

# **Dynamic Effects of Airborne Water Droplets on Air-Sea Interactions: Sea-Spray and Rain**

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## **LONG-TERM GOALS**

We anticipate that this research will lead to an improved understanding of water droplet mediated air-sea fluxes with implications in basic research, satellite or land-based remote sensing of the ocean surface, electromagnetic communication, military surveillance, and weather forecasting. We foresee that this work will become the initial stages of a long-term effort involving further development of theoretical work, and laboratory and field experiments.

## **OBJECTIVES**

In recent years, small-scale surface dynamics (waves, turbulence, bubbles, and drops) have been recognized as crucial to global climate through their impact on air-sea fluxes. However, the dynamics of a turbulent surface can be quite complicated, and at times (at high wind speed) the main problem is to identify the surface which then resembles a mixture of bubbles and drops. While the upper ocean bubbly mixture has been relatively well studied, especially in the context of the acoustics, it appears that airborne water droplets have been widely ignored despite their undeniable importance.

Recent work point toward the fact that airborne water droplets can exchange with the atmosphere a consequent amount of momentum, energy, and enthalpy, especially at high wind speeds (Andreas et al., 1995; Andreas, 2004). At low wind speed, it appears that a significant fraction of shear stress can be carried by falling rain and transmitted to the wind field (Caldwell and Elliot, 1971). The direction and amplitude of the momentum and enthalpy fluxes depend on the origin of the droplet (the upper atmosphere for the rain, the ocean surface for sea spray), and in the case of sea spray, if it evaporates entirely or falls back.

This project is aimed at improving and using an existing sea-spray Lagrangian turbulent transport and evaporation model to study the heat, moisture and momentum balances in the lower atmospheric boundary layer when water droplets are present. We also plan to conduct laboratory experiments to assess the effects of impacting rain on the surface and the consequent exchange of energy from the wind to the water via the droplets.

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## **APPROACH**

We propose to improve our current sea-spray Lagrangian turbulent transport and evaporation model to include several important effects that have been neglected in the past. Also, we propose to generalize part of the parameterizations such that the model is adequate for a wide range of conditions and therefore usable to study both suspended sea-spray and also rain droplets. The numerical part of this project will be aimed at further developing the model, and making use of a cluster of PC computers to run the calculations. In addition, a laboratory experimental part is proposed for the later years, in which we will examine the momentum exchanges between impacting rain and the ocean surface.

## **WORK COMPLETED**

We have implemented a large computer system consisting of twenty-four, single processor PCs on which the model processing is performed. The data are then recombined on a large server computer for analysis. We have modified the currently existing model to account for anisotropy in the Lagrangian turbulence in the air-flow above the wavy ocean surface, and include wave-turbulence interactions. This has been done via a generalization of the Lagrangian Stochastic equations for turbulent fields (Wilson and Sawford 1996). The generalization includes non-isotropic conditions allowing us to incorporate stratification effects in both the mean Eulerian, and non-homogenous conditions allowing difference in statistical properties of the turbulence upwind and downwind of surface waves. This is critical in particular for sea-spray suspension dynamics where the spray is generated on the front (leeward) face of the wave. To date, we believe we have successfully implemented turbulence closures and the wave effects. Turbulence for the passive scalars has also been included. Furthermore, we have developed a general description of the wind, temperature and humidity velocity profiles above the wavy surface which includes the diffusive molecular layer based on hybrid equations from the classical Van Driest (viscous) and logarithmic layers. The full wave spectrum also generates a moving bottom boundary which then interacts with the mean profiles as well as the turbulence. Based on the wave spectrum and breaking statistics, we have also incorporated the effects of air-flow separation on the momentum flux. These effects feed into the determination of the viscous and turbulent partition and thereby influence the calculation of the wind profiles. This leads to a non-linear formulation for the sea surface stress. To date, we have competed to coding of the Lagrangian model and have performed full runs with full droplets size distribution that will generate the bulk of the results. We also have initiated runs that incorporate and account for the feedback from the spray on the mean environmental conditions. Finally, we have performed the experiments on the effect of impacting rain on the surface and the consequent transport of kinetic energy from the wind to the surface. Our results show that significant kinetic energy is injected in the surface layers of the water and that penetration depth and rate are functions of the rain rate.

