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THE STABILITY OF A TERMINATING WATERSPOUT

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ABSTRACT

Two approaches have been made in the study of waterspout genesis: one has concentrated on cloud scales but been unable to resolve the waterspout scales (Simpson et al, 1986); the other has represented the cloud environment by imposing time independent boundary conditions around a more compact axisymmetric vortex domain (Howells et al, 1983).

This study seeks the advantages of both approaches by embedding an axisymmetric vortex domain within a model cloud. When the boundary conditions applied to the embedded vortex are stationary (as in previous axisymmetric models) vortex breakdown has been initiated from the lower boundary, a result obtained in other vortex models. When more realistic cloud evolving boundary conditions are applied, however, it has been found that vortex decay is initiated by growth of an instability at cloud level. These two decay modes are examined and their implication for numerical simulation of vortices discussed.

INTRODUCTION

On 26 June 1985 a waterspout was observed over the Great Salt Lake in Utah, and the parent cloud and ambient conditions were documented sufficiently well to provide data for a numerical simulation. The cloud has since been modelled numerically using the Goddard version of the Schlesinger cloud model (Simpson et al., 1986). This has produced reasonably good agreement with the cloud evolution and has shown, as is now expected both from cloud models and from the most sensitive doppler radar observations, the development of cyclonic and anticyclonic cores of approximately vertical vorticity at cloud scale. It has become clear that these vortex cores are present in very many clouds without visible vortices below cloud base and they cannot be sufficient in themselves to ensure the genesis of a waterspout or tornado although they may be necessary precursors. Unfortunately the evolution of a waterspout cannot be followed directly in the Schlesinger model as the horizontal grid spacing of 600m and vertical grid spacing of 400m cannot resolve waterspouts which have radii of order 100m (Schwiesow, 1981).

In an alternative but complementary approach, Howells and Smith (1983) concentrated attention on the evolution of the subcloud vortex using an axisymmetric model with much higher resolution in which the vortex grows in an arbitrarily specified cylindrical region which may be regarded as representing a portion only of the parent cloud and corresponding subcloud region. They used time–independent boundary conditions and, in particular, imposed time independent circulation at the lateral boundary with specified distribution with height. The effect of cloud buoyancy was simulated by imposing an artificial body force specified at each point of the computational grid; some results were given also for a vortex driven by cloud thermodynamic processes. Dietachmayer (1987) later extended this model by embedding it in the Goddard cloud model; surface conditions on the vortex domain were taken from the cloud fields at a selected time and thereafter maintained constant.

We have improved and extended the Dietachmayer embedded model, where 'embedded' implies that the cloud determines the boundary conditions for the axisymmetric inner vortex calculation but that the vortex does not in turn affect the cloud behaviour, on the grounds that the vortex although locally vigorous has only a small part of the energy of the whole convective cloud.

The model is based on the vorticity–streamfunction form of the Navier Stokes equations and incorporates: the Arakawa representation for the advective term; Miller time stepping; grid stretching in both radial and vertical directions to provide increased resolution near the axis and lower boundary; a drag coefficient formulation appropriate for flow over water; and Smagorinski/Lilly turbulence parameterisation corresponding to an eddy diffusivity representation for isotropic turbulence in an anelastic fluid. Axisymmetry is imposed and computation is carried out in a cylindrical domain of radius 1200m (two grid lengths) and height 5000m, and both initial and boundary conditions are taken from the output of the parent cloud model. The simulation is numerically stable, and there is no difficulty in following the evolution of a concentrated vortex for 1500s or more, which normally allows it to be followed until either cloud or vortex, or both, decay.

An important difference between our model and previous simulations of concentrated atmospheric vortices is that we operate in two distinct modes:

(i) with boundary conditions at the surface of the embedded cylinder taken from the cloud output fields at a specified time of assumed initiation and thereafter held constant; and

(ii) with boundary conditions that continue to follow the evolution of the cloud from the assumed time of initiation.

