Impact of Typhoons on the Western Pacific Ocean DRI: Numerical Modeling of Ocean Mixed Layer Turbulence and Entrainment at High Winds

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LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:

- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior

OBJECTIVES

This ongoing collaborative effort is measuring and modeling the response of the upper ocean to strong typhoons both in simple, open ocean conditions and in the more complex conditions caused by ocean eddies and preconditioning by prior storms. The measurement and modeling activities include a focus on the impact of surface waves, air-sea fluxes and the temperature, salinity and velocity structure of the upper ocean. The goals of this effort are to understand key upper ocean processes, test upper ocean models, develop and test new parameterizations of upper ocean physics used and study the feedback from the ocean to typhoon intensity.

APPROACH

The approach of the the modeling component is to use field observations to force Large Eddy Simulation (LES) and upper ocean turbulence models in equivalent numerical cases and to use model-data comparison to test the theoretical basis of mixed layer turbulence scalings and parameterizations. The strategy is to test our physical theories and parameterizations of mixed layer dynamics against data by incorporating them realistically in turbulence-resolving LES models with embedded virtual measurements. Verification of the underlying theories can then be achieved through direct model-data comparison, using observations of ocean waves and turbulence under a wide range of oceanic conditions, and leading to improved parameterizations of upper ocean turbulence. The strong and isolated wind forcing in tropical cyclones provides an ideal environment for testing theories and parameterizations of the role of surface waves in the ocean mixed layer. This follows similar work in CBLAST exploiting the comprehensive view of boundary layer turbulence made possible by the combination of Lagrangian float and EM-APEX measurements. In FY2011, work has continued on developing an improved second moment closure to represent the impact of Langmuir turbulence. This model is remarkably novel because it involves a vertical momentum flux that is directed down the gradient of surface wave Stokes drift, in addition to the conventional one proportional to the Eulerian (non-wave) shear.

WORK COMPLETED

Simulations with LES techniques have doubled the number of completed forcing cases where wind and waves are not directionally coherent. One focus of the new cases is to identify clearly the anisotropy between positive and negative angles between wind and wave direction. This appears to result from Coriolis effects on the upper boundary layer shear, and the anisotropy between positive and negative wind-wave angles is reversed when the sign of planetary rotation is reversed. Forcing and case development is ongoing to simulations observed cases from the 2010 field program, and several wave modelers in the Typhoons DRI group are approaching solution sets that may be used to force LES and second moment closure models for DRI observed upper ocean turbulence.

Following generally positive comparisons between LES models and Lagrangian float observations in Harcourt & D'Asaro (2008), and subsequent refinements in the interpretation of observations in Harcourt & D'Asaro (2010), we have identified a closure model based primarily on the Craik-Leibovitch vortex force as likely to predict upper ocean turbulence, including under the winds of tropical cyclones. Work has therefore continued on the development and implementation of a second moment closure that more correctly represents the effect of these vortex force terms, due to the interaction of surface wave Stokes drift and Eulerian current shear within the mixed layer. The results below focus primarily on progress in this endeavor.

RESULTS

What is most unique about the new second moment closure model is that it predicts that a component of the vertical momentum flux is proportional by a diffusivity K_M^S to the Stokes drift gradient $\partial_z v^S$, in addition to the conventional term related to mean Eulerian shear $\partial_z \bar{v}$:

$$\overline{v'w'} = -\left(K_M \partial_z \bar{v} + K_M^S \partial_z v^S\right),$$

while the heat flux retains the downgradient, $\sim \partial_z \bar{\theta}$ form

$$\overline{w'\theta'} = -K_H \partial_z \bar{\theta}.$$

A down-Stokes-gradient momentum flux component has been hypothesized by several prior LES-based studies, it is arrived at here as the necessary component for solution of a second moment equilibrium closure model derived from the Reynolds flux equation.

Initially, the new closure adopted to reasonable effect the closure constants used in Kantha & Clayson (2004), but further comparisons with LES results have motivated tuning adjustments in these parameters. The new model has been used to investigate the response of entrainment work to misaligned wind and wave directions across the breadth of a tropical cyclone, illustrated below in Fig. RRH1. A series of column models aligned across the storm track is used to demonstrate the effect of including surface wave forcing.

