of the surface mixed layer (magenta dots in Fig. 5) accompanying the deepening of strong vertical shear associated with inertial waves.

Observations of velocity, temperature and density fields were linearly decomposed into subinertial, inertial, diurnal and semidiurnal components. A strong westward subsurface subinertial jet was observed to the right of the eye (Fig. 6), presumably a result of the geostrophic adjustment to the typhoon induced pressure gradient. Strong inertial waves, upward vertical phase propagation implying downward energy propagation, and inertial pumping (isopycnal heaving) were also observed (Fig. 6).

The time evolutions of the meridional structure of the temperature averaged in the surface mixed layer, the surface mixed layer heat content, and the temperature averaged between the surface and 100-m depth T_{100} are shown in Fig. 7. As expected, the maximum cooling of the surface mixed layer, –2.5°C, occurred to the right of the typhoon track due to combined turbulence mixing and upwelling. The cold wake generated by the typhoon had a cross-track spatial scale of about 75 km. The surface mixed layer heat content dropped by about 70 kJ/cm^2, and the T_{100} decreased by –2°C during the passage of Typhoon Fanapi.

The horizontal kinetic energy of inertial waves integrated in the upper 100 m have strong spatial variability (Fig. 8) — strongest in the inertial resonance region and weakest in the far field. Inertial wave energy peaked at about one day after the eye of Fanapi passed the float array and decayed exponentially with an e-folding time scale about 2–3 days. The e-folding time scale for inertial current velocity was about 4–6 days.

Before the arrival of the tropical cyclone, the background thermal field was almost horizontally homogeneous (Fig. 9). Six hours after the eye of Fanapi passed the float array, an upwelling of ~50 m was present behind the center of the storm, and the 26.5°C isotherm out-cropped to the sea surface from about 70-m depth before the storm. The surface outcrop occurred to the right of the typhoon track due to combined Ekman pumping upwelling and turbulence mixing.

ITOP Moorings

Several typhoons passed the ITOP mooring array in 2009. On 20 October 2009 the eye of Typhoon Lupit passed the A1 mooring (Fig. 10). Within the eye, the air pressure dropped to 941 mb. The maximum wind speed reached ~120 kt. Within the eye, the wind was light, ~20 kt. A strong and rapid oceanic response was observed. The temperature in the upper ocean dropped by nearly 5°C. Strong upwelling and inertial responses were observed. Typhoon Lupit passed the A3 mooring later (Fig. 11). The minimum pressure recorded on A3 was 955 mb and the maximum wind 90 kt. As expected, to the left of the typhoon in the northern hemisphere, a weaker inertial response was observed. Surprisingly, stronger cooling, –6°C, was observed on the typhoon's left side (A3) than under the eye (A1).

In 2010 typhoons Fanapi and Megi passed moorings A1 and A3. Both surface buoys broke off from their mooring lines during the passage of Megi. Unfortunately, realtime data transmissions from these two moorings were broken before the typhoons' arrivals. All data and instruments were lost from these two moorings. We are analyzing the data from the subsurface moorings and two undamaged surface moorings.

IMPACT/APPLICATION

Oceanic heat content may modulate significantly the strength of the passing tropical cyclones. Tropical cyclones cause strong oceanic responses, e.g., surface waves, inertial waves, and a deepening of the surface mixed layer. To improve the modeling skill of oceanic responses to tropical cyclones and the prediction of tropical cyclones, we need to understand the small-scale processes responsible for the air–sea fluxes and interior oceanic mixing, and the meso-scale oceanic processes that modulate the background oceanic heat content. The present field experiment will provide direct observations of oceanic responses forced by tropical cyclones and the ocean's recovery, as well as aid understanding of the dynamics of small- and meso-scale oceanic processes. These observations will help improve the prediction skill of oceanic and atmospheric models in high wind regimes.

