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 the 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 under extreme wind speeds. 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, in collaboration with Taiwanese colleagues, on the frequent paths of tropical cyclones in 2009 and 2010. During the 2010 typhoon season (the 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. Two arrays of three Lagrangian floats each were also air-launched in front of Fanapi and Megi by Eric D'Asaro.

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. 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. A graduate student, Ya-Ting Chang, at National Taiwan University analyzed mooring observations and obtained her Ph.D. in 2014.

Seven EM-APEX floats were launched from C130 aircraft on 17 September 2010, one day ahead of Typhoon Fanapi. 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, 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. 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

Drag Coefficients

R.-C. Lien mentors a graduate student, Andy Hsu, working on estimates of drag coefficients at high wind speeds. Surface wind stress is often computed using a drag coefficient (C_d). The parameterization of C_d is critical for studies of air–sea interaction. For example, the maximum potential intensity (MPI) of tropical cyclones is inversely proportional to C_d. Previous studies derive empirical formulas for C_d as a function of wind speed at 10 m from the sea surface (U_{10}). Because of few in-situ observations, empirical expressions of C_d are limited to wind speeds less than 55 m s^{-1}. Recent studies suggest that C_d may also depend on surface waves properties, which vary greatly in different sectors of tropical cyclones. It remains a challenge to parameterize C_d accurately and this is needed to better predict tropical cyclones. The C_d computed using EM-APEX float data taken during typhoon Megi shows a strong peak of the downwind drag coefficient at the wind speed between 35 and 40 ms^{-1} and a significant crosswind drag coefficient to the right of the downwind direction (Fig. 1). Results of this analysis are presented in the R.-C. Lien ITOP ESS annual report. Andy obtained his masters degree in spring 2014. He is continuing his study on the parameterization of the surface wind stress at high winds toward a Ph.D. degree.

Surface Gravity Waves

Surface waves control the air–sea fluxes of enthalpy and momentum and thus play a key role in setting the intensity of tropical cyclones. Wave fields beneath cyclones are complex, with multiple dominant wave directions varying and interacting across the different storm quadrants. Furthermore, the air–sea surface at these high winds, of which surface waves are a major component, is poorly characterized. The new generation of coupled tropical cyclone models includes explicit wave fields from which the air–sea heat and momentum fluxes are computed. More practically, the surface waves produced by typhoons are of great interest in themselves, particularly for operations at sea. ITOP aimed to measure the surface wave field underneath typhoons, to compare these measurements with models, and to assess their impact on air–sea exchange and remote sensing signatures.

Data from EM-APEX and Lagrangian floats deployed in typhoons Fanapi and Megi were used to estimate surface wave parameters. The EM-APEX floats compute profiles of horizontal velocity from measurements of the electric field induced by the Earth's magnetic field by these currents. Fits to 50-s long data segments are used to compute the velocity profile. Surface waves appear in these data as a residual from the fit that increases exponentially toward the surface (Fig. 2). Surface wave properties are extracted from these data by fitting the residual curve with an exponential whose amplitude gives the significant wave height and whose decay scale gives a characteristic wavenumber/frequency of the waves.

Surface wave spectra were computed from Lagrangian float data using the gradient of pressure measured at two vertically separated sensors on the floats. The floats accurately follow the Lagrangian trajectories induced by surface waves. Because there are no pressure fluctuations along such trajectories to at least second order in wave amplitude, the pressure fluctuations measured at the floats (many mm's of depth) are very much smaller than the amplitude of the waves (many meters of amplitude). The floats thus measure the pressure gradient due to the surface waves from their vertical gradient using two pressure sensors. These fluctuations are compensated for the exponential decrease with depth and for the float's vertical motion to compute a frequency spectrum of wave displacement. A test of this method at Ocean Weather Station Papa shows excellent agreement between the spectrum of surface waves computed from the float and from a wave rider buoy.

These methods have been applied to the floats deployed in typhoons Fanapi and Megi. Comparison of these two methods during T. Fanapi (Fig. 3) shows good agreement in significant wave height. Waves on the right-hand side of T. Megi peak about 2 hours before the winds (Fig. 4). This is consistent with wave models that show the waves propagating ahead of the storm on the right-hand side. More importantly, it may explain the very high downwind drag coefficients and strong crosswind drag coefficient found in this region by graduate student Andy Hsu and supports the use of coupled wind–wave–ocean models to compute air–sea fluxes in tropical cyclones rather than using transfer coefficients that vary only with wind speed.

