THE GFDL SKYHI GENERAL CIRCULATION MODEL: SOME RESULTS OF RELEVANCE FOR NUMERICAL WEATHER PREDICTION

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Summary: This article presents an informal survey of some recent results from the GFDL "SKYHI" general circulation model with a particular focus on those aspects of relevance for numerical weather prediction. After a brief description of the SKYHI model, the large scale climatological simulation and its dependence on model resolution are examined. Particular attention is paid to the ability of the model to adequately simulate the midwinter sudden warming phenomenon. Some preliminary experiments involving parallel runs with slightly perturbed initial conditions suggest that there may be a rather abrupt increase in model predictability associated with the development of stratospheric sudden warmings.

1. INTRODUCTION

The role of the middle atmosphere in determining the circulation of the troposphere has been studied by a number of investigators in the context of both simplified and comprehensive simulation models. The early work of *Bates* (1979) and *Geller and Alpert* (1980) dealt with linear models of the large-scale stationary wave fields. These papers documented considerable dependence of the tropospheric stationary wave field on conditions in the stratosphere. *Boville* (1984) showed that the tropospheric simulation in the winter Northern Hemisphere (NH) of a comprehensive general circulation model (GCM) was sensitive to the simulation of the stratosphere. In particular, Boville found that the strength of the westerly vortex in the stratosphere affected many aspects of the simulated tropospheric climatology. These results have important implications for numerical weather prediction (NWP). It seems that a good representation of the stratosphere is likely important even for tropospheric prediction. One particular issue that arises in design of NWP models is the placement of the upper boundary condition. Since most formulations of the upper boundary condition will result in substantial reflection of incident upward-propagating waves, the upper boundary has the potential to seriously distort the solutions obtained with a NWP model. This issue was investigated by *Kirkwood and Derome* (1977) using their linear stationary wave model with a conventional "rigid lid" boundary condition (pressure velocity is zero at a half level nominally at zero pressure). They found that even the tropospheric stationary wave field is adversely affected if the highest model full level is located too low in the stratosphere.

The most dramatic changes in the (NH) stratospheric flow occur in midwinter sudden warmings, and so it is logical to look to sudden warming cases to find a strong stratospheric impact on tropospheric forecasts. This is particularly so since the polar vortex breakdown during a sudden warming can appear to show an impressive continuity between the stratosphere and troposphere (*Quiroz*, 1977; *O'Neill and Taylor*, 1979). It is tempting to speculate that, while the initiation of a sudden warming largely results from the tropospheric forcing of the stratosphere (e.g., *Matsuno*, 1971), the mature stage of the warming may involve significant stratospheric influence on the troposphere. In particular, one might imagine that the weakening of the mean westerly vortex in the stratosphere could lead to enhanced trapping and downward reflection of topographically-forced quasi-stationary waves. This in turn could lead to larger tropospheric wave amplitudes and with a consequent effect on the tropospheric mean flow. It is also conceivable that the development of the stratospheric warming itself may be relatively predictable (at least once it starts) and so there exists the possibility of enhanced tropospheric predictability during stratospheric warming events. This scenario remains essentially speculation, but it is interesting that one of the most impressive extended range numerical forecasts that have been discussed in the literature was obtained for January 1977 (*Miyakoda et al.*, 1983), a month in which a very strong midwinter warming occurred in the stratosphere.

In this paper the ability of a state-of-the-art comprehensive GCM to simulate the climatology of the stratosphere will be examined, with an emphasis on the model simulation of the variability of the NH winter circulation. The model to be examined is the GFDL "SKYHI" GCM which has been used in a number of earlier studies of aspects of the middle atmospheric circulation (e.g., *Fels et al.*, 1980; *Mahlman and Umscheid*, 1984, 1987; *Hamilton and Mahlman*, 1988; *Hayashi et al.*, 1989; *Hamilton*, 1993a,b,c,d). A brief description of the model formulation is given in Section 2. Section 3 then examines some aspects of the time-mean circulation in integrations of the SKYHI model run at three different horizontal resolutions. Section 4 looks at the interannual and day-to-day variability evident in a long (>25 year) SKYHI integration. Section 5 considers the decay of the vertically propagating wave field in the model simulations, with implications for the design of NWP models. Section 6 discusses some preliminary experiments designed to look at the predictability of sudden warmings in SKYHI. Conclusions are summarized in Section 7.

