Aspects of Dynamics of the Middle Atmosphere Inferred by Using Data from a Satellite and from a Numerical Model [and Discussion]

T. D. A. Fairlie, A. O'Neill and M. E. McIntyre

Phil. Trans. R. Soc. Lond. A 1987 **323**, 679-692
doi: 10.1098/rsta.1987.0114

Phil. Trans. R. Soc. Lond. A **323**, 679–692 (1987)
Printed in Great Britain

Aspects of dynamics of the middle atmosphere inferred by using data from a satellite and from a numerical model

By T. D. A. Fairlie and A. O'Neill
Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, U.K.

The data used in this study are from a stratospheric sounding unit (SSU) on a polar-orbiting satellite, and from a numerical model of the middle atmosphere based on the primitive equations. They are used to discuss the dynamics of the major stratospheric warming of 1984–85. The warming is of note because the westerly circulation started to break down rapidly when the westerly vortex was larger than might be expected of a state 'pre-conditioned' for a major warming. At the height of the warming, there is a sudden loss of high values of Ertel's potential vorticity on isentropic maps derived from the SSU. Ground-based measurements and a simulation of the warming with the numerical model indicate that strong gradients of temperature arise in westward-sloping 'fronts', which the SSU is unable to resolve fully. The simulated stratospheric fronts have features in common with observed fronts that form in the upper troposphere, although there may turn out to be dynamical differences between the two cases.

1. Introduction

Data from satellites are greatly improving our knowledge of the middle atmosphere. They have revealed a wealth of flows evolving on a wide range of scales in space and time. Before such data came along, information on the region came mainly from radiosondes and rocketsondes. A long and valuable sequence of hand-drawn analyses of the lower stratosphere of the Northern Hemisphere has been made daily from these sources by workers at the Free University of Berlin. But the coverage of data is not uniform, being extremely sparse over the oceans and in the Southern Hemisphere. Moreover, measurements are not made with instruments of equal reliability. Instruments on satellites, on the other hand, can make measurements globally and with consistent quality. These attributes are especially important for diagnostic studies of dynamics (measured fields often have to be differentiated), and for initializing and validating simulations with numerical models.

As more complex flows have been observed, our dynamical thinking about the middle atmosphere has changed. Many diagnostic studies have been based on the theory of wave, mean-flow interaction. In a typical application (Palmer 1981), a wave is taken as the departure from the current zonal-mean state, and is supposed to propagate quasi-linearly on that state. It is now becoming recognized that when the middle atmosphere is strongly perturbed, a partition into a wave and a mean flow may not be useful. A return to a synoptic description has been prompted by recent papers by McIntyre & Palmer (1983, 1984, 1985). They emphasized the dynamical importance of Ertel's potential vorticity, Q, and based their studies of the stratosphere on isentropic maps of Q derived from measurements by a stratospheric sounding unit (SSU) on board the satellite, *Tiros-N*, of *NOAA*'s operational series.

A good approximation to Q for large-scale circulations is given by

$$Q \approx -g(\zeta+f)\,\partial\theta/\partial p, \tag{1}$$

where g is the acceleration due to gravity, ζ is the relative vorticity, f is the Coriolis parameter, θ is potential temperature (constant θ defines an isentropic surface), and p is pressure. Q has two important properties for a dynamical analysis. (1) For adiabatic, inviscid flow, it is conserved along an air parcel's trajectory, as is θ. Contours of Q on isentropic maps are then material lines, which can be used to follow the movement of air. In the mid-stratosphere, this can be done for only a week or so at a time, owing to the non-conservative effects of radiation; in the upper stratosphere, the limit is a few days. (2) Under balanced conditions (e.g. thermal wind balance) and with boundary conditions, all other fields can, in principle, be derived from the three-dimensional distribution of Q. Hoskins *et al.* (1985) elaborate on these properties and give examples of their use. The uniform quality of satellite data is an advantage in calculating Q because measurements of temperature or thickness must be differentiated twice (first to obtain winds, then to obtain relative vorticity).

Satellite-borne instruments do not take readings at a point in the atmosphere but average over a volume of it. Thus they yield only a somewhat blurred view of the distribution of Q, and smaller-scale features embedded in the large-scale flow are smoothed or lost altogether. As we shall see, sharp changes in the variation of temperature with height, captured in radiosonde measurements, are smeared out; and narrow tongues of material that growing anticyclones draw from the westerly vortex are inadequately resolved, so the transport of material is obscured.

Failure to resolve such features in a numerical model could be detrimental to the model's ability to reproduce accurately even the large-scale flow of the middle atmosphere, especially in long integrations. Resolution in the middle atmosphere comparable with or, indeed, exceeding that now used by general circulation or forecasting models of the troposphere could well be needed.

In this paper, we give an example of how data from a satellite can be used in conjunction with a numerical experiment to learn about the dynamics of a tantalizing phenomenon that has yet to be fully understood: the stratospheric sudden warming. The first major warming to be studied extensively with such data happened in the Northern Hemisphere in February 1979 (see, for example, Palmer 1981). We focus on a major warming that took place in mid-winter, 1984–85. In this spectacular event, the westerly vortex was split into two roughly equal parts. Scales of motion arise that SSU measurements do not adequately resolve, as is signalled by a sudden loss of high values of Q at the centre of the newly formed vortices. We use a numerical model of the middle atmosphere with a prescribed lower boundary to simulate the warming. The model has better spatial resolution than our observations, and we find that narrow, westward-tilting zones with strong temperature gradients develop in the stratosphere. We refer to them as 'fronts'. The atmospheric structure near these fronts is reminiscent of that found near fronts that have been observed in the upper troposphere.

The plan of our paper is as follows. In §2, we describe the data and the method of analysis, after which we summarize the features of our numerical model. The observations and the model are used in §3 to discuss aspects of the dynamics of the major warming of 1984–85. Concluding remarks are in §4.

