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# DYNAMICAL CONSTRAINTS ON THE MAXIMUM INTENSITY OF HURRICANES


by

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## 1. INTRODUCTION

There is observational evidence to suggest that there is little relationship between the intensity of tropical cyclone and its size, measured for example by the maximum near-surface wind speed and the radius of gale-force winds, respectively (see e.g. Merrill, 1984). However, theories have been put forward to account for the maximum possible intensity that a storm in a given location and environment can achieve. A critique of these theories and list of references is given by Camp and Montgomery (2001). As far as we are aware there are no theories to account for the range of sizes of tropical cyclones that are observed. In this report of "work in progress", we seek to explore the questions: how does the background rotation strength, characterized either by the Coriolis parameter or the width of the initial vortex, influence the intensity and size of a tropical cyclone?

## 2. THE IDEA

Some of the basic ideas are motivated by the theoretical discussion of geophysical vortices by Morton (1966) and on the results of laboratory experiments (Turner and Lilly 1963) and numerical simulations of vortex flows in simple flow configurations (Smith and Leslie 1976, 1978). There are two fundamental requirements for vortex intensification: a source of rotation and some forcing mechanism to concentrate the rotation. An example is a laboratory experiment by Turner and Lilly (1963) in which a vortex was produced in water contained in a rotating cylinder by releasing bubbles along the upper part of the rotation axis. The drag exerted by the ascending bubbles generates a secondary circulation in the water, producing convergence in the region below the source of bubbles. Except in a shallow boundary layer near the lower boundary, converging rings of fluid conserve their angular momentum and spin faster. The ultimate degree of amplification of the rotation depends on the background rotation rate and on how far inwards rings of fluid can be drawn in. The latter quantity depends, *inter alia*, on the forcing strength, i.e. the bubbling rate. If the forcing is sufficiently large for a given rotation rate, rings of fluid may be drawn in to relatively small radii before the centrifugal and Coriolis forces opposing the inward motion balances the radial pressure gradient that drives them in. If the forcing is comparatively weak, or if the rotation rate is sufficiently strong, this balance may be achieved before the radial displacement is very large so that a significant amplification of the background rotation will not be achieved. Of course, if there is no background rotation, there will be no amplification, and if the background rotation is very weak, the centrifugal forces never become large enough to balance the pressure gradient.

Clearly one would expect the existence of an optimum forcing strength to produce the maximum amplification for a given strength of background rotation, or an optimum background rotation for a given forcing strength. These ideas were demonstrated in related numerical experiments by Smith and Leslie (1976, 1978). The dust-devil-like vortices investigated in the first of these papers are driven by the buoyancy arising from thermal heating of the surface. It turns out that the high rotation rate regime produces warm-cored, two-cell vortices reminiscent in some ways of tropical cyclones.

The present paper investigates the importance of such rotational constraints for tropical cyclones. One difference between the foregoing experiments and a tropical cyclone model is that, in the latter, one does not have the flexibility to independently vary the rotation rate and the forcing strength, since the energy supply for a cyclone, primarily the moisture flux from the sea surface depends, *inter alia*, on the intensity. However, one can control the background rotation by varying the Coriolis parameter, *f*, and/or by varying the size of the initial vortex used in the simulation. In this paper we examine both these methods.

## 3. THE MODEL AND CALCULATIONS

A ten-layer axisymmetric version of the minimal hurricane model described by the first two authors (Zhu and Smith, 2003) is used to investigate the dynamical constraints on the maximum intensity of hurricanes. The model has a horizontal grid resolution of 10 km and latent heat release is represented explicitly using a simple algorithm. One series of calculations is carried out in which a vortex growing from the same initial barotropic disturbance in an otherwise quiescent environment is exposed to different levels of background rotation. A second series is carried out in which the size of the initial vortex is varied, keeping its intensity and the background rotation held fixed. The initial vortex profiles are shown in Fig. 1


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## 4. RESULTS

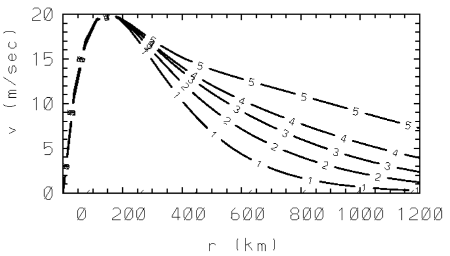


Fig. 1 Initial vortex profiles used in the calculations.