RELATED PROJECTS

Study of Kuroshio Intrusion and Transport Using Moorings and EM-APEX Floats (N00014-08-1-0558) as a part of QPE DRI: The primary objectives of this observational program are 1) to quantify and to understand the dynamics of the Kuroshio intrusion and its migration into the southern East China Sea (SECS), 2) to identify the generation mechanisms of the Cold Dome often found on the SECS, 3) to quantify the internal tidal energy flux and budgets on the SECS and study the effects of the Kuroshio front on the internal tidal energy flux, 4) to quantify NLIWs and provide statistical properties of NLIWs on the SECS , and 5) to provide our results to acoustic investigators to assess the uncertainty of acoustic predictions. Results of this DRI program will help understand oceanic physical processes on the southern East China Sea, e.g., the cold dome. Typhoons may modulate the Kuroshio, the Kuroshio intrusion, and other oceanic processes that result in cold pools on the continental shelf of the southern East China Sea.

HONORS/AWARDS/PRIZES

Gledden Sr. Visiting Fellowship at University of Western Australia (Sanford, October 2008).

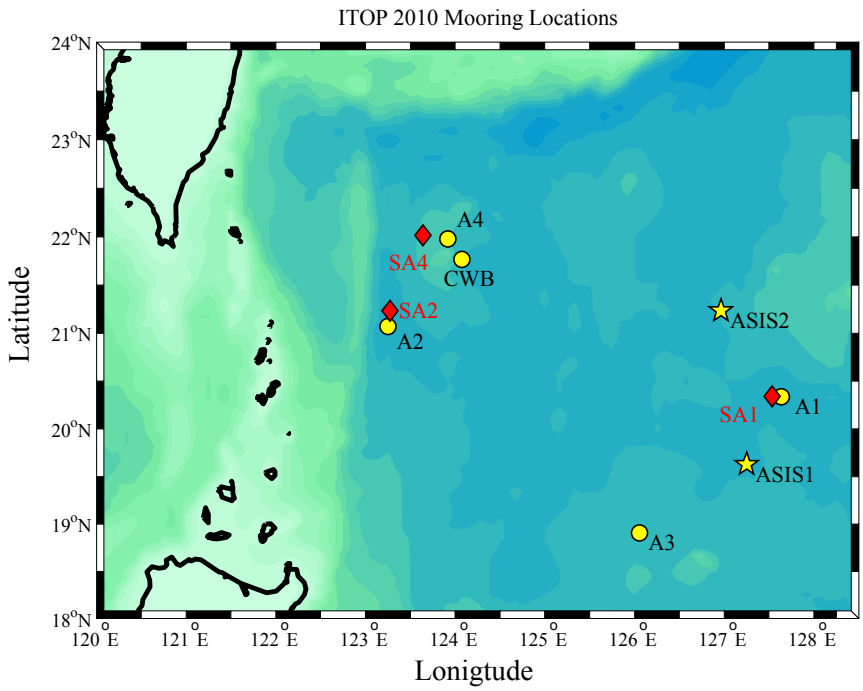

Figure 1. Locations of ITOP surface moorings (A1, A2, A3, and A4), and subsurface moorings (SA1, SA2, and SA4). ASIS1 and ASIS 2 are air-sea flux platforms deployed by Graber. CWB represents the mooring belonged to Central Weather Bureau of Taiwan.