2. DESCRIPTION OF DATA AND NUMERICAL MODEL

(a) *Data and method of analysis*

We use data mainly from a stratospheric sounding unit (SSU) on board the satellite, *NOAA* 7, of the *Tiros-N* series. Pick & Brownscombe (1981) describe the instrument. The satellite is in Sun-synchronous orbit at a height of 850 km making about 14 orbits a day. Stratospheric analyses are made from radiances measured by the SSU, by a microwave sounding unit (MSU), and by a high-resolution infrared sounder (HIRS/2). All three are nadir-sounding radiometers, which scan across the orbital path giving almost global coverage with good horizontal resolution. The measuring channels of the SSU have weighting functions centred in the stratosphere near 15, 5, and 1.5 mbar†. Statistical tests show that the vertical resolution of measurements is about 10 km. Resolution is somewhat poorer for the SSU providing data for this study because the channel for 5 mbar was inoperative. The performance of the system was not seriously degraded, however. We compared analyses with those derived from an SSU on the satellite, *NOAA* 6, and found that differences could be neglected for our purposes. (Data from *NOAA* 6 were received only sporadically, and its HIRS instrument was inoperative at the time.)

Details of the calculation of isentropic maps of potential vorticity are given by Clough *et al.* (1985), who also discuss the errors involved. Briefly, thicknesses are derived from radiances by statistical regression. They are then added daily to a global analysis of geopotential height at 100 mbar made at the Meteorological Office as part of an operational forecasting cycle. Fields of geopotential height in the stratosphere are thus obtained at 20, 10, 5, 2 and 1 mbar, and they are supplemented by an operational analysis at 50 mbar. Potential vorticity is calculated by differentiating and interpolating these fields.

(b) *The numerical model*

We use a global model of the stratosphere and mesosphere based on the primitive equations. The height of its lowest isobaric surface, 100 mbar, is prescribed using observations. A full description of the model is given by Butchart *et al.* (1982), although our version uses finite differencing accurate to fourth order rather than to second order. Summarizing its main features, it has a regular grid in spherical coordinates with grid points at intervals of 5° in latitude and longitude, and 33 levels equally spaced in logarithmic pressure, about 2.5 km apart. In the experiment discussed here, radiative processes are approximated by newtonian cooling, whereby temperature is reduced towards its local value in a reference state (the zonally averaged state at the start of an experiment) on a timescale of about 20 days in the lower and middle stratosphere and of about 5 days in the upper stratosphere. Drag due to the dissipation of gravity waves is represented by using Holton's (1976) parametrization of Rayleigh friction.

Initial data needed to start an integration with the model are obtained for the stratosphere from the analyses described above. For the mesosphere, we used a climatology prepared from satellite data at the University of Oxford (courtesy of J. J. Barnett and M. Corney).

---

† 1 mbar = 10^2 Pa.

3. The major warming of 1984–85

(a) *Observations*

A dramatic and unusually early major warming developed at the end of December 1984 in the stratosphere of the Northern Hemisphere. A summary of its main synoptic features is given by Labitzke *et al.* (1985). Figure 1*a* shows the zonally averaged, geostrophic wind on 20 December 1984. There is a broad jet with winds exceeding 80 m s^{-1} in the upper stratosphere. By 2 January 1985, figure 1*b* shows that westerlies have been replaced by easterlies in the zonal

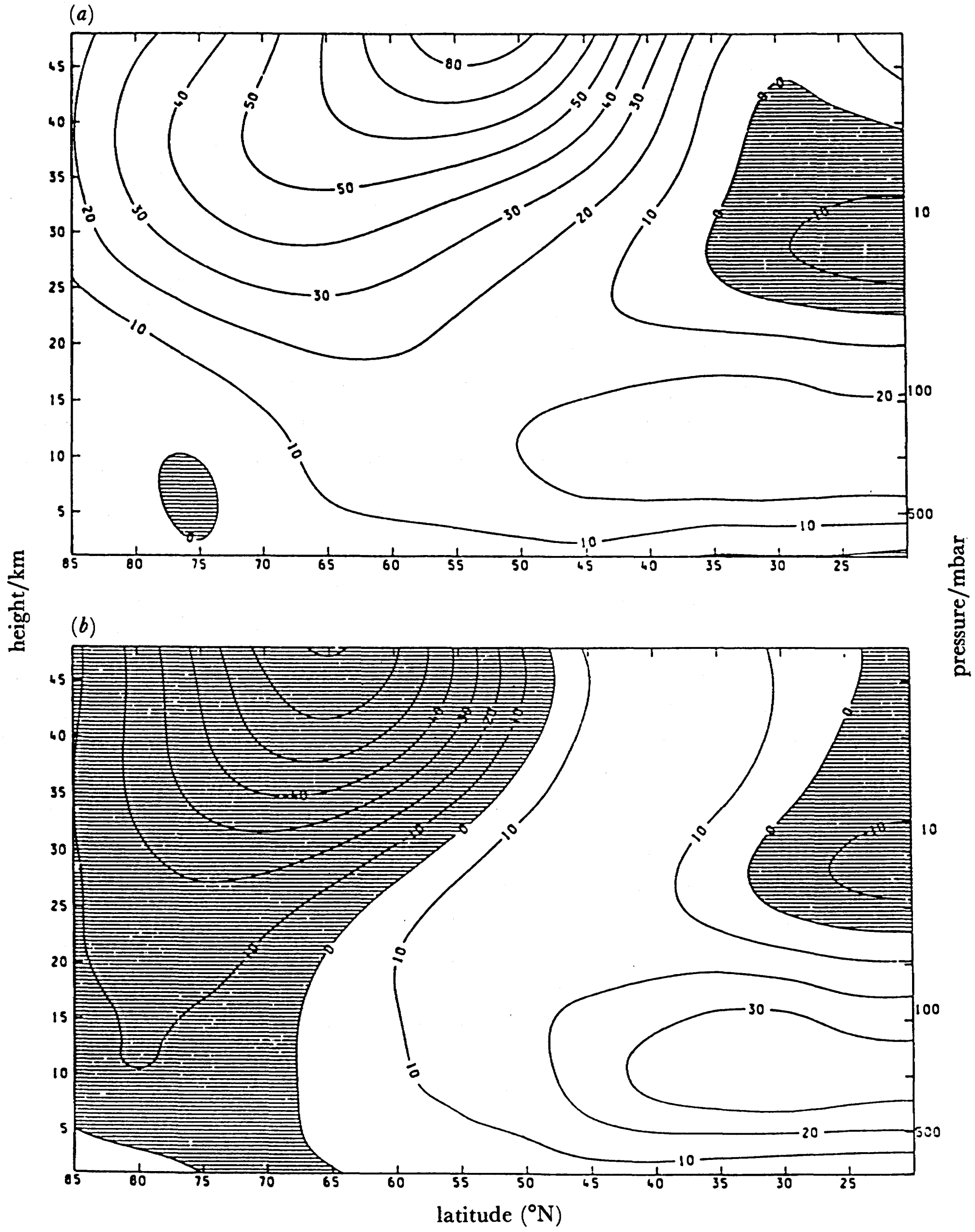


FIGURE 1. (*a*) Cross section of zonal-mean, geostrophic wind for the Northern Hemisphere on 20 December 1984. Contours are plotted at intervals of 10 m s^{-1}, and shading denotes easterly winds. (*b*) The same, but for 2 January 1985.

