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An investigation of the tipping term as a prognostic tool in short-range thunderstorm forecasting

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Abstract. A Met Office nowcasting system - GANDOLF - was operated by the Met Office and the University of Salford during the Sydney 2000 Forecast Demonstration Project. The purpose of this project was to test and evaluate the current state-of-the-art in nowcasting technology, and initial verification by the University of Salford has shown GANDOLF's performance to be poor. The system uses a conceptual model of the life cycle of an idealised convective cell to forecast the evolution of radar-observed storms in an object-oriented fashion. Analysis has shown the *implementation* of the model to be inadequate due to in part to its reliance on relatively low resolution NWP model forecasts – rather than the use of conceptual modelling itself. The advent of very high resolution 3D wind fields produced by 4DVAR modelling techniques offers a way of circumventing many of the problems inherent in GANDOLF, and such data have been obtained for the cases during which GANDOLF was operational. These were produced by the National Center for Atmospheric Research's VDRAS system, which was also operated during the FDP, as part of the Autonowcaster system. The wind data allowed the calculation of time series of the 3D tipping term field, which, it has been theorised, can be used as a prognostic tool in automated convection nowcasting. Potential uses of the tipping term include automatically distinguishing between stratiform and convective systems, classifying convective systems by intensity, determining the stage of development of observed storms and guiding their evolution forecasts within a conceptual model, and identifying and forecasting mesocyclones. This paper summarises the theory of the tipping term, and presents the results of a number of tests performed on the data. The conclusions of these tests indicate that the theory of the tipping term is valid. Observations of the increasing asymmetry in the tipping term couplet predicted by theory as convection reaches its maximum intensity may offer a way of improving objective analysis of the life cycle of cells.

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1 Introduction

Currently, established algorithms for nowcasting convection are heavily weighted towards the identification, analysis and tracking of radar-observed storms - the SCIT (Johnson et al., 1998) and TITAN (Dixon and Wiener, 1993) algorithms are good examples. Forecasting future states of such storms is most frequently done by the extrapolation of recent motion, usually determined by cross-correlation or cell centroid tracking. Despite the relative success achieved in forecasting storm location to date, little progress has been made in forecasting storm evolution, since simple linear extrapolation is not well suited to this function (Collier, 2000). However, skilfully capturing storm evolution is an essential facet of the nowcasting process, especially when quantitative precipitation forecasts are required (as is the case in flood forecasting, for example). Consequently, numerous techniques for forecasting convective evolution are being developed, but all have yet to come to fruition.

The recent World Weather Research Programme (WWRP) Sydney 2000 Forecast Demonstration Project (FDP) was conducted with the aims of demonstrating, comparing and evaluating the current state-of-the-art in automated nowcasting technology, and many such techniques were implemented for the project (Keenan et al., 2001). The GANDOLF system (Pierce et al., 2000) was operated during the project by the Met Office and the University of Salford; it is of particular interest because of its novel and unique method of forecasting storm evolution. The forecast model, called the Object-Oriented Model (OOM), employs a conceptual model of a simple thunderstorm cell, which includes a full, idealised realisation of its life cycle. Five stages of development are recognised - Developing (d), Early Mature (m), Mature (M), Early Dissipating (E) and Dissipating (D) - each of which is characterised by fixed values of cloud base height, cloud depth, rain rate, base area, etc. The model also accounts for the generation of daughter cells by existing convection, and allows the initiation of convection in clear air where the NWP model-forecast convergence is sufficiently strong at low levels.

Verification of GANDOLF forecasts was peformed, both subjectively by examining the imagery and collating the feedback of Sydney forecasters who used the products, and objectively by using performance measures such as POD, FAR and bias. The principal flaw noted was that the system frequently forecast rapid decay when, in fact, convection was intensifying or remaining in a steady state. A lack of knowledge of the small-scale dynamical features that were, in all likelihood, responsible for maintaining the convection, was identified as the most likely cause of this behaviour. This was compounded by a lack of time series data regarding the observed history of the convection - GANDOLF reanalysed all storms each time the OOM ran, and paid no regard to the observed history of convective cells.

Consequently, an investigation into the utility of high resolution wind fields, which might enable the inclusion of small scale dynamical features in the GANDOLF forecast scheme, was initiated. It was decided that the tipping term of the vorticity equation would be an ideal parameter to incorporate into GANDOLF, since it represents the horizontal vorticity strongly present in convergence zones and storm inflow regions, and also the horizontal gradients in vertical velocity associated with convection. It was also expected to be an ideal parameter to track over time in an object-oriented scheme such as the GANDOLF forecast model.

