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WATERSPOUT STUDIES I - GENESIS AND EVOLUTION

B.R. MORTON, G.L. ROFF and J. SIMPSON

Centre for Dynamical Meteorology
Department of Mathematics, Monash University
Clayton, VIC 3168, AUSTRALIA

Analytic studies of vortices of small diameter/height ratio have shown that a sensitive balance is needed between vertically forced motion and available circulation about the vertical to maintain intense vortices (Rossman, 1960; Morton, 1969). Ambient rotation provides the normal source of vorticity, but is much too weak to exercise control over the vortex core. Forcing for dust devils and fire whirls is generated from a lower heated surface, but for tornadoes and waterspouts is due to convective clouds aloft.

The life cycles and vortex dynamics of weak tornadoes (Holle and Maier, 1980) and waterspouts (Golden, 1974) have been well documented and are similar (Simpson et al, 1986). Indeed, the distinction between the two is not always clear although waterspouts tend to be less common and less violent than tornadoes.

Our study is concerned with waterspouts forced by convective clouds, and particularly with the complex interactions between the larger scales of the environment and parent cloud and the smaller scales of the vortex core and its terminating boundary layer.

1. THE NUMERICAL SIMULATION

The case studies discussed below relate to a waterspout observed under a parent cloud line over the Great Salt Lake, Utah at 0525 LST on 26 June 1985 (Figure 1). The sighting was well documented and provides a basis for our numerical simulations. A particular feature was the apparent anticyclonic sense of the funnel. Numerical models used to simulate convective clouds are mostly based on a grid length of 500m or more. Such models can resolve cloud velocity fields, and have shown that approximately vertical cores of cyclonic and anticyclonic vorticity develop at almost cloud scale as the clouds evolve. The models cannot, however, resolve waterspouts as these are tall and narrow with height exceeding that of cloud base and diameter of order 10m. Our objective is to study the role of cloud-generated vertical velocity fields within the enhanced vorticity cores in the development of waterspouts. We do this in two stages: first extracting velocity fields from cloud models, and then using these fields to provide an environment at waterspout scale for a separate model of waterspout growth.

1.1 THE CLOUD MODEL

A modified form of the Goddard-Schlesinger three-dimensional model (Simpson et al, 1991) was run at Goddard to provide the model output fields for our waterspout simulation. The original Schlesinger model (1978) used a moving grid to ensure that the boundary conditions did not interfere with cloud evolution, and assumed: anelastic motion; negligible Coriolis force, friction and diffusion of heat and moisture; liquid water occurring only as cloud droplets moving with the air; and no ice phase. Principal improvements include:

(a) a turbulence scheme incorporating a variable eddy exchange coefficient depending on local Richardson number

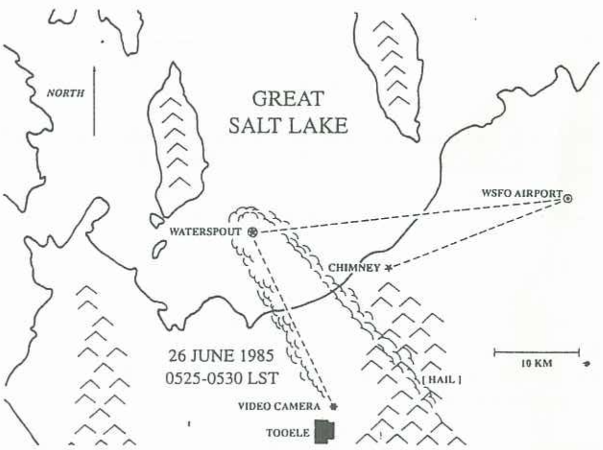

Figure 1: The Southern part of the Great Salt Lake with video camera (∗), waterspout (⊛) and airport site of soundings and photographs (⊙). The cloud line was oriented along the wind shear, with individual towers leaning approximately ESE.

(Clark, 1979), resulting in a reduced vertical component of vorticity in the unstable lower layers;

(b) the ice phase microphysics of Lin et al (1983) to allow for freezing at 1.4km above the Great Salt Lake; and

(c) cloud initiation using either the customary axisymmetric projected moist warm bubble (excess vertical velocity w', excess potential temperature θ', relative humidity RH) or an alternative line perturbation (suggested by initialization experiments of Blechman et al, 1988).

