Early Student Support for a Process Study of Oceanic Responses to Typhoons

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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. 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.

A graduate student, Andy Hsu, is supported by the ONR Early Student Support program. He earned a M.S. degree in spring 2014 and was recommended to the Ph.D. program in physical oceanography. He will pursue the degree with a focus on the estimates of surface wind stress and drag coefficients under tropical cyclones in the western Pacific and Atlantic oceans using direct observations and numerical model simulations.

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}). Recent studies suggest that C_d may also depend on surface gravity wave properties, which vary greatly in different sectors of tropical cyclones. It remains a challenge to parameterize C_d accurately. Further study on the parameterization of C_d is needed to improve predictions of tropical cyclones.

APPROACH

During the 2010 typhoon season (the intensive observation period of ITOP), 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. The data from EM-APEX floats are used to study oceanic responses to typhoons and to compute C_d. The PWP3D (Price et al., 1994) model is also used to facilitate the process study.

WORK COMPLETED

The graduate student, Andy Hsu, attended the ONR ITOP workshop in Taiwan in April 2012, the AGU meeting in San Francisco in fall 2012, and the Ocean Sciences Meeting in Honolulu in February 2014, where he presented results from the EM-APEX float data. His past and ongoing work is on the data analysis of ITOP EM-APEX observations, estimates of C_d, and performing PWP3D model simulations. A paper is ready to be submitted in fall 2015 (Hsu et al., 2015). He earned a Master's degree in physical oceanography in spring 2014 and is pursuing a Ph.D. — extending his research on the drag coefficient under tropical cyclones in the western Pacific and Atlantic oceans.

RESULTS

Estimates of Drag Coefficients

Fourteen EM-APEX floats, seven Lagrangian floats, drifters, and dropsondes were deployed from C130 aircraft in front of typhoons Fanapi and Megi in the western Pacific during ITOP in 2010. Our analysis focuses on measurements taken during Typhoon Megi because maximum wind speeds observed were greater than 60 m s^{-1}. Megi's track, float positions, wind speed at 10-m height above the sea surface, and AVISO derived surface currents are shown in Fig. 1. Seven floats were deployed to the right hand side of Megi's center one day before the arrival of the eye. Measurements of horizontal velocity and temperature taken from three floats closest to the typhoon's eye are shown in Fig. 2. Strong inertial waves and cooling in the surface mixed layer were observed. Inertial waves near the eye, float #3763, were weaker than those at 42 km and 73 km on the right hand side of the eye, floats #4913 and #3766.

The C_d is estimated assuming a balance between the time rate change of the depth-integrated horizontal momentum, Coriolis force, and the wind stress. This assumption is justified using the PWP3D model simulation. Before passage of the tropical cyclone eye, the momentum balance is nearly linear, with a negligible pressure gradient effect. Most of the observed horizontal kinetic energy is within the upper 100 m. The available potential energy and kinetic energy from 100 to 200 m are negligible. This is also in agreement with the method used by Sanford et al. (2011).

We compute both the downwind and crosswind components of wind stress and compare these with previous results (Fig. 3). Errors generated by the method are analyzed, estimated, and removed when possible. Significant results are summarized as follows:

- Our estimates of the downwind drag coefficient at the front-right quadrant of a tropical cyclone peak at wind speeds between 30 and 40 m s^{-1} and are significantly greater than those reported previously.
- At wind speeds of a category 4 tropical cyclone, the downwind drag coefficient is about 1.7 x 10^{-3}. At wind speeds greater than 45 m s^{-1}, the drag coefficient is nearly constant.
- The crosswind surface wind stress is significant; it is toward the right of the downwind direction with a peak drag coefficient of ~1.5 x 10^{-3} at wind speed 45 m s^{-1} (not shown).
- The angle between the wind and wind stress can be more than 15 degrees at wind speeds greater than 30 m s^{-1}.
- The observed time rate of the surface mixed layer momentum is better simulated using the PWP3D model by including both the downwind and crosswind stress components estimated from our analysis, especially under Megi's eye (not shown).