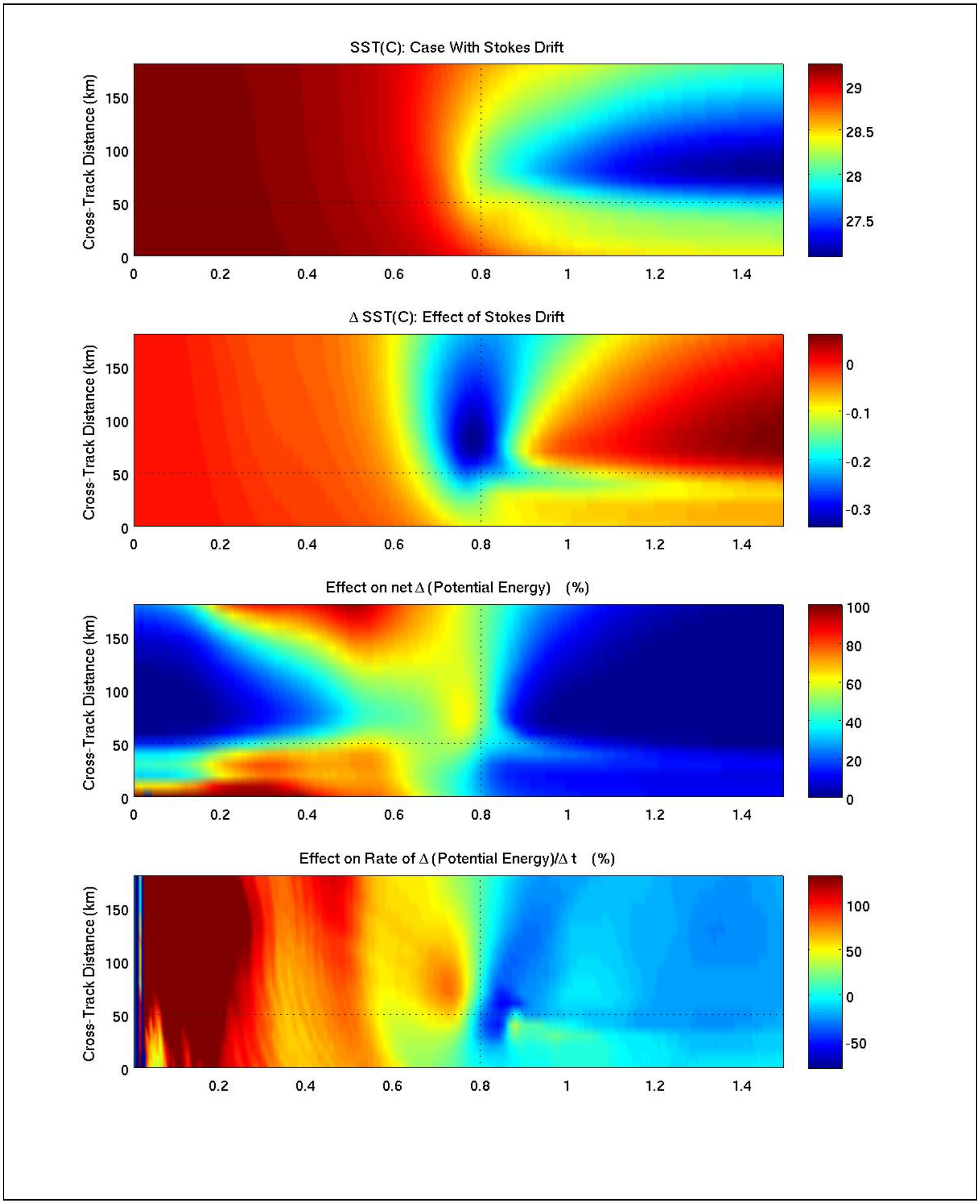

Fig. RRH1. [X-axis is time in days, formatted to correspond to along-track distance for storm moving to left.] Upper ocean simulations of the passage of a tropical cyclone (based on hurricane Frances), using the new second moment closure and wave fields from a Wave Watch model simulation: a) Net change in surface temperature with time. b) Difference in SST due to inclusion of wave effects. c) Relative effect of wave forcing on net change in potential energy of the water column. d) Relative effect of waves on the rate of change in ocean potential energy.

The new closure model shows the effects of waves on the net change *after* the passage of a typhoon or hurricane are relatively small, particularly in the cold wake. However, there are sizable differences as the cyclone passes overhead that may impact air-sea interactions and the evolution of cyclone strength. Both the SST (Fig 1b) and the change in geopotential energy reflect enhanced mixing in the forward right quadrant that lowers SST by an up to additional 0.3C below the highest winds while increasing mixed layer depth. The misalignment of wind and waves in the rear of the storm tends to counteract these effects resulting in relatively minor changes surviving mainly in the rear left quadrant after storm passage.

There are, however, still some defects with this model that limit its application. In particular, the strong near-surface mixing down the Stokes $\partial_z v^S$ can drive the mean Eulerian shear $\partial_z \overline{\boldsymbol{v}}$ to reverse it's direction and run counter to wind and waves. This defect appears to stem from closure assumptions customarily made for the pressure-velocity transport terms in the Reynolds flux equation. Some more appropriate assumptions have been identified, but these make the solution to the Equilibrium model less tractable and it is unclear if the solution can proceed the same approach as in other second moment closures. Current tasks in progress include finding some way to remove these defects, as well as determining how severe they are if they cannot be.

IMPACT/APPLICATIONS

Surface waves are believed to play a key role in the upper ocean boundary layer, yet do not appear explicitly in any of the major boundary layer parameterizations used in ocean circulation or climate models. Addressing this defect will lead to mixed layer models with turbulence intensity and entrainment efficiency, scaled by wind stress, that increase with surface wave age, in the presence of swell. While subsurface shear may dominate pycnocline mixing under inertially resonant wind forcing conditions, variability in mixed layer energy due to surface waves will play a significant role in deepening the layer when this is not the case. A boundary layer model that includes sea state dependencies, in addition to the usual dependencies on surface stress, buoyancy flux, and subsurface shear, will ultimately be more accurate than one which does not.

RELATED PROJECTS

Typhoons DRI continues previous work in the Hurricane component of CBLAST DRI. Development of the field program system for archiving and serving images and compact data to ship science parties has been done in conjunction with work in the LatMix DRI.

REFERENCES

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PUBLICATIONS

Harcourt, R.R., and E.A. D’Asaro, 2010: Measurement of Vertical Kinetic Energy and Vertical Velocity Skewness in Oceanic Boundary Layers by Imperfectly Lagrangian Floats, *J. Ocean. Atmos. Tech.* DOI: 10.1175/2010JTECHO731.1, 27, p. 1918-1935 [published, refereed].