DISCUSSION OF MODEL RESULTS

Previously, almost all models, whether analytic, numerical or laboratory, have imposed stationary boundary conditions and have then explored the consequential evolution towards steady state of any vortex growing axisymmetrically in the domain, or have studied instabilities of otherwise steady vortices in the domain. While it is true that the analytic/numerical models have simulated the laboratory situation of a vortex growing in a container of fixed geometry, neither they nor the laboratory models have really simulated dust devils, waterspouts or tornadoes. The atmosphere is characterised by a variability in circulation; and if air is drawn in across the lower boundary towards a waterspout, the circulation at fixed radius is unlikely to remain constant but may increase with convergence, or may decrease as a patch of vorticity of the opposite sign is drawn in. Thus the boundary condition of constant circulation is unlikely to represent the atmospheric situation well, and although the mode using constant boundary conditions is simpler and directly comparable with Howells and Smith (1983) and Dietachmeyer (1987), that with time dependent boundary conditions drawn from the evolving cloud fields is likely to give a much more realistic representation of the growth and decay of the vortex as the cloud grows and decays.

It has been argued (Morton, 1969) that concentrated narrow vortices are characterised by their gross circulation and by the strength of the updraft or forcing that maintains them, and it should follow that the likelihood of a waterspout appearing below cloud base will be greatest where the combination of updraft and circulation is most favourable. Using the first version of our embedded vortex model we have centered the cylindrical domain at four points: the cloud centre of cyclonic rotation, the cloud centre of anticyclonic rotation, the cloud centre of maximum updraft and halfway between the last two centres, in each case at 1.2km cloud height. Each of these cases was initialised using data from cloud model time 28 minutes, since by this stage in the cloud evolution strong updrafts and vorticities had been generated.

Maximum values of the components of wind velocity for the four cases are plotted against time in Figure 1a; it should be noted that these maxima at each time are selected regardless of position in the domain. Maximum radial velocities are shown for inflow as well as outflow, with much less variation in the inflow than the outflow. Azimuthal velocities are everywhere anticyclonic in all but the "cyclonic" case, and are plotted in modulus; and the vertical velocities show systematically larger updrafts but smaller downdrafts for "anticyclonic" and "cyclonic" than for "updraft" and "midway" cases. The "updraft" and "midway" cases are quick to evolve, but produce only weak, short lived vortices with core radii never less than 270m. The "anticyclonic" and "cyclonic" cases, on the other hand, show the strongest rotation and generally similar behaviour; they concentrate to core radii of 90m, attain higher azimuthal speeds and maintain them, and have stronger updrafts but weaker radial flow, behaviour typical of strong vortices (Morton, 1969). Only the vortex based on the "anticyclonic" centre achieved the azimuthal velocity 22ms^{-1}, regarded as sufficient to produce a "spray ring" at the sea surface, and then only briefly. This suggests that in the real situation the anticyclonic waterspout might be expected to develop more strongly and to dominate vortices which might otherwise have formed at the other sites, and it is pleasing to note that the Great Salt Lake waterspout was anticyclonic.

All cases showed similar vortex breakdown phenomena to that of the "anticyclonic" vortex, except that they occurred earlier. Figure 2 shows contour plots of absolute zonal velocity, perturbation Exner function, radial velocity and vertical velocity for the "anticyclonic" vortex subject to time constant boundary conditions set at initiation for 8, 14 and 16 minutes after initiation of the "anticyclonic" vortex as the vortex approaches breakdown.

In Figure 2a, 8 minutes into its evolution, the vortex has a maximum azimuthal speed of 19ms^{-1} and has just passed into the two–cell structure (Harlow and Stein, 1974) because inflow near the lower boundary has increased the circulation about the core, with corresponding decrease in axial pressure in approximate equilibrium with the centrifugal acceleration, and downflow on the axis of the vortex.