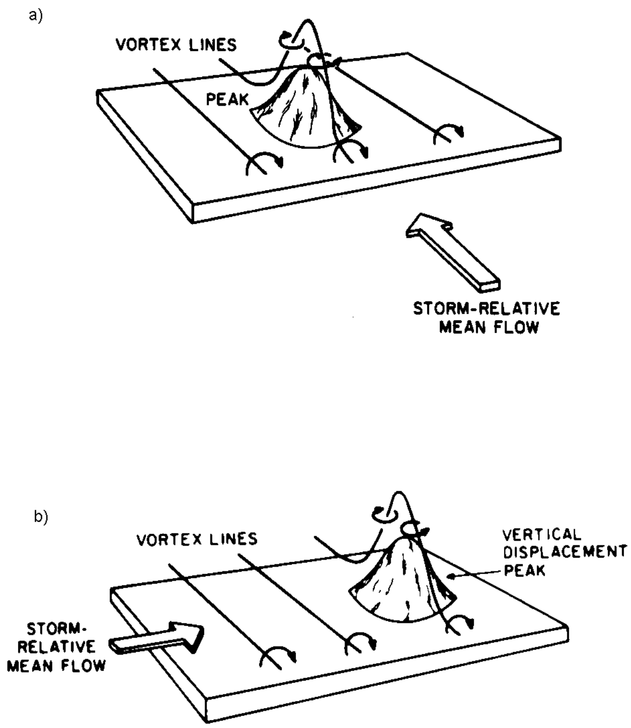

Fig. 1. Rotation associated with a Supercell (after Davies-Jones, 1984).

2 Tipping term of the vorticity equation

The atmospheric vorticity equation is given by:

$$\frac{d(\zeta+f)}{dt} = -\left(\frac{\partial w}{\partial x}\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y}\frac{\partial u}{\partial z}\right)$$
$$-(\zeta+f)D - \left(\frac{\partial \alpha}{\partial x}\frac{\partial p}{\partial d} - \frac{\partial \alpha}{\partial d}\frac{\partial p}{\partial x}\right) + \left(\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}\right) \quad (1)$$

Here, ζ is the vertical component of relative vorticity, f the Coriolis parameter, u, v and w the components of the wind velocity in the x, y and z (that is, east, north and vertical) directions respectively, D the divergence of the velocity field, α the specific volume (reciprocal density), p the pressure and F_x and F_y the two Cartesian components of the horizontal frictional force. The equation states that the rate of change of the vertical component of absolute vorticity is a function of four processes, which are, from left to right:

1. Tipping of horizontal vorticity into the vertical by gradients in vertical velocity

2. Vertical compression of vertical vorticity by horizontal divergence effects

3. Generation of vertical vorticity by solenoidal effects due to barotropy in the atmosphere

4. Frictional effects

Only the first process has been considered, and the tipping term is hereafter designated t. The tipping term of the vorticity equation has traditionally been ignored in dynamic meteorology, for two important reasons. Firstly, in synoptic scale situations hydrostatic balance is usually assumed, meaning that vertical velocities, and thus the tipping term, are considered negligible. In the case of strong vertical convection, vertical velocities can have magnitudes of order a few tens of metres per second. Hydrostatic balance thus breaks down, and the tipping term becomes important in the vorticity equation - of comparable magnitude with the divergence term. It is on these scales - in mesoscale and more importantly cloud scale situations - that the lack of high resolution wind measurements required to accurately determine the tipping term become the limiting factor. Previous studies have relied on data from single radiosonde ascents (Barnes, 1970) or on numerical simulations (Davies-Jones, 1984). However, the Sydney 2000 project made available time series of high resolution, 3D wind fields during a number of convective and stratiform precipitation cases, so that a detailed analysis of the tipping term based on real data has been conducted for the first time.

Davies-Jones, 1984, presented a simple, physical model of how the rotation associated with supercell updraughts is generated. The model represented a three-dimensional region of the atmosphere using a stack of flat, horizontal surfaces. Note that, because potential temperature, θ, is a conserved quantity, such material surfaces are also isentropic surfaces, and shall be called such hereafter. Horizontal vorticity was introduced, and, although the horizontal vortex lines were not strictly material lines, they were considered as such in the model. Making this approximation required the assumption that the solenoidal generation of horizontal vorticity, which would serve to divert the vortex lines, was negligible; consequently, the vortex lines remained in their original isentropic surfaces. In this initial, pre-storm state, the vertical vorticity was zero everywhere.