mean throughout the stratosphere at high latitudes. Near 1 mbar, zonal-mean easterlies have speeds greater than 70 m s^{-1}, and locally temperatures rise to about 20 °C in the mid-stratosphere according to measurements made with lidars at Haute Provence and at the University College of Wales, Aberystwyth (Labitzke *et al.* 1985, figure 7).

It has been argued that major warmings such as this one are favoured after the stratosphere has been 'pre-conditioned' (Kanzawa 1984). That is, the stratosphere attains some state, perhaps as a result of an earlier minor warming, that lends itself to disruption by a large-scale, tropospheric disturbance. Such a state has been taken to be one in which the zonal-mean jet in the stratosphere is narrow and confined to high latitudes. The argument is based on the theory of wave, mean-flow interaction. Because stationary waves propagate only where the winds are westerly (Charney & Drazin 1961), the theory predicts that they will be focused by a narrow jet into high latitudes and that a strong polar warming and rapid deceleration of zonal winds are thereby favoured. McIntyre & Palmer (1983) extended this idea to include flows that are asymmetric about the pole. They predict that an unusually small westerly vortex in the stratosphere will typify conditions before a major warming.

The major warming of 1984–85 is surprising in that the stratosphere was not pre-conditioned in either way. The flow depicted in figure 1*a*, at the start of rapid deceleration of the zonal-mean wind, comprised not only a broad zonal-mean jet but also a westerly vortex that was not unusually small for the time of year, as we have verified using SSU data for 8 years. Moreover, although in the troposphere the large-scale disturbances driving the warming were strong (as measured by variations of geopotential height around latitude circles), they were not much stronger than disturbances that develop in winters not having major warmings. During the build-up to a major warming, the flow is too disturbed for the linear approximation to be valid. We conclude that predictions about warmings are unreliable when they are based on the supposed quasi-linear propagation of planetary waves. O'Neill & Pope (1987) discuss this point further.

The movement of material during the warming can be followed, albeit with a blurred view, by using isentropic maps of potential vorticity, Q. Figure 2 is such a map for 22 December 1984 and for the 850 K isentropic surface that lies near 10 mbar, at a height of about 30 km in the mid-stratosphere. Arrows representing the speed and direction of the winds on this surface are also shown. There is a strong anticyclonic circulation, associated with the so-called Aleutian High, centred on the date line at mid-latitudes. Air in the anticyclone has low values of Q, characteristic of air from sub-tropical latitudes. On the map, there are two patches of low Q that, according to the winds near them, would circulate around the anticyclone. The location of individual contours of Q are not known reliably near the anticyclone, however, because gradients of Q are weak, and a small error in calculating Q (caused, perhaps, by poorly resolved vertical structure) can make a big difference to a contour's position. The main westerly vortex is highly elliptical, and there is an intense jet stream across the polar cap where the anticyclone abuts the cyclone. This figure illustrates our earlier remark: it would be hard to justify a dynamical description of the ensuing warming that took the zonal mean of such a state as a 'basic state' for the propagation of planetary waves. For such a strongly disturbed flow, O'Neill & Pope (1987) advocate a description based on vortices interacting with each other rather than one based on waves interacting with a mean flow (although the theory of vortex interactions developed, for example, by Dritschel (1986) is still rudimentary for stratospheric applications).

Figure 3 shows the circulation and distribution of Q on 26 December 1984. The westerly

