16C.6 TROPICAL CYCLONE ENTHALPY AND ANGULAR MOMENTUM FLUXES

William D. Ramstrom[1]
Massachusetts Institute of Technology, Cambridge, Massachusetts

1 Introduction

A hurricane can be thought of as a heat engine which derives its energy from the thermodynamic disequilibrium between the tropical atmosphere and oceans. Heat is input at the surface by sensible and latent heat fluxes, aided by the strong winds. Convective updrafts then transport this heat through the troposphere, and it is exported at the temperature of the tropopause.

The turbulent processes that enable the flux of momentum and enthalpy at the sea surface can be idealized using bulk formulas. This allows a description of the magnitude of the flux based on observable features of the boundary layer, without resorting to resolving the small-scale eddy field. Instead, the momentum and enthalpy fluxes are represented by functions of the 10m wind speed and non-dimensional exchange coefficients. For enthalpy, the flux is also a function of the enthalpy difference between the values at the sea surface and at 10m.

Previous work has been done measuring these coefficients under low wind speeds, but it is difficult to directly measure them under the extreme conditions of a hurricane. In general, direct measurements require a stable platform at some elevation above the sea surface and a continuous period of observations. In hurricanes, instead, more indirect approaches must be used, due to the difficulty of making such fixed-site observations. These are generally based on analyzing a budget of angular momentum and total energy in the storm and using the assumption that the residual must be a flux across the sea surface.

2 Data Sources

This study makes use of the GPS dropsonde and flight-level data sets gathered by the Hurricane Research Division (HRD) to estimate fluxes of enthalpy and angular momentum using the bulk aerodynamic formulae. The greatly increased vertical resolution and consistent collection of data down to very close to the sea surface is an important improvement over what was previously available. The low-level observations are crucially important in this effort, as the wind, moisture, and temperature profiles can vary strongly in the frictional layer near the surface, so interpolation from higher levels may not be accurate.

Several cases of very strong hurricanes (Floyd, Georges, and Mitch) were examined, as these storms had very high surface wind speeds (> 60 ms^{-1}) and good dropsonde coverage of the important eyewall region. Expendable bathythermographs were deployed for these storms; their data will be used to assess the temperature structure of the upper levels of the ocean under the hurricane eyewall and inflow regions.

3 Calculation of Fluxes

The drag coefficient, C_d, can be estimated by considering a budget of angular momentum. The aerodynamic flux formula for angular momentum is then expressed by equation 1, where τ_θ is the shearing stress in the $\Theta - Z$ plane, ρ_0 is the density of the air at the surface, C_d is the momentum flux coefficient, V is the tangential wind at 10m, and $|\mathbf{V}|$ is the magnitude of the wind speed at 10m.

$$\tau_\theta = \rho_0 C_d V |\mathbf{V}| \quad (1)$$

The flux of enthalpy serves as the source of energy for the development and maintenance of the hurricane. The total energy is a similar quantity that includes the effect of gravity and the kinetic energy of the wind. Enthalpy, k, is defined in equation 2, where c_{pd} is the heat capacity at constant pressure for dry air, q_t is the total specific water content, c_l is the heat capacity of liquid water, T_0 is a reference temperature, L_v is the latent heat of vaporization of water, and q is the specific humidity,

$$k = (c_{pd}(1 - q_t) + c_l q_t)(T - T_0) + L_v q \quad (2)$$

Total energy, is defined in equation 3, where g is the gravitational constant, z is the geopotential height, and $|\mathbf{V}|$ is the wind speed. For calculations

[1]Corresponding author's address: 77 Massachusetts Avenue, Room 54-1611, Cambridge, Massachusetts 02139
e-mail: ramstrom@mit.edu

of E of the sea surface, a value of $|\mathbf{V}|$ which is the gradient wind at that radius will be used.

$$E = (c_{pd}(1-q_t)+c_l q_t)(T-T_0)+L_v q+gz+\frac{|\mathbf{V}|^2}{2} \quad (3)$$

The flux of enthalpy across the sea surface is the only source of total energy in this system; away from the surface, total energy is approximately conserved. The aerodynamic flux formula for enthalpy is shown in 4, where F_k is the air-sea flux of enthalpy, C_k is the enthalpy flux coefficient, k_s^* is the saturation enthalpy of the sea surface, and k is the enthalpy of the atmosphere, and $|\mathbf{V}|$ is the magnitude of the wind speed at 10m.

$$F_k = \rho_0 |V| C_k (k_s^* - k) \quad (4)$$

These coefficients have been extensively estimated in laboratory and field studies, but only for relatively light wind speeds (up to about 20 ms^{-1}); (Large and Pond, 1981). A few observational studies have provided values for these coefficients by estimating values from budget residuals, rather than direct observation, and they show that drag coefficients continue to increase as winds approach hurricane force (33 ms^{-1}) (Hawkins and Rubsam, 1968).

Many models of tropical cyclones make use of bulk aerodynamic formulae for parameterizing air-sea fluxes of heat, moisture, and momentum. It has been shown (Emanuel, 1995) that models are quite sensitive to the ratio of these values, so determining accurate values for the full range of hurricane conditions would be a great help in improving the accuracy of these models.

4 Budgets

Since the budget equations are based on radial and vertical transport of angular momentum, enthalpy and total energy, they are very sensitive to the transformation of wind data into radial and tangential components. This transformation is straightforward, but is very dependent upon the position chosen to represent the center of the storm, as was noted in Hawkins and Rubsam (1968). Thus, more precise track estimates are required; there were generated by minimizing the radial winds at mid-levels of the storm. In an ideal hurricane, we would expect that the radial winds would be close to zero at mid-levels. Track estimates were generated by taking an initial best track from HRD, then adding noise with a Gaussian distribution of standard deviation $.1^o$ at selected points. The wind observations were then transformed into radial and tangential components, and a score assigned to rank how well mid-level radial winds were minimized. With each scored track, calculations of the budgets were run, giving a range of estimates of C_d and C_k and a measure of the variability due to different estimates of the hurricane track.

5 Results

Budgets of angular momentum, enthalpy, and total energy were performed in angular momentum coordinates, idealizing the storms as axisymmetric. Aircraft data with high radial resolution was used to calculate estimates of eddy fluxes of enthalpy and total energy at flight level. The eddy fluxes proved to have a significant effect on of estimates of C_k.

The drag coefficient, C_d, produced for the three cases ranged from 0.0026 to 0.0030. These values correspond to 10m winds in the range of 40-60 ms^{-1}. For Floyd and Georges, the enthalpy transfer coefficient, C_k, was in the range 0.0029 to 0.0036. The values for Mitch were much smaller, but the storm had begun weakening at the time of the calculations. These produce a ratio C_k/C_d that is slightly larger than unity, which is in line with modeling results in Emanuel (1995).

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