Wave-Related Modification of Ocean Surface Fluxes

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1. Introduction

Should we attempt to use wave data to improve surface turbulent flux fields? To answer this question we must determine the extent to which surface turbulent fluxes are modified by surface water waves. To address this question, we need

- a reliable flux model (Bourassa 2005) that accounts for sea state influences on stress, and
- reliable wind, wave (WW3), temperature and humidity (ECMWF) data.

Prior to attempting this study with historical (or satellite) data, the problem will be explored with modeled data. Previous observational studies found that wave-related changes in heat fluxes were smaller than natural variability. A new physical mechanism is used to explain more of the variability.

Why might waves influence surface turbulent fluxes? Surface stress over water is primarily dependent on the vertical wind shear, which can be determined from the profile of wind speed. This profile is mainly dependent on wind speed differences between the surface and a know height, and secondarily dependent on the stratification of the atmosphere (atmospheric stability) and sea state (i.e., characteristics of the surface wave field). In the mid-latitude storm belts there can be great variations in sea state, both in the magnitude of the waves, and in the direction of wave propagation relative to the wind direction. These wave propagate widely, modifying surface surface stresses in areas far from where the waves were generated. This study focuses on the impacts of sea state on surface turbulent energy fluxes.

2. Why Is Sea State Be Important for Climate Applications

Waves can be divided into two categories: wind waves and swell. Wind waves are created by the local winds. Swell is created by distant events, and has propagated into regions where the local wind cannot maintain the waves.

- **Wind and Swell patterns are systematic over much of the global ocean**
  - The swell need not move in the same direction that the wind moves.
  - Both the directional characteristic and the non-directional characteristics (e.g., wave height and wavelength) influence surface turbulent stresses.
  - In some locations with very strong winds, the waves do not grow to reach equilibrium with the winds.
- **Not Considering Sea State Can Result in Regional Biases in Stress**
  - Rising seas result larger surface surface stress
  - Waves moving with the wind reduce surface stress
  - Waves moving at substantial angles to the wind can increase surface stress.
  - Surface stress influences horizontal and vertical transport
    - Consequently there can be biases in energy transport
- **Surface turbulent fluxes of energy are proportional to the squareroot of the kinematic stress**
  - Regional biases in air-sea transfer of heat are expected.

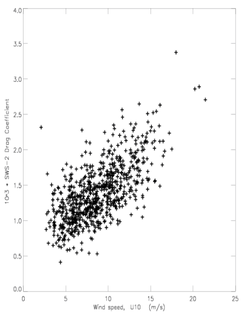

Figure 1. Drag coefficients as a function so wind speed, observed in the Severe Wind Seas 2 (SWS2) experiment. Data courtesy of Peter Taylor.

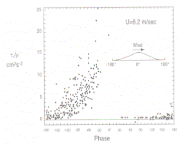

Figure 2. The stress is much greater on the windward side of the wave (*Okuda et al.*, 1997; and *Csanady*'s Fig. 2.16).

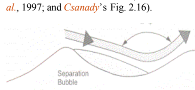

Figure 3. Typically, in the lee of the waves, the streamlines detach from the waves (*Csanady*'s Fig. 2.17).

3. Observations of Variable Drag Coefficients

Example Drag Coefficients from the Severe Wind Seas 2 (SWS2) experiment.

- Preliminary version of the SWS2 data set provided by Peter K. Taylor (Taylor and Yelland, 2001).
- These drag coefficients are based on high quality observations.
- Observations that are mostly from rough seas.

The drag coefficient clearly increases as wind speed increases.

- There is tremendous variability over even a small range of wind speeds.
- It will be shown that much of the variability in stress can be explained in terms of sea state.
- Directional sea state information for this experiment has not yet become available.
- Directional variability observed in SWADE (Donelan et al. 1997), for low wind speeds, is well explained by the model that will be described.