2. THE SKYHI MODEL

The SKYHI model is a comprehensive GCM designed to simulate the global atmosphere from the ground to the mesopause (0.0096 mb). In SKYHI the primitive equations are discretized on a latitude-longitude grid. In this paper three different versions with 3^ox3.6^o, 2^ox2.4^o and 1^ox1.2^o resolution will be considered (referred to as N30, N45 and N90 respectively, where the notation denotes the number of grid rows from equator to pole). In each case a hybrid sigma-pressure coordinate with 40 levels in the vertical is employed (with roughly 2 km resolution throughout the stratosphere). At the top of the domain the usual "rigid lid" boundary condition (i.e. the pressure velocity is zero at zero pressure) is used along with a linear damping applied to eddy motions at the highest full model level (see *Fels et al.*, 1980). The model is integrated with explicit leapfrog time differencing using time steps of 60 s, 180 s and 225 s for N90, N45 and N30, respectively. A realistic unsmoothed topography and land-sea distribution are employed. The model is forced with a seasonal cycle of diurnally-averaged radiative heating rates computed using sophisticated longwave and shortwave algorithms. Mean ozone amounts are prescribed, but locally the mixing ratio is allowed to vary linearly with temperature in order to account for the photochemical acceleration of radiative eddy damping (see *Fels et al.*, 1980). The cloud field used in the radiation code is also prescribed.

The SKYHI model includes a representation of the hydrological cycle, with parameterizations of runoff, evaporation, moist convection and stable precipitation. A dry convective adjustment and a Richardson number-dependent vertical diffusion are also employed. A nonlinear horizontal subgrid scale diffusion is included (*Andrews et al.*, 1983). The coefficient of the horizontal diffusivity is a function of the model resolution (e.g., 9 times smaller in the N90 version than in the N30 model). In contrast with most other current GCMs, no attempt has been made to parameterize the effects of subgrid scale gravity waves in SKYHI.

3. RESULTS FOR THE GLOBAL SCALE CIRCULATION

As mention in the Introduction, a number of published papers have described various aspects of the SKYHI model simulations. The most detailed descriptions of both the time mean circulation and its interannual variability are given in the recent papers of *Hamilton et al.* (1994) and *Hamilton* (1994). Here only a brief survey of some basic results from a series of control integrations will be given. The N90 integration was started from data interpolated from a lower resolution integration on September 30, "1982" in the arbitrary dating scheme used. The N45 and N30 integrations were initialized from the N90 data on June 6, "1983". Results for the N30 climatology from the 25 year period commencing February "1985" are available for analysis. For N45 the climatology is based on two years starting in February "1984". The N90 results discussed in this section are for December "1983" through February "1984" and for June-August "1993". All these integrations employed a specified annual cycle of sea surface temperature based on observed climatology.

Fig. 1 shows the zonal-mean zonal wind in the December-February (DJF) season for the three versions of SKYHI along with an observed climatology from *Fleming et al.* (1988). Even at N30 resolution the overall simulation is rather impressive, with a clear separation of the tropospheric and polar night jets. The polar night jet is quite realistic in the lower stratosphere. In the upper stratosphere the jet is of roughly the correct strength, but it is centered too far poleward. In the mesosphere the simulated jet closes off, in at least qualitative agreement with observations. The Northern Hemisphere simulations at N45 and N90 resolution are rather similar to that for the N30 model. As will be shown below, there is too much interannual variability in the winter stratospheric simulation to regard the differences among the models in Fig. 1 as statistically significant.

The SKYHI simulation of the zonal-mean state of the NH stratosphere looks strikingly like that obtained by *Boville* (1991) with an intermediate-resolution version of the NCAR spectral model that included a parameterization of topographically-forced gravity waves. As Boville notes, the parameterized drag is critical to the solution he obtains in the NH winter stratosphere (without the drag the simulated polar night jet in his model is much too strong). The reasons for this major difference between SKYHI and the NCAR spectral model are not clear. Hamilton et al. (1994) have examined the effect of smoothing the topography used in SKYHI to something similar to what might be used in an intermediate-resolution spectral GCM. This was found to have little effect on the zonal-mean NH stratospheric circulation.