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

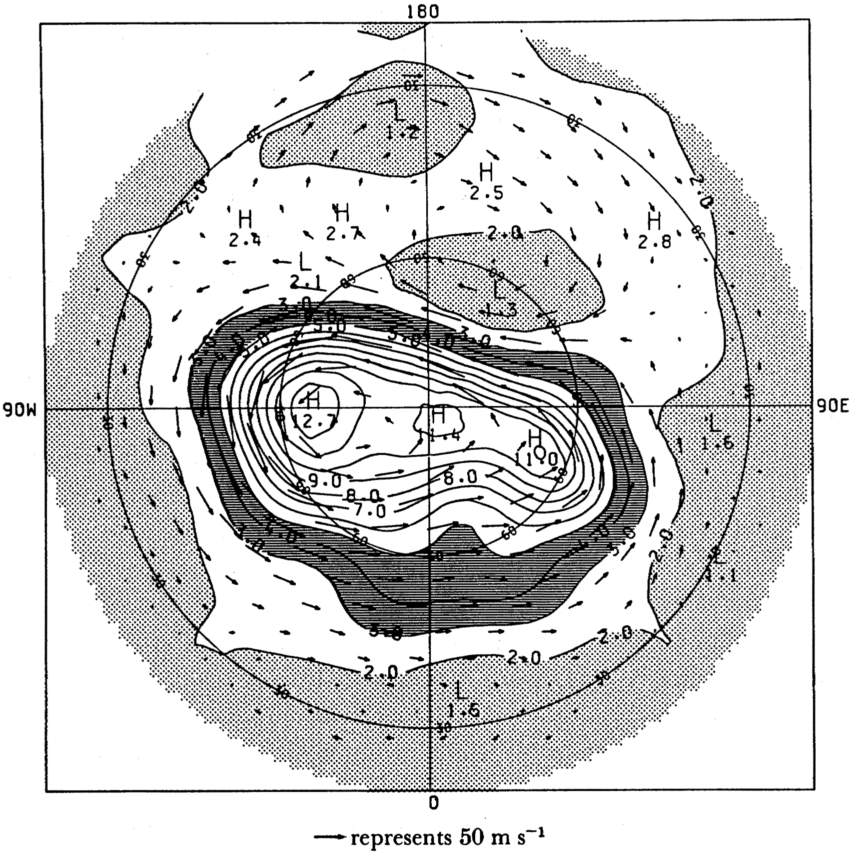
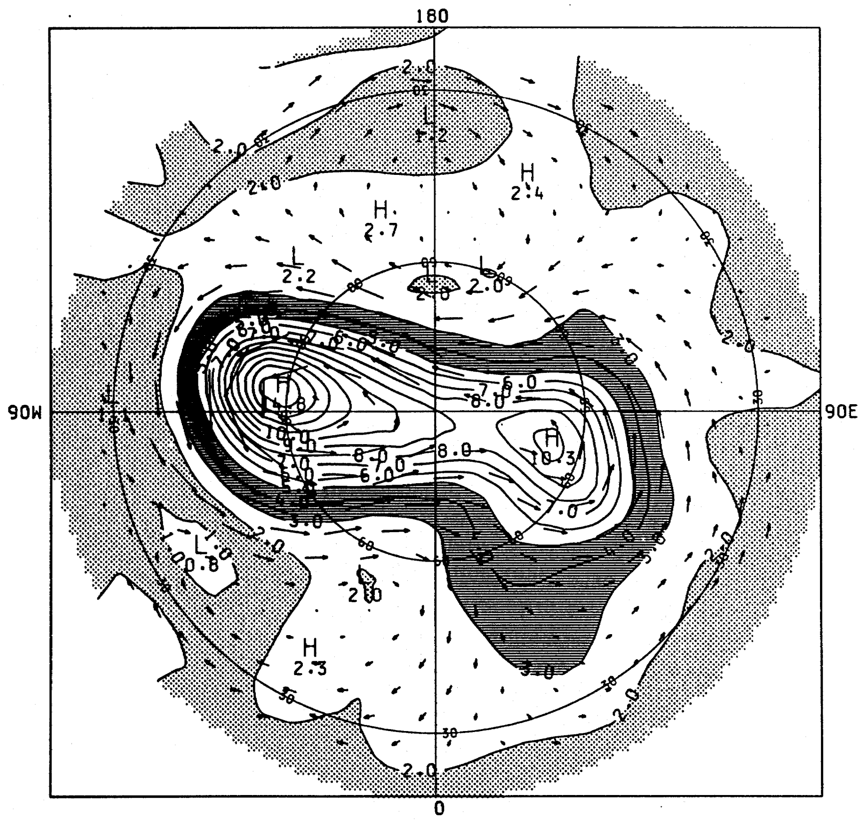


FIGURE 2. Synoptic map of Ertel's potential vorticity, Q, and winds on the 850 K isentropic surface, near 10 mbar, for 22 December 1984. Contours of Q are plotted at intervals of 10^{-4} K m^2 kg^{-1} s^{-1}. In these units, dark shading denotes values between 5 and 3; light shading denotes values between 2 and 1. Wind speeds can be read by using the scale at the bottom of the figure.

vortex is now even more elongated and there are two closed cyclonic circulations within it centred on local maxima in Q. An anticyclone has developed over the Atlantic, and the associated circulation is drawing out a tongue of high Q into low latitudes. Such advection of material by developing anticyclones is common in the winter stratosphere. Its occurrence was first pointed out by McIntyre & Palmer (1983). They regard such irreversible (time-oriented) advection of Q as being the hallmark of breaking planetary waves although, as O'Neill & Pope (1987) demonstrate, the phenomenon is not restricted to cases for which a propagating wave is readily defined. The area covered by the westerly vortex shrinks as high Q is drained away by growing anticyclones. We are still assuming in interpreting figure 3 that Q contours are approximately material lines. This assumption gets poorer as the warming develops for two reasons. (1) Temperatures rise in the upper stratosphere and warm air overrides cold air; the vertical resolution of the SSU is then a limitation. (2) Temperatures are far from their values at radiative equilibrium so air cools more quickly and Q is not conserved for so long.

Eventually, the westerly vortex splits, as shown in figure 4 for 30 December 1984. Air from low latitudes streams over the pole between the two cyclones. The maximum values of Q ought to be conserved for a few days at least, although advection might move the maxima somewhere else on an isentropic map. Figure 5 for 2 January 1985 shows, however, that peak values are

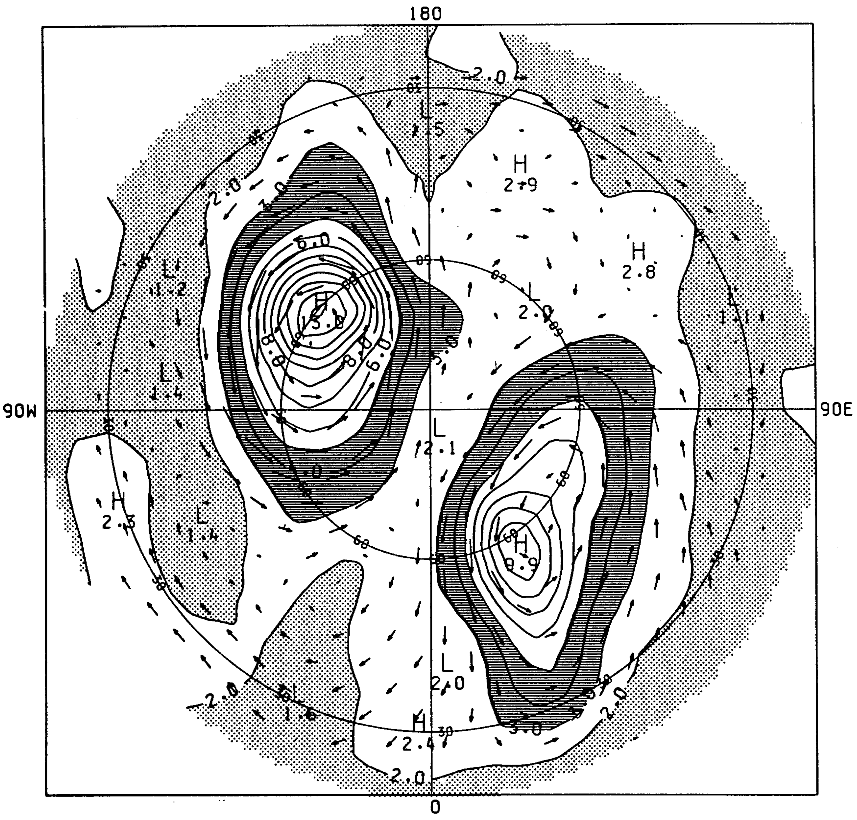


⟶ represents 50 m s^{-1}

FIGURE 3. As for figure 2 but for 26 December 1984.