4. New Insights in The Surface Turbulent Flux Model or How to Model Influences of Directional Sea State

The key new concept is an improved treatment of the bottom boundary condition of the atmospheric boundary layer.

- In particular, the bottom boundary of the log-wind profile.
- Bottom condition on velocity (i.e., a frame of reference), and
- A vertical offset.

Both considerations are due to waves.

- The surface stress in non-uniform over waves (Fig. 2).
- The stress is much greater near the peak on the windward side of the crest.
- The wind interacts with short waves riding on these crests (Fig. 3).

4a. Horizontal Motion Due to Waves

Wave motion is not simply up and down. The surface moves in an orbital pattern, with the velocity at the crest being in the direction of wave propagation, and the direction in the trough in the opposite direction.

- This orbital motion modifies the velocity frame of reference of the shorter waves riding near the crest of the longer waves.
- The new flux model assumes that the orbital velocity represents the lower boundary condition for the log wind profile.
  - A fraction (χ) of this motion is vector subtracted from the wind speed.
  - This consideration modifies the vertical wind shear (Fig. 4).
    - Waves moving with the wind decrease the shear and hence decrease the stress.
    - Waves moving against the wind decrease the shear and hence increase the stress.
  - This concept is supported by comparison of scatterometer and buoy winds: the residual is correlated relatively strongly with the magnitude of orbital velocity.

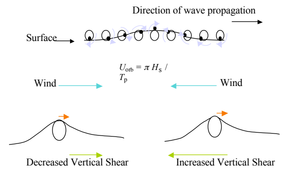

Figure 4. Orbital motion of surface waves results in a horizontal motion near the crests of waves, resulting in a change in the vertical shear of the wind.

4b. Complications and Simplifications

This approach requires that friction velocity (u*), wind speed, and orbital velocity be considered as two dimensional vectors, with stress parallel the friction velocity: $\vec{\tau} = \rho \vec{u}_* |\vec{u}_*|$.

A great advantage of this approach is that the sea state is not considered in the roughness length (z_o), thereby greatly simplifying the calculation. In this case, a constant value can be used for Charnock's parameter.

- The only free parameters (in Eq. 1) to be determined for this model are Charnock's parameter, (a in Eq. 3) which will differ from traditional values, and χ the fraction of the orbital velocity that is used in the bottom boundary condition.

$$\vec{\bar{u}}(z) - \vec{\bar{u}}_{current} - \chi \vec{\bar{u}}_{orb} = \frac{\vec{u}_*}{k_v} \log\left[\left(\frac{z}{z_o}+1\right) + \phi(z, z_o, L)\right] \qquad \text{(Eq. 1)}$$

4c. Displacement Height

Displacement height is a vertical offset of the log-wind profile (left circle in Eq. 2). The displacement height acts to increase shear. The bottom boundary condition for velocity has a matching condition for a vertical offset to the height corresponding to the bottom velocity. Typically the displacement height is considered to be zero – matching the typical assumption for velocity. This result is the first model for displacement height due to waves.

$$U_{10EN} - u_{current} - \chi U_{orbital} = \frac{u_*}{k_v} \log\left[\left(\frac{z - \chi H_s}{z_o}+1\right) + \phi(z, z_o, L)\right] \qquad \text{(Eq. 2)}$$

$$z_o = \left[\left(\frac{0.019\sigma}{\rho u_*^2}\right)^2 + \left(0.035\frac{u_*^2}{g}\right)^2\right]^{0.5} \qquad \text{(Eq. 3)}$$

5. Evaluation of New Stress Model

The best fit value of a=0.035, and the value of χ=0.8, based on comparison with the SWS2 observations (Fig. 5). Considering displacement height and orbital velocity (in a non-directional sense) reduces the rms difference in friction velocity (u_*) by approximately 10%, with much larger corrections for greater values of u_*.There is a great improvement in the accuracy of the mean.