Figure 2a shows time-series of maximum tangential wind speed in the lowest layer, $v_{max}$, in the set of calculations with different values of *f*. There is a considerable dependence on *f* with the maximum intensity increasing as *f* decreases, but the larger wind speeds for $f = 0.5f_o$ and $f_o$ are not sustained, so that after about 4 days of integration these vortices are less intense than that for $f = 1.5f_o$. These results appear to indicate that the vortex lies in the regime where the background rotation exerts the main control for the strength of forcing that can be maintained. The situation is more complicated than in the idealized cases described in the introduction because the larger maximum wind speeds at the smaller values of *f* imply larger surface moisture fluxes in these calculations, which, in turn imply stronger forcing, i.e., the rotation strength and forcing strength are not independent.

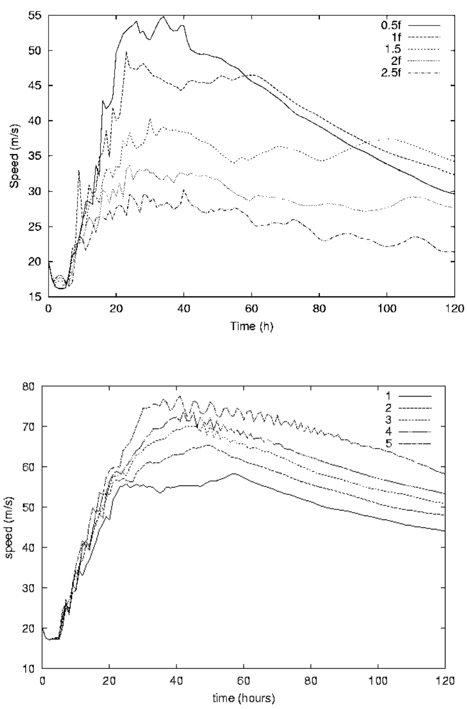


Fig. 2 Time series of maximum tangential wind speed in the lowest layer in the set of calculations with (a) different values of *f* as indicated, and (b) different initial vortex profiles as indicated.

Figure 2b shows time-series of maximum tangential wind speed in the lowest layer and minimum surface pressure in the set of calculations with different initial vortex profiles. In this case the maximum intensity increases monotonically as the initial vortex width increases and, not surprisingly, the more intense vortices have a smaller radius of maximum tangential wind speed. Since the broader vortex would imply a larger rotational constraint, we must conclude that the strength of the forcing must increase also to explain these results. Of course the broader vortex implies a broader region of enhanced surface moisture fluxes so that the equivalent potential temperature in the boundary-layer $\theta_e$ should be larger also.

## 4. CONCLUSIONS

It is shown that other things being equal, a given vortex growing in a region of enhanced background rotation, characterized by a larger Coriolis parameter, reaches a significantly lower maximum intensity than one that grows in a more weakly rotating environment. In contrast, vortices that are initially broader reach a higher intensity than those that are narrower for the same background rotation. The initially broader vortices are accompanied by a larger area of enhanced surface moisture fluxes and therefore have larger values of boundary-layer equivalent potential temperature. In these cases, the larger rotation provided by the initial vortex appears incapable of restraining the maximum intensity attained as when the background rotation is increased. The calculations point to the existence of dynamical constraints that are not explicitly included in existing theories for the maximum possible intensity of hurricanes.

The questions concerning vortex size will be discussed at the meeting.

## 7. ACKNOWLEDGEMENT

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## 10. REFERENCES

Camp, J. P., and M. T. Montgomery, 2001: Hurricane maximum intensity: Past and present. *Mon. Wea. Rev.*, 129, 1704–1717.

Merrill, R. T., 1984: A comparison of large and small tropical cyclones. *Mon. Wea. Rev.*, 112, 1408-1418.

Morton, B. R., 1966: Geophysical vortices. *Prog. In Aeronautical Sci.*, (Ed. Küchemann). Pergamon **7**, 145-194.

Smith, R. K., and L. M. Leslie, 1976: Thermally driven vortices: a numerical study with application to dust devils. *Quart. J. Roy. Meteor. Soc.*, **102**, 791-804.

Smith, R. K., and L. M. Leslie, 1978: Tornadogenesis. *Quart. J. Roy. Meteor. Soc.*, **104**, 189-198.

Smith, R. K., 2003: A simple model of the hurricane boundary layer. *Quart. J. Roy. Meteor. Soc.*, **129**, 1007-1027.

Turner, J. S., and D. K. Lilly, 1966: The carbonated-water tornado vortex. *J. Atmos. Sci.*, **20**, 468-471.

Zhu, H., and R. K. Smith, 2003: Effects of vertical differencing in a minimal hurricane model. *Quart. J. Roy. Meteor. Soc.*, **129**, 1051-1069.