halved for one of the vortices and are almost so for the other. The reason is that there are now sharp changes in vertical temperature gradient which the SSU cannot resolve, and the vertical derivative in equation (1) is accordingly underestimated. Figure 6 shows the variation of temperature with height (solid curve) recorded by a radiosonde launched from Berlin on 2 January. Whereas the lower stratosphere is nearly isothermal, there is a highly stable layer in the mid-stratosphere where temperatures increase with height at about 10 K km^{-1}. The broken curve on the figure is computed from analyses of geopotential height derived by using SSU data. The profile is co-located with the Berlin radiosonde. The sharp transition to a stable layer is not captured; the stability of the mid stratosphere is underestimated, and so is Q. This figure clearly exposes the limitations of data from satellites on such occasions, but there is mitigation. We find with Clough *et al.* (1985) that Q derived from SSU data is usually well conserved from day to day. So when it is not, we are warned that our analysis is poorly representing the state of the stratosphere.

With the split of the vortex, an anticyclonic circulation enclosing air drawn from low latitudes (as indicated by low Q) encompasses the polar cap (figure 5). The two cyclones are being stretched around it. Because the easterly winds around the anticyclone increase in speed with height, we might expect that the cyclones would move westward faster at 1 mbar than at 10 mbar, i.e. that the cyclones would lean over. This is confirmed by our analyses, with the caution that they are not as reliable at this stage of the warming as they are at its inception.



— represents 50 m s^{-1}

FIGURE 4. As for figure 2 but for 30 December 1984.

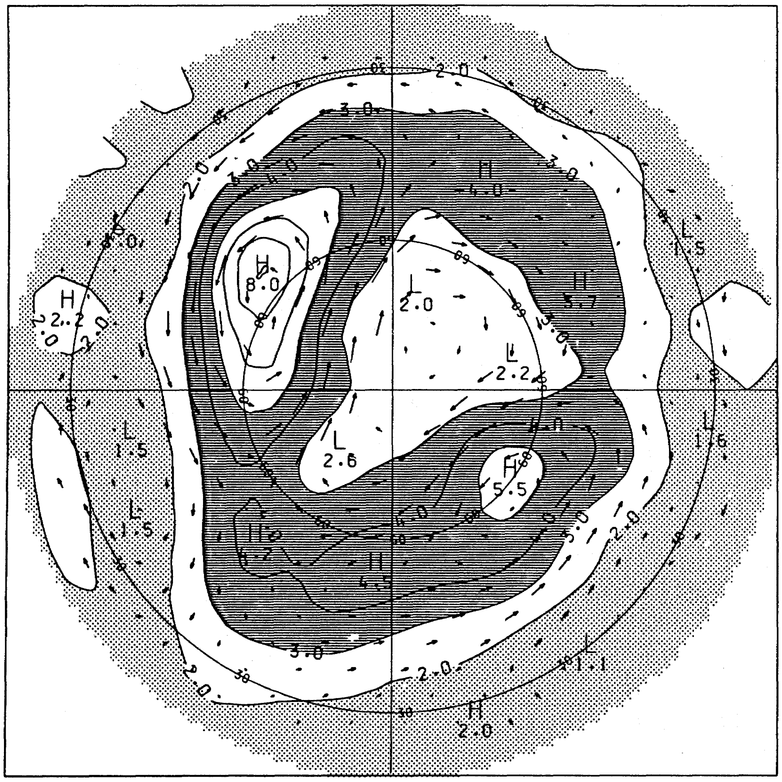
We ascribe the loss of resolution in the vertical to a generation of structure by a combination of such differential advection and adiabatic warming as air sinks. (Without vertical motion, temperatures could not attain the values observed.)

Satellite measurements do not reveal fully the strong temperature gradients and wind shears that develop during major stratospheric warmings. A numerical simulation that we made of the warming of 1984–85 reproduces strong vertical temperature gradients that are more in keeping with the observations made by lidars and radiosondes. We are able to discern what we call 'fronts' in the stratosphere. Their three-dimensional structure would not be well exposed even by lidars and radiosondes because there are few such measurements in the middle and upper stratosphere. We now turn to a description of the simulated circulation.

(*b*) *Simulation with a numerical model*

The simulation of the major warming was initialized by using observational data for 22 December 1984, and the lower boundary of the model was updated daily with analyses of geopotential height at 100 mbar. In the simulated stratosphere, the split in the westerly vortex was successfully reproduced, the elongating vortex having about the correct orientation but splitting a day late.

Figure 7 shows the simulated distribution of Q and winds on the 850 K surface on 30 December 1984, just before the vortex splits. Contours of Q, or material lines, are being



→ represents 50 m s^{-1}

FIGURE 5. As for figure 2 but for 2 January 1985.

irreversibly deformed. The bottom half of the figure shows a long tongue of high Q drawn around an anticyclone, which itself is centred on a patch of low Q injected from low latitudes. The top half of the figure shows another long tongue, this time of low Q, in the process of wrapping around the other anticyclone.

Figure 7 shows clearly why it may prove necessary to use models with high resolution to simulate well the seasonal evolution of the middle atmosphere. Tongues of low or high Q get narrower as they lengthen and fail to be resolved by our model. They may vanish through numerical truncation. Such truncation (and other numerical devices used to keep an integration stable) affects small scales of motion more than large scales. In flows containing highly deformed Q contours, the simulated circulation might therefore be damped more than it should be because Q is not conserved well enough. Such flows are common in the stratosphere during winter, especially in the Northern Hemisphere. Although our model (5° × 5° grid boxes) simulates well the development of a stratospheric warming, the flow observed after a warming is not reproduced so well, even when we use a radiation scheme that is thought to be reasonably accurate (provided by K. Shine). Part of the explanation is probably that small scales of motion that develop in the horizontal and in the vertical are inadequately resolved.