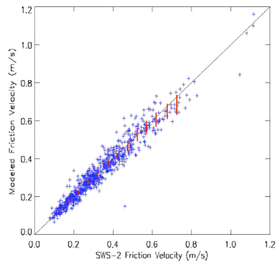

Figure 5. Comparison to SWS2 Observations. Red error bars indicate ±3 standard deviations from the mean.

6. Impact of Waves on Indian Ocean Fluxes

For this preliminary examination, data from April 1999 are examined. Fluxes are calculated every six hours. In the fields for one time, the passage of fronts have a very large influence, change latent heat fluxes by ±100Wm^{-2}. However, these are transitory and propagating features. Monthly averages of the impacts are considerably smaller, typically between –10 and 15 Wm^{-2}.

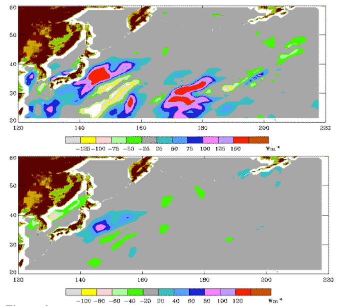

Figure 6. Change in latent (top) and sensible (bottom) heat flux for 6Z on April 01, 1999 in the NW Pacific (considering sea state minus ignoring sea state.

7. Closing Remarks

Based on this very preliminary investigation, it appears that

- Directional sea state can have a large influence on short (daily or less) time scale.
- The influence on monthly averages is large enough be be considered important in calculating climatological surface fluxes.

References

- Bourassa, M. A., 2005, Satellite-based observations of surface turbulent stress during severe weather, Atmosphere - Ocean Interactions, Vol. 2., ed., W. Perrie, Wessex Institute of Technology., in press.
- Taylor. P. K., and M. J. Yelland, 2001: The dependence of sea surface roughness on the height and steepness of the waves, *J. Geophys. Res.*, **31**, 572–590.

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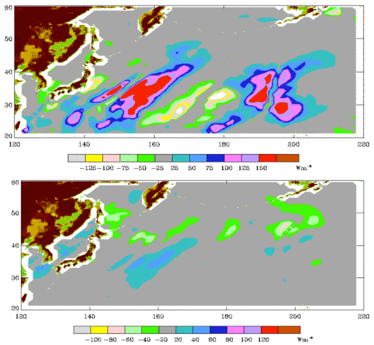

Figure 7. Change in latent (top) and sensible (bottom) heat flux for 18Z on April 02, 1999 in the NW Pacific (considering sea state minus ignoring sea state.

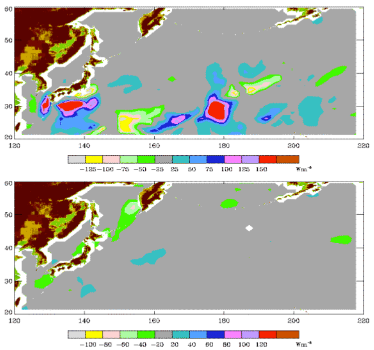

Figure 8. Change in latent (top) and sensible (bottom) heat flux for 18Z on April 02, 1999 in the NW Pacific (considering sea state minus ignoring sea state.

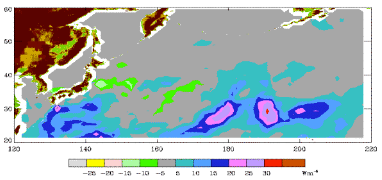

Figure 9. Change in latent heat flux for April 1999 in the NW Pacific (considering sea state minus ignoring sea state.

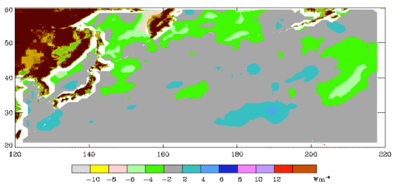

Figure 10. Change in sensible heat flux for April 1999 in the NW Pacific (considering sea state minus ignoring sea state.