Estimates of Surface Wave Properties

Using the exponential decay and dispersion characteristics of linear deep-water waves, Sanford et al. (2011) estimate the significant wave height and period of the dominant waves from residual rms velocity of demodulated EM-APEX float velocity estimates. Because surface gravity waves often have a broadband spectrum, the rms velocity does not have a simple exponential form, in contrast to the assumption by Sanford et al. (2011). The graduate student is working to improve estimation of surface wave properties using a broadband spectrum.

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 ITOP field experiment provides direct observations of oceanic responses forced by tropical cyclones and the ocean's recovery, as well as aids 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

Studying the Origin of the Kuroshio with an Array of ADCP-CTD Moorings (N00014-10-1-0397) as a part of the OKMC DRI: The primary objectives of this observational program are to quantify Kuroshio properties at its origin and as it evolves downstream, and to study the effects of mesoscale eddies on Kuroshio transport. Kuroshio transport off Luzon is computed using direct velocity measurements from a moored array. The annual mean transport is 15 Sv. Large variations of >10 Sv within 10s of days are caused by westward propagating eddies interacting with the Kuroshio.

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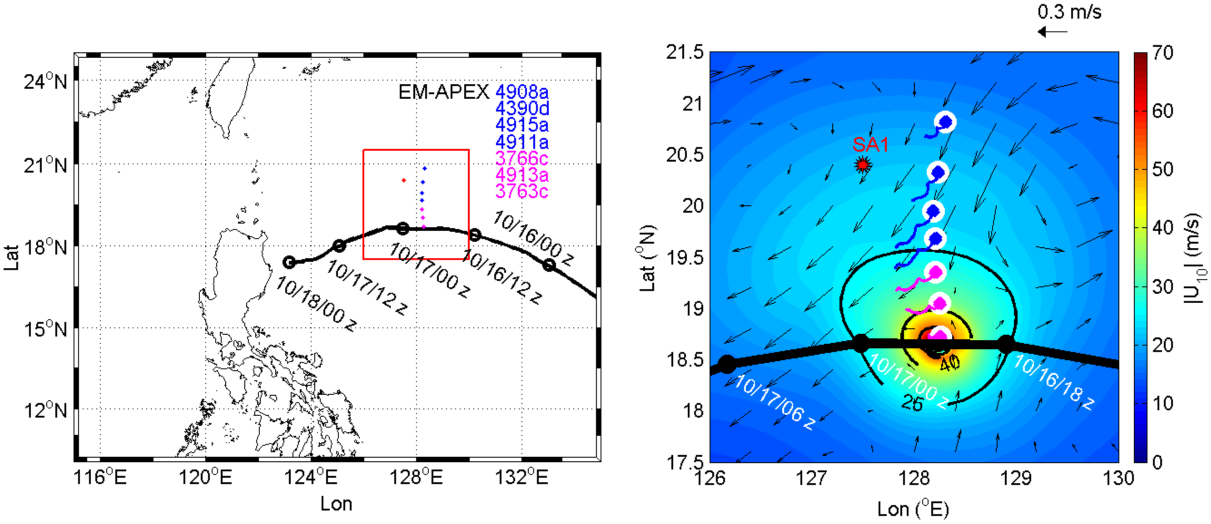

Figure 1. Typhoon Megi 2010 in the tropical western Pacific. (Left) Typhoon Megi track (black thick line) with date/time indications in five locations and the EM-APEX deployment positions on 16 October. (Right) Detail from red square area in the left panel. Color shading and black contour lines are the observed 10-m wind speed at 2030 UTC 16 October, the arrival time of Typhoon Megi at the float array. Black thick line is the typhoon's track with date/time indications in three locations. Blue and magenta dots are the initial EM-APEX float deployment positions on 16 October; blue and magenta lines are the floats' trajectories over 3 days. Black arrows are the geostrophic current on 17 October; amplitude around magenta dots is 0.1–0.2 m s^{-1}. Red star is the location of a subsurface mooring SA1.