Fig. 2 shows the DJF zonal mean temperature departures from the Fleming et al. climatology. The unrealistically cold tropical upper stratospheric temperatures seen in all the simulations reflect inadequacies in the ozone distribution employed (current satellite measurements would suggest higher mixing ratios in the upper stratosphere; e.g., compare *Fels et al.*, 1980, with *Keating and Young*, 1985). Near the winter polar stratopause the simulated temperatures are colder than observed at all resolutions. This is consistent with the unrealistic features of the simulated polar

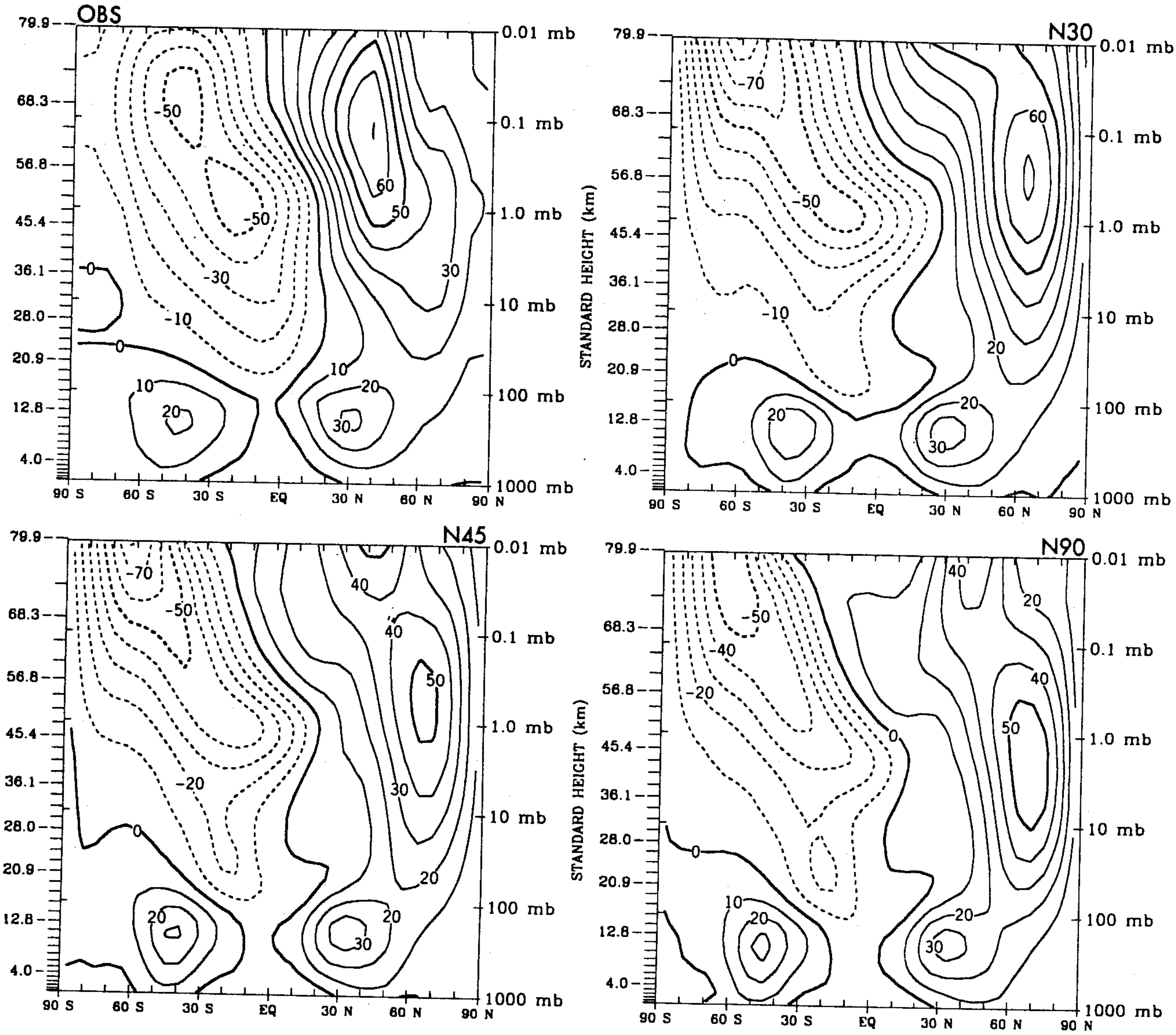

Fig. 1. DJF mean zonally-averaged zonal wind climatologies from observations and from the model control runs. The contour interval is 10 m-s^{-1} and dashed contours denote easterly winds. The tick marks on the left show the locations of the 40 SKYHI model levels.

night jet noted earlier.

Fig. 3 is an attempt at a detailed comparison between the NH winter stationary wave field seen in time mean of the SKYHI integrations and in comparable observations. The N30 simulation is considered since there are long term means available. The left hand panels in Fig. 3 show the NH 10 mb, 30 mb and 50 mb DJF mean geopotential heights averaged over 25 years of the N30 integration. The corresponding right hand panels show the same quantities computed from the subjective NH analyses produced at the Free University of Berlin averaged over comparably long records (34 years at 50 and 30 mb, and 17 years at 10 mb). The same basic features of the wave field are apparent in both model and observations. The combination of zonal wave 1 and 2 components result in an elongation of the polar vortex roughly along the 90^{o}E-90^{o}W axis, and a displacement of the vortex center off the pole roughly along the Greenwich meridian. The phase of the whole pattern tilts westward with height, so that in the observations the Aleutian high is centered near 150^{o}W at 50 mb and near 175^{o}E at 10 mb. The N30 simulated stationary wave phase