Further examples of small-scale features are the 'fronts' that form in the stratosphere at the height of the simulated warming. Figure 8 is a cross section of temperature near 60° N on 31 December 1984. (Figures 7 and 8 are chosen one day apart to highlight particular features.) There are two zones where temperatures change rapidly with height and longitude. These

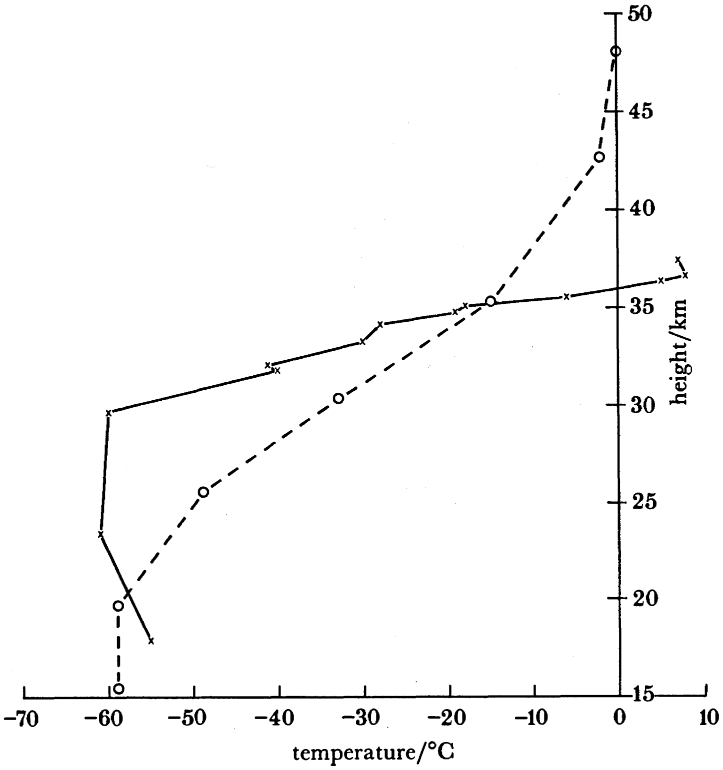


FIGURE 6. Co-located profiles of temperature (°C) on 2 January 1985. The solid curve is plotted from measurements made by a radiosonde launched from Berlin. The broken curve is derived by differentiating in the vertical fields of geopotential height obtained from SSU data.

strongly baroclinic zones, or fronts, slope westward with height and are embedded in a flow having a variation in temperature on a much larger scale, mainly in wavenumber 2 around a circle of latitude. Below a front, the stratosphere is approximately isothermal, whereas in a front temperatures increase with height at about 10 K km^{-1}, variations in good agreement with those found from observations (figure 6, solid curve). Between the fronts lie deep isothermal layers where the stratopause (the level where temperatures start to decrease with height) is not well marked.

The steep gradients in temperature are associated with strong shears in winds. There are strong poleward jets to the east of the fronts and weaker equatorward flow just to their west (this may be inferred for the mid-stratosphere by locating the temperature fronts on figure 7). The fronts are also well marked by steep gradients in relative vorticity (not shown). The magnitude of relative vorticity about equals that of planetary vorticity (the Coriolis parameter) near the front. Ageostrophic motions must therefore be important, as is confirmed by the large rises in temperature. They far exceed what could be achieved by warm advection by the geostrophic winds. Air warms as much as it does because it sinks near the front (at up to 15 cm s^{-1} in the plane represented by figure 8), and isentropic surfaces dip there as a result.

A cross section of $\ln(Q)$ is shown in figure 9. (Taking the logarithm gives an even distribution of contours.) There are folds in the contours near the fronts. Near 120° W, a downward-pointing tongue of high Q lies next to an upward-pointing tongue of low Q. The fold does not develop solely by a two-dimensional circulation in height and longitude, although air is indeed

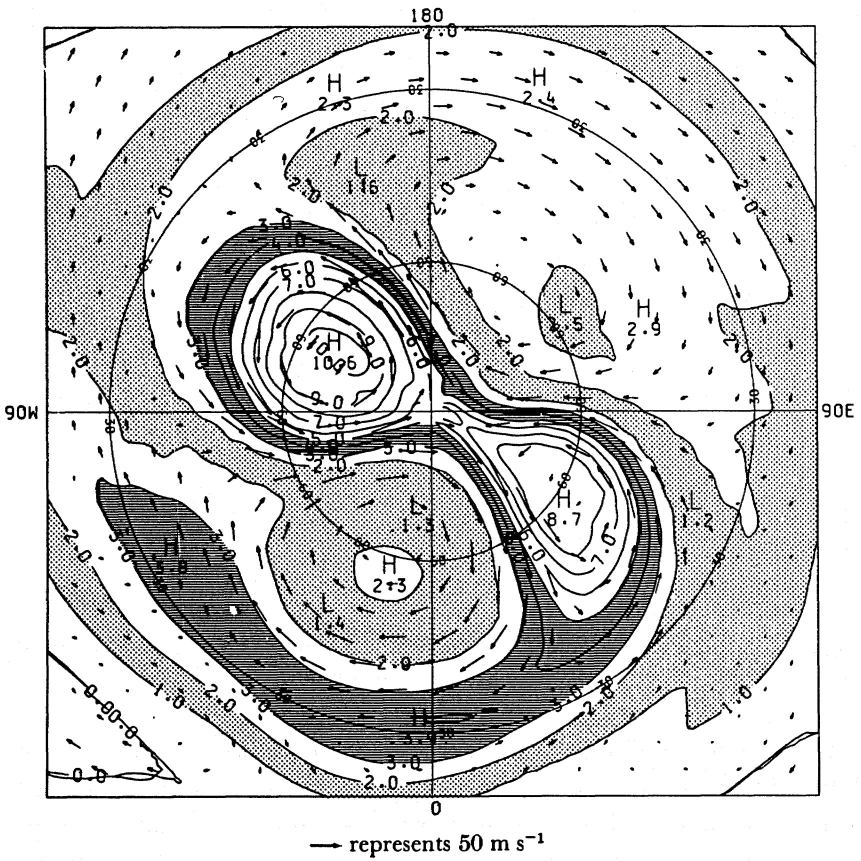


FIGURE 7. As for figure 2 but for simulated fields for 30 December 1984. The numerical experiment started from the observed state of the stratosphere on 22 December 1984.

