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Typhoon Impacts

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LONG-TERM GOALS

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

OBJECTIVES

This 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 pCO_2. 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.

- *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 was a large international program. Details of the program operations are included in my 2011 annual report. This grant supports my role as Chief Scientist in ITOP, the analysis of my own measurements during this project and supervision graduate student working on ITOP data.

During ITOP, Lagrangian floats were deployed by Air Force C130's: 3 in Typhoon Fanapi and 3 in Typhoon Megi. The Lagrangian floats are designed to accurately follow the three-dimensional motion of water parcels within the ocean mixed layer while measuring their temperature and salinity. This is accomplished by matching the density of the floats to that of the water surrounding them, as measured by onboard CTDs, so that the net buoyancy of the floats is less than 1g, and by a large vertical drag provided by a folding cloth drogue with approximately 1 m^2 area. The floats are deployed in specialized air-deployment packages which protect the floats during handling and deployment from the C130, release the parachute upon water impact and then release the float from the package 20-40 minutes after water entry.

The floats measured pressure, temperature and salinity, thus allowing vertical velocity, vertical kinetic energy and vertical heat and salt fluxes to be estimated. The floats also measured ambient sound (30 Hz – 50 kHz) from which wave breaking rates could be estimated and the difference in pressure between their top and middle, from which surface wave height could be estimated. Some of the floats carried oxygen sensors (supported by a separate NSF grant) from which oxygen flux could be computed. They thus could relate atmospheric forcing, surface wave properties and ocean boundary layer turbulence under extreme wind and test ocean boundary layer turbulence models.

WORK COMPLETED

I-I Lin , Chunzai Wang and I organized a tropical cyclone session at the 2014 Ocean Sciences meeting at which 24 talks and posters were presented, many from ITOP

A paper describing the ambient noise data from ITOP has been accepted in JPO.

A paper with Tobias Kukulka and students comparing LES simulations with observations in Hurricane Gustav (an ITOP pilot deployment partially funded by NSF) was submitted to JPO and is in review.

Ambient noise spectra from ITOP were compared to those predicted by Grant Deane on the basis of wave breaking calculations (see results). A paper describing this work is in preparation.

Andy Hsu, a graduate student supervised by Ren-Chieh Lien and myself, completed his Masters' thesis on drag coefficients observed during ITOP and is writing this up.

RESULTS

The combined ITOP and CBLAST measurements allow us to study the dependence of the ocean response on the storm properties. Theoretically, we expect the nondimensional storm speed $S/ 2 f R_{max}$ to be especially important. Here S is the speed of the storm, f is the Coriolus parameter and R_{max} is the radius of maximum winds. Figure 1 compares two properties of the cold wake, its location and its strength, from 6 storms. The Typhoon Megi observations provide particularly important data points as its small size in the Pacific make it a non-dimensionally very fast storm here, while its large-size and slow speed in the South China Sea, make it a non-dimensionally very slow storm there. These outlier points, along with the 4 other, less unusual storms, show a clear dependence of the wake properties on the nondimensional storm speed, as expected from theory.

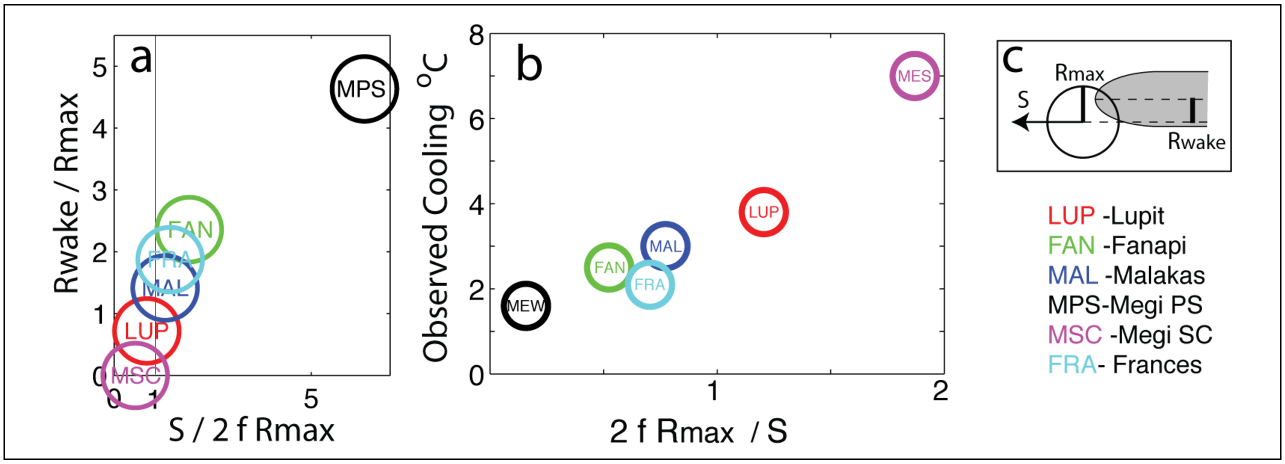

Figure 1. Variation of cold wake properties with the non-dimensional storm speed for 6 ITOP/CBLAST storms. a) The position of the cold wake moves away from the storm track with increasing storm speed. b) The amount of cooling decreases. Thus a slow storm has strong cooling along the track while a weak one has weak cooling to the right of the track. c) This sketch shows defines the wake and storm geometry.