Then, a vertical deformation of the isentropic surface was introduced, which represented the upward displacement associated with a convective updraught. The vortex lines became tilted and vertical vorticity was induced. The streamwise component of the horizontal vorticity served to generate anticlockwise vertical vorticity on the near side of the peak and clockwise vorticity on the far side (when looking in the direction of the storm inflow vector), and the crosswise component served to generate clockwise vorticity on the left side of the peak and anticlockwise on the right side (again looking in the direction of the storm inflow vector). These components are illustrated in Figs. 1a and b respectively (note that the directions would be reversed if the sense of the horizontal vorticity were reversed). In a zone of uniform horizontal vorticity, and given an isotropic updraught, the regions of opposing rotation generated by each component of the tipping term should be of equal size and magnitude. However, even given an isotropic updraught, the likelihood is that the convergence in the inflow region and divergence in the low-level outflow region of a thunderstorm will serve to modify the horizontal vorticity field. This will be exacerbated by the strengthening of the horizontal vorticity by horizontal stretching of the air parcels, and by solenoidal effects. The manifestation of the weakening inflow to the cell is therefore expected to be increasing asymmetry in the tipping term couplet field.

3 Experimentation and results

The VDRAS system (Sun and Crook, 2001), which was operated during Sydney 2000 as part of the NCAR Autonowcaster, generated 3D fields of the three Cartesian components of wind velocity in the boundary layer. The model domain was 45 by 45 points wide, with a horizontal grid spacing of 2.5 km, and 7 points deep, with a vertical grid spacing of 0.375 km. The lowest layer was 0.1875 km above ground level. Fields were generated every 10 min. Crook and Sun (2002) found a mean magnitude vector difference of 2.6 ms^{-1} between the VDRAS winds and aircraft wind data. Composite reflectivity fields (where the value at each point in the horizontal 2D grid was set to the maximum value measured by any beam passing above that point) from the C-POL radar (Keenan et al., 1998) were interpolated to the same horizontal grid spacing. Three cases of convection (08:05–10:35 UTC, 26 September 2000; 00:05–15:25 UTC, 3 November 2000; 01:05–03:55 UTC, 30 November 2000) and one case of widespread stratiform rain (02:01–04:51 UTC, 18 November 2000) were studied. Hereafter these shall be referred to as 26 S, 03 N, 30 N and 18 N, respectively. Note that 03 N was a particularly severe event, having been associated with giant hail, flash flooding and tornadoes. The 18 N case probably contained some relatively weak embedded convection. The 30 N case represented the early stages of a developing storm system, but reliable wind velocity data were not available during later stages.

Preliminary tests were conducted to investigate whether or not characteristics of the 3D tipping term fields would be useful in the applications described above, or any others. These tests: (a) examined the typical values of the tipping term during the three cases, and compared values for cyclonic and anticyconic tilting; (b) investigated the typical separations (in space and in time) between tipping term peaks and reflectivity peaks for each case; and (c) determined the degree of correlation between fields of tipping term and fields of subsequent convective development.

During the convective cases, the order of magnitude of the largest observed values of the tipping term was $10^{-6}\,\mathrm{s}^{-2}$ - precisely what was expected based on scale analysis. During the stratiform case, the value was $10^{-7}\,\mathrm{s}^{-2}$, which, although it is significantly greater than that predicted for synoptic weather, is an order of magnitude smaller than for convection. Despite this positive result, a surprising lack of correspondence between the magnitude of the maximum values of tilting and the general severity of the convective events (determined subjectively), was noted. The 03 N case was the most severe storm event, yet the tipping term for the 26 S case tended to be somewhat larger. This suggests that the magnitude of the tipping term might not be useful as an indicator of the vigour of convection from storm to storm, although these storms occurred on different days and this may complicate the situation. Conversely the 30 N data showed a gradual increase in the tipping term magnitude towards the end of the time period, which reflected the concurrent increase in storm severity that was observed.

On the whole, the magnitude of the cyclonic values of tipping mirrored that of the anticyclonic values, with couplets being observed as the convection developed. As the convection began to weaken the couplets became asymmectric.