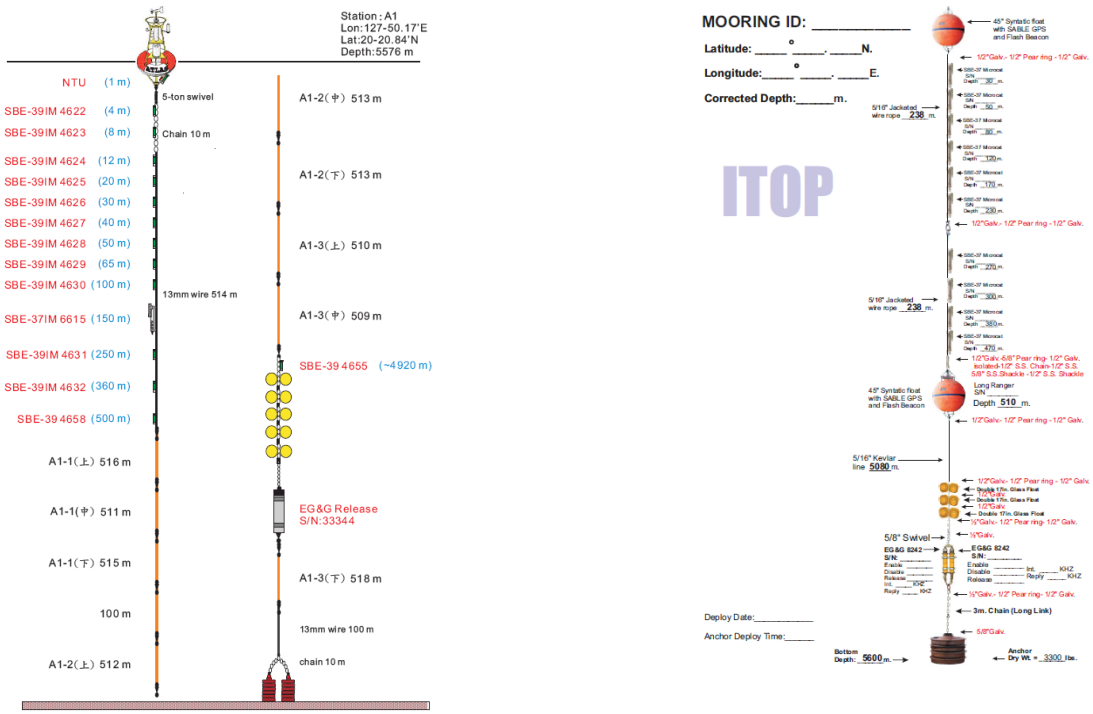

Figure 2. Schematic diagrams of surface mooring (left) and subsurface mooring (right).

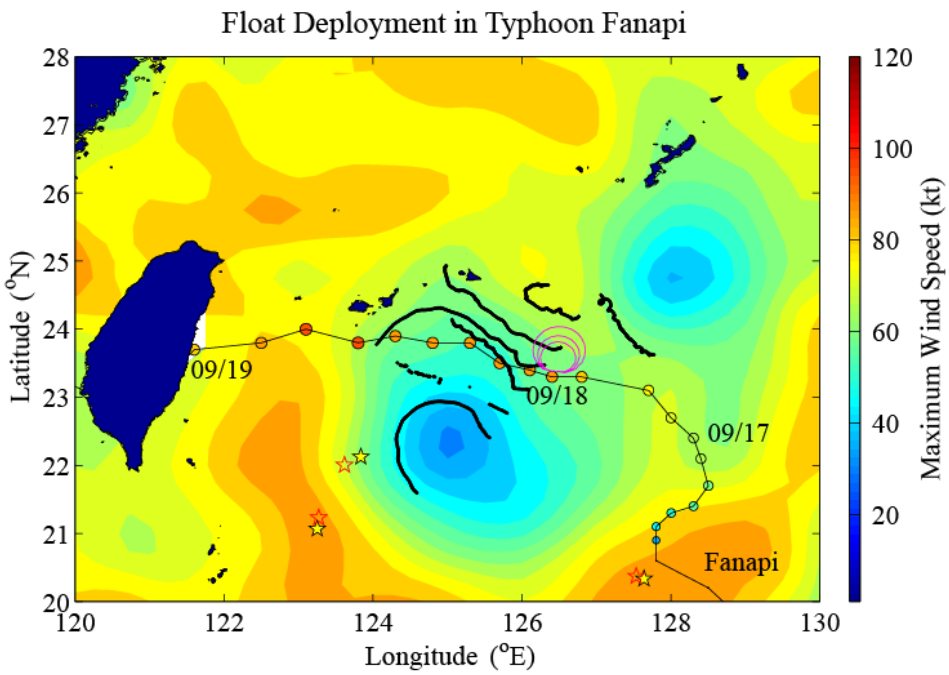

Figure 3. Trajectory of seven EM-APEX floats (thick black curves) deployed ahead of Typhoon Fanapi. The background shading represents the sea surface height anomaly derived from AVISO (no scale). The thin black curve represents the track of Typhoon Fanapi and the color of the filled circles (scale on right) represents the maximum wind speed at that location. Stars represent ITOP moorings.