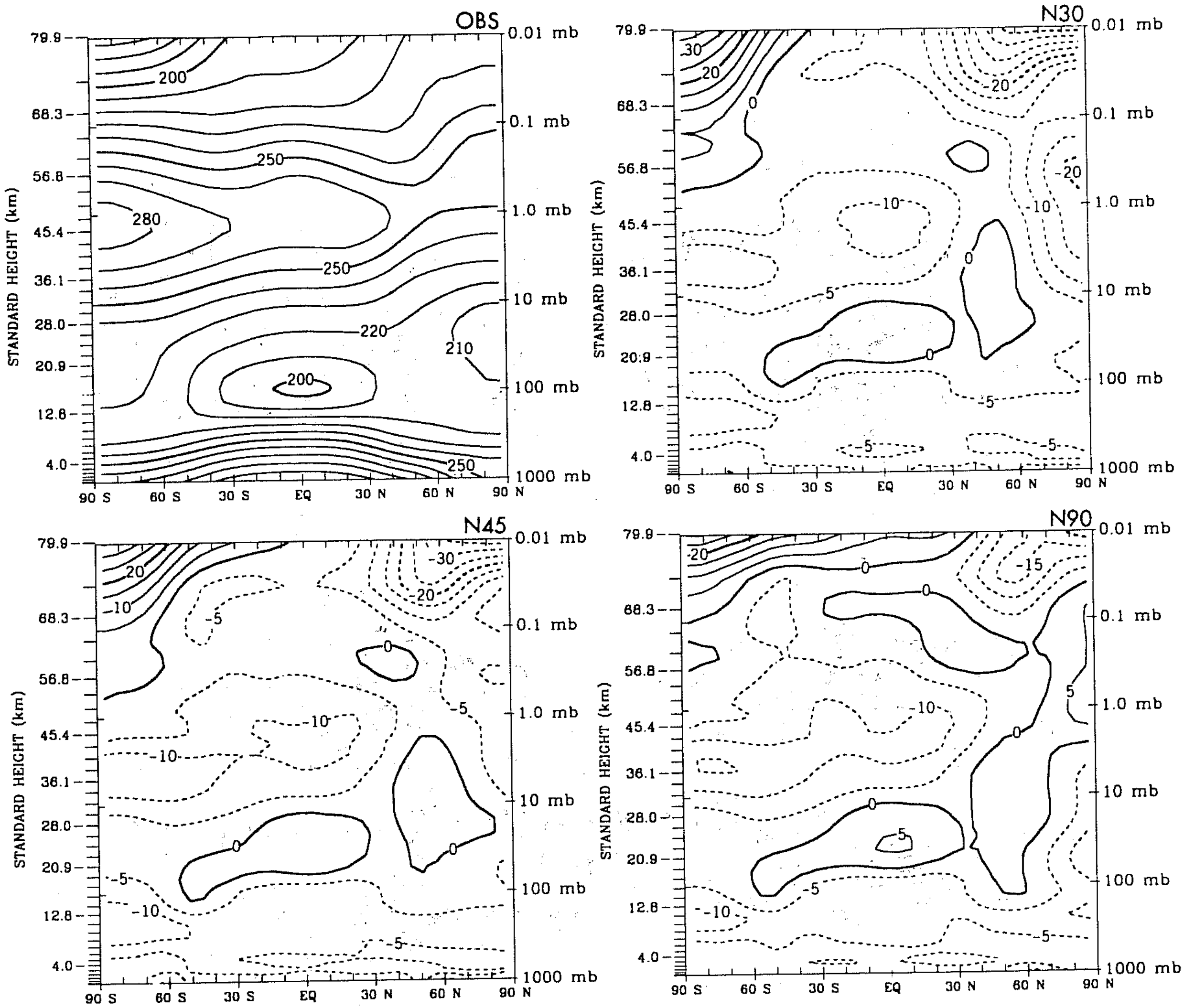

Fig. 2. The top left panel shows the DJF mean zonally-averaged temperature from observations (contours labeled in °K with interval of 10°). The other three panels show the difference of the model climatologies from these observations. The contour interval in these panels is 5°C, and dashed contours denote regions where the model temperatures are lower than observed.

tilt is even more pronounced, with the Aleutian high at 10 mb centered near 160°E. The magnitude of the geopotential gradients seen at 50 mb and 30 mb in the model agree quite well with those observed. However, a comparison of the time mean geopotential maps at 10 mb shows signs of the model bias towards simulating a polar vortex that is unrealistically confined to high latitudes. The geopotential gradients in the model vortex are clearly stronger than those indicated in the observations.

Fig. 4 shows the zonal-mean zonal wind for June-August (JJA) in the different resolution SKYHI versions compared with observations. In the winter hemisphere, the tropospheric and lower stratospheric flow is reasonably well simulated at all resolutions. In the upper stratosphere and mesosphere, however, there are large discrepancies between observations and all the simulated climatologies. In particular, the polar night jet is much too strong in the SKYHI simulations, although there is some improvement with increasing resolution in this respect. The problems with the simulation of the SH winter middle atmosphere are known to be shared by other GCMs.