## **RESULTS**

We have developed a Spray Lagrangian Turbulent Transport and Evaporation model (hereafter SpLaTTE) which includes droplet microphysics, propagating surface waves, atmospheric stratification, turbulence, and the complete linear unsteady equation of motion for the droplets. Our results indicate that the short thermal and inertial response time of small droplets is such that they decelerate and warm up significantly as they approach the thermal and momentum boundary layer near the ocean surface. We have therefore spent considerable effort in developing a generalized form for the wind and scalar profiles (including stability), which account for the viscous layer close to the interface. Figure 1 shows

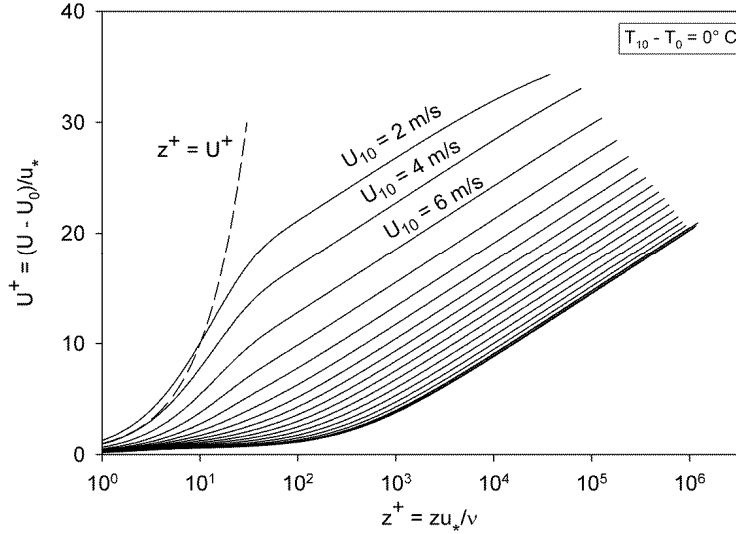


Figure 1. Wind profiles from 2m/s to 40m/s in 2m/s increment and plotted in wall layer coordinate. Note the presence of a well defined viscous sub-layer and the effect of stratification at low wind speed (the top most profiles for large  $z$ ).

the wind profile above the surface (plotted in wall layer coordinate) for wind speeds from 2 to 40m/s in increments of 2m/s. The departure from the log-layer at the lowest wind speed is due to effects of atmospheric stratification, effects that disappear at higher wind speeds. Another significant improvement to the model was the inclusion of fully non-isotropic Lagrangian turbulence for the velocity, temperature and humidity variables. Figure 2 shows spectra for the vertical velocity of both a 150 $\mu$ m droplet and the air velocity around the droplet. In order to assure a sufficiently long residence time to obtain statistical properties for this test case, the droplet was released at 10 meters above the wavy bottom boundary. We found that the air velocity around the droplet is not significantly different from the true Lagrangian velocity that would be experienced by a fluid particle. Because the air velocity at the droplet is decorrelated in both time and separation from an idealized fluid trajectory, the spectrum is slightly flatter than the theoretical  $\omega^{-2}$  behavior for a fluid Lagrangian spectrum. The spectrum of the drop velocity, however, shows an  $\omega^{-4}$  dependence as is expected. Figure 2 shows that at lower frequencies, the particle and air at the particle are in phase and then move out of phase around the stokes response frequency, 14.3 Hz in this case. The results in figure 2 suggest that our model correctly simulates the trajectory of a particle in a Lagrangian turbulent airflow. It should be noted here that the simulated turbulence will uniformly have an approximate  $\omega^{-2}$  dependence, and therefore, the very high frequencies at which a dissipation range should exist will not be accurately modeled. But considering that the spectrum for the particle velocity follows a  $\omega^{-4}$  law, the contribution of very high frequencies to the total particle velocity variance is expected to be negligible. In addition, it should also be noted that the particle moves through the atmospheric surface boundary layer and that consequently, the nature and strength of the turbulence will also change as the particle, for example, changes altitude. As a result, since individual droplets are followed through their course in the boundary layer, we did not expect to obtain an  $\omega^{-2}$  dependence in the air-velocity spectrum surrounding a droplet along its path. Finally, as the particle stays suspended in the air-flow, its density and radius will change which will affect its response time and behavior vis-à-vis the forcing from the turbulence in the air during the entirety of its flight. This will in turn render spectral analysis along the flight rather difficult to interpret. We feel however, that this is one of the strength of the Lagrangian