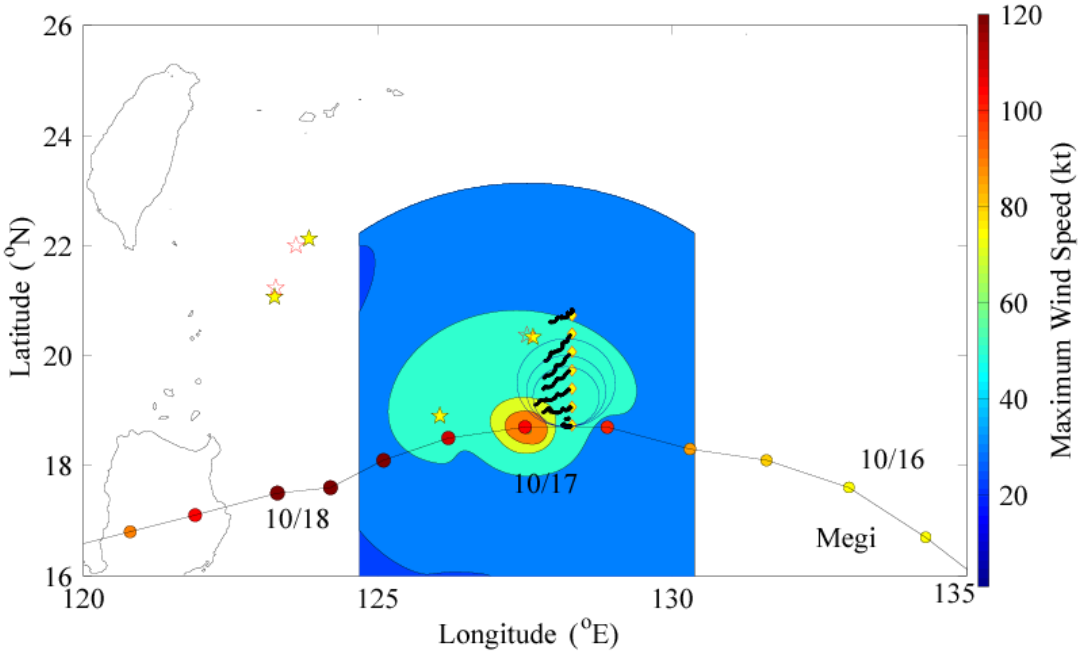

Figure 4. Trajectory of seven EM-APEX floats (thick black curves) deployed ahead of Typhoon Megi. The background shading shows the wind field observed on 17 October 2010 (no scale). The thin black solid curve represents the track of Typhoon Megi and the color of the filled circles (scale at right) represents the maximum wind speed at that location. Stars represent ITOP moorings.

