Typhoon Impacts and Student Support

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LONG-TERM GOALS

I seek to understand the interactions between the ocean and tropical cyclones including typhoons and hurricanes.

OBJECTIVES

These grants support efforts in the TC10/ITOP (Tropical Cyclone 2010 / Impacts of Typhoons on the Ocean in the Pacific) program. This program, joint between ONR and Taiwanese investigators, studied the ocean response to typhoons in the western Pacific Ocean in 2010. ITOP focused on the following scientific questions:

- *How does the cold wake of a typhoon form and dissipate?*

Typhoons produce a complex three-dimensional response of the underlying ocean including strong surface currents, upwelling of the thermocline, intense mixing across the thermocline, the radiation of near-inertial internal waves and the formation of a cold wake behind the storm. The cold wake persists for at least several weeks after the typhoon passage, with a combination of solar heating, lateral mesoscale stirring, lateral mixing by baroclinic instability and continued vertical mixing determining the rate and character of wake dissipation. The wake is also expected to modify the atmospheric boundary layer and the biology and chemistry of the upper ocean, particularly pCO2. ITOP seeks to measure the ocean response in detail, with particular emphasis on the mechanisms of cold wake formation and dissipation, and to compare these measurements with model results.

- *What are the air-sea fluxes for winds greater than 30 m/s ?*

Tropical cyclones draw their energy from the underlying warm ocean. Their intensity depends on the exchanges with the ocean; a greater flux of heat and moisture to the storm leads to a stronger storm, but a larger drag on the ocean leads to a weaker storm. These exchanges are poorly parameterized in existing typhoon forecast models leading to errors in the ability of these models to predict typhoon intensity. The first reliable estimates of the exchange coefficients at these high wind speeds, made during the last decade, have shown a dramatic decrease in drag coefficient relative to previous parameterizations. ITOP seeks to make additional measurements, at higher wind speeds and under a larger variety of conditions.

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- *How do ocean eddies affect typhoons and the response to typhoons?*

Ocean mesoscale eddies are expected to modulate the ocean response to typhoons by varying the depth of the pycnocline and thus the intensity and location of the cold wake. This, in turn, will change the air-sea fluxes and thus the intensity of the typhoon. Thus warm eddies act as typhoon boosters, by limiting the amount of cooling in the wake and cold eddies act as typhoon dampers. ITOP seeks to study these interactions in detail.

- *What is the surface wave field under typhoons ?*

The air-sea exchange depends critically on the state of the ocean surface, most importantly characterized by the surface waves. The wave fields beneath typhoons are complex, with multiple dominant wave directions varying and interacting across the different storm quadrants. Modern coupled air-sea models of tropical cyclones include explicit models of the wave fields from which the air-sea exchange rates are computed. More practically, the enormous surface waves produced by typhoons are of great interest in themselves. ITOP seeks 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.

- *How is typhoon genesis related to environmental factors?*

Over the tropical western North Pacific, the monsoon environment contains favorable large-scale conditions related to tropical cyclone formation and intensification. The monsoon and tropical cyclone activity vary in response to multiple synoptic-scale and intraseasonal phenomena such as waves in the monsoon trough and the Madden-Julian Oscillation. ITOP seeks to examine how these large-scale environmental factors affect the formation and intensification of tropical cyclones.

- *Typhoon forecasting*

Although the primary aim of ITOP is typhoon research, much of the data gathered by ITOP will be immediately useful for operational forecasting of typhoons. ITOP seeks to make such data available to all regional forecasting organizations and, as much as possible, work with them to improve typhoon forecasting during the experimental period.

APPROACH

ITOP focused on typhoons in the Western Pacific Ocean. The experimental domain was approximately the region shown in the figure below, but east of the Phillipines, Taiwan and the Ryukyu (Okinawa) island chain and the Kuroshio current, west of Guam and between 10N and 32N. This is climatologically the region of highest tropical cyclone occurrence in the world. The ITOP used a variety of experimental approaches to measure typhoons and the ocean’s response to them. The experimental measurements began in 2008, with enhanced measurements through the Spring, Summer and Fall of 2010 and an intensive operations period in September – October of 2010.