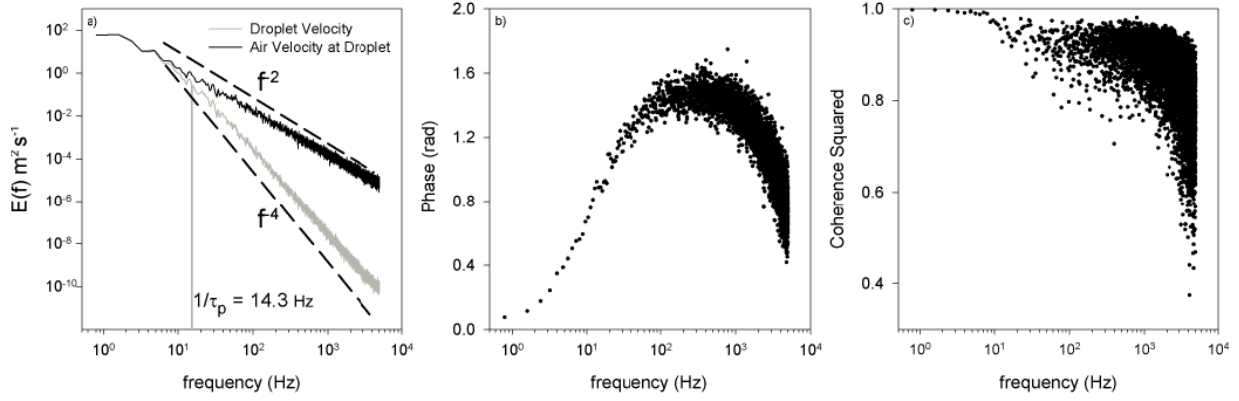


Figure 2 (a) Lagrangian frequency spectra for the vertical air velocity at the particle location (black), and for the vertical droplet velocity (gray), (b) phase relationship between the air and particle velocities, and (c) the coherence squared values between the air and particle velocities.

approach since we can keep track of both the droplet and the atmospheric properties surrounding it at all times.

We believe we have successfully implemented the closures and wave effects in the simulation of the Lagrangian turbulence. Finally, we have also incorporated the effects of air-flow separation on the full air-sea momentum balance. The air-flow separation is based on breaking wave statistics (in turn based on the balance of wave growth and dissipation), and on the physics of the detachment over back facing steps. The air-flow separation past a breaking wave reduces the viscous stress in the recirculating bubble and also enhances turbulence thereby affecting the partition of air-sea stress into its viscous, turbulent, and wave-induced components. This new parameterization of the air-sea stress amounts to a non-linear formulation as the air-flow separation feeds on other stress components, but also on the determination of the mean velocity profile, which in turn affect the wave spectrum. This sub-model reproduces the observed features of the drag coefficient from low to high wind speeds despite extrapolating empirical wave spectra and breaking wave statistics beyond known limits. The model shows the saturation of the drag coefficient at high wind speeds for both field and laboratory fetches, suggesting that air-flow separation over ocean waves and its accompanying effects may play a significant role in the driving physics of the air-sea stress, at least at high wind speeds (figure 3).

The sea-spray generation function is a significant source of uncertainty for the spray-mediated fluxes. For our model, we have developed a new spume generation function that is physically based. Our total produced mass flux remains roughly constant with wind forcing after  $20 \text{ m s}^{-1}$ . The additional wind energy at higher wind speeds instead goes into breaking up the spume drops into smaller drops rather than creating additional mass. Some of this energy could originate from wave energy dissipated by breaking waves. Ultimately, our suspended mass flux matches the mass flux found in Fairall et al. (1994) if scaled by whitecap A coverage rather than whitecap B coverage. This makes sense because spume droplets presumably only form at the crests of breaking waves. Our droplet distribution include more larger drops, however, which leads to strong difference form of the spray-mediated momentum flux. For comparison, we have also performed some preliminary laboratory experiments for the spume generation function. There is better agreement between our generation function and the results as can be seen in figure 4.

