HIGH–RESOLUTION CONTOUR ADVECTION USING NWP PRODUCTS

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Summary: The evolution of material contours in a flow can be simulated at high resolution using Lagrangian advection with low–resolution winds from global analyses or forecasts. We describe applications of such a technique to the investigation of transport in the lower stratosphere and discuss the extent to which results differ when using different analyses or forecasts as the basis of the advection.

1. THE CONTOUR ADVECTION WITH SURGERY (CAS) TECHNIQUE

High–resolution numerical simulations of the winter stratosphere, either from simplified, one–layer models (*e.g.*, *Juckes and McIntyre*, 1987) or general circulation models (*Mahlman and Umscheid*, 1987), reveal a rich structure in potential vorticity and chemical tracers even in situations where the flow field is dominated by planetary scales. Aircraft measurements of chemical species made *in situ* in the lower stratosphere during recent polar campaigns (see, *e.g.*, the special issues of J. Geophys. Res., 94, nos. D9 and D14, 1989, and Geophys. Res. Lett., 17, no. 4, 1990) confirm the presence of this structure down to the smallest measurable scales. Much of this variability appears to be indicative of "planetary wave debris" (*Strahan and Mahlman*, 1993) rather than, for example, gravity wave activity. Quantitative modeling of small–scale features, in a way that links these features with the planetary–scale flow, is necessary in order to estimate net transport rates within the stratosphere and to facilitate analysis of high–resolution *in situ* data.

Since the relevant scales may be tens of kilometers, it is impracticable to model these features explicitly in a general circulation model. However, fine–scale features can be generated, apparently successfully, by particle–following Lagrangian models, advecting the particles by winds obtained from model output or from observationally based analyses. The success of this kind of approach depends on the deformation field being adequately resolved in space and time by the wind data; this issue will be addressed below. If this is so, the obtainable resolution is limited only by the number of particles used in the calculation.

High resolution can be achieved by using a large but fixed number of particles to define a material contour (*e.g.*, *Pierce and Fairlie*, 1993) or domain (*Fisher et al.*, 1993). In the approach we describe and use here, contour advection with surgery (CAS), material contours are represented not by specifying a fixed number of particles (or "nodes") on the contour, but by specifying a resolved scale and dynamically modifying the number and position of particles to achieve that resolution. *Schoeberl and Bacmeister* (1993) have done this by adding particles when the distance between adjacent particles exceeds some specified value. In our approach (described in more detail in *Waugh and Plumb*, 1993) we use the techniques of contour surgery (*Dritschel*, 1988), which include allowance for contour curvature as well as node separation, as well as "surgery" to remove scales below some specified cutoff value. A similar approach, though without the surgery, has been used by *Norton* (1993).

As we shall show below, material contours simulated using this approach rapidly develop very small scales, far smaller than the resolved scale of the wind analyses used as the basis of advection. The question arises as to whether the spatial and temporal resolution typically available is adequate for this purpose. In a stratospheric context, this was addressed by *Waugh and Plumb* (1993), who showed that wind data with resolution of 5^o latitude $\times$ 5^o longitude, available once per day, appeared to be adequate. An example of the weak sensitivity to wind resolution, using winds available every 6 hrs from the $1^o \times 1.2^o$ resolution version of the "SKYHI" GCM (*Mahlman and Umscheid* 1987), is shown in Figure 1.

2. A CASE STUDY: JANUARY 1992

2.1 An intrusion event

During late January 1992, an intrusion occurred into the lower stratospheric polar vortex (one of three such events during that winter). Lower stratospheric analyses (450K potential vorticity from NMC analyses for the period 16–28 January are shown in Figure 2, the ECMWF analysis for 24 January in Figure 6a) show no more than a hint of this occurrence,