Ambient sound measurements during ITOP provided a detailed measurement of sound levels as a function of frequency and wind speed. At 160 Hz (Fig. 2a), the sound level increases as a function of wind speed and can thus be used to measure the wind speed. At higher frequencies, the sound level begins to saturate and then decrease with wind speed. The first hints of this are apparent near 400 Hz (Fig. 2b). The variability around the best fit (heavy) line is partially due to strong decoupling of the wave field and wind field in the different quadrants of the storm.

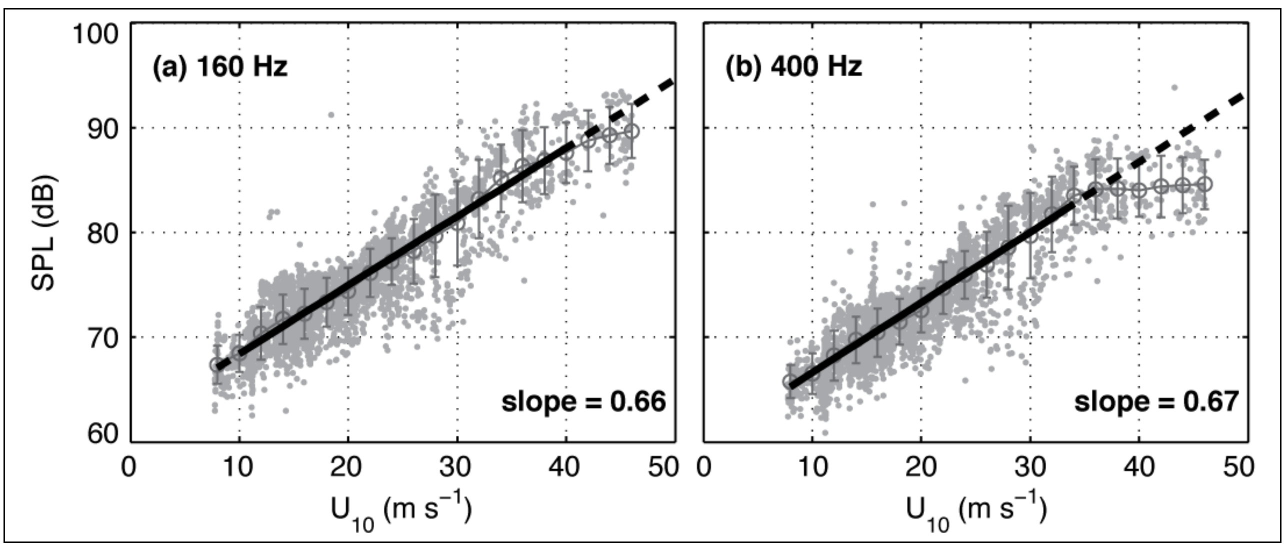

Figure 2. Low frequency ambient sound as a function of windspeed from ITOP storms. a) At 160 Hz, the sound level increases as a function of frequency. b) At 400 Hz, the sound level saturates above 35 m s^{-1}. Such saturation, and a decrease, becomes increasingly strong at higher frequencies.