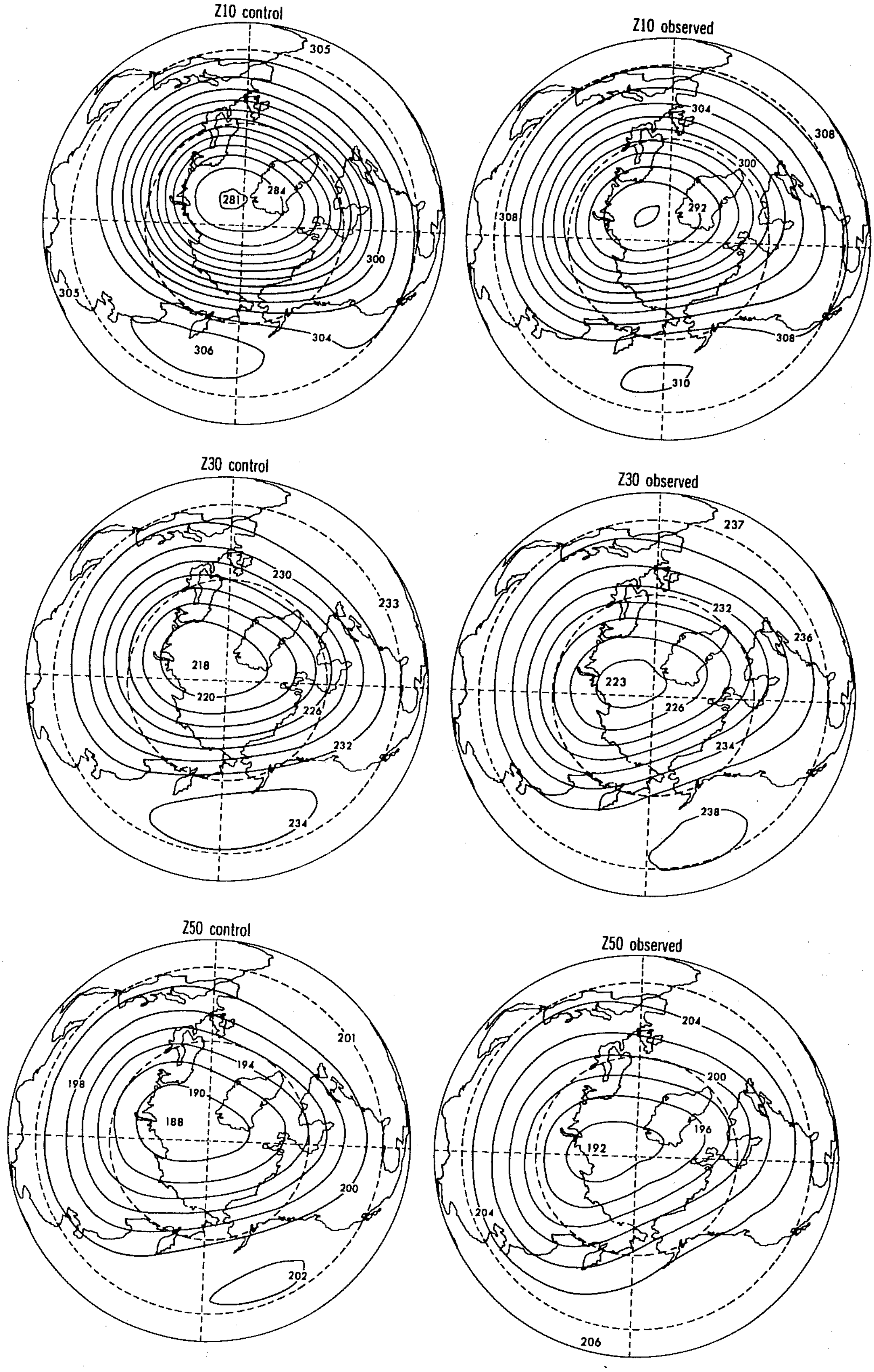

Fig. 3. The long term mean DJF geopotential heights at 10 mb (top), 30 mb (middle) and 50 mb (bottom) from the N30 SKYHI simulation (left) and observations (right). The contour labels are in 100's of m and the contour interval is 200 m. The dashed circles show 30°N and 60°N.