Name	Initiation	w' (ms^{-1})	θ' (K)	RH (%)	TURB	ICE
RAIN	$10\Delta x$ radius	1.5	0.6	92	New	No
ICE	$10\Delta x$ radius	1.0	0.4	87	New	Yes
LINE	$4\Delta x$ wide $30\Delta x$ long	1.2	0.5	87	New	Yes

Table 1: Cloud model initiations and model improvements.

param	W^+ (ms^{-1})	W^-	θ^+ (K)	θ^-	q_c (gm^{-3})	q_r	q_i	q_s	q_g
RAIN	8.9	-7.1	2.7	-2.6	2.0	3.8	-	-	-
ICE	8.1	-5.8	2.4	-2.4	1.3	0.7	0.4	1.1	0.7
LINE	10.4	-6.0	3.5	-3.3	1.7	1.2	0.5	1.2	1.5

Table 2: Model extrema: W^+ and W^- are peak up- and downdrafts; θ^+ and θ^- are peak +ve and -ve potential temperature anomalies; and q_c to q_g are, respectively, peak mixing ratios of cloud water, rain water, ice, snow and graupel, each over the domain and lifetime of the cloud.

The three model runs cited in Table 1 tested the consequences of these modifications: RAIN used the traditional bubble initialization with improved turbulence modelling, ICE incorporated also the Lin ice microphysics, and LINE used an elongated initialization region with ice and improved turbulence. Table 2 shows key output features of the model clouds and Figure 2 illustrates time evolution for the RAIN cloud.

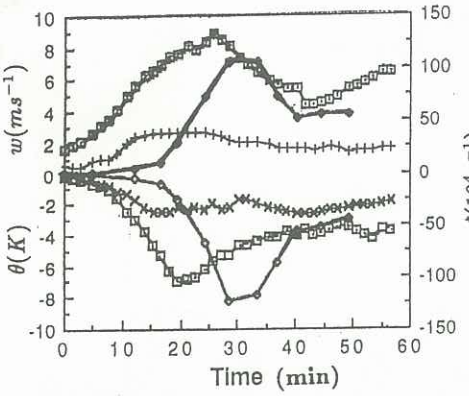

Figure 2: Evolution of peak values of key variables for cloud model RAIN: low-level (0-0.2km) cyclonic (◆) and anticyclonic (◇) vorticity; peak updraft (⊞) and downdraft (□); and peak potential temperature excess (+) and deficit (✱).

1.2 THE WATERSPOUT MODEL

Howells and Smith (1983) were able to model intense atmospheric vortices by concentrating an axisymmetric computational grid of much higher resolution on the sub-cloud vortex and using boundary conditions and distributed forcing to simulate essential features of cloud forcing. This approach was extended by Dietachmayer (1987) and Roff and Morton (1989), and the present model assumes axisymmetric flow in a cylindrical domain embedded in the output field of the cloud model. Initial and boundary conditions are obtained from the cloud fields by averaging round the cylindrical domain. The waterspout model uses: Arakawa representation of the advective term (Roache, 1976, p105); Miller and Pearce (1974) time stepping; radial and vertical grid stretching for increased resolution near the axis and base of the cylindrical domain of radius 1200m and height 5000m; a lower drag coefficient formulation for flow over water (Munn, 1966); Smagorinsky/Lilly turbulence parameterization (Proctor, 1982); and a lower boundary on the sea surface with free flow across the lateral and upper boundaries.

Our model represents an embedded vortex in the sense that domain of integration is small relative to the whole volume of the cloud, and initial and boundary conditions are provided by the cloud fields but the cloud is assumed unaffected by the growing waterspout. The model may be operated in time constant (TC) mode with boundary conditions at the surface of the cylindrical domain fixed at an assumed time of initiation, or in time varying (TV) mode with surface conditions evolving with the growth and decay of the cloud (the former included for comparison with earlier studies). It may be operated also with the domain centre fixed in its initiation position, or moving with the cloud.

Both circulation and forcing are important and one index for identifying a combination favourable to the development of strong vortices is the swirl parameter $Sm = |V|/W$, where V and W are at time t the maximum azimuthal and updraft velocities, respectively, within the cylindrical embedded domain. Values of Sm close to unity should correspond to an embedding position in the cloud field producing the strongest and most stable waterspout vortices (Morton, 1969).