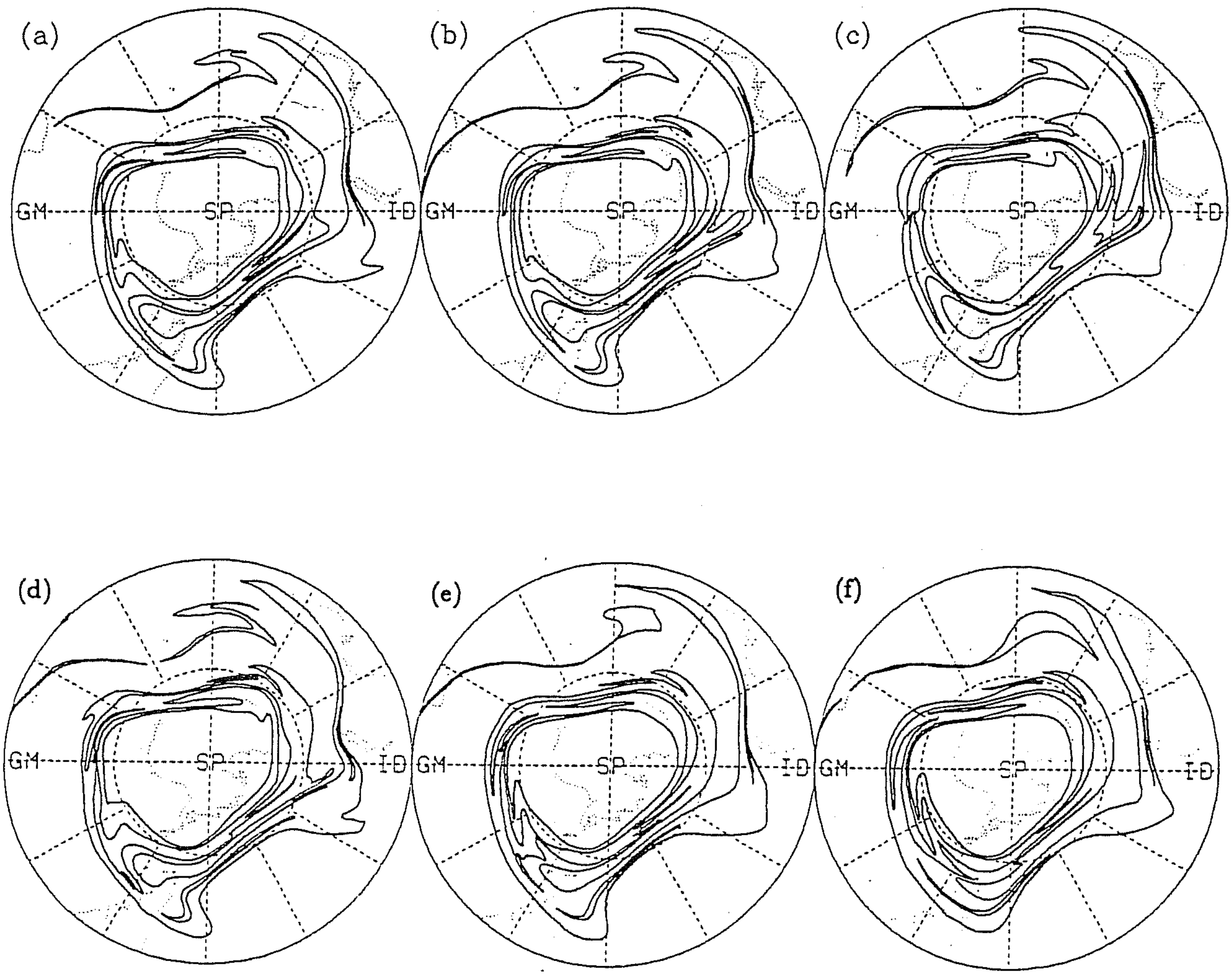

Fig 1. Material contours after 6 days of CAS integration using winds on the 450K isentropic surface, taken from the SKYHI GCM. Contours were initialized with smoothed potential vorticity contours from the model on 7 June. Runs using the full spatial wind resolution and interpolated in time from winds specified every (a) 6 hrs (b) 24 hrs (c) 48 hrs, and from winds specified every 12 hrs with spatial resolution degraded to (d) $3^{o}\times3.6^{o}$ (e) $5^{o}\times6^{o}$, and (f) $10^{o}\times12^{o}$. After *Waugh and Plumb* (1993).

but CAS calculations using analyzed winds show it clearly. Figure 3 shows the evolution of material contours on the 450K isentropic surface initialized with contours of NMC 450K potential vorticity on 16 January, advected with 450K balanced winds from daily NMC analyses. Although the large scale features of the CAS results are extremely similar to the evolution of potential vorticity from the analyses, the CAS results show much more structure. In particular, an intrusion begins around the 22nd north of Scandinavia, leading to a long filament of air from the vortex edge being entrained around the vortex center. During the period, there are also several extrusion events in which vortex material is shed into midlatitudes by Rossby wave breaking. Aerosol measurements made on the 24th from the DIAL lidar on the NASA DC–8 aircraft confirmed the existence and locations both of the intrusion and of the ejected filament of vortex air stretching across NW Canada (*Plumb et al.*, 1993).

2.2 CAS results using ECMWF analyzed winds

CAS results for the same period using 450K analyzed winds from daily ECMWF analyses are shown in Figure 4. The calculated evolution of material contours is very similar to that determined from the NMC balanced winds, even down to fine details. Note in particular the location of the intrusion on the 24th and of the ejected air near 90°E on the 28th. The similarity of two simulations of the latter feature, after 12 days of integration, implies a high degree of similarity of the Lagrangian properties of the two wind analyses. There are some differences, however, even in the large scale features, such as the shape of the vortex "tail" around 90°E on the 24th. The large scale aspects of these differences are in fact very similar in those evident in the respective potential vorticity analyses at the appropriate times. As we shall see below, however, we do not find such good agreement when using different sources of wind data in southern hemisphere calculations.

During the course of these calculations we discovered that, contrary to what the tests of *Waugh and Plumb* (1993) had led us to expect, there was some sensitivity of predicted CAS results using analyzed winds to the temporal resolution with which the winds were specified. Figure 5 compares predicted contour locations on 21 and 24 January (from calculations begun on the 16th) from a calculation with winds specified every 24hr with one in which winds were specified every 6hr. Although the overall behavior is very similar, results from calculations with six–hourly winds show widespread "wiggles" in the predicted contours;

