Enthalpy Flux in Extreme Winds and the Roles of Sensible, Latent and Spray Heat Transfer Processes

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LONG-TERM GOALS

- To determine the coefficients for sensible and latent heat transfer (Stanton and Dalton numbers) in high and extreme winds.
- To understand, quantify and parameterize the role of spray in these fluxes.

OBJECTIVES

- To conduct laboratory tests of the cooling of a heated water body under unstable and stable conditions, with neutral conditions deduced from the asymptotic matching of unstable and stable conditions.
- To separate the sensible and latent parts of the enthalpy flux by repeating calorimetric experiments at different Bowen ratios.
- To observe and measure the spray production in both fresh and salt-water and to relate the production rate to the wind speed, the intensity of wave breaking and the entrainment of bubbles.

APPROACH

This project has been undertaken in the wind-wave facility at the Rosenstiel School of Marine and Atmospheric Science, University of Miami. ("Air-Sea Interaction Saltwater Tank - ASIST"). ASIST (http://www.rsmas.miami.edu/groups/asist/) has a working section of 1 m x 1 m x 15 m. The water depth can be selected up to 0.5 m and at this maximum depth the (centerline) wind speed can be selected between 0 and 30 m/s (equivalent to greater than 100 knots at 10 m height). At this maximum speed wave breaking is intense and the tops of the wave crests are blown into spume. The calorimetric use of the tank over the full range of wind speeds provides accurate estimates of the surface heat transfer. The approach is to heat or cool the water (using built in heat exchangers) by 2 to 5° C

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above/below the air temperature and observe the cooling/heating rate of the water body with 4 precision thermistors placed upstream and downstream in both air and water. The room temperature (hence wall temperature) is maintained close to the temperature of the water to minimize the radiative transfer. Remaining radiative transfers are estimated by observing the heating/cooling of the water without any air flow.

The water is continuously pumped at a slow speed (0.08 m/s) to assure that the water column is well mixed. However, in calculating the heat and vapor fluxes across the air-sea interface it is necessary to account for the difference between the surface skin temperature and the bulk temperature. To directly observe the skin temperature and compare it to bulk measurements a FLIR infrared radiometer imaged the water surface during the experiments. The ("Black Stack") thermistor system provided accuracy and precision of ± 0.002° C and this enables a 2% estimate of the heat loss/gain in 5 minutes to 30 minutes depending on the wind speed. Figure 1 shows an example of the measured temperature and wind speed during such a run. Polynomial fits to the temperature allow a continuous estimate of the total heat loss. The specific humidity was measured with Li-Cor infra-red absorption devices at both the upstream and downstream ends of the wind tunnel.

This facility was acquired through DURIP grant number N00014-98-1-0261. A recent DURIP grant (number ONR N000140510852) has provided upgrades to its instrumentation systems that will be exploited in the second year of this project. In particular, a newly acquired particle generation system for the air-flow in ASIST will enable the mapping of the velocities above the surface. In combination with a newly acquired 3-D traverse, full volume mapping of the air flow above breaking waves will be possible.