2. EXPERIMENTS WITH THE EMBEDDED MODEL

We have inferred the likely position for waterspout development over the Great Salt Lake on June 26, 1985 by placing the cylindrical domain so that at height 1200m its axis coincided, respectively, with the centres of cyclonic rotation (C), anticyclonic rotation (A), maximum updraft velocity (W) and midway between the anticyclonic and updraft centres (M). Rotation centres were chosen as the "eyes" of the horizontal wind vectors, and the height 1200m because it was hard to discern rotation centres below this level. The waterspout model was initiated at each of the four centres in each of the three cloud model runs starting at 28min cloud time, as by then all clouds had established reasonable vorticity and updrafts (eg RAIN, Figure 2).

Maximum values of absolute azimuthal velocity, maxima and minima of radial and vertical velocities and swirl parameter values are plotted against time in Figure 3 for the TV runs in which boundary conditions vary with the cloud fields. Azimuthal velocities were anticyclonic in all cases calculated except only when the cylindrical domain was centred at the "cyclonic" centres C for both TC and TV runs.

All runs start with relatively small azimuthal velocities characteristic of the parent clouds at 28 min cloud model time, although it may be noted that cyclonic and anticyclonic circulations for bubble-initiated model clouds, ICE and RAIN, are similar whereas the circulation round the anticyclonic center is appreciably larger than that round the cyclonic center in the LINE model cloud due to stronger stretching and tilting near the surface.

One-cell intense vortices, indicated by very weak downdrafts well off the axis, are produced in all cases and this is characteristic of the weaker range of intense vortices (Howells et al, 1988). All runs display an initial period of slow development ranging from ≈5min in LINE to at least 10min for ICE during which time there is an increase in vertical velocity with a smaller increase in inward radial velocity, producing a small increase in vorticity near the central axis. A lag in the spin up is expected because the radial inflow takes several minutes to traverse the 1200m vortex radius and transport high angular momentum air inwards from the boundary. This also explains why w_{max} increases before $|v|_{max}$ does in Figure 3. Centers where this lag time is smallest form the strongest vortices.

Although only partly reported here, we have run the RAIN model for comparison with earlier studies, and the ICE model for comparison with RAIN, while the LINE model is most directly relevant for the Great Salt Lake sighting. One striking feature of these runs has been that both cyclonic and anticyclonic vortices are considerably greater in the LINE cloud than either RAIN or ICE, with the anticyclonic vorticity peaking earlier and 65% stronger than the cyclonic vorticity. The LINE cloud differs also in that the cyclonic centre is poorly sited relative to the updraft.

TC vortices have boundary conditions frozen at initiation and therefore increase progressively in strength and cannot respond to the evolution and decay of the cloud. Howells and Smith (1983), who also used frozen boundary conditions, found similar behaviour. Thus TV vortices spin up earlier than TC vortices, with the most extreme example being the anticyclonic runs in LINE where the TV vortex gains a 2 min lead on the corresponding TC vortex and exceeds it in vorticity for 12min before being overtaken. Not only do frozen boundary conditions invalidate the vortex model late in the lifetime of the cloud but they also miss the early response of the vortex to the evolution of the cloud.

Anticyclonic vortices in all clouds, whether with TC or TV boundary conditions, evolve to the strongest vortices, as seen from the maximum absolute azimuthal velocities in Table 3, although none reach Golden's criterion of $22ms^{-1}$ for the production of a spray ring (Golden, 1974). Most vortex model calculations of this type, however, show vorticity enhancement but not enough to produce a visible waterspout.