IMPACT/APPLICATION

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

Generation and Evolution of Internal Waves in Luzon Strait (N00014-09-1-0279) as a part of IWISE DRI: The primary objectives of this observational program are to quantify 1) the generation of NLIWs and internal tides in the vicinity of Luzon Strait, 2) the energy flux of NLIWs and internal tides into the Pacific Ocean and South China Sea (SCS), 3) the effects of the Kuroshio on the generation and propagation of NLIWs and internal tides, 4) the seasonal variation of NLIWs and internal tides, and 5) to study other small-scale processes, e.g., hydraulics and instabilities along internal tidal beams and at the Kuroshio front.

PUBLICATIONS (wholly or in part supported by this grant)

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HONORS/AWARDS/PRIZES

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

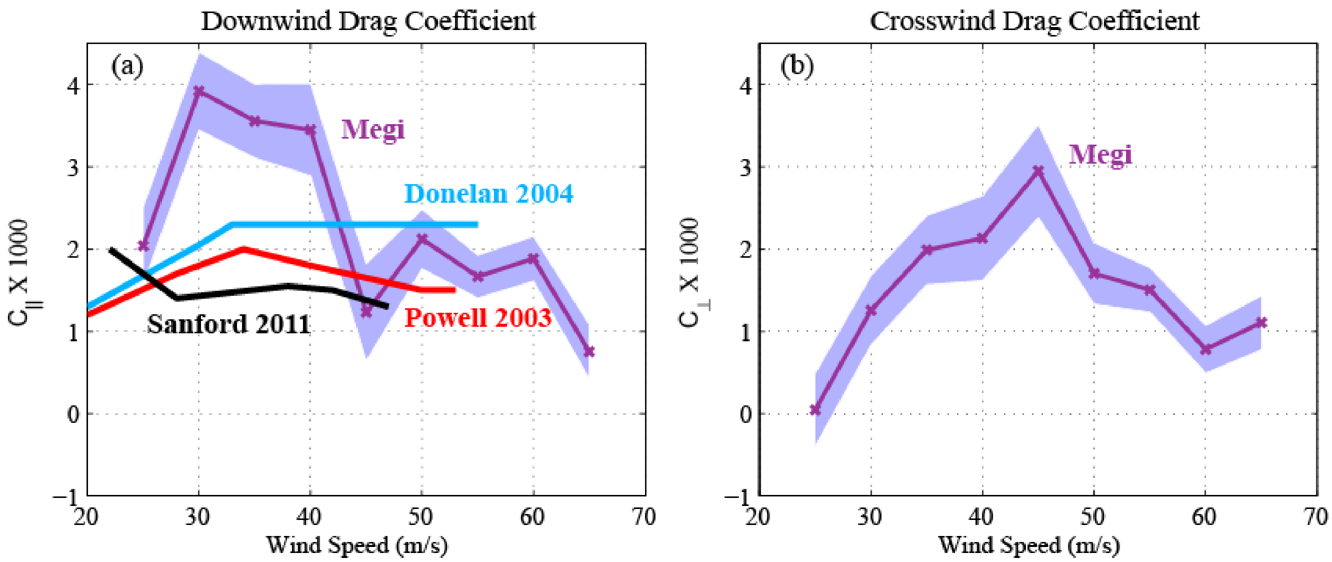

Figure 1. Downwind and crosswind drag coefficient computed using EM-APEX float measurements taken during typhoon Megi in 2011. Shading shows the 95% confidence interval. Downwind drag coefficients concluded by Powell (2003), Donelan (2004), and Sanford et al. (2011) are shown for comparison.