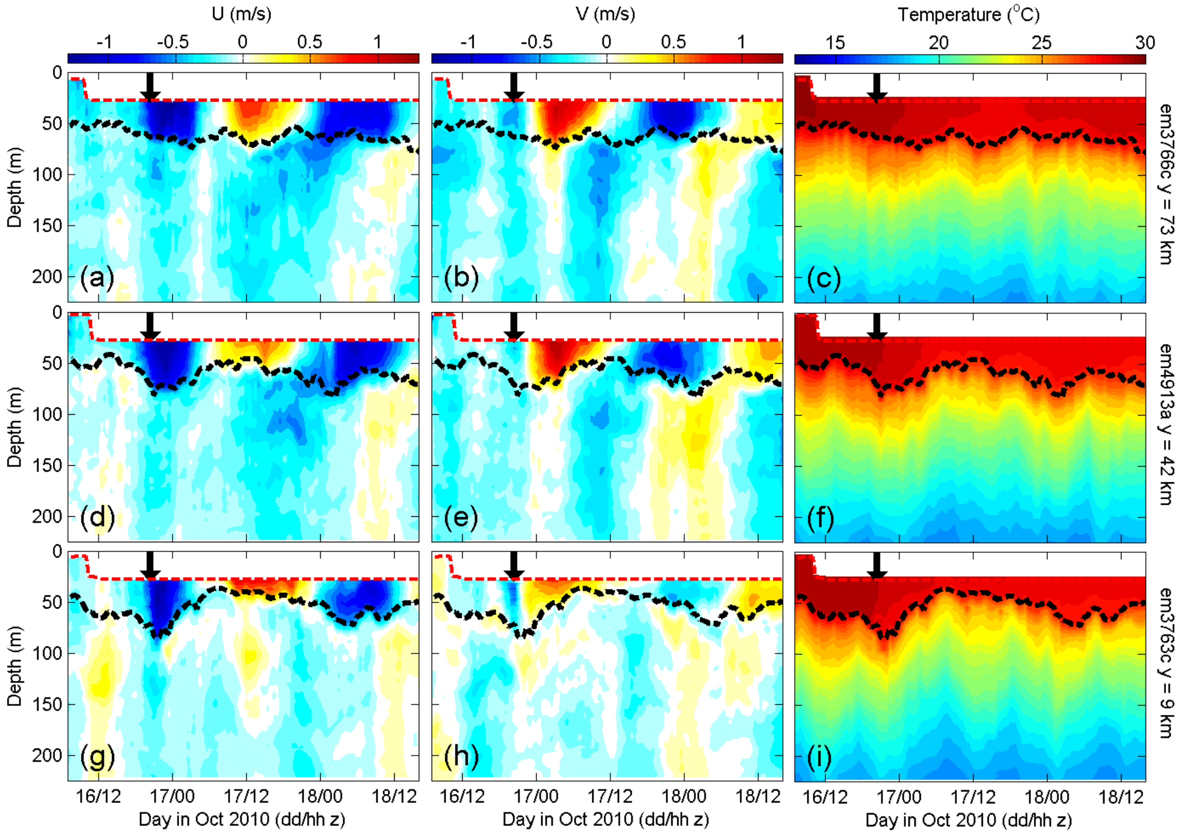

Fig. 2. Contour plots of current velocity and temperature measured by three EM-APEX floats in October 2010. (a), (d), (g) Zonal current velocity (m s^{-1}). (b), (e), (h) Meridional current velocity (m s^{-1}). (c), (f), (i) Ocean temperature (℃). The x axis is the day (dd/hh) in UTC. Label to the right of each row is the cross-track distance (km) for each float, positive to the right hand side of the storm track (mostly to the north because Typhoon Megi's motion is westward). The dashed red lines mark the shallowest depth of float measurements. The black arrows indicate the arrival time of Typhoon Megi at the float array, about 2030 UTC on 16 October. The black dash lines are the mixed layer depth.

