Models and Observations of Tropical Cyclone Boundary-Layer Winds

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Introduction

The tropical cyclone boundary-layer (TCBL) has until recently been the least well-observed part of the storm. It is too low for safe aircraft reconnaissance operations, and limited vertical resolution in the presence of high gradients and sea clutter limits the use of radars. Yet the boundary-layer (BL) is crucial, since it is the habitation layer (Jelesnianski 1993), and it is through the BL that the cyclone interacts with the ocean, obtaining heat and moisture, and transferring momentum to the ocean in the form of currents and waves. Because of limited observational coverage, modellers have typically extended physical parameterisations far beyond their validated regime, and little detailed analysis of full-physics model results within the BL has been carried out.

Much of this changed in the late 90's. Observational coverage was greatly improved by the use of a new instrument, the GPS dropsonde (Hock and Franklin 1999), which gave 6-m resolution measurements of wind, temperature, pressure and humidity down to the ocean surface. Concurrently, the further development of theoretical (Kepert 2001) and idealised numerical (Kepert and Wang 2001) models of the tropical cyclone boundary-layer (TCBL) provided the first indication that the TCBL has a complex 3-dimensional structure.

The purpose of this paper is to review these developments, present some comparisons of predictions and observations, discuss the sensitivity of the structure to details of the storm as a whole, and to look at landfall.

Models – Numerical and Analytical

Early research on the TCBL had two main aims: to guide its parameterisation in models with insufficient vertical resolution to directly represent it, and to enable the estimation of surface winds from aircraft observations. For the former application, the strength and location of the frictionally-forced updraft was a particular interest. Rosenthal (1962) developed a two-dimensional axisymmetric analytic linear model which showed that the TCBL winds form a modified Ekman spiral, in which the boundary-layer depth decreased markedly towards the storm centre due to the effects of rotation. Anthes (1971) gave numerical solutions to a similar model which produced supergradient flow in the upper boundary-layer inside the eye, but analysis of his results (Kepert 2002c) shows that this is due in his model to an unrealistically large horizontal diffusion. Eliassen (1971) compared the effect of different surface boundary conditions, showing that a semi-slip condition produced an updraft at the radius of maximum winds (RMW) as observed, while a no-slip condition gave uniform ascent across the eye. Eliassen and Lystad (1977) extended this work to a full cyclone and studied the frictional spindown. Carrier (1971) and McWilliams (1971) showed the sensitivity of the vertical motion to the shape of the outer wind profile.

Shapiro (1983) modelled the horizontal structure of the BL with a depth-averaged model, allowing the study of the asymmetric flow induced by storm motion. He showed that the frictional updraft and winds were strongest at the front of the storm, and showed that the depth-mean flow could be supergradient just inside the RMW. Mitsuta et al. (1988) confirmed the latter with an analysis of observations from small islands in typhoons, in which the 10-minute mean 10-m wind was indeed supergradient.

Powell (1980) compared the ability of column models to determine the surface wind from aircraft observations. Such models are typically similar to those discussed by Hess (this conference), consisting of a surface layer matched to an outer layer. Powell found that the models had useful skill, but that simply multiplying the aircraft wind by 0.8 was as accurate as any of the physical models. Nevertheless, such models continue to be used due to their ability to account for the effects of stability and surface roughness (e.g. Powell et al. 1996).

Kepert (2001) and Kepert and Wang (2001) presented the first idealised three-dimensional models of the TCBL. The former is a linear analytical model similar to that of Rosenthal (1962) but with the addition of storm motion, while the latter can be regarded as a descendent of the two-dimensional models of Miller (1965, axisymmetric) and Shapiro (1983, depth-averaged). In each case, the BL flow is diagnosed by solving the equations of motion, including a turbulence parameterisation, subject to forcing at the model top by a translating pressure field representative of a tropical cyclone. A key result of Kepert (2001) was that the motion-induced asymmetry consists of two frictionally stalled wavenumber-one inertia waves, which rotate in either direction with height. The anticyclonically-rotating one is dominant, and its depth scale is several times that of the symmetric component. In addition, the flow in the upper BL was shown to be weakly supergradient, and the surface wind factor (SWF; the ratio of the surface wind speed to that aloft) was shown to increase towards the centre of the storm, and to be higher on the left of the storm than on the right in the Northern Hemisphere. The numerical model of Kepert and Wang (2001) confirmed these results, but the inclusion of vertical advection in the dynamics lead to a markedly supergradient low level jet in the upper BL. The BL flow was shown to be sensitive to the size, intensity and motion of the forcing cyclone, as well as to location within the storm. Essentially, horizontal advection, both radial and azimuthal, is critical in determining the local boundary layer structure, and so a “one size fits all” approach to the TCBL is inherently unsatisfactory, as are less-than-3-dimensional models.

Observational Analyses

A major focus has been the relationship between near-surface winds and those above the BL. This lack of attention to conditions in between is due partly to a lack of intervening observations, and partly to operational considerations. The ability to determine surface winds from those aloft is important not only in interpreting aircraft data, but also in the use of parametric tropical cyclone models such as Holland (1980) to estimate surface winds for driving ocean wave, storm surge or damage models. Early observations suggest that the SWF has a value of around 0.7 to 0.8, with some of the variation due to stability (Powell and Black 1990) and some due to random effects and the difficulty of obtaining collocated observations. Franklin et al. (2003) used GPS dropsonde data in 17 hurricanes from 1997 to 1999 to show that the SWF is larger in the eyewall than in outer parts of the storm, has a small left-right asymmetry, and decreases with the height of the upper observation. These are consistent with earlier predictions of some of theoretical work cited above, and with the cyclone warm-core structure.