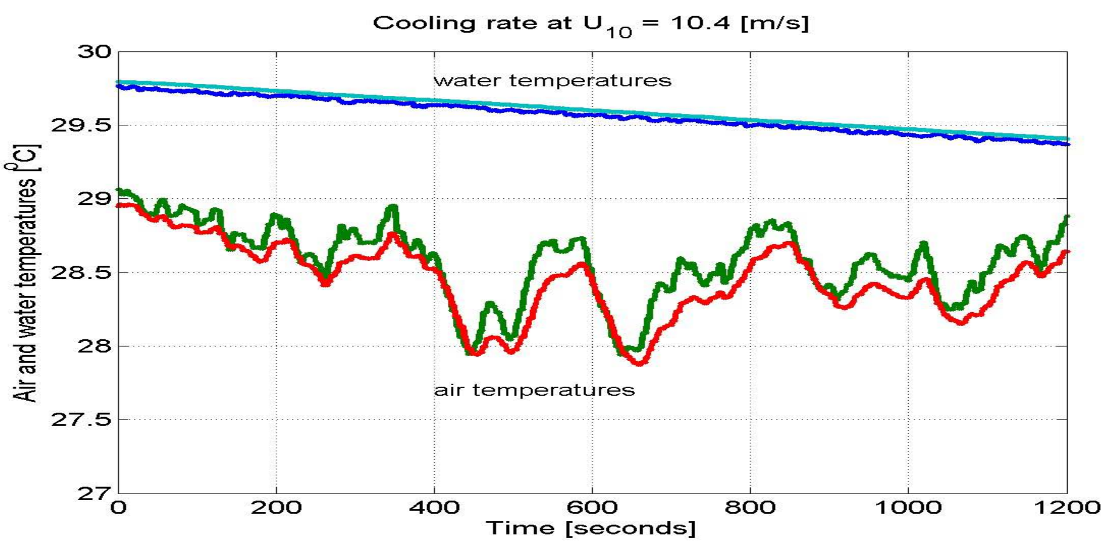


Figure 1. An example of the method of measurement of heat exchange. The upper water temperature curve is the input (upstream) water temperature, while the lower air temperature curve is the input (upstream) air temperature.

WORK COMPLETED

We have successfully executed a series of laboratory experiments in ASIST that included caliometric measurements of the bulk exchange coefficients at 17 wind speeds ranging from a minimum speed of U10 = 4 m/s to a maximum of U10 = 42 m/s. These measurements were conducted in high humidity conditions and provide a contrast to the preliminary work done in low ambient humidity. Analysis of this expanded set of measurements is ongoing and will be presented at the fall American Geophysical Union meeting by Dahai Jeong.

RESULTS

Measurements of the enthalpy flux (assuming the Stanton and Dalton numbers are equal) are shown in Figure 2. The vertical scatter at a given wind speed is due to (deliberate) Bowen Ratio differences. Therein lies the information that will lead to a separation of the estimates of sensible and latent heat. The ongoing measurement program will greatly extend the observed Bowen Ratios and would use both salt and fresh water. Preliminary calculations are in accord with the estimates derived from the cooling of the water in Figure 1 and demonstrate the ability of the method to isolate the Stanton and Dalton numbers by using the heat balance of both the air and the water components.

In principle the Dalton numbers can also be isolated from the moisture balance of the air component, but this requires great care in the measurement of upstream and downstream mixing ratio (or specific humidity). Fortunately, modern infra-red absorption devices, such as the Li-Cor closed path H2O/CO2 analyzers, have both the accuracy and stability to make these measurements feasible. The Li-Cor closed path humidity sensors can be damaged by condensation in the measurement cell. To prevent damage in the high humidity and spray conditions of interest, dry air was mixed with the tank air sampled by the sensor. The optimal ratio of dry air to tank air for sampling was determined to be 25% which required a dry air flow rate of 5 L/min (Figure 3).

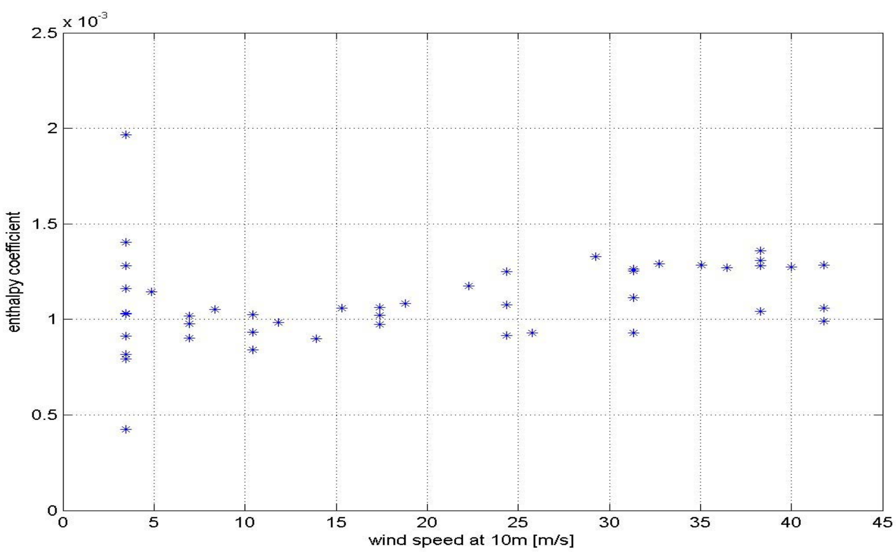


Figure 2. Measured enthalpy coefficients for different Bowen ratios assuming equality of Dalton and Stanton numbers.