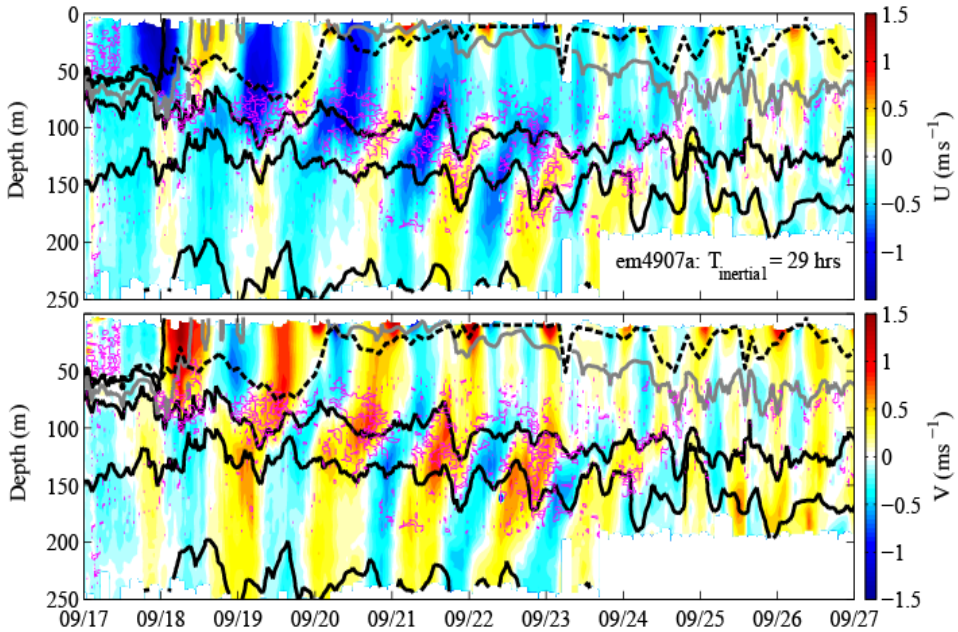

Figure 5. Contour plots of the zonal velocity (upper) and meridional velocity (lower) observed by EM-APEX float #4907 deployed in the inertial resonance zone to the right of Typhoon Fanapi. Three solid curves in the panels represent isopycanls of 1022, 1023, and 1024 kg m^{-3}, and the grey curve represents the 1022.5 kg m^{-3} isopycnal. The dashed curve marks the base of the surface mixed layer. Magenta dots represent the area where the reduced shear squared, S^2–$4N^2$ > 0, where S2 is the sum of the vertical shear squared of zonal and meridional components of velocity, and N^2 is the square of buoyancy frequency.

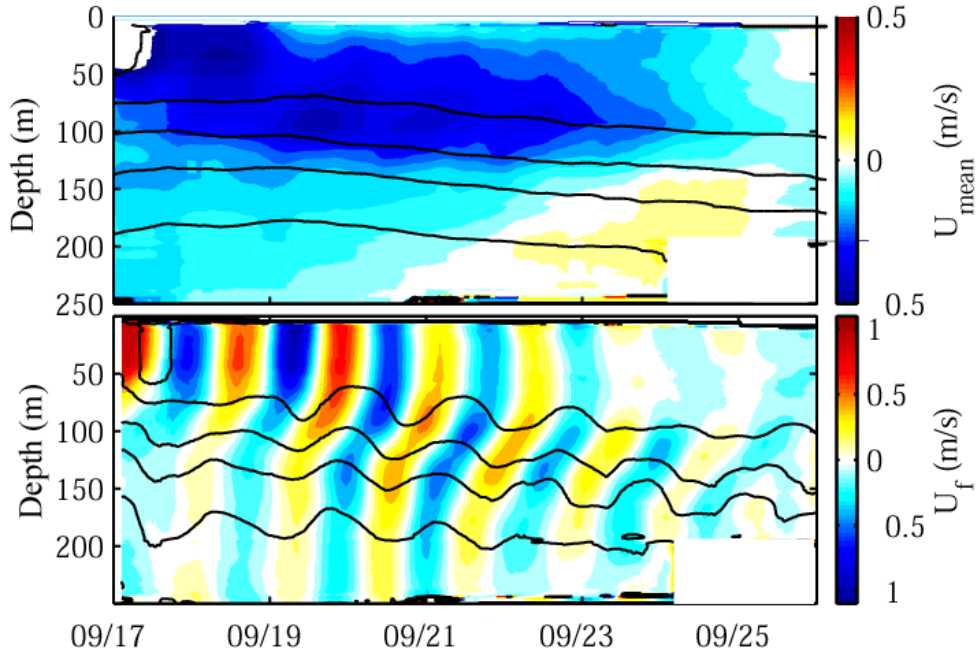

Figure 6. The subinertial component (upper) and inertial component (lower) of zonal velocity observed by EM-APEX float #4907. Black curves represent isopcynals with 0.5 kg m^{-3} interval.