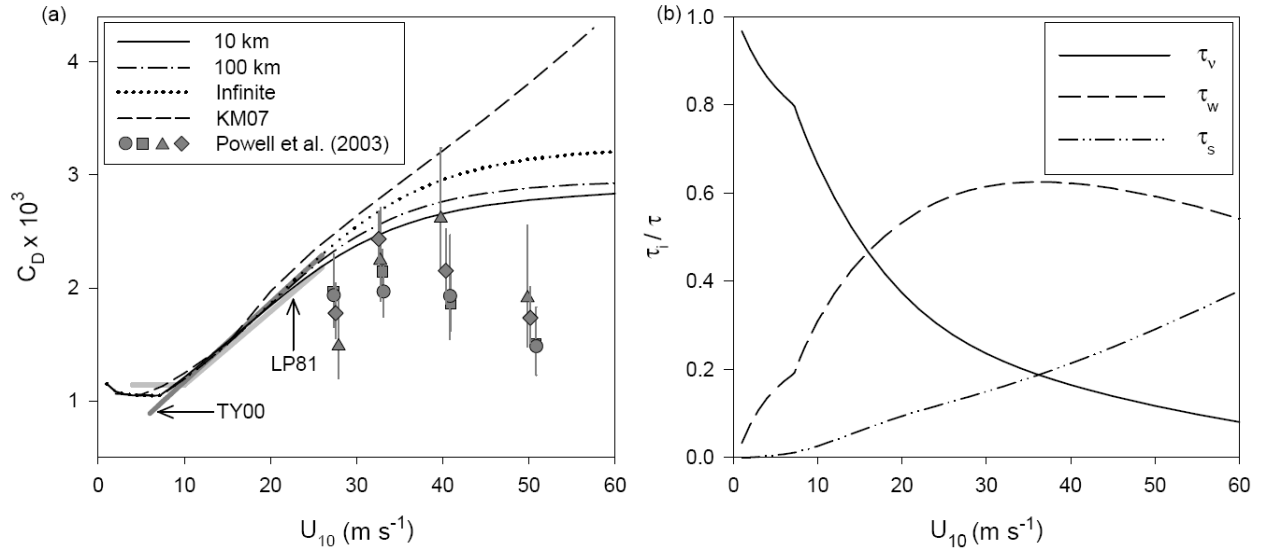


Figure 3 a) Drag coefficient as a function of wind speed for 10 km (solid), 100 km fetch (dash-dotted), and infinite (dotted) fetches along with the experimental data of Large and Pond (1981) (light gray), Taylor and Yelland (2000) (dark gray) and Powell et al. (2003) (gray symbols). Model results from Kudryavtsev and Makin (2007) (dashed line) are also included. b) Fraction of the viscous (line), wave-induced (dashed), and separation (dash-dotted) stresses as a function of wind speed for a 100 km fetch