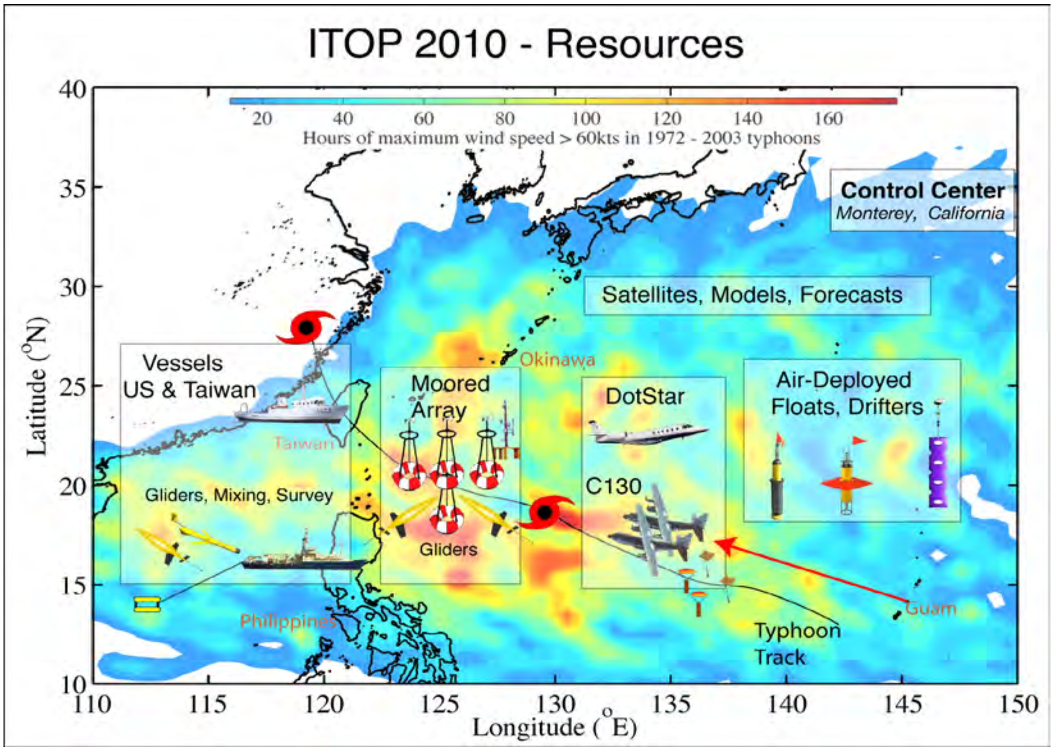

Figure 1. Resources for ITOP/TCS10 included ships, moorings, aircaft and autonomous platforms deployed by the ships and the aircraft

As shown in the figure, a **moored array**, located in the region of maximum typhoon frequency near 20N 125E was deployed starting in 2008. During ITOP, it was enhanced to include 10 moorings, deployed and recovered by US and Taiwanese **research vessels**. During the intensive measurement period, two **C130**s of the 53rd Air Force Reserve Hurricane Hunter Squadron were based in Guam. These aircraft measured the properties of typhoons using onboard sensors and deploy dropsondes. These efforts complemented those of the existing **DotStar** typhoon surveillance program based in Taiwan. The C130s also deployed arrays of **floats** and **drifters** in front of typhoons to measure the ocean response. After the passage of the typhoon, additional floats and drifters were deployed into the wake. A **US research vessel** was rapidly deploy into the wake of Typhoon Fanapi, **surved** the wake, deployed additional **gliders** and drifters and recovered some of the air-deployed floats and drifters. The measurements were guided by **satellite measurements**, of the storm location, evolution and structure and the ocean surface properties and numerical **models** of the atmosphere and of the coupled atmosphere-ocean evolution of the typhoons. During the intensive operations period, operations were directed and coordinated from a **control center** located at the Naval Postgraduate School in Monterey, California.

My role within ITOP has been both as PI with my own scientific program and as the Chief Scientist. During 2010, I worked at the Monterey control center coordinating the ship and aircraft operations during the intensive operations period. Subsequently, I have coordinated the analysis efforts, organizing a meeting in Santa Fe in May, 2011.

My personal science program within ITOP consisted of the construction and deployment of 10 Lagrangian floats ahead of typhoons along with other components of the float and drifter arrays. These were programmed to sample the upper ocean boundary layer measuring the boundary layer turbulence intensity, heat and salt fluxes, surface waves and ambient noise.

WORK COMPLETED

The ITOP experimental program proceeded much as planned. Three typhoons were sampled as shown in the graphic below. Typhoon Fanapi was sampled in most detail with the full complement of ITOP resources. Typhoon Malakas was sampled with a few aircraft flights and drifters. At the very end of ITOP, supertyphoon Megi, one of the strongest storms in the Pacific Basin, was extensively measured with aircraft, floats and pre- and post- storm ship transits.

My personal scientific component of ITOP included the deployment of 10 Lagrangian floats ahead of T. Fanapi and ST. Megi and a study of the internal tide in this region.