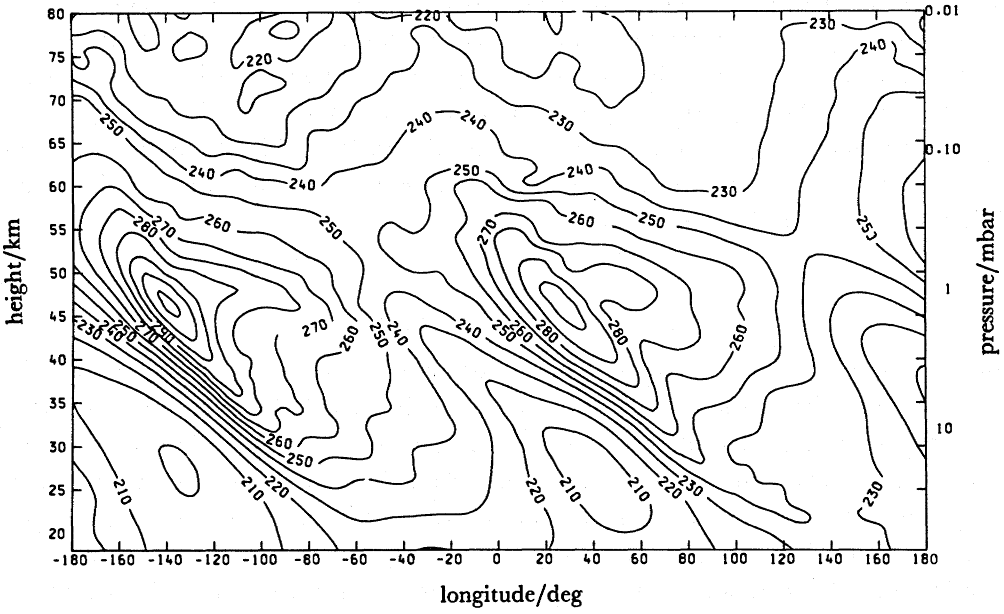


FIGURE 8. Longitude–height cross section at 57.5° N of simulated temperature on 31 December 1984. Contours are plotted at 10 K intervals.

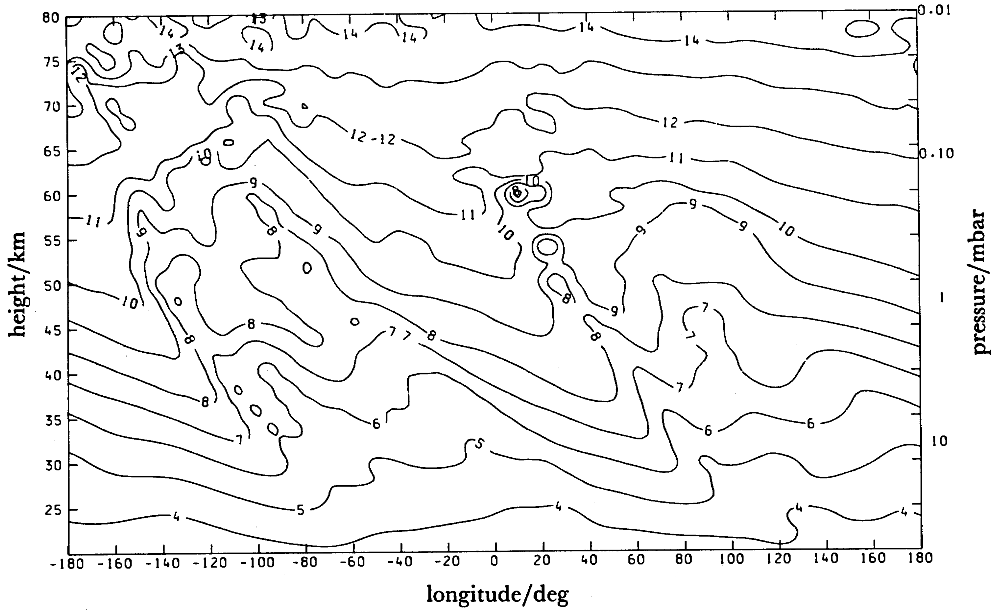


FIGURE 9. Longitude–height cross section at 57.5° N of simulated $\ln(Q)$ on 31 December 1984. Q is converted to units of 10^{-6} K m^2 kg^{-1} s^{-1} before taking logarithm.

sinking near the protrusion of high Q and rising near that of low Q. Contours of Q on the west side of the fold coincide with isentropic surfaces (not shown) and dip as air sinks. The tongue of low Q does not coincide with isentropic surfaces, and forms mainly by quasi-horizontal motion. Air with low Q is drawn from low latitudes on the east side of the developing front, cutting across the plane represented by the figure.

The folds shown in figure 9 and associated atmospheric structures resemble those found near fronts observed in the upper troposphere (Uccellini *et al.* 1985, figure 10), although the patterns are on a much larger scale in the stratosphere. The dynamics of formation of the two types of front may differ, however. For the upper troposphere, a two-dimensional numerical model reproduces some of the features of observed fronts and folds (Hoskins 1972). But for the stratosphere, results from our model indicate that advection of Q in three dimensions must be represented. Having two examples of a phenomenon in different parts of the atmosphere should further our understanding of both.

4. CONCLUDING REMARKS

Despite the improved coverage that observations from satellites bring, many diagnostic studies of the dynamics of the middle atmosphere begin by zonally averaging such data. One motivation for this is provided by the theory of wave, mean-flow interaction. It contains a body of results on which arguments of cause and effect can be based if departures from some average state are assumed to be small. This assumption is not always valid, however, as synoptic maps for the major warming of 1984–85 vividly illustrate. What constitutes a so-called 'pre-conditioned' state for a major warming according to quasi-linear theory is at odds with the actual state of the stratosphere when this warming started to develop rapidly.