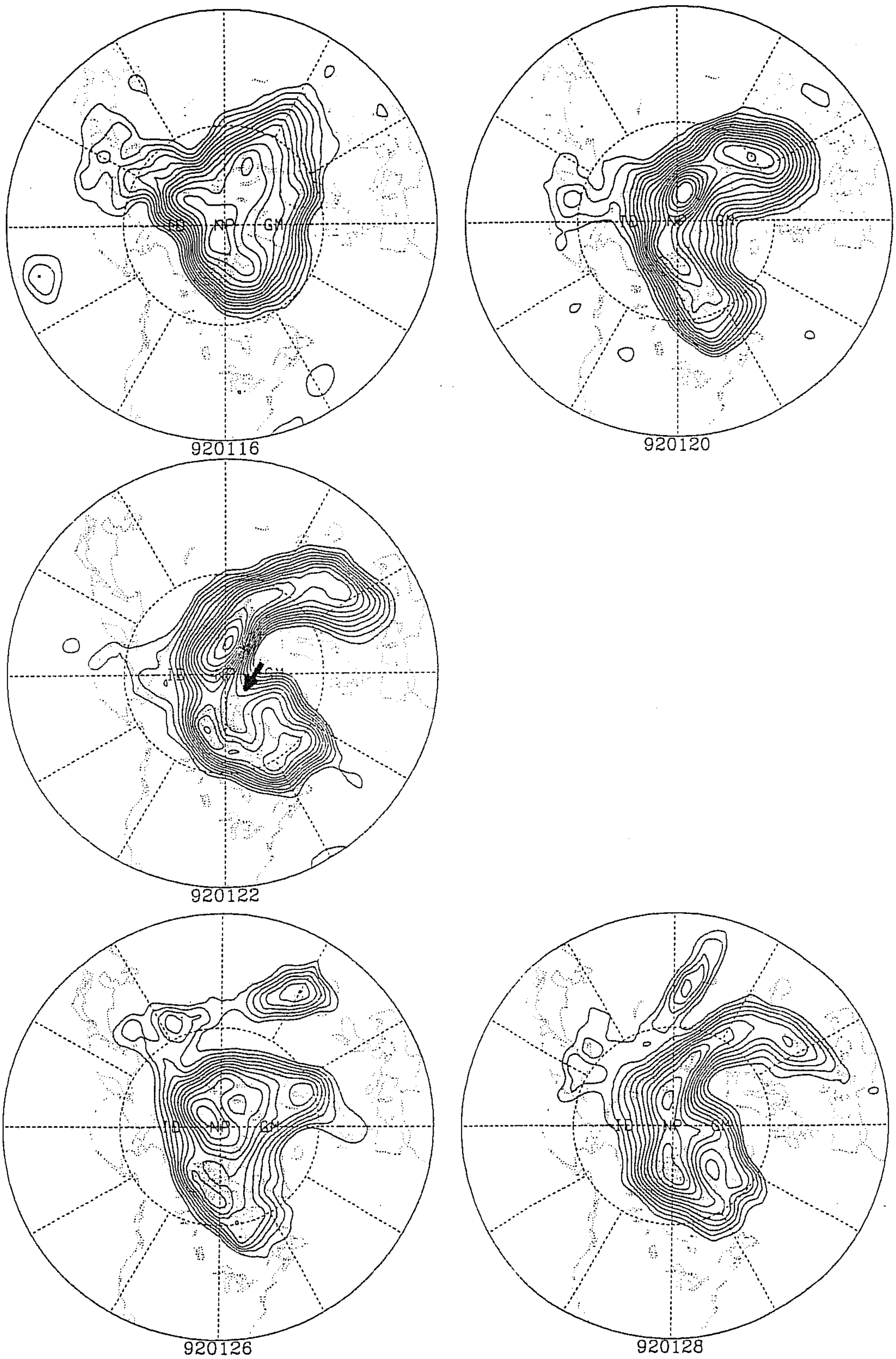

Fig 2. Ertel potential vorticity on the 450K isentropic surface at 12Z for several days during the period 16–28 January 1992, from NMC analyses. Contour interval is 2 10^{-6} $Ks^{-1}Pa^{-1}$, beginning at 2 10^{-5} $Ks^{-1}Pa^{-1}$. (After *Plumb et al.*, 1993.)