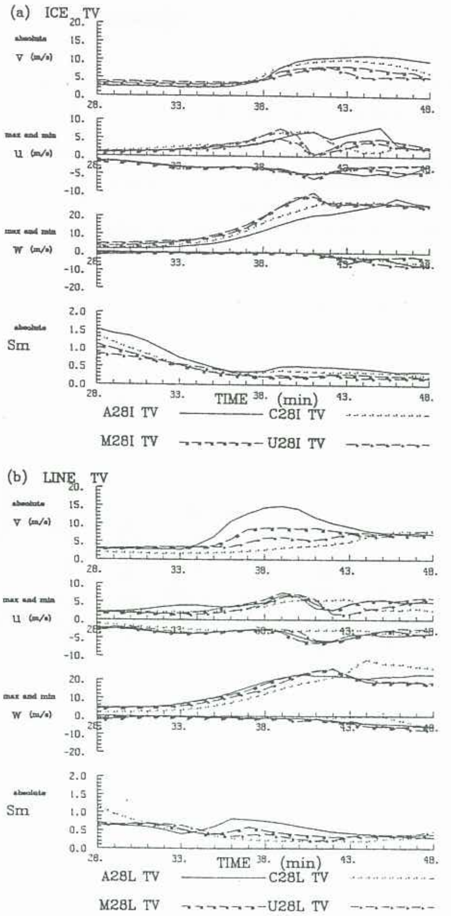

Figure 3: Evolution against cloud model time of maximum | azimuthal velocity |, maximum and minimum radial and vertical velocities and swirl parameter for vortex model domain centred at anticyclonic (A), cyclonic (C), updraft (W) and mid-AW (M) centres at 1200m AGL and 28min cloud model time with time varying boundary conditions for (a) ICE and (b) LINE clouds.

Cloud	LINE cloud				ICE cloud			
Center	W	M	C	A	W	M	C	A
TC S_m	.52	.58	.42	.65	.42	.49	.55	.68
$\|v\|_{max}$	11.6	15.2	4.8	19.3	6.3	10.2	12.2	13.3
TV S_m	.45	.48	.40	.54	.40	.43	.51	.66
$\|v\|_{max}$	8.2	8.8	7.9	14.8	8.0	8.3	10.1	11.4

Table 3: Average S_m and maximum $|v|_{max}$ (ms^{-1}) values for embedded vortices in LINE and ICE clouds with TC and TV boundary conditions at upflow (W), mean (M), cyclonic (C) and anticyclonic (A) centres.

The table gives mean values for the swirl parameter (Sm) for each run; these are all somewhat less than one, as expected for strong vortices, while those for TV runs are generally less than for TC runs as the latter are influenced by large but spurious boundary values after the clouds have started to decay. The mean Sm relationships between centres are broadly the same as those between maximum azimuthal velocities ($W < M < C < A$ for bubble initiated clouds and $C < W < M < A$ for LINE).

The LINE anticyclonic vortices with either TC or TV boundary conditions dominate; thus the vortex model suggests at best a short-lived waterspout of anticyclonic rotation, consistent with both the line form of the Great Salt Lake cloud on June 26 and with the sense of rotation of the observed waterspout.

Run	A12L	A16L	A20L	A24L	A28L	A32L
VS S_m	0.62	0.64	0.69*	0.72*	0.53	0.54
$\|v\|_{max}$	20.9	20.0	16.9*	17.1*	15.2	4.7
MC S_m	0.67	0.68	0.75*	0.81*	0.74	0.63
$\|v\|_{max}$	18.7	18.6	15.8*	18.5*	18.3	15.8

Table 4: Averaged S_m and maximum $|v|_{max}$ (ms^{-1}) values for the LINE cloud runs with Variable Start times, VS, and Moving Centers, MC (* denotes two-cell vortices).

3. EFFECT OF TIME OF INITIATION OF VORTEX

The effect of starting the vortex at different cloud times is now considered. Figure 4(a) shows plots of maximum vertical and absolute azimuthal speeds against time for these runs, while the average Sm and $|v|_{max}$ are given in Table 4.

As expected, the model vortices first strengthened and then decayed in all runs except A32 which achieved a maximum azimuthal velocity of only 4.7 ms^{-1}. The earliest runs A12 and A16 form strong one-cell vortices as they build circulation over a long period (Howells and Smith, 1983; Howells et al, 1988) and these vortices decay only late in the life of the cloud. The weaker one-cell vortex formed by A28 was initiated at the peak development of the anticyclonic vortex of the parent cloud and evolved quickly but did not have time to grow into a two-cell vortex before decaying with the cloud. For run A32L, an even weaker one-cell vortex formed but since it was initiated after the cloud had begun to dissipate it remained weak.

Sm is a measure of vortex strength, with the strongest vortices corresponding with values yet to be determined but a little less than one. Average Sm values closest to one occur for runs A20 and A24; in sharp distinction to all other runs discussed so far these produced two-cell vortices. Both have strong downdrafts (Figure 4) to be distinguished from off-axis downdrafts associated with A12 and A16, also seen in all previous TV runs, but not indicating two- cell vortices.