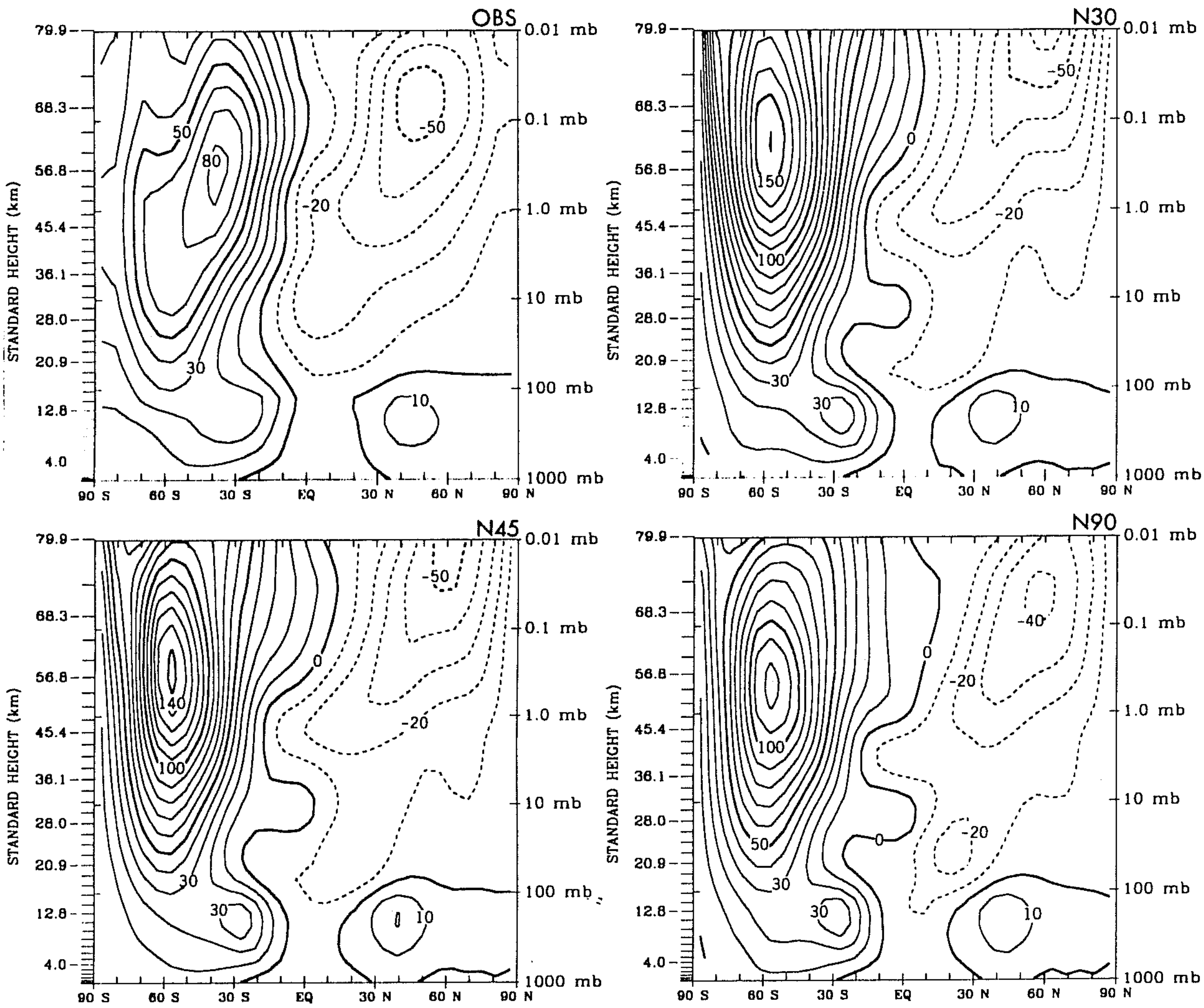

Fig. 4. As in Fig. 1, but for the JJA period.

4. INTERANNUAL VARIATION IN THE NH WINTER STRATOSPHERE

The availability of the long N30 integration presents an excellent opportunity to investigate the interannual variability in the simulated circulation. Fig. 5 shows the standard deviation of the monthly-mean, zonally-averaged temperature for each of December, January and February in the SKYHI control run and in observations (*Randel*, 1992; available only up to 1.0 mb). In each month the standard deviation in the model is strongly concentrated in the high latitude upper stratosphere and mesosphere. This polar concentration of the variance is also apparent in the observations. However, the model results clearly show the variability in the NH polar region in December being greater than in January or February (at least above 10 mb), while Randel's observational analysis suggests that December temperatures actually have lower interannual variability. The net result is that the model and observations agree quite well in January and February, while the model quite significantly overestimates the standard deviation in December between 10 mb and 1mb. Below 10 mb the agreement between SKYHI and the observations in all three months is reasonably good.