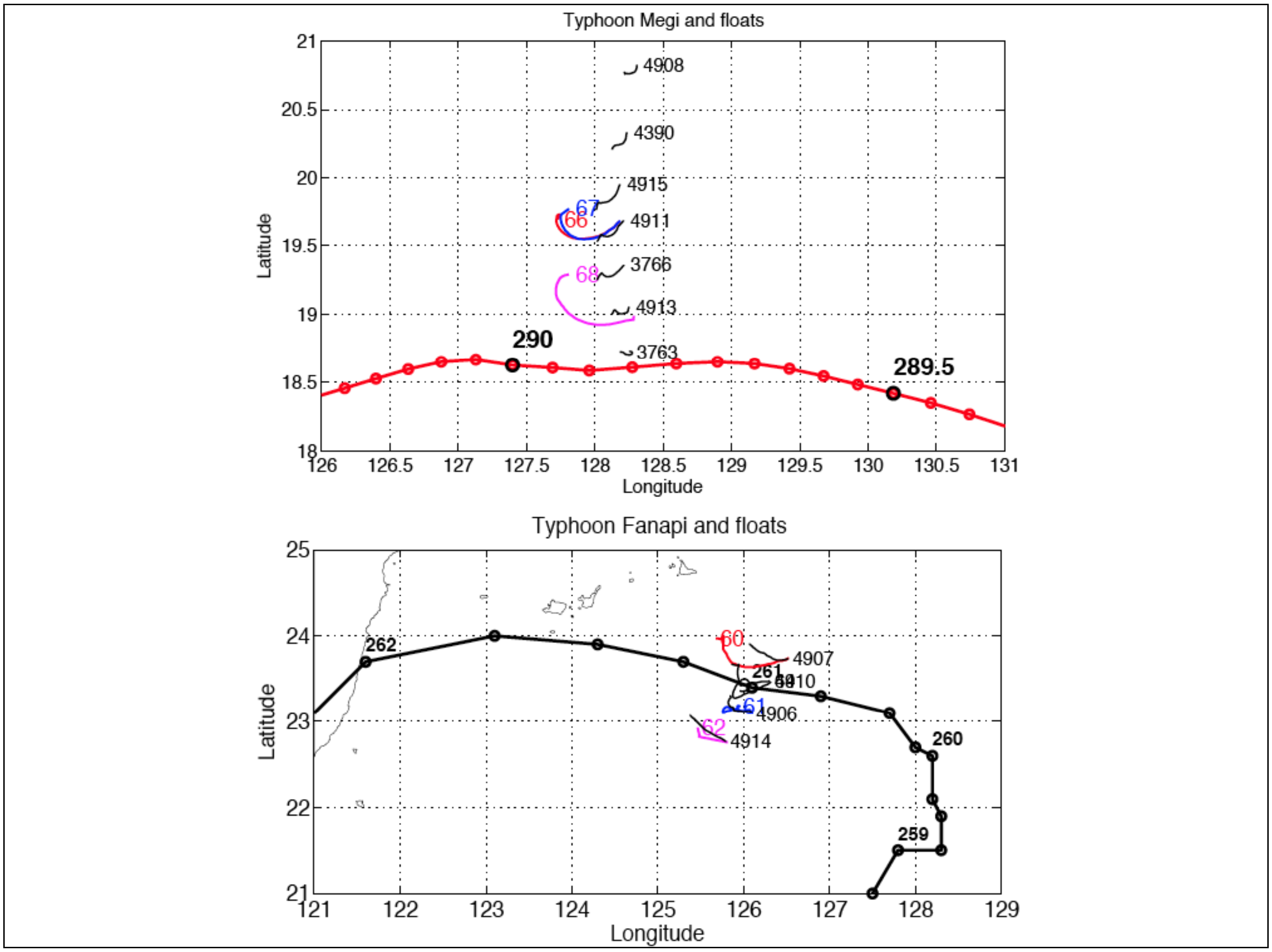

Figure 2. Locations of Lagrangian float and EM-APEX deployments in T. Fanapi and ST. Megi. The deployments spanned Fanapi, but were to the north of the track of Megi

The student support grant is paying for the support of a graduate student Rosalinda Fortier. Rosalinda participated fully in the work at the Monterey control center throughout the ITOP intensive period. This was a great help to our operations as well as providing Rosalina with an excellent educational experience. Rosalinda finished her Masters thesis on the cold wake of Fanapi in July 2011 and will proceed with a Ph.D.