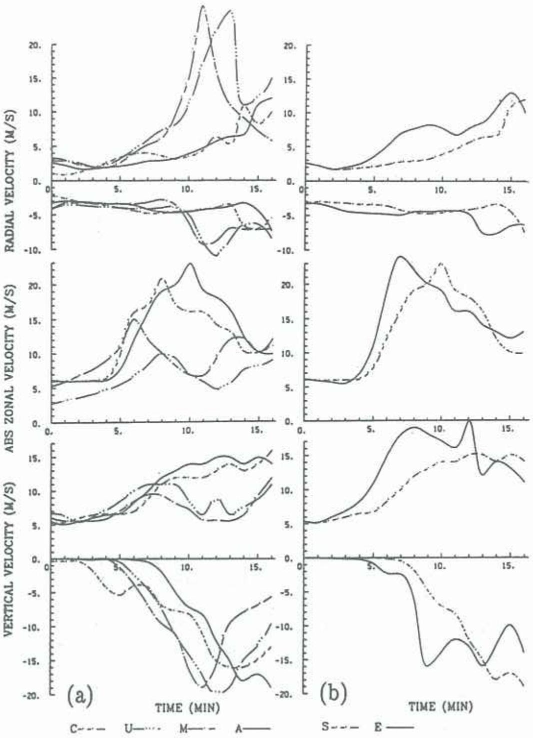


Figure 1(a) Plots of maximum and minimum radial and vertical velocity and maximum absolute zonal velocity in the inner cylindrical domain for "anticyclonic" (A), "cyclonic" (C), "updraft" (U) and "midway" (M) vortices with stationary cloud boundary data.

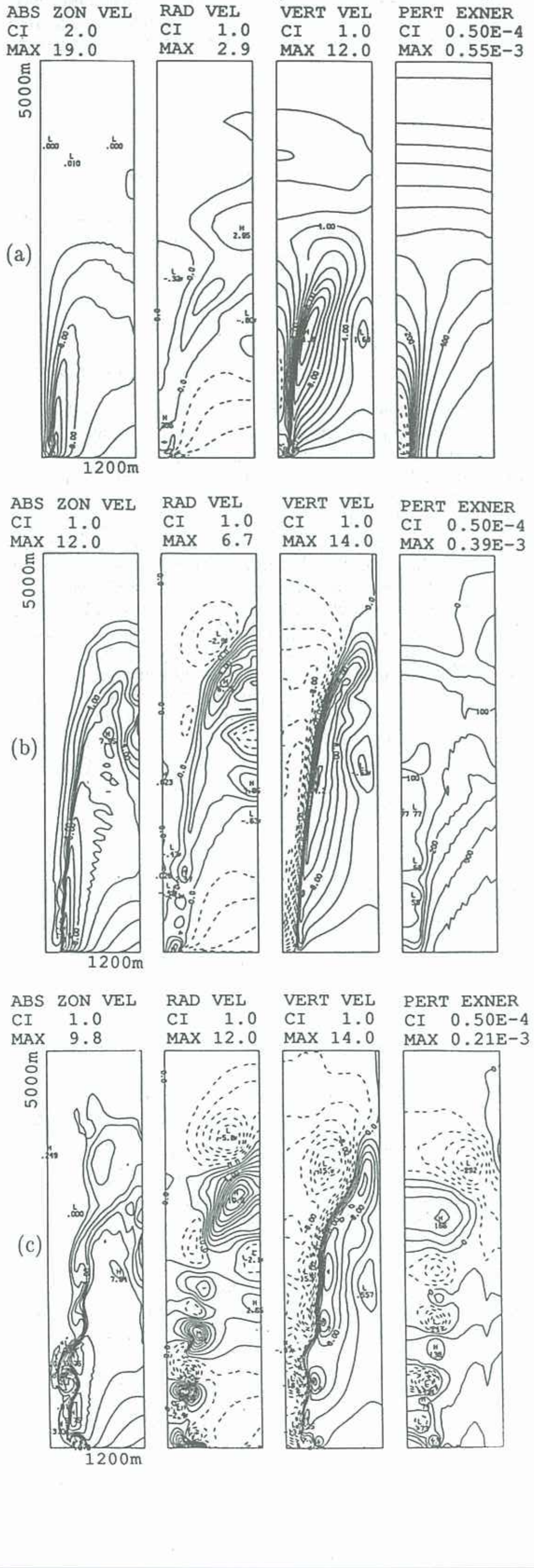
Figure 1(b) Plots as in (a) for the "anticyclonic" (A) centre with stationary (– – – –) and evolving (——) cloud boundary data.