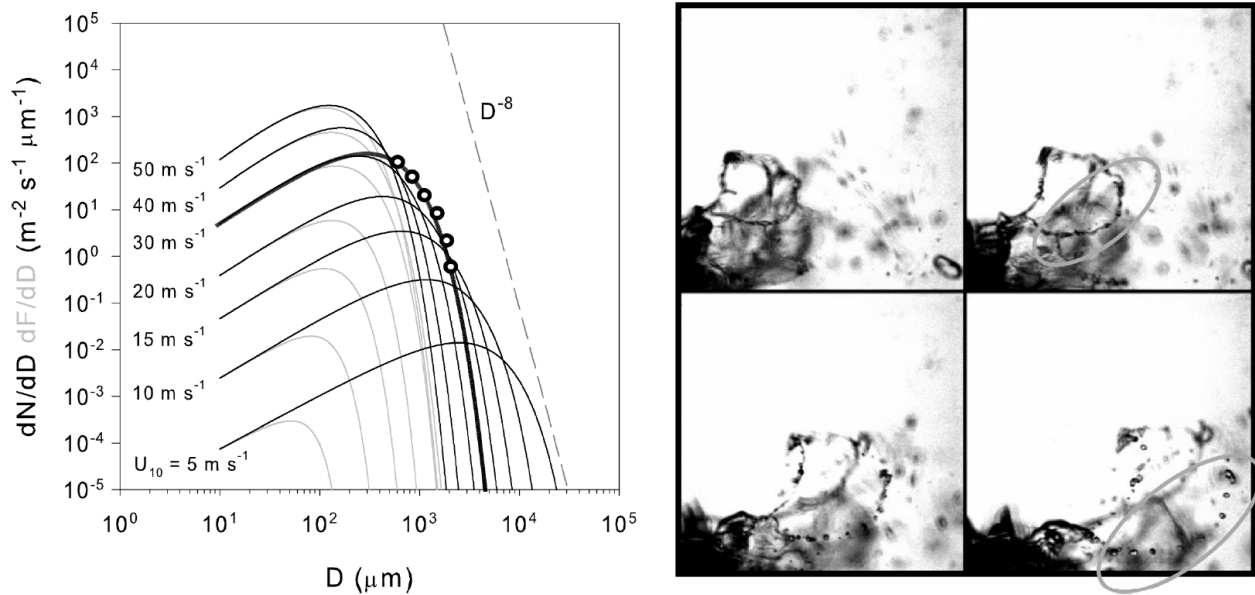


Figure 4 a) The modeled spume production functions for different wind speeds and for a laboratory fetch of 22m. The thick black line shows the production function for a fetch of 4.7m at a wind speed of 30m/s and the symbol show the size distribution collected from the high speed video. b) High speed imagery showing the production mechanism for large droplets. Filaments are formed and break up under the effect of the wind shear generating a number of large spume droplets.

Without compensation from feedback effects, the spray-mediated stress increases the drag coefficient, as seen in figure 5a. Although the total mass flux is the roughly the same when using our generation function and that from Fairall et al. (1994) scaled with whitecap A coverage, the two distributions are still different. This leads to different spray-mediated fluxes. Our generation function accounts for more spray stress at lower wind speeds but less at high winds. Figure 5b shows the partition of stresses with wind speed for our generation function. The fraction of spray-mediated stress to the total stress peaks somewhere between  $15 \text{ m s}^{-1}$  and  $20 \text{ m s}^{-1}$ . The total stress continues to increase with wind speed, but it never reaches a substantial fraction of the total stress at high winds. Instead, the spray-mediated momentum flux remains roughly constant at a few percent of the total stress. This implies that even though the concentration of sea spray increases substantially under high wind conditions, the additional stress will never overtake the total stress. The presence of spray could therefore account for the reduction of the drag coefficient due to stability effects, turbulence absorption or the wave damping. We hope to continue to investigate the impact of these possible mechanisms on the drag coefficient at high wind speeds.

In the laboratory, we have initiated the study of the impact on the rain on the air-sea momentum flux. Our results indicate that the rain can significantly alters the wind speed profiles as momentum is exchanged between the two phases (air and airborne water). As the rain droplets fall they decelerate while approaching the surface, thereby accelerating the wind in the near-surface layers. Impact velocity is approximately 85% of the 10-m wind speed. It should be noted that this effect also exist with sea spray, albeit to a lesser extent because of the size/mass difference. Also, the momentum exchange is in the oposite direction as spray significantly accelerates while airborne, thereby exctracting momentum from the airflow. Upon impact, the rain transmits it kinetic energy to the water in the form of turbulence and currents. Figure 6 below shows turbulent kinetic energy profiles up to depths of approximately 15cm (under no wind conditions) as the rain starts falling of the water column. Our results indicate that the penetration depth, as well as the peneration speed is dependent on the rain rate.