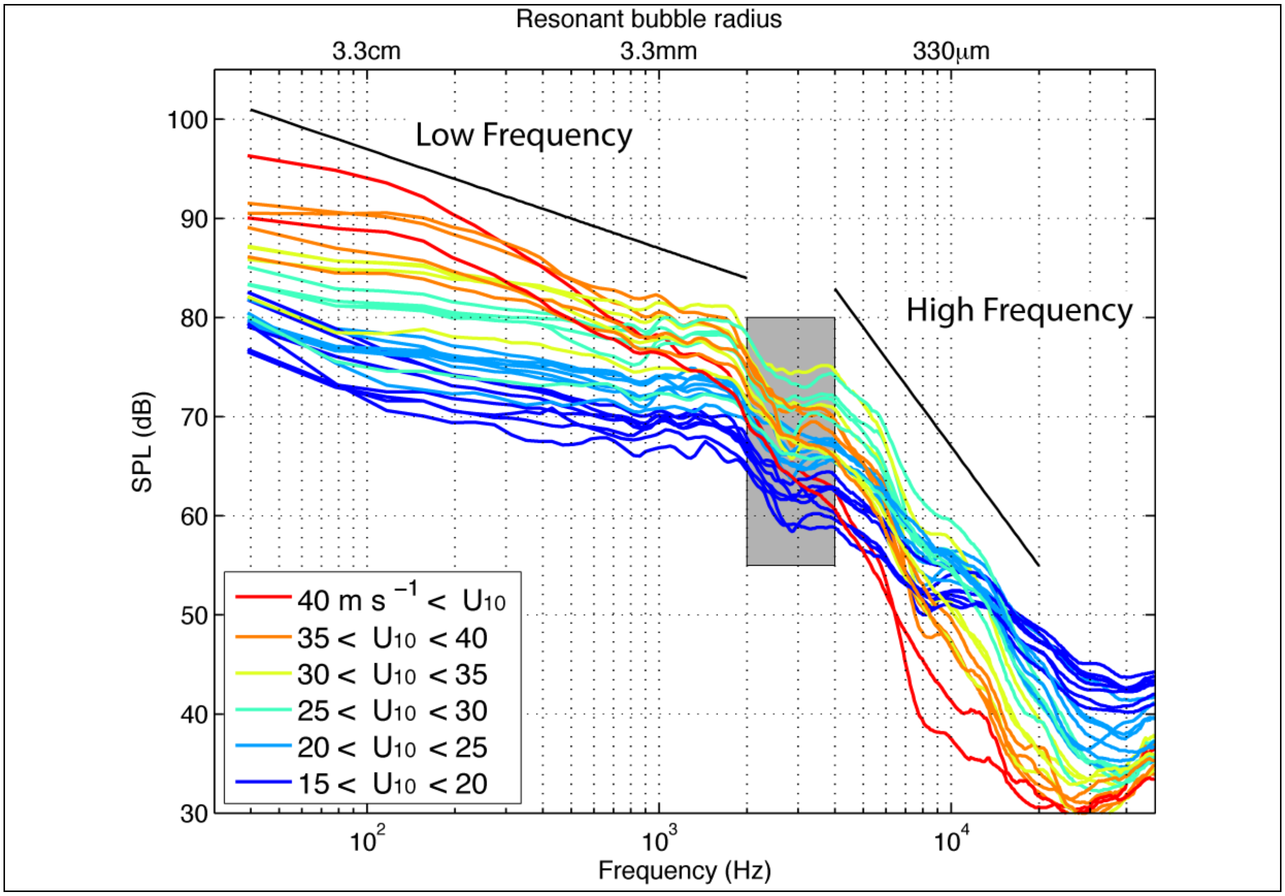

Figure 3. Sound spectra within selected wind speed catagories. At all wind speeds, a clear break in spectral slope occurs near 3 kHz, corresponding to a bubble size of approximately 1mm.

Sound spectra show two distinct regimes (Fig. 3): low frequencies where the sound level varies only slowly with frequency (~ 10 dB per decade) and increases nearly monotonically with wind speed (Fig. 2) and high frequencies where the sound level decreases rapidly with frequency (20-50 dB per decade) and the wind speed dependence is complex. The transition between these two regimes (grey in Fig. 3) is remarkably constant with wind speed. Deane and Stokes (2010, JASA 127, 6, 3394-3410) model sound in breaking waves and attribute this break point to the kinetic energy dissipation rate in the active bubble formation region of breaking waves. These results thus suggest that the dissipation rate is nearly constant over a wide range of wind speeds and that the necessary increase in average dissipation rate with wind speed is due to more frequent and widespread wave breaking and not an increase in the intensity of individual breaking events.

IMPACT/APPLICATIONS

Tropical cyclone forecasts have shown little improvement in storm intensity over the last 20 years. The newest generation of predictive models, including the Navy's COAMPS system, couple atmospheric, oceanic and surface wave components in a attempt to properly model the storm, ocean and air-sea physics which govern storm intensity. ITOP has gathered a comprehensive data including all three of these components, which is thus suitable for testing these new models.

PUBLICATIONS

D'Asaro, Eric; Peter G. Black; Luca Centurioni; Ya-Ting Chang; Shuyi Chen; Hans C. Graber; Patrick Harr; Verena Hormann; Ren-Chieh Lien; I.-I. Lin; Thomas B. Sanford; Tweng-Yung Tang; Chun-Chieh Wu, 2013, Impact of Typhoons on the Ocean in the Pacific: ITOP, *Bulletin of the American Meteorological Society*, in press

Rabe, T. J.; T. Kukulka; I. Ginis; T. Hara; B. Reichl; E. A. D'Asaro; R. Harcourt; P. Sullivan, 2014,Langmuir Turbulence Under Hurricane Gustav, *J. Phys. Oceanogr*., in review

Zhao, Z., E.A. D'Asaro, and J.A. Nystuen, 2014: The sound of tropical cyclones. *J. Phys. Oceanogr.*, doi:10.1175/JPO-D-14-0040.1. (http://journals.ametsoc.org/doi/abs/10.1175/JPO-D-14-0040.1)

HONORS/AWARDS/PRIZES

Eric D'Asaro was elected to the National Academy of Sciences, the first experimental physical oceanographer so honored in many years. This undoubtedly reflects scientific contributions made possible by ONR support over the last 30 years.