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THE IMPACT OF LANDFALL ON TROPICAL CYCLONE BOUNDARY LAYER WINDS

Jeffrey D. Kepert
Bureau of Meteorology Research Centre, Melbourne, Australia

1. INTRODUCTION

Landfall is often the period during which a cyclone presents the major hazard to life and property, and is also one of the major causes of the weakening of tropical cyclones. Understanding the changes in the cyclone structure that occur at landfall is therefore important.

Several observational studies have shown there may be important changes in the distribution of the low level winds at landfall. For instance, Powell (1982) made composite analyses of the surface winds in Hurricane Frederick over the open ocean, and at landfall. The open ocean composite showed the strongest winds in the right forward quadrant, with the maximum inflow angle to the right rear, in agreement with many other studies. At landfall, the winds over the land weakened and turned towards the storm centre, due to the increased surface roughness. A secondary wind speed maximum developed over the water in the offshore flow on the left of the storm.

Similar studies of Hurricanes Alicia (Powell 1987) and Hugo (Powell *et al* 1991) did not find this latter feature. However, the surface wind analyses of Hurricane Andrew at landfall (Powell and Houston, 1996), did show a secondary maximum in the offshore flow, just inland of the coast.

Hurricane Danny (Blackwell, 2000) remained nearly stationary over Mobile Bay, Alabama, for nearly 12 hours during landfall. During this period, it was under surveillance from a Doppler radar and reconnaissance aircraft. A low level jet within the eyewall was detected by the radar at the two azimuths where the flow was directly along a radial. In the onshore flow, the jet maximum was approximately 31 m/s at a height of 1.5 km and located about 20 km from the storm centre. On the other side, in the offshore flow, the jet was stronger (41 m/s), lower (below 500 m) and closer to the centre (11 km).

Shapiro (1983) presented a slab model of the boundary layer beneath a translating hurricane, and found that the strongest earth-relative winds (averaged through the boundary layer depth) were at the front of the storm, with the maximum storm-relative inflow ahead of the storm. Kepert (2001) and Kepert and Wang (2001; henceforth KW) presented 3-dimensional analytical and numerical models, respectively, of the hurricane boundary layer. Additional findings included that there is a supergradient wind maximum in the upper boundary layer, which is stronger and closer to the surface on the left of the storm. The asymmetry was shown to be the sum of two components: one component is weak, rotates cyclonically, and decays rapidly with increasing height, while the other is several times stronger at the surface, rotates anticyclonically, and decays much less rapidly.

These three idealized studies were each formulated in a coordinate system which moved with the cyclone. The storm-relative gradient wind was symmetric, and the asymmetries arose because of the asymmetry in the surface boundary condition from the storm motion. The results are thus applicable to other situations with asymmetric surface friction, such as a stationary storm that is partly over land. One difference is that the asymmetric friction due to motion has a pure azimuthal wave-number one structure. Thus the response in linear models is confined to wave-number one, and higher wave-numbers can arise in non-linear models only through the non-linear interaction of lower wave-numbers. In contrast, a cyclone which is partly over land will have an asymmetric lower boundary condition which when represented as a Fourier series contains an infinite series of wave-numbers, of which wave-number one would generally be the dominant component.

This study will use the numerical model of KW to model the flow in a cyclone at landfall. Results will include comparison with the afore-mentioned observational studies. While landfall has been extensively studied using full tropical cyclone models, comparatively little attention has been paid to the boundary layer – even though this is where the changes originate. Indeed, almost the only work has been to apply the well-developed theory of internal boundary layers. Here, we will show that larger-scale, inherently three-dimensional, changes are important.

2. MODEL DESCRIPTION

The model has been fully presented in KW so will only be briefly discussed here. It is a dry hydrostatic numerical model of the full primitive equations on an *f*-plane. The upper boundary condition is a parametric pressure field which represents that part of the cyclone above the domain. The lower boundary condition uses a wind-speed dependent surface roughness given by the Charnock relation. This is modified here to allow the prescription of a constant roughness over the land.

3. RESULTS

Hurricane Danny presents an interesting case for analysis, as it was to a first approximation stationary and half over land, although it was not in a steady state. We estimated that a radius of maximum winds of 15 km, maximum gradient wind of 35 m/s, and Holland *B* parameter of 1.3 were adequate approximations to Danny at the time of the radar cross-section shown in Blackwell (2000). The model was initialised with these parameters and the left half of the domain set to land with a constant roughness length of 50 mm, while the Charnock coefficient was 0.011 over the right half of the domain, giving a maximum roughness length there of 3.1 mm.