4 Case study 3 November 2000

The 03 N case was the most severe event to be studied, and as such was the case for which the tipping term of absolute magnitude greater than 0.05 $\mathrm{m}^2\,\mathrm{s}^{-2}\,\mathrm{km}^{-2}$ was observed until approximately 02:25 UTC. Thereafter a tipping term couplet developed in the southern area of the VDRAS domain with the negative region (cyclonic) overlapping an area of reflectivity that peaked later at around 60 dBZ.

The couplet reached its most intense by 05:05 UTC being symmetric on the northern edge of the region of greater than 30 dBZ (Fig. 2a). Ten minutes later an independent mesocyclone detection algorithm (Zrnic et al., 1985; Stumpf et al., 1998) placed mesocyclones at the centre of the cyclonic tipping (Fig. 2b) and the couplet had begun to become more asymmetric. By 05:35 UTC (Fig. 2c) the anticyclonic side of

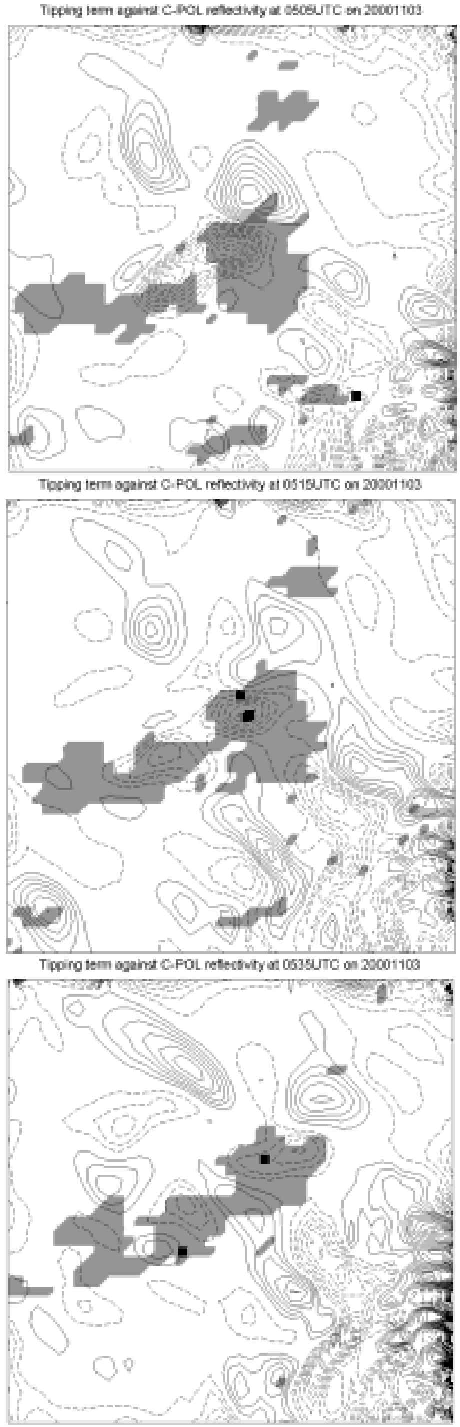

Fig. 2. Tipping term vorticity fields derived on 3 November 2000 over the VDRAS domain. The area of radar reflectivity greater than 30 dBZ is shaded. Broken contours delineate cyclonic tipping term and solid contours anticyclonic tipping term. The contours range from $\pm$ 0.025 ms^{-2} km^{-1} to $\pm$ 10 ms^{-2} km^{-1} in increments of 0.025 ms^{-2} km^{-1}.

the couplet dominated.

The symmetric couplet as the cell reached its maximum intensity is consistent with the Davies-Jones (1984) theory (Sect. 2). As the inflow is weakened by the downdraught the couplet becomes more asymmetric with a bias towards anticyclonicity on the inflow side.

5 Conclusions

The generation of vorticity in convective storms through the tipping of horizontal vorticity by the strong updraught was described some thirty years or so ago. A model of this process was proposed by Davies-Jones (1984). However, it is only comparatively recently that high resolution three dimensional velocity fields derived from the assimilation of Doppler weather radar into a mesoscale numerical model have become available. The Sydney 2000 Project provided on excellent opportunity to verify this model. Whilst the magnitude of the tipping term was not directly related to the severity of the convection, the convective development seemed to be related to the symmetry or otherwise of the tipping term field. Increasing asymmetry indicated a weakening of the inflow to a convective cell and its subsequent decline. This limited analysis indicates the potential of four dimensional wind fields derived by the assimilation of Doppler radar data into high resolution models.

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