	Georges	Mitch	Vance	Andrew	Hugo	Danielle	Isabel
Supergradient jet	No	Yes	Yes			No	Yes
BL asymmetry	Yes	Landfall				Yes	No
SWF high at core	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SWF asymmetry	Yes	Landfall		Yes	Yes	Yes	Partial

Table 1: Summary of the success of the theoretical predictions of Kepert (2001) and Kepert and Wang (2001) against analyses of boundary-layer flow in seven tropical cyclones. Blank squares indicate that verification was not possible in that case, and landfall that the wind asymmetry was due to landfall rather than motion.

Kepert (2002c, 2004a,b) conducted detailed case-studies of Hurricanes Georges and Mitch, and severe tropical cyclone Vance, and briefer analyses of already-published data in Hurricanes Hugo and Andrew, with a focus on validating theoretical predictions. Schwendike (2004) undertook similar studies on hurricanes Danielle and Isabel. The success of the comparison with theory is summarised in Table 1.

Landfall

The coastal zone is typically where the combination of cyclone intensity and population leads to the greatest hazard to humanity. Some of the few observational studies available hint at the existence of different asymmetries in the BL winds at landfall, to those over the ocean. For instance, Powell (1982) found that Hurricane Frederic developed a secondary surface wind maximum in the offshore flow at landfall, in addition to the usual right-front motion-induced maximum. Blackwell (2000) showed a marked asymmetry in the strength and height of the low-level jet in the eyewall of the nearly stationary Hurricane Danny at landfall.

The asymmetric friction forcing due to proximity to land is similar to that due to motion, and experiments using the Kepert-Wang model have shown that similar structures arise in the BL of a stationary cyclone near land, to those in a moving storm over the ocean. For a storm making landfall, the modelled surface flow is in good agreement with Powell's analysis of Hurricane Frederic. Comparisons of model results with observations in Hurricanes Mitch (Kepert 2002c, 2004b), Danny (Kepert 2002a) and Floyd (Kepert 2002b) have yielded an encouraging level of agreement.

Air-Sea Exchange

Parametrising the air-sea fluxes is crucial to understanding not just the boundary-layer, but the storm as a whole. Direct observations at low to moderate wind speeds show that the drag coefficient C_d increases approximately linearly with wind speed, while the transfer coefficients for heat C_h and moisture C_e are close to constant. Modelling studies (Emanuel 1995) have tended to show that cyclones cannot attain their observed intensity with these parameterisations, and it is necessary to either cap C_d, allow C_h and C_e to increase, or add an additional air-sea exchange mechanism such as sea spray. Extensive research on spray-mediated fluxes has not achieved a consensus, due to large uncertainties in the droplet production rate, atmospheric interaction, and transport. Tentative earlier evidence of a cap on C_d (Frank 1984, Hubbert et al. 1991) has been recently bolstered by the dropsonde analysis of Powell et al., who showed that C_d begins to markedly decrease once the wind speed exceeds 30 m s^{-1}. This analysis has provoked the growth of a small industry, with at least four subsequent papers (Andreas 2004, Donelan et al. 2004, Makin 2004, Moon et al. 2004) offering distinct (although not mutually exclusive) physical explanations for the phenomenon. Two of these explanations rely on the effects of sea spray, and two on ocean surface waves. Probably the only conclusion that can be confidently drawn is that we have insufficient knowledge of the air-sea interface under such conditions.

On the other hand, there are issues with the data used by Powell et al. The dropsondes have a tendency to fail to report winds in the lowest few tens of metres. The cause, or causes, of this are not known for certain, but it is thought that a major factor may be the inability of the GPS receiver to cope with large accelerations (Franklin et al. 2003, Powell et al. 2003). Consistent with this, the failures tend to be more frequent and further from the surface in higher mean winds, when both the mean shear and the turbulent contributions to dropsonde acceleration are greater. Unpublished work by the present author has shown that this may lead to a sampling bias in which profiles with below-average instantaneous shear are preferentially reported. This in turn causes a negative bias in Powell et al.'s calculation of the roughness length and drag coefficient at very high winds. Thus their conclusion that C_d decreases at very high wind speeds may not be correct.

Boundary-Layer Rolls

Boundary-layer roll vortices are known to play an important role in dynamics of the atmospheric BL under a range of conditions. Wurman and Winslow (1998) presented high-resolution Doppler radar observations of similar features in the BL of Hurricane Fran at landfall. These consisted of bands several hundred metres wide aligned along the mean wind, in which the mean wind speed varied between bands by some 30 m s^{-1}. This is of vital importance both to BL transport and to understanding wind-damage. Rolls exist in the atmospheric BL due to a hydrodynamic instability of the cross-stream flow in the Ekman spiral (Brown 1972a,b). Foster (2004) used Kepert's (2001) analytical model to show that a similar instability can exist in the TCBL; indeed, he concluded that the TCBL is ideal for the production of BL rolls.

The Future

Theoretical and observational advances have greatly improved our understanding of the TCBL. The parameterisation of surface fluxes remains a major gap in our understanding, relevant to theoretical BL studies, TC thermodynamics, observation interpretation, forecasting and warning, and numerical modelling. Recent observational advances including the airborne step frequency microwave radiometer (Uhlhorn and Black 2003) for measuring surface wind speed, the IWRAP (Imaging Wind and Rain Airborne Profiler) for measuring BL wind profiles, as well as longer-established technologies such as airborne synthetic aperture radar (Walsh et al. 2002) for measuring the wave field, portable high-resolution Doppler radar (Wurman et al. 1997), portable mesonets and towers (Schroeder et al. 2003) and the GPS dropsonde could help refine theory, parameterisation and modelling.

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