RESULTS

An internal tide focus from the Mariana Arc

The Mariana Arc of ridges and islands forms an ~1300-km-long arc of a circle, ~630 km in radius centered at 17°N, 139.6°E. The hypothesis that the westward-propagating internal tides originating from the arc converge in a focal region is tested by examining the dominant M2internal tides observed with air-launched expendable bathythermographs (AXBTs) and altimetric data from multiple satellites. The altimetric and AXBT observations agree well, though they measure different aspects of the internal tidal motion. M2 internal tides radiate both westward and eastward from the Mariana Arc, with isophase lines parallel to the arc and sharing the same center. The westward-propagating M2 internal tides converge in a focal region, and diverge beyond the focus. The focusing leads to energetic M2 internal tides in the focal region. The spatially smoothed energy flux is about 6.5 kW/m, about four times the mean value at the arc; the spatiallyun-smoothed energy flux may reach up to 17 kW/m. The size of the focus is close to the Rayleigh estimate; it is thus a perfect focus.

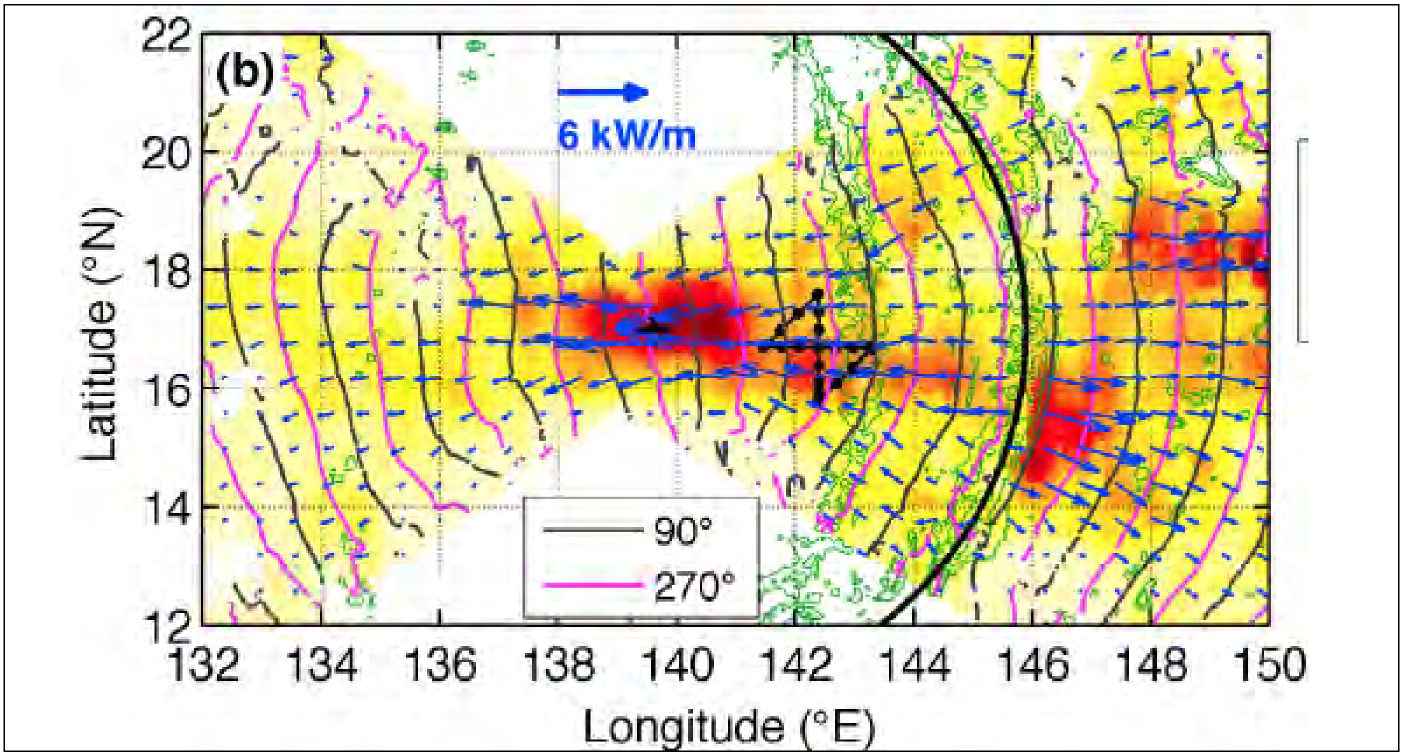

Figure 3. The internal tidal focus west of the Marianas ridge. The black arc shows the idealized ridge crest; the green lines are topographic contours at 1000, 2000, and 3000 m. Arrows are internal tidal fluxes from satellite altimetry, colors are flux strength ranging from 0 to 6 kW/m2. The black/magnenta lines are internal tidal phase. The black dotted figure-4 is the AXBT sampling pattern used during ITOP to verify the satellite calculations.