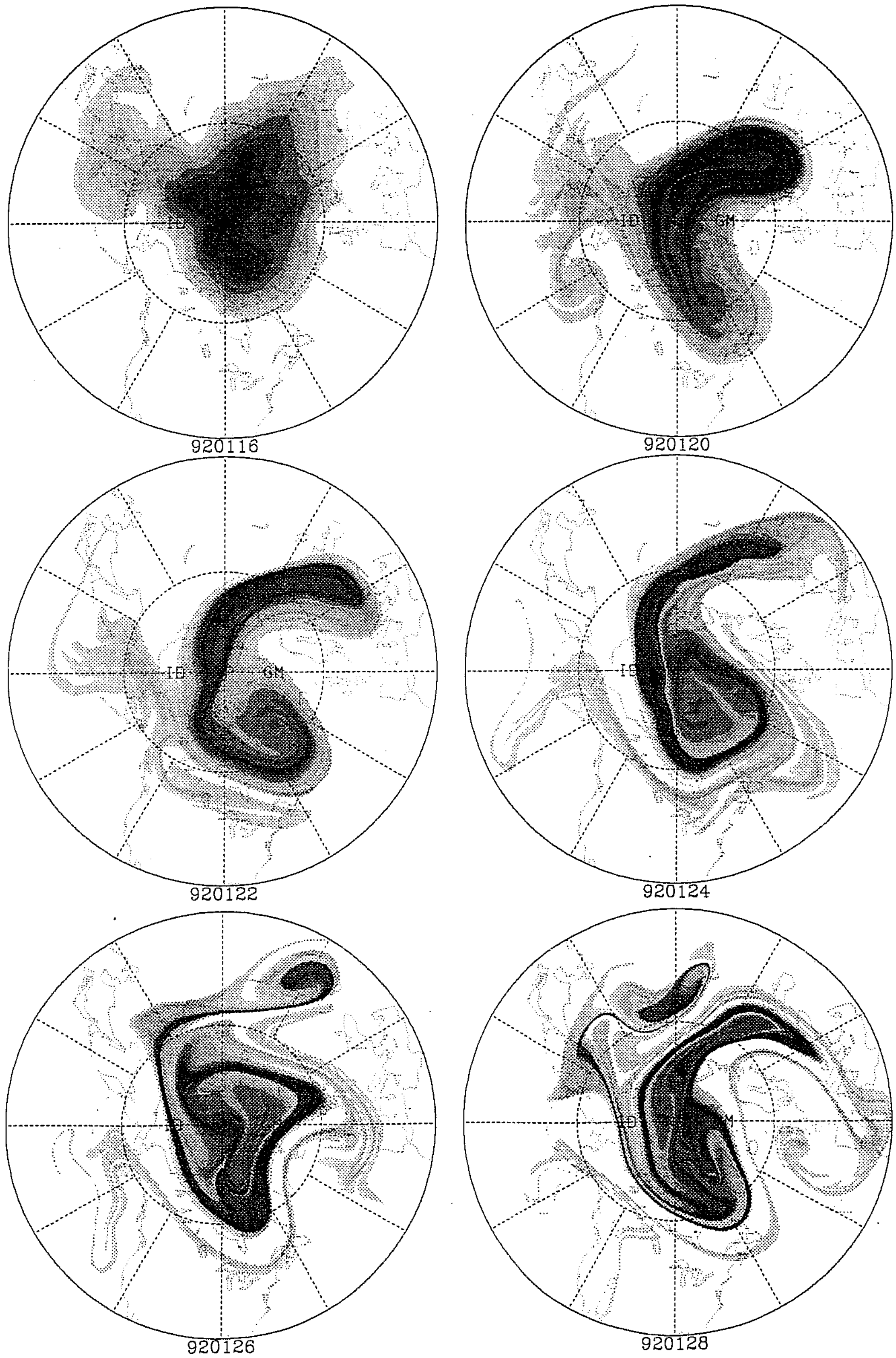

Fig 3. Evolution of material contours, initially coincident with the NMC analysed potential vorticity (those contours shown in Figure 2), on the 450K isentropic surface for the period 16–28 January 1992, from a CAS integration in which the contours were advected with the 450K balanced winds from daily NMC analyses. (After *Plumb et al.*, 1993.)