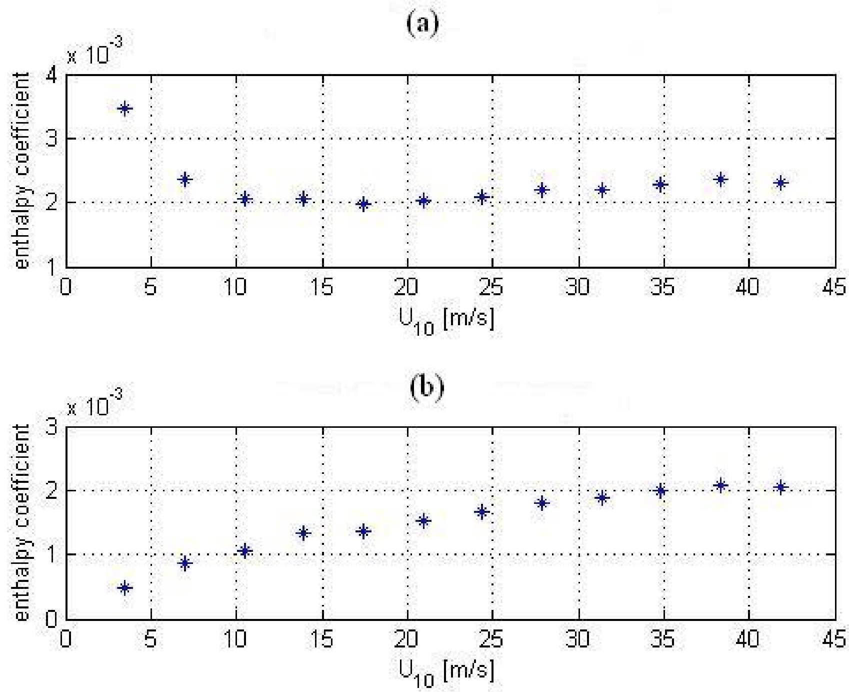
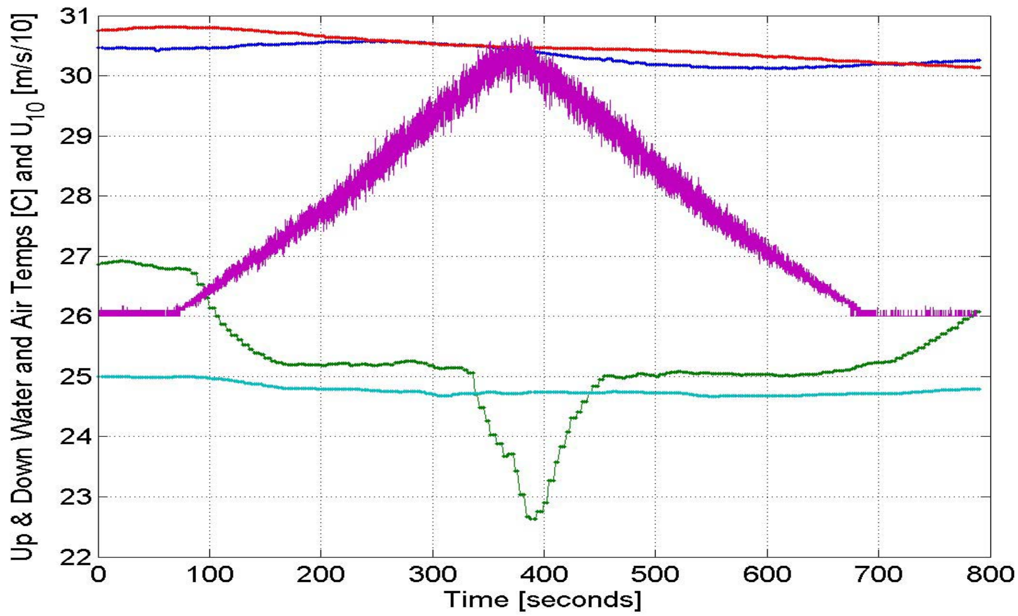


Figure 3. a) Measured enthalpy coefficients for different Bowen ratios assuming equality of Dalton and Stanton numbers. Example with radiative effects minimized but not explicitly removed. Dilution 25%, dry air flow rate 5 L/min. b) Measured enthalpy coefficients with radiative effects removed by subtracting the heat transfer at zero wind speed. Dilution 25%, dry air flow rate 5 L/min

The treatment of radiative transfers from the tank walls and the piping can significantly influence interpretation of the results. In the initial measurement series the room air temperature was maintained as close as possible to the water temperature to minimize radiative transfer (Figure 2a). While this is an appropriate procedure to implement, it is difficult to achieve because of non-uniform heating/cooling of the room air space and the range of water temperatures desired. A second step was implemented to remove radiative transfers, by observing the heat loss when there was no wind forcing. After equilibration of the temperature and humidity in the air space above the water, it was assumed that observed heat losses resulted from radiative transfers. Subtracting this quantity from the total heat flux resulted in a very different behavior of the enthalpy coefficient (Figure 2b), particularly at low winds.