More realistic runs should result if the vortex model follows the chosen cloud centre as it moves. Figure 4(b) shows maximum values of $|v|$ and w plotted against cloud model time for "moving center" (MC) runs initiated at cloud times 12, 16, 20, 24, 28 and 32 min at the appropriate locations; the vortex model domain is now translated at 4min intervals with the anticyclonic center of the model cloud. The $|v|_{max}$ and average Sm values for these runs are shown in Table 4.

The azimuthal velocities neither reach as large values nor decay as quickly as with fixed model domain. The early (A12 and A16) and late (A28 and A32) MC runs produce one-cell vortices because they begin at times of moderate circulation, but the middle runs (A20 and A24) start with strong circulation and strong model cloud influence, producing two-cell vortices with vigorous axial downdrafts. They have the largest Sm values and are the only vortices under these conditions to show significant increase and then decrease in $|v|max$ indicating strong evolution and decay.

4. A WATERSPOUT LIFECYCLE

All one-cell vortices evolve similarly, as do all two-cell vortices. We shall limit discussion to the two-cell, moving centre case A20MC (Figure 5).

The A20MC vortex is shallower but briefly stronger than the evolving, A28L TV; it also decays more rapidly. In this case decay occurs from the top of the vortex before the bottom weakens transitorily, but by 21min re-establishes near the lower boundary. The two-cell nature of this vortex is seen in the vertical velocity plots which show axial downdraft at mid-height with consequent widening of the core. By 15min this downdraft has penetrated to the surface.

From 15min a wave is seen moving down the core edge and widening the core. This disrupts the top and middle sections of the core while leaving the bottom relatively unaffected. The core edge wave is seen in the radial velocity

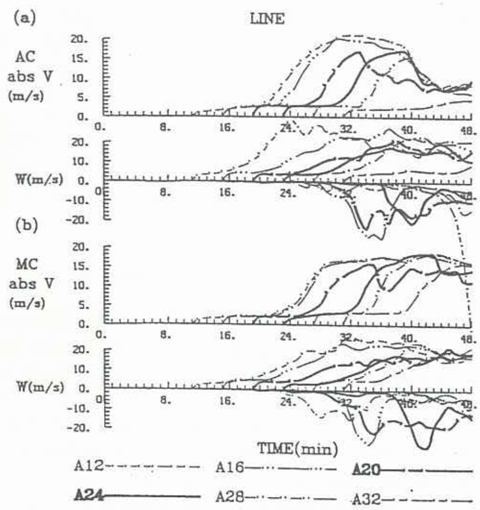

Figure 4: Vortex evolution against cloud model time showing $|V|$ and maximum and minimum W for (a) TV vortices centred at the anticyclonic centre of the LINE model cloud, and (b) TV vortices centred at the moving anticyclonic centre of the LINE cloud. Solutions shown for vortices started at model cloud times 12, 16, 20, 24, 28 and 32min (A12L, A16L, ...A32L, respectively). Heavy lines show the only two-cell vortex solutions.

which with vertical velocity shows the toroidal nature of these instabilities. Once the system of toroids has formed in the core, downflowing air from the cloud is cut off, the toroids are dissipated, upflow is re-established and the vortex is at least partially regenerated. These toroidal cells appear to be associated with an upper instability of the vortex, not previously reported.

5. REFERENCES

Blechman,JB, Simpson,J and McCumber,MC (1988) Initialization Experiments using a three-dimensional convective cloud model. Conf. on Severe Local Storms, 15, Baltimore, J83-J86.

Clark,TL (1979) Numerical Simulations with a 3D Cloud Model. J. Atmos. Sci., 36, 2191-2215.

Dietachmayer,GS (1987) On the Numerical Simulation of small scale intense atmospheric vortices. Ph.D, Monash University, Australia.

Golden,JH (1974) The Life Cycle of Florida Keys Waterspouts. I. J. Atmos. Sci., 13, 676-692.

Holle,RL and Maier,MW (1980) Tornado formation from downdraft interaction in the FACE mesonetwork. Mon. Wea. Rev., 108, 1010-1028.

Howells,PAC, Rotunno,R and Smith,RK (1988) A comparative study of atmospheric and laboratory-analogue numerical tornado-vortex models. Quart. J. Roy. Meteor. Soc. , 114, 801-822.

Howells,PAC and Smith,RK (1983) Numerical Simulations of Tornado-Like Vortices. Geophys. Astrophys. Fluid Dyn., 27, 253-284.