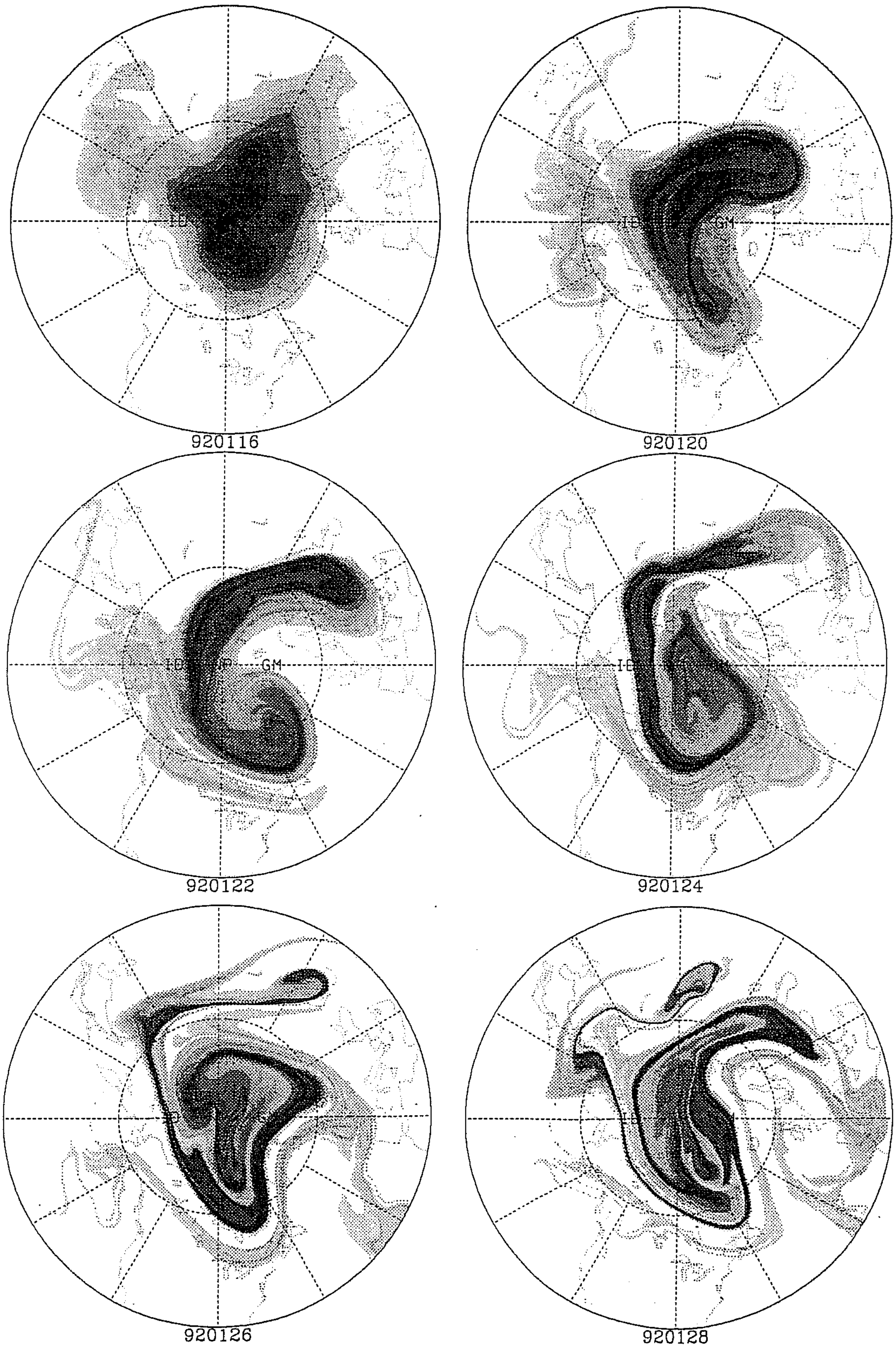

Fig 4. As Fig 3, but using daily winds from ECMWF analyses. (After *Plumb et al.*, 1993.)

these wiggles are not present in the results of calculations using daily winds. In our experience, this behavior is not typical of contour evolution in high–resolution dynamical models nor, as we shall show below, is it reproduced if forecast winds are used (*cf.* Figure 7). We find similar results, however, using winds from NASA assimilations. It seems likely that this behavior occurs because the time series of analyzed winds is not smooth but is jarred when the influence of observations is inserted at every analysis time. When this is done frequently, it leads to anomalous Lagrangian behavior. If analyzed winds are used less frequently, however, the linear interpolation used between each analysis to obtain winds every time step of the CAS calculation acts as a smoothing agent, thus suppressing the effect. Consequently (and somewhat paradoxically) the evolution of contours may be less well simulated when frequent wind analyses are used.

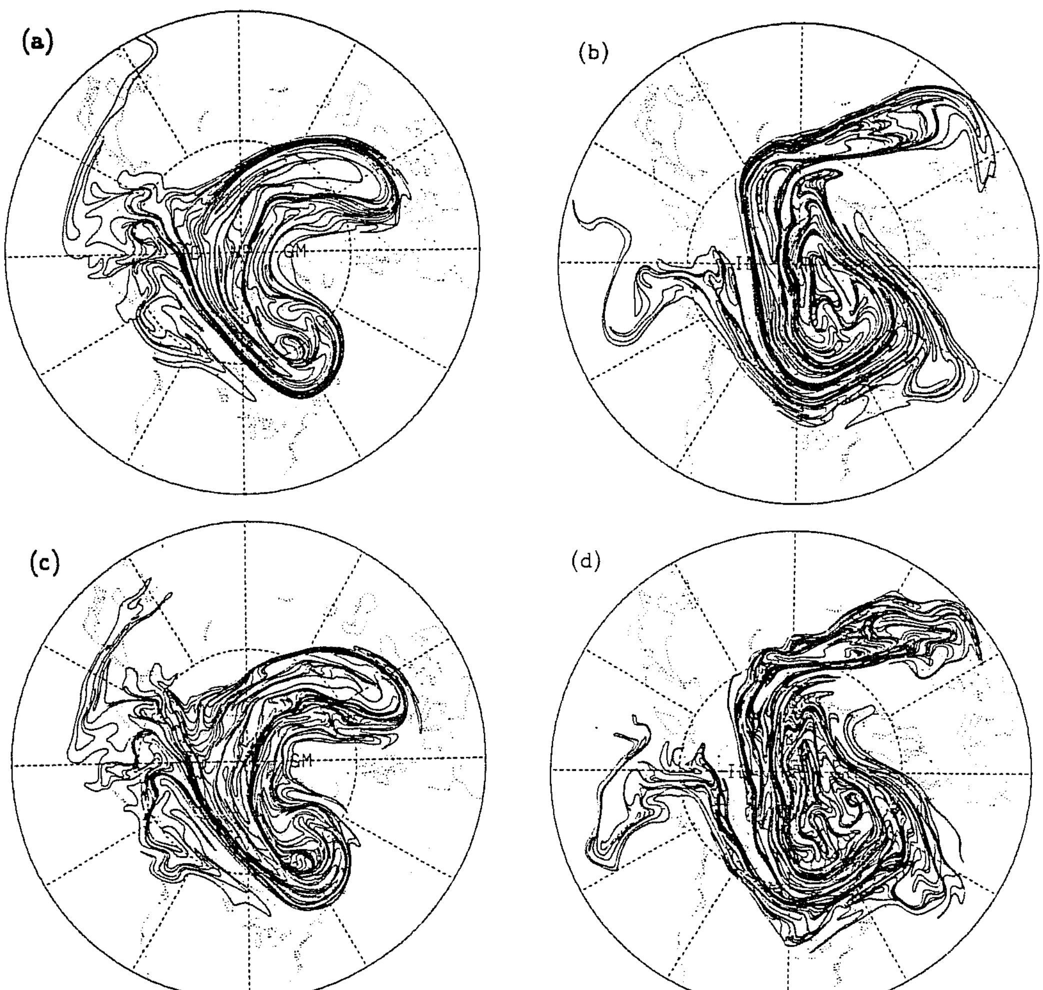

Fig 5. Material contours from CAS integrations on the 450K initialized on 16 Jan 1992 with potential vorticity from analyses. Calculations using daily ECMWF analyzed winds on (a) 21 Jan and (b) 24 Jan; and using 6–hourly ECMWF analyzed winds on (c) 21 Jan and (d) 24 Jan.