How long did the cold wake of Fanapi persist?

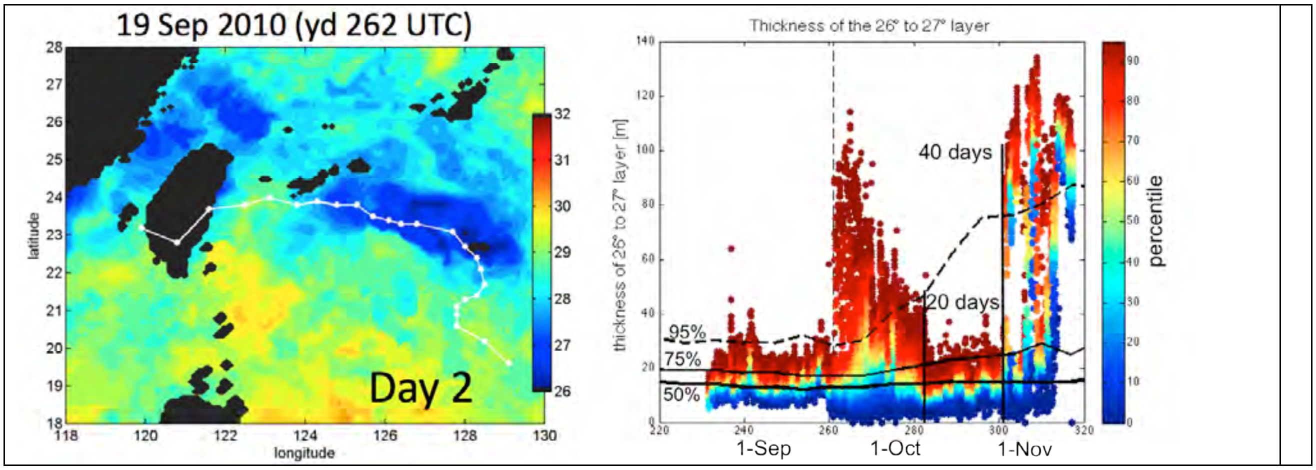

Fig. 4. Left: The cold wake of T. Fanapi seen in a microwave SST image 2 days after the storm passed over the ITOP array. It is seen as a band of 26-27C water to the right of the storm track. Right: All ITOP observations of the wake, surface and subsurface as a function of time (horizontal) and thickness of wake (vertical). Colors indicate the percentiles at each time. The wake lasts between 29 and 40 days with decreasing thickness over time.

Rosalinda Fortier analyzed the evolution of T. Fanapi's cold wake for her Masters' thesis. The wake is created by intense mixing beneath and behind the storm. Observations, for example Fig. 4, show that the wake had a temperature of 26-27C immediately after the storm. Accordingly, all ITOP temperature profiles, approximately 3000, were searched for nearly isothermal layers between 26.5C and 27.5C. The time evolution of these thicknesses (Fig. 4 right) showed a large increase in the thickness of this layer immediately after the storm followed by a decrease over the next 40 days. The average thickness reached approximately the pre-storm conditions sometime after 20 days, when the measurements in this region stopped, and sometime before 40 days, when the layer was absorbed by the deepening Fall mixing layer. The decrease in layer thickness was caused by capping, due at least in part to solar radiation, and by advection and straining by the mesoscale eddy field. The analysis indicates that the wake persists as a subsurface feature for 20-40 days after the storm.

IMPACT/APPLICATIONS

The execution of ITOP has promoted a close cooperation between ocean experimentalists, meterologists and operational Navy typhoon and ocean prediction products including those related to the NLOM and COAMPS models. The operations center relied on output from a total of about 10 operational and research models, including atmospheric, oceanic and coupled varieties as well as dozens of remote sensing products. This information, and the location and status of all ITOP platforms, was rapidly and consistently presented to us by several data systems, some of which were specifically designed for ITOP. This degree of integration, both across the air-sea interface, between models and observations, and between platforms from many different PIs will hopefully set a new standard for future programs.

PUBLICATIONS

Zhao, Z., and E. D’Asaro(2011), *A perfect focus of the internal tide from the Mariana Arc*, **Geophys. Res. Lett**., 38, L14609, doi:10.1029/ 2011GL047909

HONORS/AWARDS/PRIZES

During FY 2011 I was made a fellow of the American Meterological Society and a fellow of the American Geophysical Union and was awarded the Sverdrup Gold Medal of the American Meterological Society.