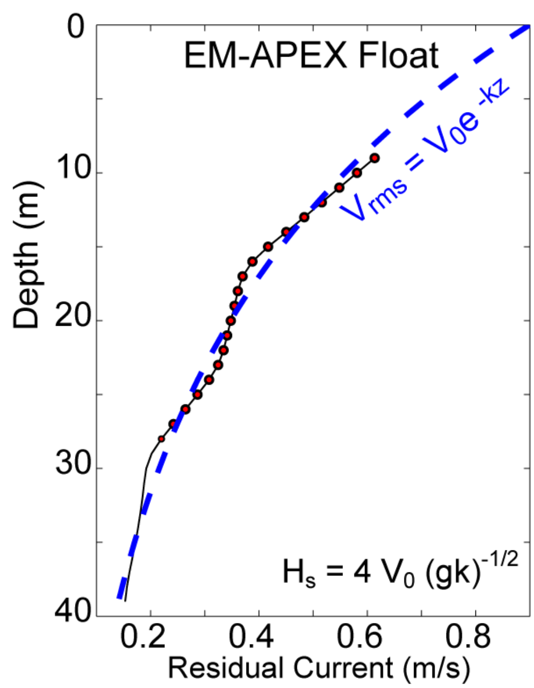

Figure 2. Exponential increase in high-frequency velocity measured on each EM-APEX profile is used to compute the significant wave height H_s and wavenumber as shown in this example. Wave frequency is computed from the dispersion relationship $\sigma = (g\ k)^{1/2}$.

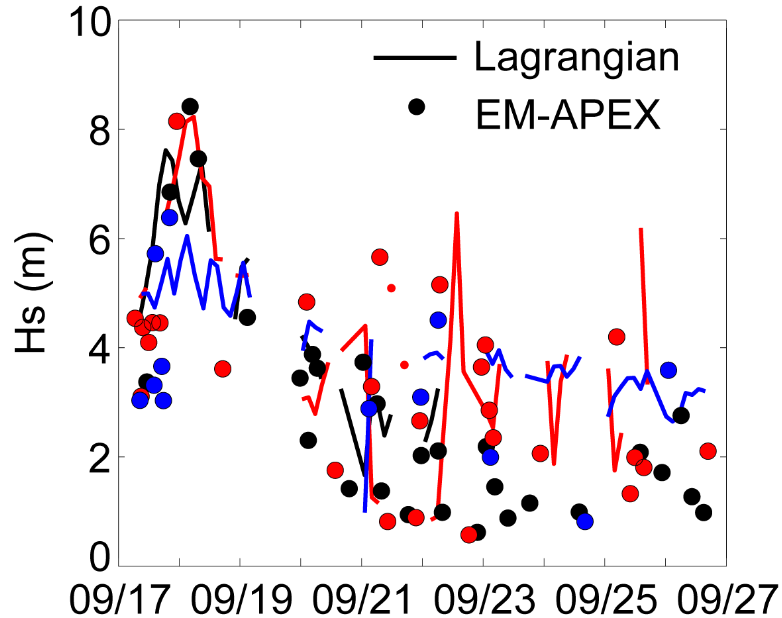

Figure 3. Significant wave height from EM-APEX floats (dots) and Lagrangian floats (lines) in Typhoon Fanapi. Floats of the same colors were deployed together.

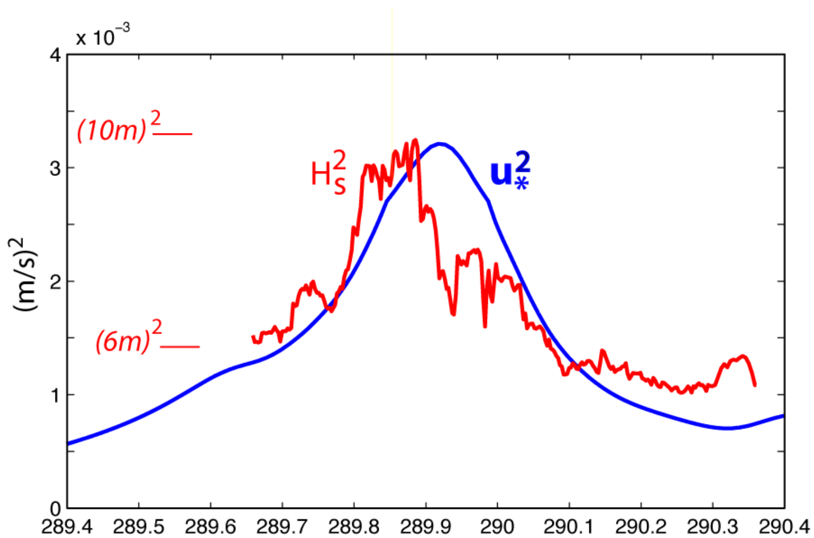

Figure 4. Significant wave height squared (red) and wind stress (blue) on the right side of Typhoon Megi computed from Lagrangian float data. The peak waves occur before peak winds. This may explain the very high drag coefficients found near the peak waves.

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