2.3 ECMWF analyses and forecasts

Ertel potential vorticity on the 450K surface at 12Z on 24 January is shown in Figure 6a. This shows hints of the intrusion into the vortex (near 90°E) more clearly than the NMC analyses. There is also much more small–scale detail, though this is mostly in the form of almost–circular features, quite unlike the fine–scale filamentary structures generated in the CAS calculations. These analyzed features are also not evident in ECMWF forecasts, examples of which, valid at 12Z on 24 January, are also shown in Figure 6. Both the operational forecast, and experimental forecasts with reduced diffusion (*Simmons* 1993), show the intrusion and general characteristics of the vortex evolution in agreement with the

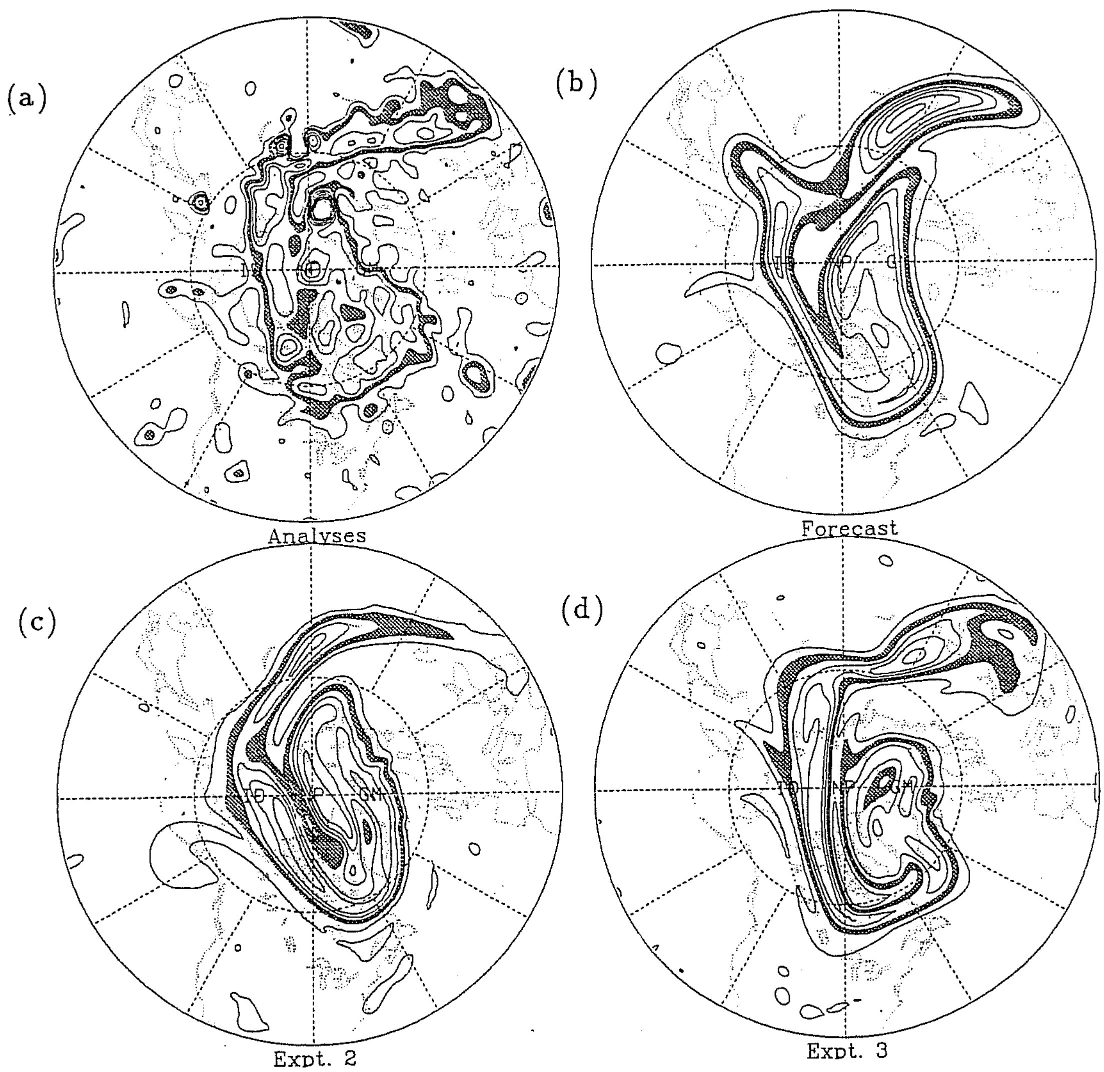

Fig 6. Potential vorticity on the 450K isentropic surface, 12Z 24 January 1992. ECMWF analysis (a), T213 operational 8–day forecast (b), and experimental (c) 8–day and (d) 5–day forecasts with reduced diffusion. (After *Plumb et al.*, 1993.)

CAS results valid at this time, though there are substantial differences both between different forecasts and between forecasts and the CAS results. Only the 5–day experimental forecast produces an intrusion extending as far as the CAS runs, and the aircraft data, show.