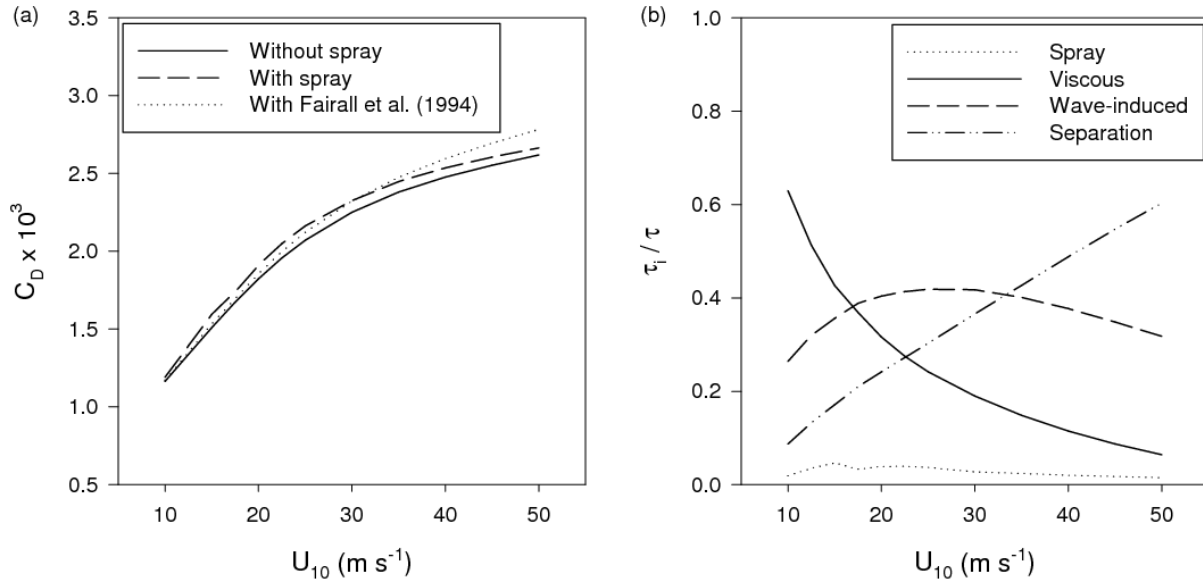


Figure 5 (a) The drag coefficient without the spray-induced stress (line), with our generation function (dashed) and with that of Fairall et al. (2004) as a function of wind speed (b) Fraction of the viscous (line), wave-induced (dashed), separation (dash-dotted), and spray-induced stresses as a function of wind.

