SURFACE PROCESSES IN HURRICANE DONNA
EXTENDED ABSTRACT

by

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In previous studies of hurricane mechanisms (Palmén and Riehl 1957, Malkus and Riehl 1960, Riehl and Malkus 1961) interactions at the ocean boundary always had to be inferred. Many uncertain aspects of the actual physics of the interaction processes exists, such as regarding surface drag and constraints relating surface pressure and heat sources.

Hurricane Donna offered an unusual opportunity for examining the low-level structure and mechanisms, since this storm passed in nearly steady state through a dense network of surface and upper-air stations while approaching Florida. Reports from these stations may be composited with respect to the moving center and thus offer insight into certain aspects of the low-level hurricane structure which of necessity is not available through research aircraft missions.

Surface Data

Compositing proved easy for surface pressure, including asymmetries around the center. But the attempt to composite the windfield led to a very curious result, a very rapid drop of wind speed outward along the line $vr^{1.3}$ = const. This is much stronger than the drop obtained from low-level aircraft data or from records of well-exposed stations. A check was made by computing momentum balance holding the surface wind constant through a layer of 100-mb thickness. The check failed as there was divergence of momentum flux through the bulk of the hurricane's area with nothing left for transfer to the ocean. Conclusion is that even the records of stations on small flat islands and along flat coasts are not representative of oceanic surface conditions.

Upper-Air Data

Next, the rawin observations were composited, at first in 1,000-foot steps to 4,000 feet altitude. Then 2,000-foot steps to 10,000 feet and 5,000-foot steps to 50,000 feet were added, for the area up to the 6^0-radius. The main inflow layer was below 4,000 feet, with weak inflow from there to 25,000 feet except in the inner region where there was none. Outflow was concentrated near 45,000 feet. At 50,000 feet a nearly symmetrical anticyclone, with small outflow only, was present. Perhaps for the first time in an individual case, precipitation computed from the inflow could be checked against that reported at rain gages. Excellent correspondence was obtained with use of these quite independent data sources.

At 1,000-feet the mean tangential component follows the law $v_\theta r^{0.6}$ = constant from the 3^0-radius inward; this closely corresponds to the Malkus-Riehl model and earlier studies. Three sets of data--rawins, land-surface reports, and lighthouse reports--all show 60 kn at about the 1^0-radius, with very steep slope of the land-surface winds outward from there as already mentioned. This brings out the effect of increasing mechanical turbulence at high wind speeds in reducing the vertical shear.

Momentum Balance

Balance of absolute angular momentum was computed for the layer 1000-100 mb and outward to the 6^0-radius with two main questions to be answered:

a) Is there a net stress at the level where the vertical profile of tangential velocity has a maximum or becomes quite flat -- the median of all ascents gave this level as 4,000 feet.

b) Is it necessary to make use of lateral small-scale mixing processes in order to obtain momentum balance.

The result is that total momentum flux across the 6^0-radius is equal to the momentum flux to the ocean as computed using the layer surface to 4,000 feet alone, hence that there is no net stress at 4,000 feet. Lateral mixing need not be invoked provided that the computed surface drag coefficients are accepted as realistic. These coefficients, reduced to the altitude and wind speeds of the lighthouse stations (16-18 meters), are about 1.5×10^{-3} up to tangential speeds of about 50 knots, then rise inward to 5×10^{-3}. This result is very similar to all previous calculations; for instance, Riehl and Malkus (1961) who then postulated lateral mixing on the hypothesis that 5×10^{-3} is too large in view of detailed wind observations made over the sea by other investigators. The low coefficient on the outside can be brought in agreement with previous measurements if it is assumed that the ocean water moves with a fraction of the air speed. This hypothesis is being investigated further.

Drag Coefficient from Lighthouse Data

Observations from five lighthouse stations off the Florida coast were composited with respect to the center just like the upper-air data. It is considered that by this means a first approximation to air trajectories near the sea (16 m) in hurricanes is furnished. Calculations were performed using one such trajectory which ended at pressure of 962 mb, wind 115 knots. Superposition of streamlines at 16 m and 1,000 feet showed no turning of wind with height and also, as brought out earlier, very little shear of wind speed at high speeds. Hence, following the method of Malkus and Riehl (1960), the kinetic energy equation may be integrated following the surface trajectory over a layer 4,000 feet thick. Since the stress is zero at the top of this layer, demonstrated above, the bottom stress and drag coefficient are determinable. This calculation sustains the enhanced drag coefficients from the general momentum balance, where it must be noted, however, that the computation only samples conditions ahead of the center. If valid in all quadrants, small-scale lateral mixing may be omitted as an important hurricane mechanism.

Surface Processes at Very High Speeds

In the hurricane interior, air is known to move at constant temperature. Hence, the pressure of an air particle is controlled by the direct oceanic heat source. Malkus and Riehl (1960) postulated uniform heat gain per given distance travelled, from the concept of a uniform exchange coefficient following a given mass. Thus, this mass must wind its way inward with ever decreasing inflow angle in order that the observed low pressures can be established. The Donna trajectory did not bear out this aspect of the model, though agreement in general was good. The pressure drop increased per distance travelled with wind speed; thus, the turbulent heat flux also increased.

Drag coefficients can be computed along the high-velocity trajectory with isothermal expansion with two assumptions:

a) The coefficients of heat and momentum flux are equal;
b) The height to which the surface heat flux penetrates is known. This height is obtained by imposing the condition that at the wind speed at the outer limit of the trajectory the drag coefficient is the same as that determined from momentum and kinetic energy calculations.

The value of the computation lies in the fact that it yields the drag coefficient as a nearly continuous function along the trajectory, whereas from the kinetic energy computation only bulk values over distances of not less than 30 miles can be obtained in view of the difficulties inherent in determining the production of kinetic energy by pressure forces. This is not satisfactory in the core where wind speed changes very rapidly over 30 miles.

The computed depth of the layer through which the heat flow from the surface penetrates is 1,000 feet, a satisfactory value which agrees roughly with the cloud bases. As is well known, the temperature lapse rate becomes more stable at the cloud bases and the nature of turbulence, as experienced for instance in aircraft, changes from the "washboard type" of the subcloud layer to that typical of layers with convective clouds.

The drag coefficient rose by an order of magnitude from wind speed of 60 kn to 115 kn, and a straight line is obtained in log-log representation of drag coefficient vs. kinetic energy. This relation suggests a new examination of the whole turbulence theory over sea at very high speeds, providing that the results in this single case are validated through examination of observations in other hurricane situations.

References

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