2.4 CAS calculations using forecast winds.

A series of CAS experiments were run using winds from an operational ECMWF forecast, gridded at intervals of 1°×1° or 5°×5° every 6 or 24 hr. Results for 5–day calculations at 450K initialized with potential vorticity analysis on 16 January 1992 are shown in Figure 7. Also shown is the 5–day forecast potential vorticity valid at 12Z on the 21st. All three

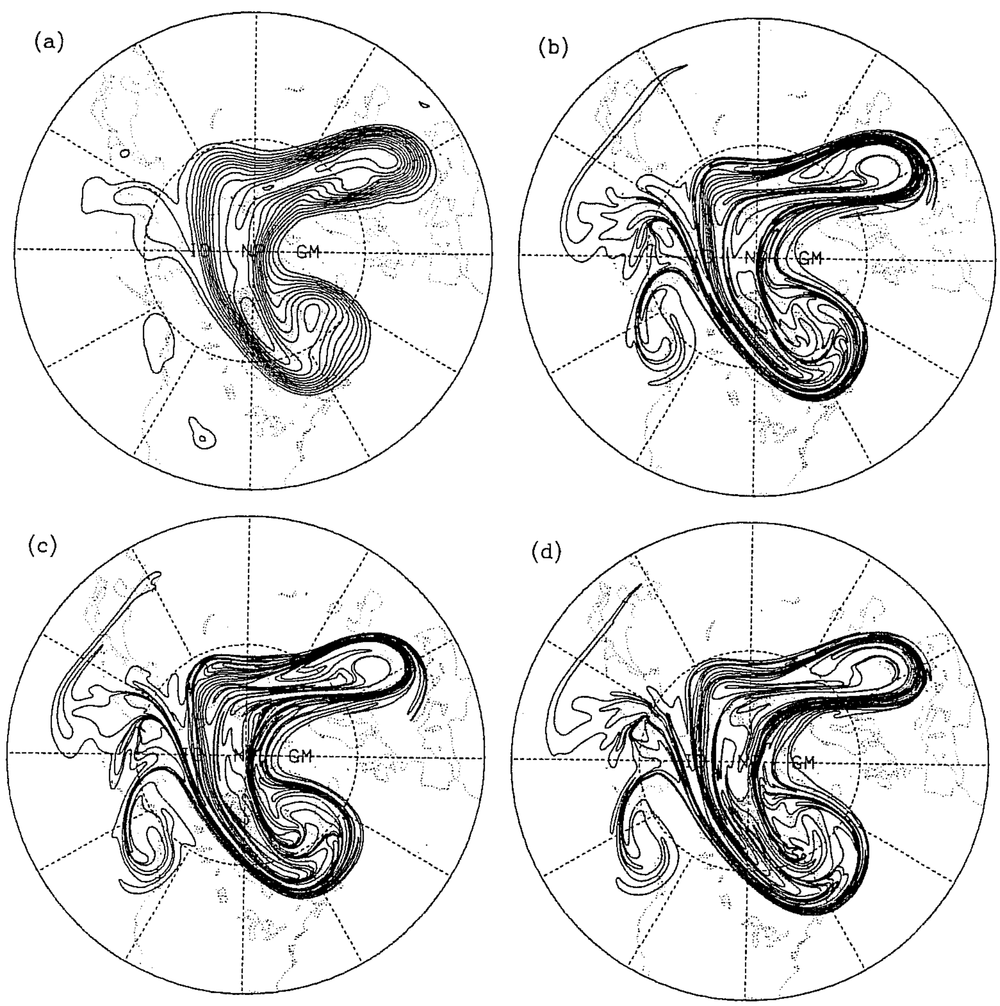

Fig 7. Potential vorticity on the 450K isentropic surface, 21 January 1992. 5–day ECMWF forecast (a) and results from CAS calculations using forecast winds gridded at a spatial resolution of Δ in latitude and longitude, and specified every ΔT in time, where (b) $\Delta = 1°$, $\Delta T = 6$hr; (c) $\Delta = 1°$, $\Delta T = 24$hr; and (d) $\Delta = 5°$, $\Delta T = 24$ hr.

forecasts are extremely similar to each other and, making allowance for differences in resolution, to the forecast. This latter fact illustrates the degree to which potential vorticity is locally conserved during the forecast. Apart from the detailed interior structure of the vortex, the only noticeable discrepancies are the absence in the forecast of the umbilical filament connecting the ex–vortex material just off the west coast of Canada with the main vortex, and the absence in the CAS results of the small feature over the western U.S. Note that neither the forecast potential vorticity nor the CAS results show the small scale "blobs" characteristic of the ECMWF analyses. It has already been noted that the CAS calculation using six–hourly forecast winds do not exhibit the "wiggly" nature of the results using six–hourly analyzed winds.

3. SOUTHERN HEMISPHERE CALCULATIONS

In northern hemisphere calculations, using winds from different analyses and forecasts, the calculated material contour evolution appears to be robust. In cases where we have been able to compare such predictions with *in situ* data, the calculations also appear to be quite accurate (*Plumb et al.*, 1993; *Waugh et al.*, 1993). In the southern hemisphere, on the other hand, calculations based on analyzed winds from different sources show substantial, even qualitative, differences. Figure 8 shows results from CAS calculations on the 470K isentropic surface, run for 24 days from 21 September 1992. The three experiments used daily winds from ECMWF and UK Meteorological Office analyses, and balanced winds calculated from NMC stratospheric analyses. Each run was initialized with potential vorticity contours from the appropriate analysis. Substantial differences are apparent between the three cases, even after 12 days, both in the structure and size of filaments of air ejected from the vortex, and in the large–scale structure of the vortex itself. (Note, *e.g.*, the shape of the edge of the vortex as marked by material contours after 12 days. These differences reflect similar differences in the analyzed shape of the vortex.) Calculated transport rates out of the Antarctic vortex would be very different in the three cases, and differences in the location and extent of the material ejected from the vortex are so large as to undermine the usefulness of such results in the interpretation of aircraft measurements.