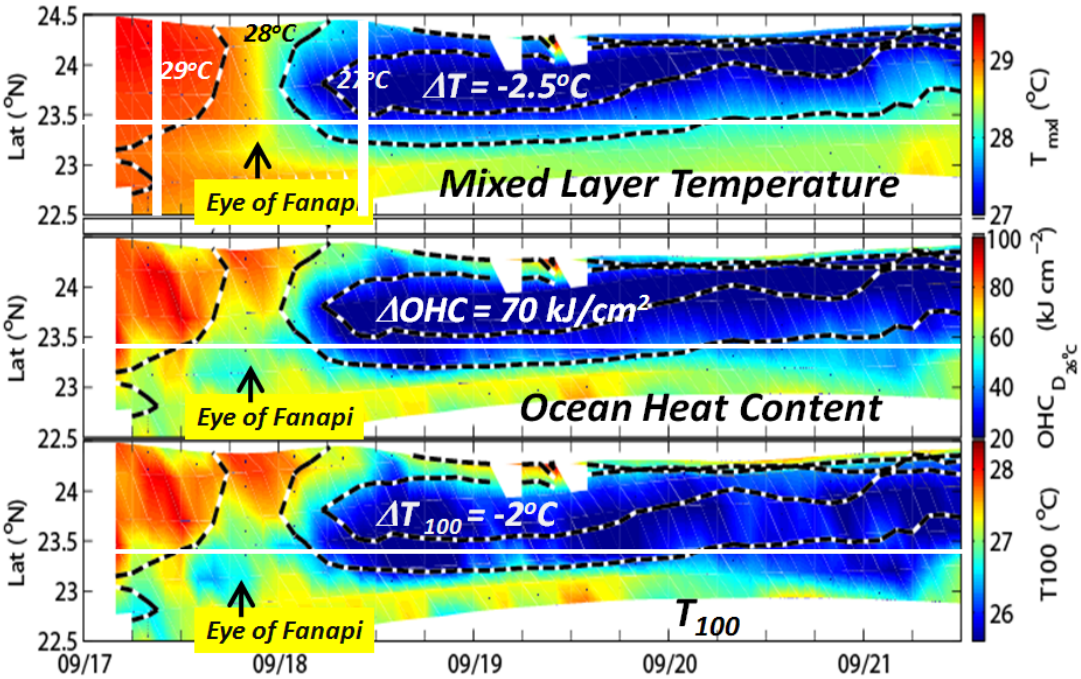

Figure 7. The time evolution and transverse structure of mixed layer temperature (upper), ocean heat content (middle), and the average temperature in the upper 100 m (T_{100}) during the passage of Typhoon Fanapi observed by the array of seven EM-APE floats. The black-white dashed curves are isotherms of 29, 28, and 27°C. The horizontal white line indicates the latitude where the eye of Typhoon Fanapi passed the float array late on 17 September 2010 (black arrow).

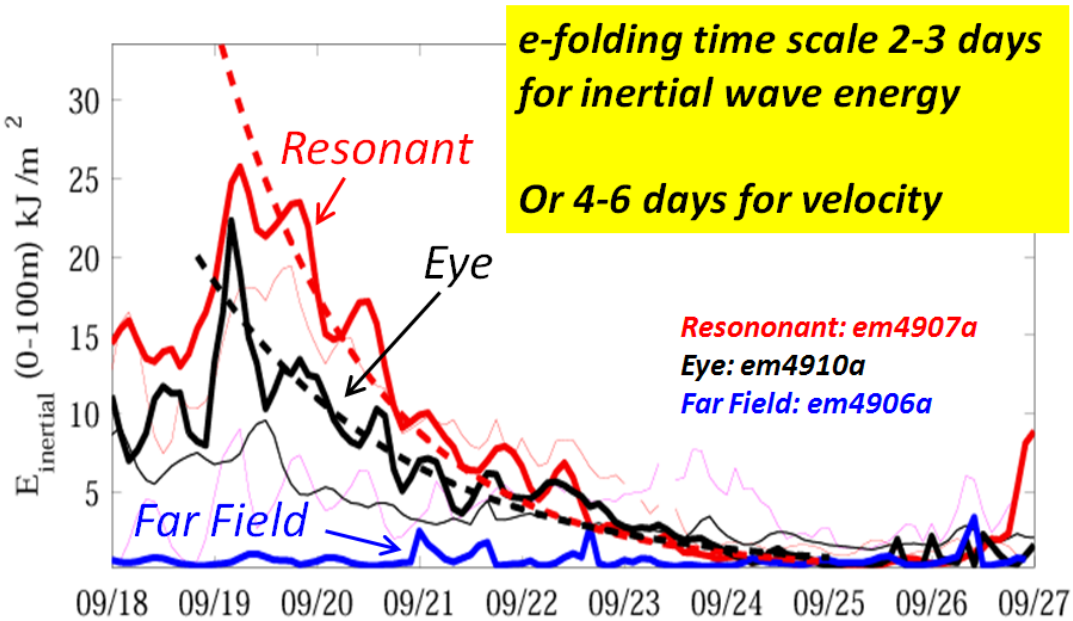

Figure 8. Time evolution of kinetic energy of inertial waves observed by all EM-APEX floats with highlights from the inertial resonance zone (thick red), the eye (thick black), and the far field (thick blue). Thick dashed curves represent the exponential fits to the thick solid curves.