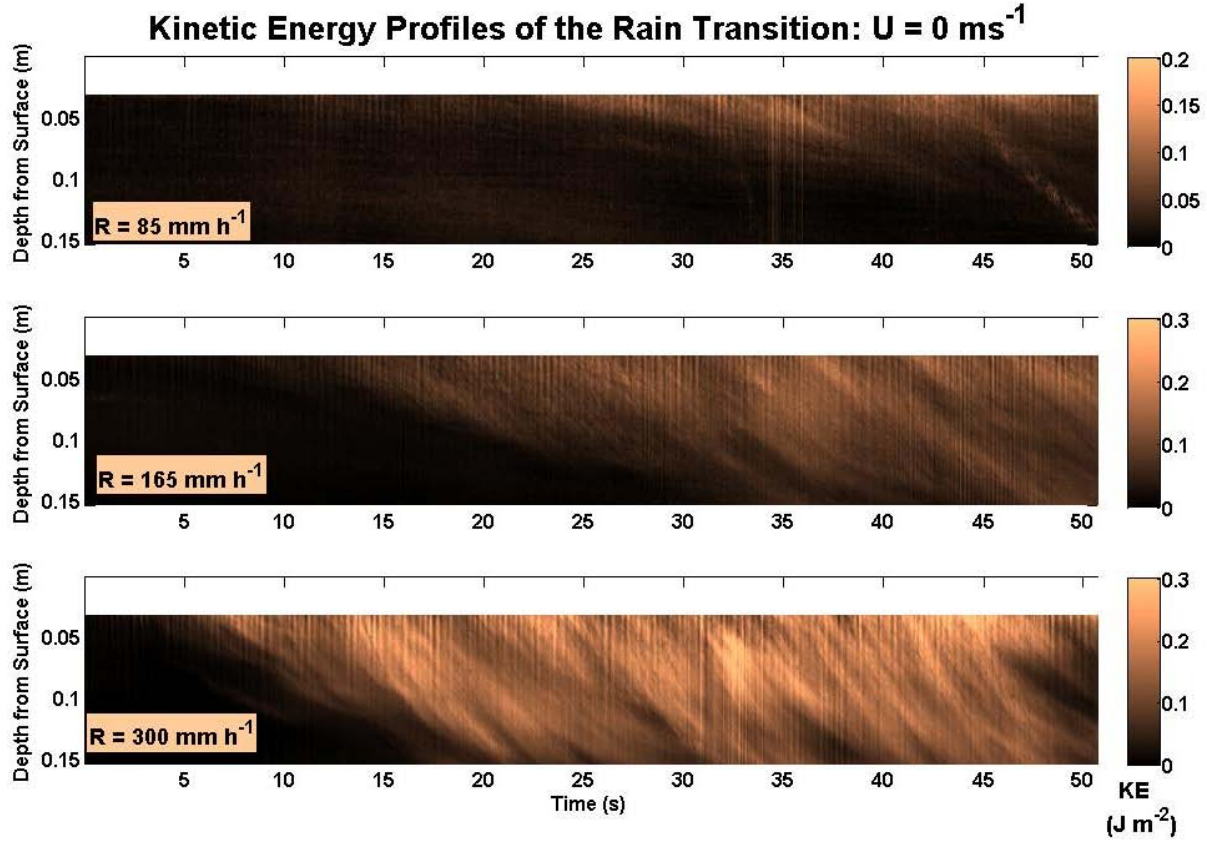


Figure 6: Profile of the turbulent Kinetic Energy under the inception of the rain, for different rain rate conditions.

## IMPACT/APPLICATIONS

We anticipate that this research will lead to an improved understanding of water droplet mediated air-sea fluxes. Potential impacts are cited above and also include a better understanding of air-sea fluxes, especially at high wind speeds when significant amount of water droplets can be suspended in the air-flow. In particular in storm conditions or hurricanes, there can be a combined effect of sea-spray and rain which then leads to competing droplet-mediated momentum fluxes. The spray is expected to carry some momentum from the ocean to the atmosphere, while the rain will impart momentum to the ocean surface. We anticipate that our model will be allowing us to determine the net momentum fluxes carried by different droplet types. In addition, the model should lead to heat and moisture fluxes as well, which are a critical component of storm dynamics.

## REFERENCES

- Andreas, E. L., J. B. Edson, E. C. Monahan, M. P. Rouault, and S. D. Smith, 1995: The spray contribution to net evaporation from the sea: a review of recent progress. *Bound.-Layer Meteor.*, 72,3-52.
- Andreas, E. L., 2004: Spray stress revisited. *J. Phys. Oceanogr.*, 34,1429-1440.
- Caldwell, D. R., and W. P. Elliott, 1971: Surface stress produced by rainfall. *J. Phys. Oceanogr.*, 1,145-148.
- Fairall, C. W., J. D. Kepert, and G. J. Holland, 1994: The effect of sea spray on surface energy transports over the ocean. *Global Atmos. Ocean Syst.*, 2, 121–142.
- Kudryavtsev, V.N. and V.K. Makin, 2007: Aerodynamic roughness of the sea surface at high winds. *Bound.-Layer Meteorol.*, doi:10.1007/s10546-007-9184-7
- Large, W.G. and S. Pond, 1981: Open ocean momentum flux measurements in moderate to strong winds, *J. Phys. Oceanogr.*, 11,324-336
- Taylor, P.K. and M.J. Yelland, 2000: On the apparent “imbalance” term in the turbulent kinetic energy budget. *J. Atmos. Ocean. Tech.*, 17,82-89
- Powell, M.D., P.J. Vickery, and T.A. Reinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature*, 422, 279-283
- Wilson, J.D. and B.L. Sawford, 1996: Review of Lagrangian Stochastic models for trajectories in the turbulent atmosphere. *Bound. Layer Meteor.*, 78, 191-210.

## PUBLICATIONS

- Mueller J. and F. Veron, 2007: Nonlinear formulation of the bulk surface stress over breaking waves: a simple feedback mechanism resulting from air-flow separation, *Bound.- Layer Meteorol.* Accepted
- Mueller J. and F. Veron, 2007: Dispersive transport model for heavy particles within the marine boundary layer, *Bound.- Layer Meteorol.* Under review
- Mueller J. and F. Veron, 2008: A sea state dependent spume generation function, *J. Phys. Oceanogr.* Under review