The vortex evolves through its maximum azimuthal speed and begins to decay from the neighbourhood of the lower boundary when axial downflow interacts with the radial inflow near the lower boundary. The instability leading to decay appears in the form of a series of toroidal vortices that appear near the lower boundary and travel up the sides of the vortex core, appearing first in Figure 2b which is 14 minutes into the vortex run. This is similar to the breakdown described in Howells et al (1988) for high applied swirls (> 4 ms^{-1}) and large eddy diffusivities (> 20m^{2}s^{-1}), both reproduced in this case. After 16 minutes of vortex run (Figure 2c), the core has expanded radially to 430m at the lower boundary and the maximum azimuthal speed has fallen to 9.8ms^{-1}; at this stage the toroidal vortices have progressed to height 3000m and all but destroyed the vortex core.

Thus, using time constant (stationary) boundary conditions for the embedded vortex at the anticyclonic centre we find a vortex breakdown mode which appears to have been initiated from the lower boundary, and is the mode described from other numerical experiments based on stationary boundary conditions.

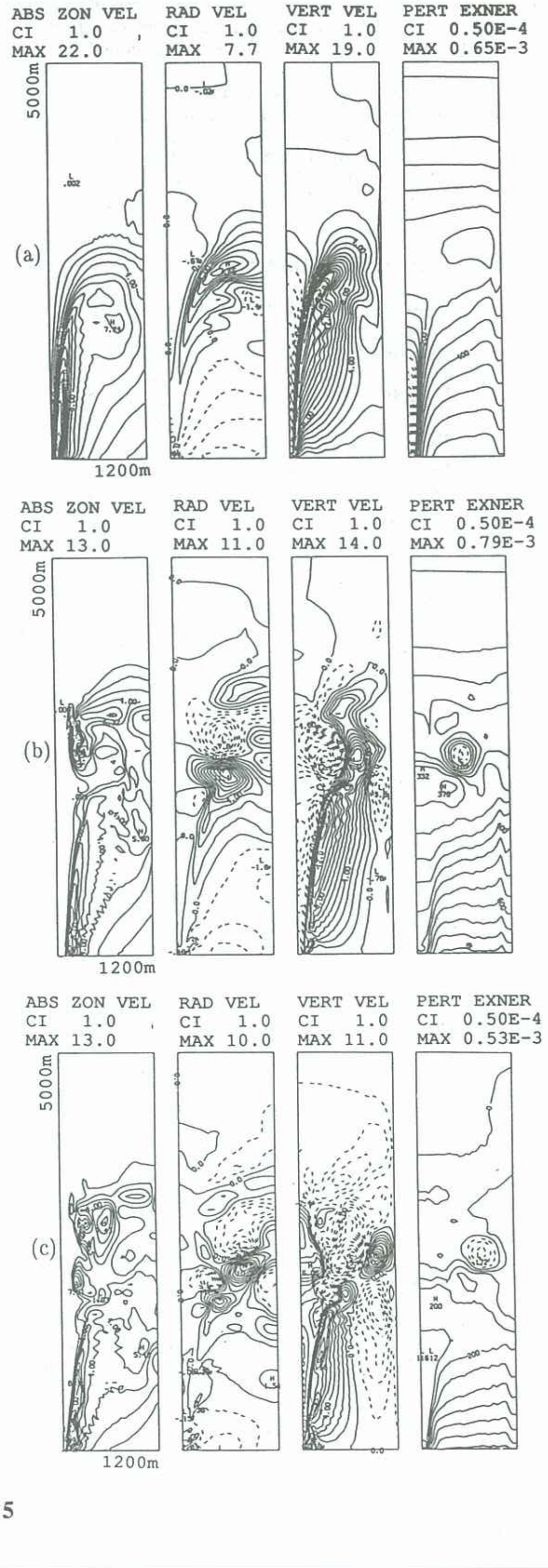
The vortex model was then run again as above in every respect except that the stationary boundary conditions were replaced by evolving boundary conditions that are regularly adjusted from the cloud output so as to follow the changing fields of the parent cloud with time. Figure 1b shows a comparison of the maximum values of radial, absolute azimuthal and vertical speeds for the "anticyclonic"vortex considered above for the two cases of stationary and evolving boundary conditions. The "evolving" vortex grows more quickly than the "stationary" vortex and produces a tighter and stronger vortex with maximum zonal speed 24ms^{-1}. Although both vortices were initiated from the same cloud fields, their paths of evolution are significantly different, as is obvious from a comparison of the absolute zonal speeds, radial and vertical speeds and perturbation Exner function contour plots at 8, 14 and 16 minutes for the "evolving" vortex in figure 3 with those for the "stationary vortex" in figure 2.