Measurements in low air humidity suggested that evaporation of spray can dramatically suppress the air-temperature (Figure 4a). The effect of spray on the moisture flux was reflected in the drop in temperature along the air path from upstream to downstream and this enabled the estimation of the total spray evaporated in the air column. Figure 4a shows this effect in a 10 minute run in which the wind speed is ramped up from 0 to its maximum (about 45 m/s referred to 10 m) and down again. The sudden cooling of the downstream air reflects the point at which wave breaking starts introducing spray into the air and provides the means to estimate the total spray evaporation rate. Measurements conducted in higher humidity conditions do not show a strong spray effect (Figure 4b). Quantifying the amount of spray in the air over a range of winds, humidities and air-sea temperature differences will be a focus of the research in the second year of this project.

(a)



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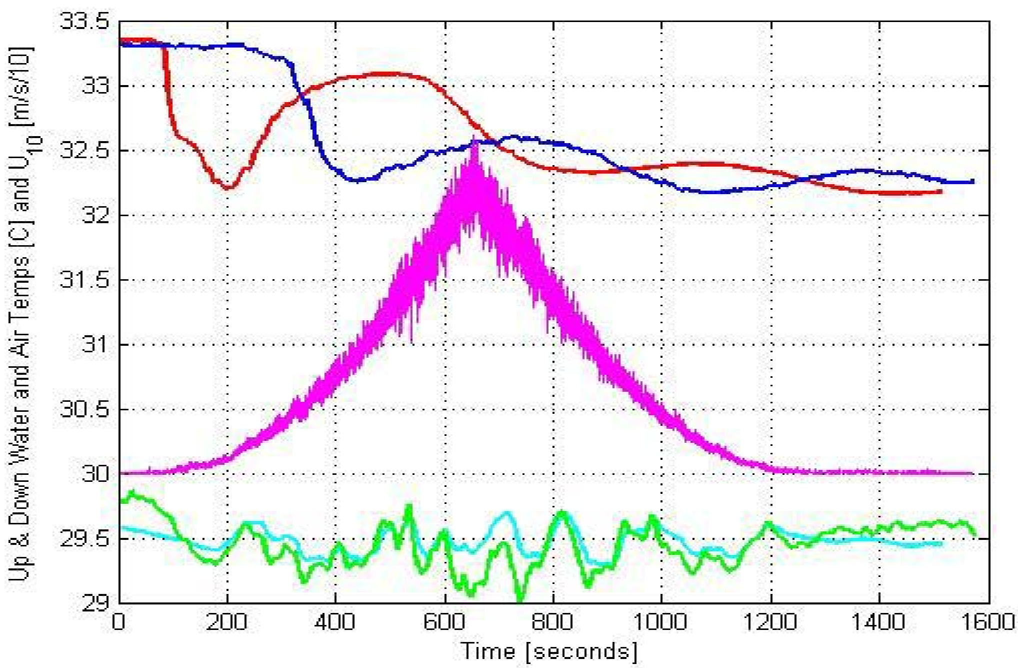

Figure 4. The changes in air and water temperatures during a run in which the wind speed (referred to 10 m height) was increased from 0 to 43 m/s and decreased again to 0 (magenta line). The red and blue curves at the top are the upstream and downstream water temperatures; the cyan line is the upstream air temperature, while the green curve is the downstream air temperature. a) Low ambient humidity, the onset of spray evaporation is reflected in the sudden drop in downstream air temperature at a wind speed of about 28 m/s. b) Higher humidity, drop in downstream air-temperature much less pronounced.

IMPACT/APPLICATIONS

The successful coupling of atmosphere and ocean in strong winds will require considerable knowledge of the transfer of momentum, heat and mass between the two fluids, i.e. across the air-water interface. The recent field and laboratory experiments of Powell et al. (2003) and Donelan et al. (2004) have shown that the expectation of increasing roughness with increasing wind speed, such as described by the generally used bulk drag transfer coefficients, finds a limit at wind speeds of tropical storms and hurricanes. The theoretical analyses of Emanuel (1995) concludes that the intensification of hurricanes depends on the relative magnitudes of the enthalpy flux and the momentum flux and that the current (pre 2003) parameterizations of the bulk drag and enthalpy coefficients would preclude the existence of category 4 and stronger hurricanes. These experiments should expand our understanding of the enthalpy coefficients and thereby facilitate progress in modeling high wind conditions at the air-water interface.

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