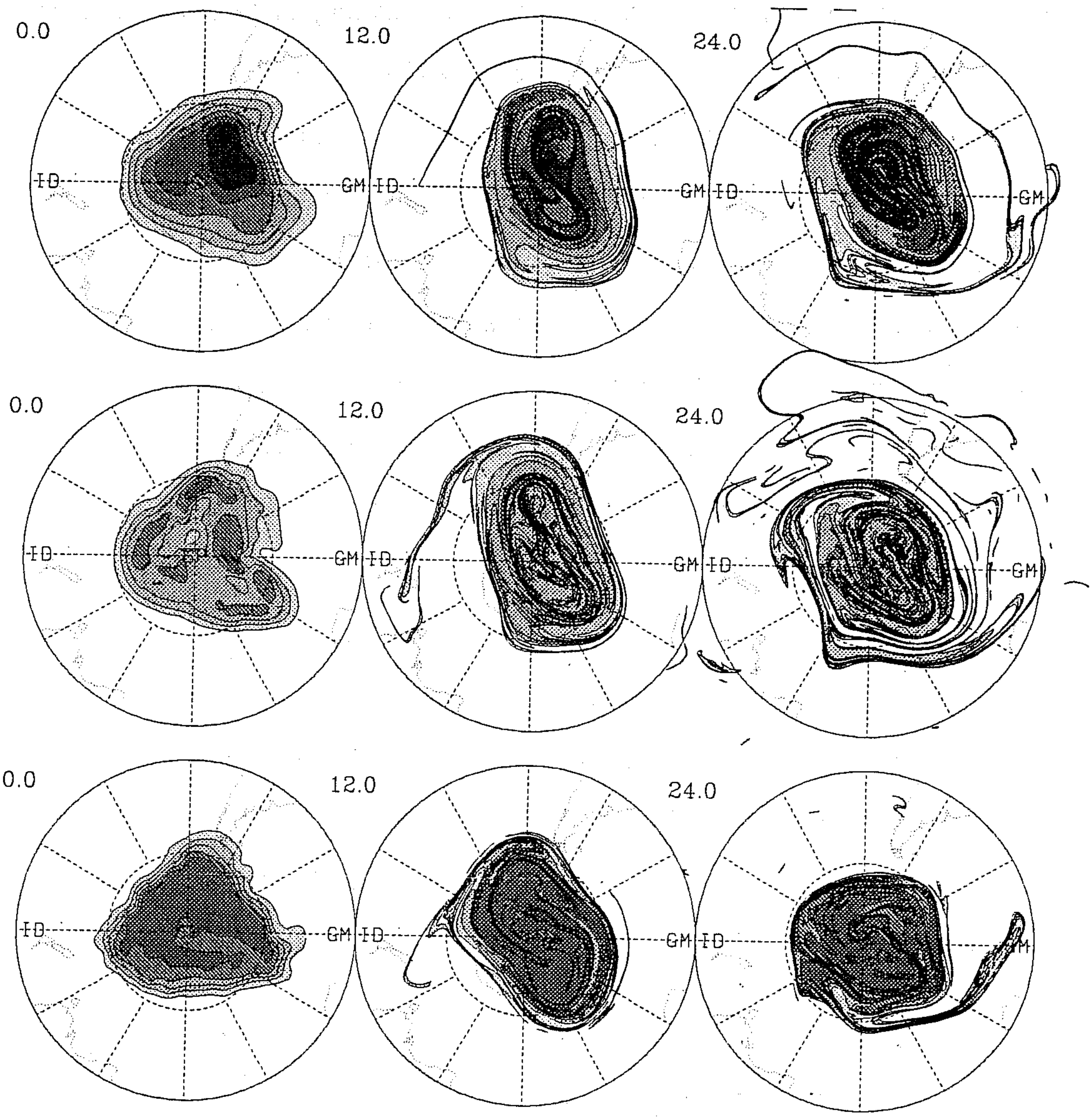

Fig 8. Calculated evolution of material contours on the 470K surface in the southern hemisphere over the 24 day period 21 Sep–15 Oct 1992. Initial conditions and CAS results at days 12 and 24, using winds obtained from (top) NMC (center) UKMO and (bottom) ECMWF analyses.

4. DISCUSSION

We have found that, in the northern hemisphere lower stratosphere, winds from routinely available analyses provide a sound basis for the calculation of the evolution of material contours within isentropic surfaces. Results from these calculations are robust with respect to changing the source of the analyzed winds. On the basis of comparison with high–resolution *in situ* measurements of chemical tracers, the calculations show remarkable accuracy, even on spatial scales much smaller than those of the analyses. The situation is very different in southern hemisphere calculations, for which different wind analyses produce very different results.

The CAS results typically reveal a very complex structure, with the vortex frequently shedding filaments into midlatitudes. Many of these filaments are strung along the polar jet; the structure of the vortex edge is thus very rich in small–scale features, a fact also evident in aircraft measurements. These features will probably include, in addition to the polar filaments evident in the calculations presented here, filaments of air entrained from the tropics in a dynamically similar way (*Waugh* 1993). The filamentary nature of the small–scale material structure is quite different from the "blob"–like structures characteristic of potential vorticity derived from ECMWF analyses. Thus, these calculations lead us to question the reality of these features.

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