Instruments on satellites make measurements of uniform quality, a boon when directly measured quantities must be differentiated one or more times to obtain fields of dynamical interest. But because of the spatial averaging inherent in the measurements, we obtain only a blurred view of the formation of small-scale features (like stratospheric 'fronts') that might affect the evolution of the large-scale flow. Lidars, radiosondes and rocketsondes measure temperature with much better resolution, but observations are unevenly distributed, if they exist at all. Different types of observations are utilized in weather forecasting by assimilating them regularly into a general circulation model. Dynamically consistent analyses of the state of the troposphere and lower stratosphere are produced as a by-product, including fields of vertical velocity, a quantity not normally measured. It is desirable to extend this procedure to include the whole of the middle atmosphere. Groups involved with the Upper Atmosphere Research Satellite (scheduled for launch in 1991) are planning to do so.

We thank David Andrews and John Pyle for their helpful comments on this paper. Betty Kingston prepared the diagrams.

REFERENCES

Butchart, N., Clough, S. A., Palmer, T. N. & Trevelyan, P. J. 1982 Simulations of an observed stratospheric warming with quasigeostrophic refractive index as a model diagnostic. *Q. Jl R. met. Soc.* **108**, 475–502.

Charney, J. G. & Drazin, P. G. 1961 Propagation of planetary-scale disturbances from the lower into the upper atmosphere. *J. geophys. Res.* **66**, 83–109.

Clough, S. A., Grahame, N. S. & O'Neill, A. 1985 Potential vorticity in the stratosphere derived using data from satellites. *Q. Jl R. met. Soc.* **111**, 335–358.

Dritschel, D. G. 1986 The nonlinear evolution of rotating configurations of uniform vorticity. *J. Fluid. Mech.* **172**, 157–183.

Holton, J. R. 1976 A semi-spectral numerical model for wave, mean-flow interactions in the stratosphere: application to sudden stratospheric warmings. *J. atmos. Sci.* **33**, 1639–1649.

Hoskins, B. J. 1972 Non-Boussinesq effects and further development in a model of upper tropospheric frontogenesis. *Q. Jl R. met. Soc.* **98**, 532–541.

Hoskins, B. J., McIntyre, M. I. & Robertson, A. W. 1985 On the use and significance of isentropic potential vorticity maps. *Q. Jl R. met. Soc.* **111**, 877–946.

Kanzawa, H. 1984 Four observed sudden warmings diagnosed by the Eliassen-Palm flux and refractive index. In *Advances in earth and planetary sciences: dynamics of the middle atmosphere*, pp. 307–331. Tokyo: Terra Scientific Publishing Company and, Dordrecht: D. Reidel.

Labitzke, K., Naujokat, B., Lenschow, R., Petzoldt, K., Rajewski, B. & Wohlfart, R. C. 1985 *The third winter of MAP-DYNAMICS, 1984/85: a winter with an extremely intense and early major warming.* Beilage zur Berliner Wetterkarte, Free University of Berlin.

McIntyre, M. E. & Palmer, T. N. 1983 Breaking planetary waves in the stratosphere. *Nature, Lond.* **305**, 593–600.

McIntyre, M. E. & Palmer, T. N. 1984 The 'surf-zone' in the stratosphere. *J. atmos. terr. Phys.* **46**, 825–849.

McIntyre, M. E. & Palmer, T. N. 1985 A note on the general concept of wave breaking for Rossby and gravity waves. *Pure appl. Geophys.* **123**, 964–975.

O'Neill, A. & Pope, V. D. 1987 Simulations of linear and nonlinear disturbances in the stratosphere. *Q. Jl R. met. Soc.* (Submitted.)

Palmer, T. N. 1981 Diagnostic study of a wavenumber-2 stratospheric warming in a transformed Eulerian-mean formalism. *J. atmos. Sci.* **38**, 844–855.

Pick, D. R. & Brownscombe, J. L. 1981 Early results based on the Stratospheric channels of TOVS on the TIROS-N series of operational satellites. *Adv. Space Res.* **1**, 247–260.

Uccellini, L. W., Keyser, D., Brill, K. F. & Wash, C. H. 1985 The Presidents' Day Cyclone of 18–19 February 1979: Influence of upstream trough amplification and associated tropopause folding on rapid cyclogenesis. *Mon. Weath. Rev.* **113**, 962–988.

Discussion

M. E. McIntyre (*Department of Applied Mathematics and Theoretical Physics, University of Cambridge, U.K.*). The model experiments described by Dr O'Neill are teaching us a great deal about the possible modes of behaviour of the real stratosphere. One question that continues to intrigue me is the following. What tacit assumptions are we making in forcing the model from an artificial lower boundary, at which geopotential is prescribed? In particular, to what extent can we assume this boundary condition to be a good measure of the actual strength of the forcing from the troposphere? The question becomes important as soon as we begin to make cause-and-effect arguments about why a particular stratospheric disturbance did or did not occur. For that matter, to what extent can we think of the troposphere as dynamically independent of the stratosphere at all?

I agonized at some length over these questions in my 1982 review (see §§5, 6), and it still seems to me that they are not at all well understood. One thing I do know is that artificial lower boundary conditions can give rise to artificial resonant responses in the model stratosphere. This is hardly surprising, but the interesting question is not whether the effect exists, but rather how important it is. It is perhaps worth mentioning again that there is some evidence, from experiments with a simple, zonally truncated numerical model of the Matsuno–Holton type, suggesting that such spurious resonances might, in fact, be quite significant in some circumstances (Hsu & McIntyre 1987). They can enhance planetary-wave amplitudes enough to make the difference between having, or not having, a major warming, in zonally truncated models at least.

References

Hsu, C.-P. F. & McIntyre, M. E. 1987 Evidence for self-tuning resonant cavity behaviour in model stratospheric warmings with an artificial lower boundary condition. *J. atmos. Sci.* (Submitted.)
McIntyre, M. E. 1982 *J. met. Soc. Japan* **60**, 37–65.