Figure 2 Contour plots of the absolute zonal velocity, radial velocity, vertical velocity (m/s) and perturbation Exner function for "anticyclonic" vortex with stationary cloud boundary data at (a) 8min, (b) 14min and (c) 16min after vortex initiation. (CI = contour interval)



Both vortices have well–defined cores at 8 minutes after initiation, but the "evolving" vortex is significantly tighter and stronger, having already reached 22ms^{-1}, and is somewhat taller. It has a larger pressure fall in its core with more tightly organised radial inflow near the lower boundary, upflow and radial outflow at mid–height. Both vortices show axial downflow, but the "evolving" vortex downflow is

Figure 3 As in Figure 2 but with evolving cloud boundary data.



greater; and the first signs of instability have appeared, with a broadening of the core flow near the top of the azimuthal and vertical velocity fields, in direct contrast with the "stationary" vortex which exhibits the first signs of incipient instability in the radial velocity field near the lower boundary.

At 14 minutes the vortex with evolving boundary conditions is still strong through much of its height, but has suffered a breakdown visible in all component fields at mid height near the top of the core. This breakdown appears to be again in the form of a toroidal vortex, but whereas breakdown in the "stationary" vortex began with the generation of a series of small toroids near the lower boundary and their advection up the core, in this case the toroid is formed at cloud height where it causes the core to widen only at this height in contrast to the "stationary" vortex where the whole core widened.

At 16 minutes the "stationary" vortex core is breaking down over its entire height, but the "evolving" vortex exhibits breakdown with vortex spreading and flow down the axis from above only, and its vortex core remains quite strong and compact in the subcloud region, with zonal speed 13.5ms^{-1} and core radius 60m.

PARAMETRIC SPECIFICATION

Howells et al (1988) characterised their vortices with a swirl parameter, $S = V/w$, where V is the imposed zonal velocity at the lateral boundary of the domain and w the mean updraft over the top of the domain. A preferred swirl parameter in our case is $S_m = V/W$ where V and W are the maximum zonal and updraft velocities, respectively, within the cylindrical embedded domain. We anticipate, as usual in vortex studies, that values of S_m close to unity will correspond with the strongest and most stable vortices (Morton, 1969). Figure 4 shows a series of curves representing the change of S_m with vortex time: 4a shows the evolving swirl parameters for the four trial vortex sites using invariant boundary conditions, and it may be noted that mean swirl parameters for the "cyclonic", "updraft", "midway" and "anticyclonic" cases are 1.23, 0.73, 1.32 and 1.18, respectively; 4b shows the four cases with evolving boundary conditions and mean swirl parameters 1.29, 0.84, 1.30 and 1.05, respectively; and 4c compares "anticyclonic" vortices with "invariant" and "evolving" boundary conditions and mean swirl parameters 1.18 and 1.05, respectively. The "anticyclonic" vortex is preferred for both stationary and evolving boundary conditions, the latter most strongly. Note also that in each case the swirl parameter for the "anticyclonic" vortex shows less violent variations and might therefore be regarded as more stable.