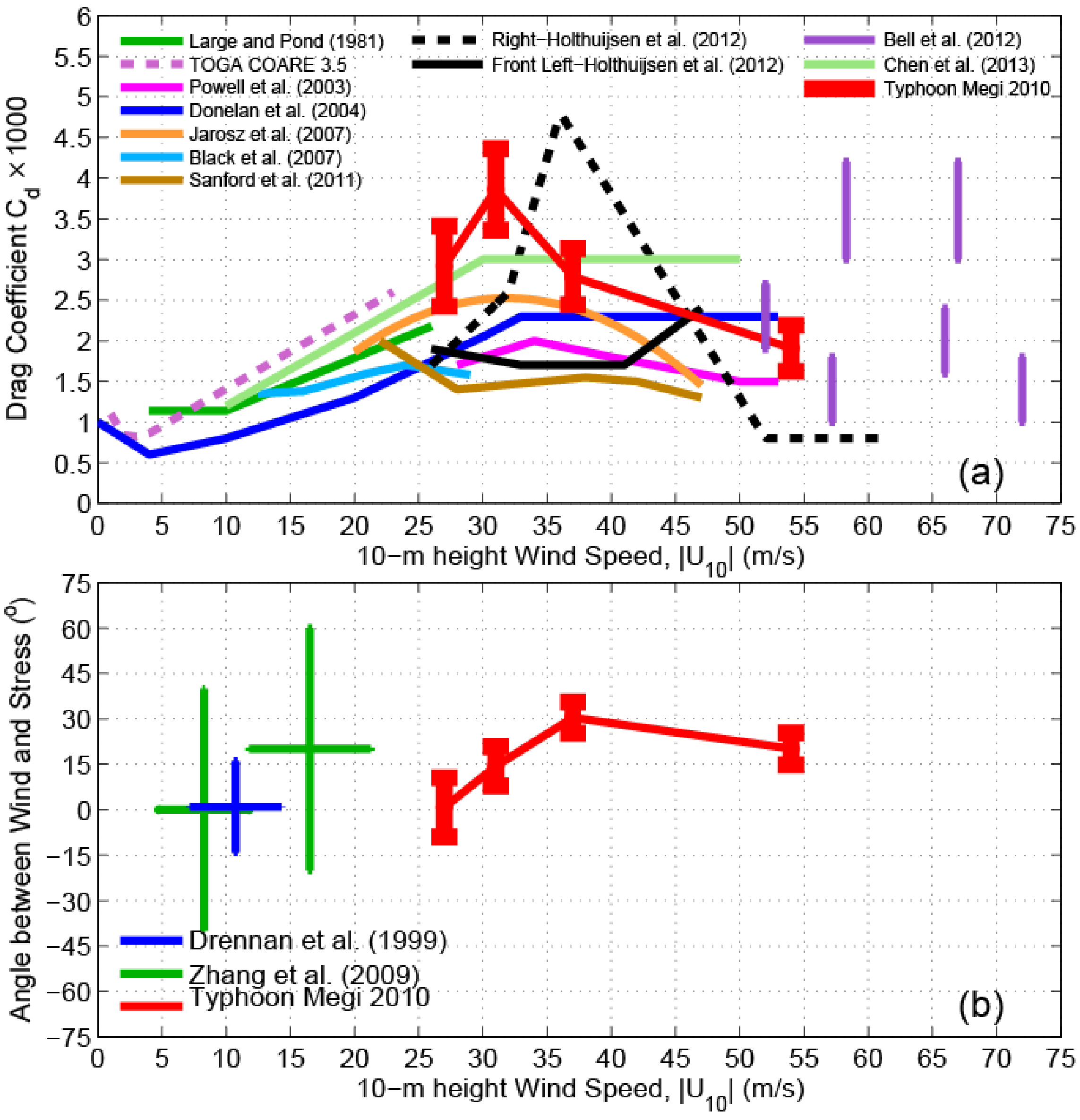

Fig. 3. (a) Parameterization of drag coefficient C_d as a function of wind speed at 10 m above the sea surface, $|\overrightarrow{U_{10}}|$, including Large and Pond (1981), TOGA COARE bulk algorithm 3.5 (Edson et al. 2013), Powell et al. (2003), Donelan et al. (2004), Jarosz et al. (2007), Black et al. (2007), Sanford et al. (2011), Holthuijsen et al. (2012), Bell et al. (2012), and Chen et al. (2013). (b) Previous estimates of the orientation difference between the surface wind and stress vectors. Values taken from Fig. 6 in Drennan et al. (1999) and Figs. 1 and 3 in Zhang et al. (2009) are plotted. Measured wind speed in Drennan et al. (1999) and Zhang et al. (2009) is extrapolated to 10 m above sea surface by assuming a logarithmic wind profile in the vertical. The horizontal and vertical bars describe the ranges of their data. The positive angle represents that the stress vector points clockwise from the wind vector.