The radial and azimuthal flow at the lowest model level (22m) are shown in Fig 1. Over land, the inflow increases along a streamline and is a maximum near the gradient radius of maximum winds (RMW) in the offshore flow. This frictionally enhanced inflow is then maintained for some distance over the sea. The azimuthal component reaches its maximum over the sea, slightly offshore. This is because the strong inflow upstream of this produces enhanced advection of angular momentum.

Radius-height sections of the azimuthal flow along the line AB are shown in Fig 2; this corresponds to the section shown in Fig 12 of Blackwell (2000). A jet maximum of 42 m/s at a radius of 12 km is apparent in the offshore flow. On the onshore side of the section, the jet is at about 1.5 km height, weaker (35 m/s), and at larger radius (14 km). These are in good agreement with Blackwell's observed section. An azimuth-height section of the azimuthal flow at the RMW is shown in Fig 3. The anticyclonic rotation of the asymmetry with height is readily apparent, as is its dominant wave-number one structure. It thus appears to be an analogue of the frictionally stalled inertia wave discussed by Kepert (2001).

4. DISCUSSION

Initial results of some studies of the changes in boundary layer wind field produced by landfall were presented. At landfall, marked asymmetries in both the surface winds, in the height and strength of the low level jet, and in the slope of the radius of maximum winds with height, are predicted. These appear to be analogues of the motion-induced asymmetry, forced by asymmetries in the surface roughness rather than by motion.

The analogy with the motion-induced asymmetry appears quite strong. In both cases, the maximum surface winds are a similar distance downstream of the maximum surface drag. Differences are likely due to a greater drag asymmetry here, and different spatial structure to the asymmetric friction.

Good agreement with observations was found for Hurricane Danny. This is particularly remarkable given that Danny was not in a steady-state at the time, and may not have had a particularly symmetric pressure field. The offshore maximum in the surface wind was qualitatively similar to that found in some other observational studies. Although not all the studies showed this, we speculate that either (i) there was lower land-sea roughness contrast, or (ii) the analysis had less surface data available in these cases, and relied more heavily on aircraft winds "reduced" to the surface. These would be inherently unable to capture this feature. Examination of the respective papers tends to support the latter hypothesis.

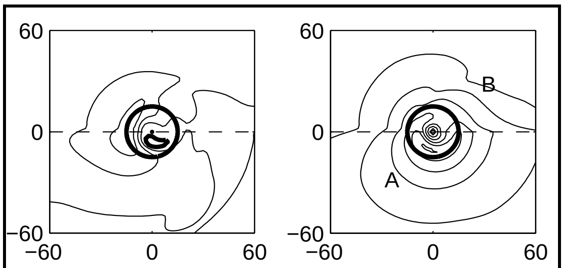

Fig 1: Radial (left) and azimuthal (right) near-surface flow in simulated Hurricane Danny. The heavy circle shows the RMW, the dotted line the coast with land to the north. Contour interval 5 m/s, zero heavy.

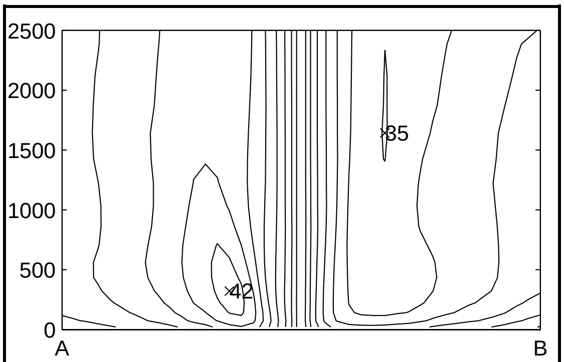

Fig 2: Azimuthal flow cross-section along the line AB in simulated Hurricane Danny.

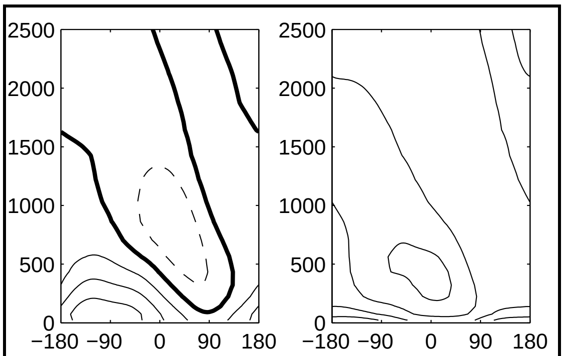

Fig 3: Azimuthal-height sections at radius 15 km of radial (left) and azimuthal (right) flow. Azimuth in degrees anticlockwise from positive x-axis (so flow is towards positive azimuth), land from -90 to 90.

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