Lin,Y-L, Farley,RD and Orville,HD (1983) Bulk Parameterization of the Snow Field in a Cloud Model. J. Climate Appl. Meteor., 22, 1065-1092.

Miller,MJ and Pearce,RP (1974) A 3D primitive equation model of cumulonimbus convection. Quart. J. Roy. Meteor. Soc., 100, 133-154.

Morton,BR (1969) The strength of vortex and swirling core flows. J. Fluid Mech., 38, 315-333.

Munn,RE (1966) Descriptive Micrometeorology. Academic Press, p245.

Proctor,FH (1982) A numerical study on the evolution of Tornadoes. Ph.D, Texas A&M University.

Roache,PJ (1976) Computational Fluid Dynamics. Hermosa Publishers, p446.

Roff,GL and Morton,BR (1989) The Stability of a Terminating Waterspout. Australasian Fluid Mechanics Conference, 10, Melbourne, 14.13 - 14.16.

Rossman,FO (1960) On the Physics of Tornadoes. Proc. First Conference on Cumulus Convection, Pergamon Press, 167-174.

Schlesinger,RE (1978) A Three - Dimensional Numerical Model of an Isolated Thunderstorm. J. Atmos. Sci., 35, 690-713.

Simpson,J, Roff,GL, Morton,BR, Labas,K, Dietachmayer, D, McCumber,M and Penc,R (1991) A Great Salt Lake Waterspout. Mon. Wea. Rev., 119, 2741-2770.

Simpson,J, Morton,BR, McCumber,MC and Penc,RS (1986) Observations and mechanisms of GATE waterspouts. J. Atmos. Sci., 43, 753-782.

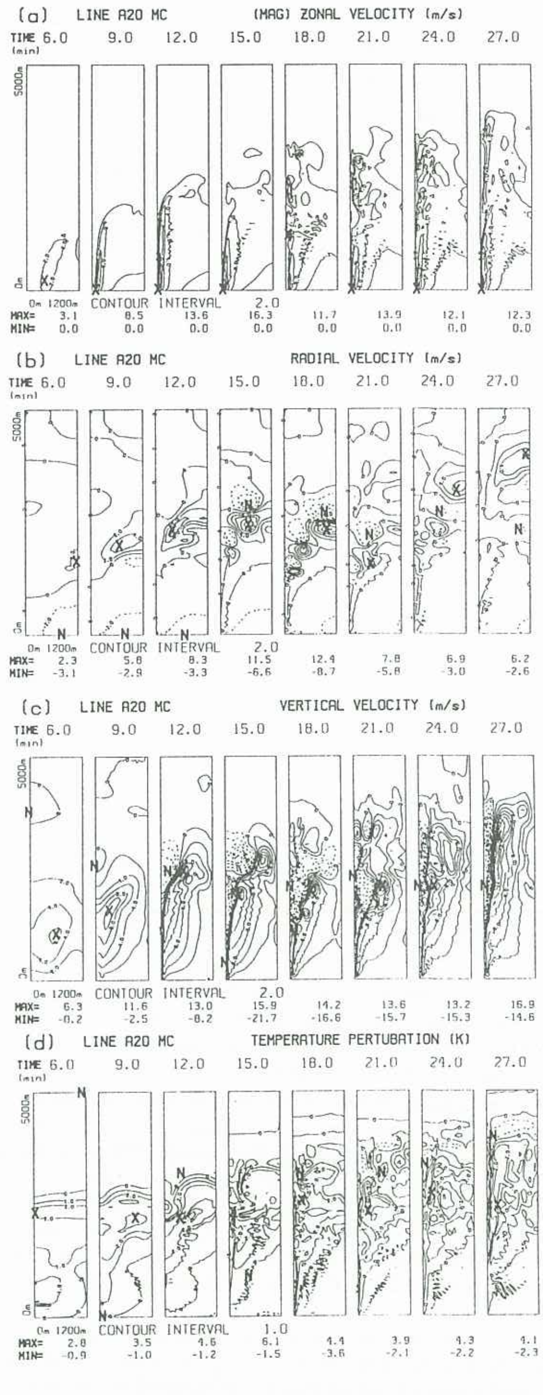

Figure 5: Time series solution contours at 3min intervals for the moving anticyclonic vortex with TV boundary conditions at 20min model time in the LINE cloud.