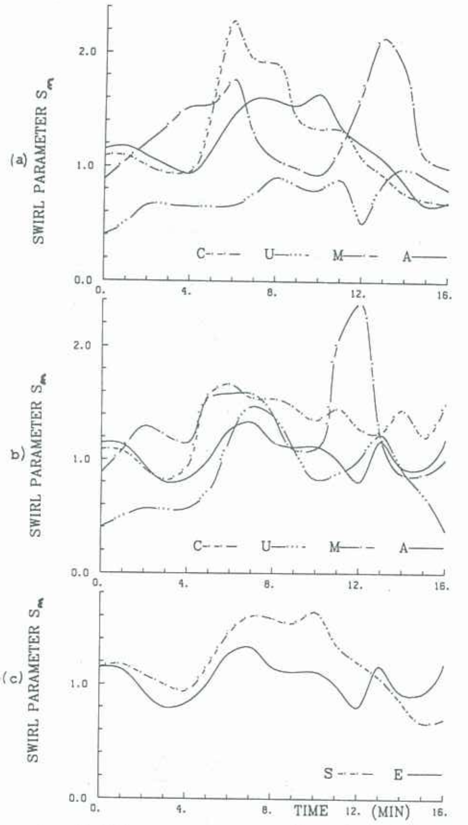


Figure 4 Swirl parameters as a function of time since vortex initiation for: (a) "cyclonic" (C), "updraft" (U), "midway" (M) and "anticyclonic" (A) cases with stationary boundary conditions; (b) as in *a* but with evolving boundary conditions; (c) for "anticyclonic" vortices with stationary and evolving boundary conditions.

SUMMARY

Many earlier studies of concentrated vortices "terminating" at a boundary have been carried out using invariant boundary conditions, especially for circulation, and a number of authors have found instabilities or breakdown phenomena in the neighbourhood of the terminating boundary (for example, Howells et al, 1988). These have been interpreted as examples of vortex breakdown, and Maxworthy (1973) has even suggested that vortex breakdown may be a feature of most atmospheric vortices from dustdevils to hurricanes. It is by no means clear whether the instabilities in our solutions with stationary boundary conditions ought to be interpreted as vortex breakdown, but it is clear that the nature of instability in vortices with evolving boundary conditions may be entirely different from that in vortices with stationary boundary conditions. Moreover, the kind of breakdown that we have found in vortices with evolving boundary conditions, in which the core becomes unstable from above and backflow opens out and weakens the vortex while its core is still strong at the terminating boundary, seems a natural mechanism for decay that is certainly worth further study. For the present, it should be noted that vortices with evolving boundary conditions determined by the development of the parent cloud can be stronger than those with stationary boundary conditions, and certainly strong enough to produce visible signs of a waterspout under conditions such as those of the Great Salt Lake on June 26, 1985.

REFERENCES

DIETACHMAYER, G.S. (1987). On the numerical simulation of small scale intense atmospheric vortices. PhD thesis', Monash University.

HARLOW, F.H., and STEIN, L.R. (1974). Structural analysis of tornado–like vortices. J. Atmos. Sci., *31*, 2081–2098.

HOWELLS, P., and Smith, R.K. (1983). Numerical simulations of tornado–like vortices. Geophys. Astrophys. Fluid Dynamics, *27*, 253–284.

HOWELLS, P., ROTUNNO, R., and SMITH, R.K. (1988). A comparative study of atmospheric and laboratory–analogue numerical tornado–vortex models. Q.J.R. Meteorol. Soc., *114*, 801–822.

MAXWORTHY, T. (1973) A vorticity source for large–scale dust devils and other comments on naturally occurring columnar vortices. J. Atmos. Sci., *30*, 1717–1722.

MORTON, B.R. (1969). The strength of vortex and swirling core flows. J. Fluid Mech., *38*, 315–333.

SCHWEISOW, R.L. (1981). Horizontal velocity structure in waterspouts. J. Appl. Meteor., *20*, 349–360.

SIMPSON, J., MORTON, B.R., McCUMBER, M.C., and PENC, R.S. (1986). Observations and mechanisms of GATE waterspouts. J. Atmos. Sci., *43*, 753–782.