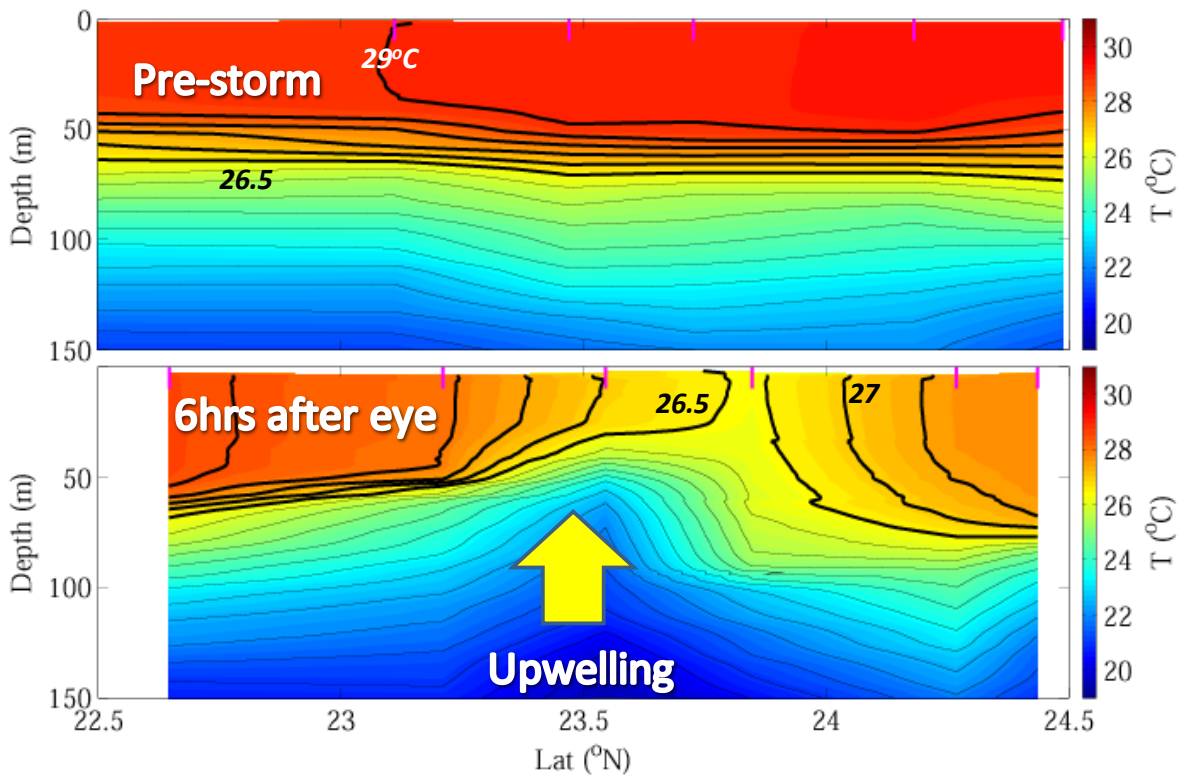

Figure 9. Depth-latitudinal structure of temperature field before the arrival of Typhoon Fanapi (upper) and 6 hr after the passage of the eye. Black curves represent isotherms with 0.5°C interval. Thick black curves are isotherms between 26.5 and 29°C. Thick yellow arrow indicates the strong upwelling under the eye of Typhoon Fanapi.

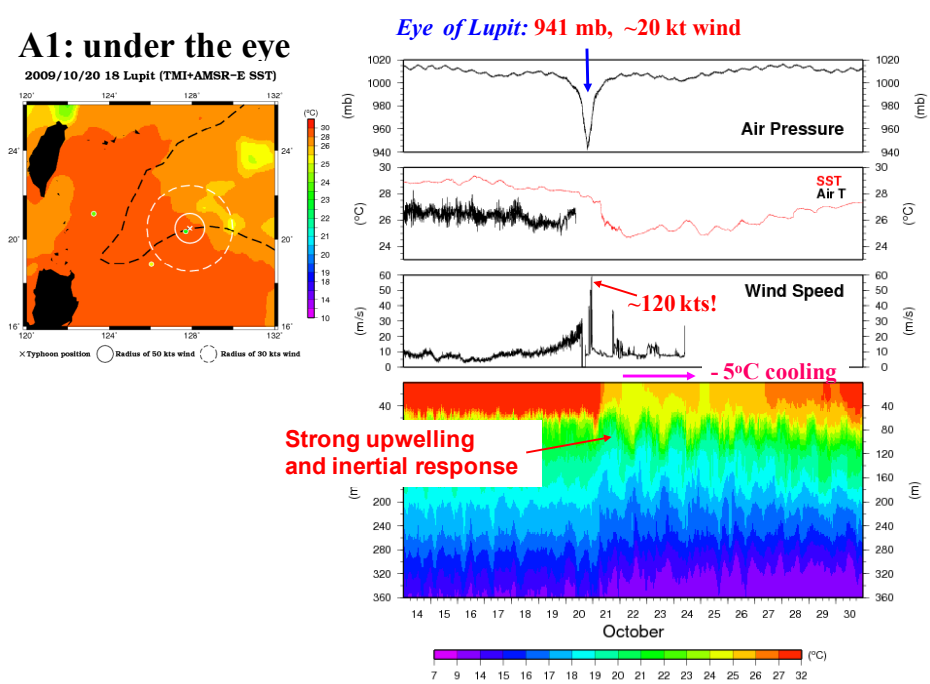

Figure 10. Measurements from the A1 mooring during the passage of Typhoon Lupit.

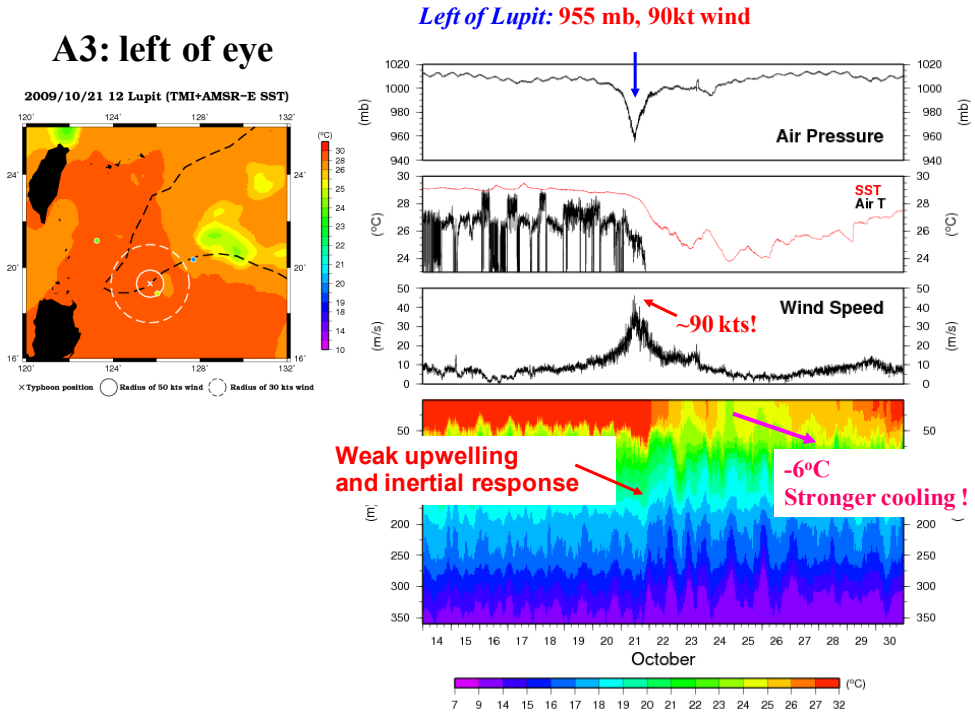

Figure 11. Measurements from the A3 mooring during the passage of Typhoon Lupit.