In low latitudes and in the summer (Southern) hemisphere there is a definite difference between

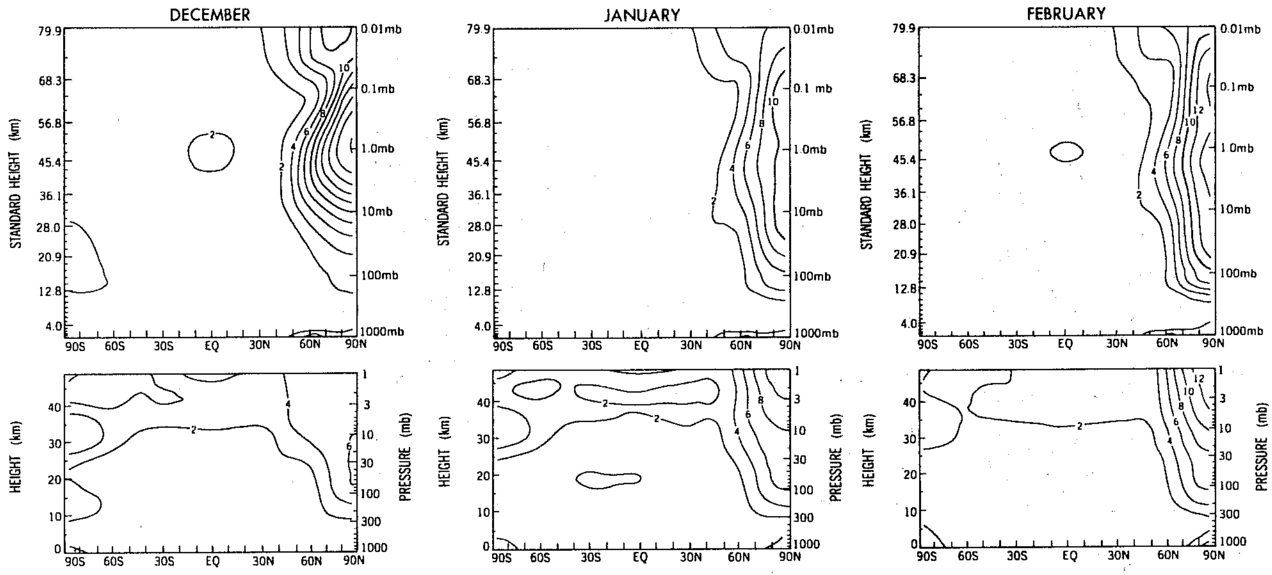

Fig. 5. The standard deviation of the timeseries of monthly-mean, zonally-averaged temperature from 25 years of the SKYHI model (top) and for 8 years of NMC analyses (bottom). Results for each of December, January and February. The contour interval is 2°C. The observational results are redrafted from figures in Randel (1992). The tick marks on the left hand side of each of the top row of panels show the locations of the SKYHI model levels.

the model results and observations in all three months, with the observed standard deviation being larger than that in the model almost everywhere. Thus, for example, in February the observed standard deviation in Fig. 1 is between 2°C and 4°C above 10 mb everywhere between 60°S and 60°N. In the model the standard deviation exceeds 2°C only in a tiny region right near the equator at 1 mb. To some extent, this difference may reflect real deficiencies in the model dynamics (notably the virtual absence of a quasi-biennial oscillation, see *Hamilton et al.*, 1994). However, the observations themselves in these regions of rather small variance need to be regarded with caution. The NMC operational analyses used by Randel could be subject to long period inhomogeneities due to changes in satellite instruments and analysis procedures. Such problems will introduce spurious contributions to the "observed" interannual variance. There is also likely a significant component of interannual variability in tropical and summer temperatures resulting from changes in atmospheric composition (notably volcanic aerosols) and solar flux in the real world that have no counterpart in the SKYHI control integration.

Fig. 6 compares the interannual variability of the January-mean zonal-mean wind in 10 consecutive years of the N30 simulation with that deduced by *van Loon and Labitzke* (1972) from 12 years of NH analyses based on radiosonde data. The overall agreement between the model and observations is impressive. This is another indication that the overall variability in the NH extratropical stratospheric circulation in the N30 simulation is rather realistic.

Fig. 7a, reproduced from *Naujokat et al.* (1988), shows another observational characterization of the variability in the NH winter stratosphere. Daily time series of the 30 mb North Pole temperature are plotted for the November-April period in ten consecutive years. The dotted curve in each panel is exactly the same and represents the long term (>20 year) mean for each calendar day. Periods of anomalously warm temperatures are denoted by shading. These observed North Pole temperatures are from the Free University of Berlin subjectively-analyzed NH analyses based

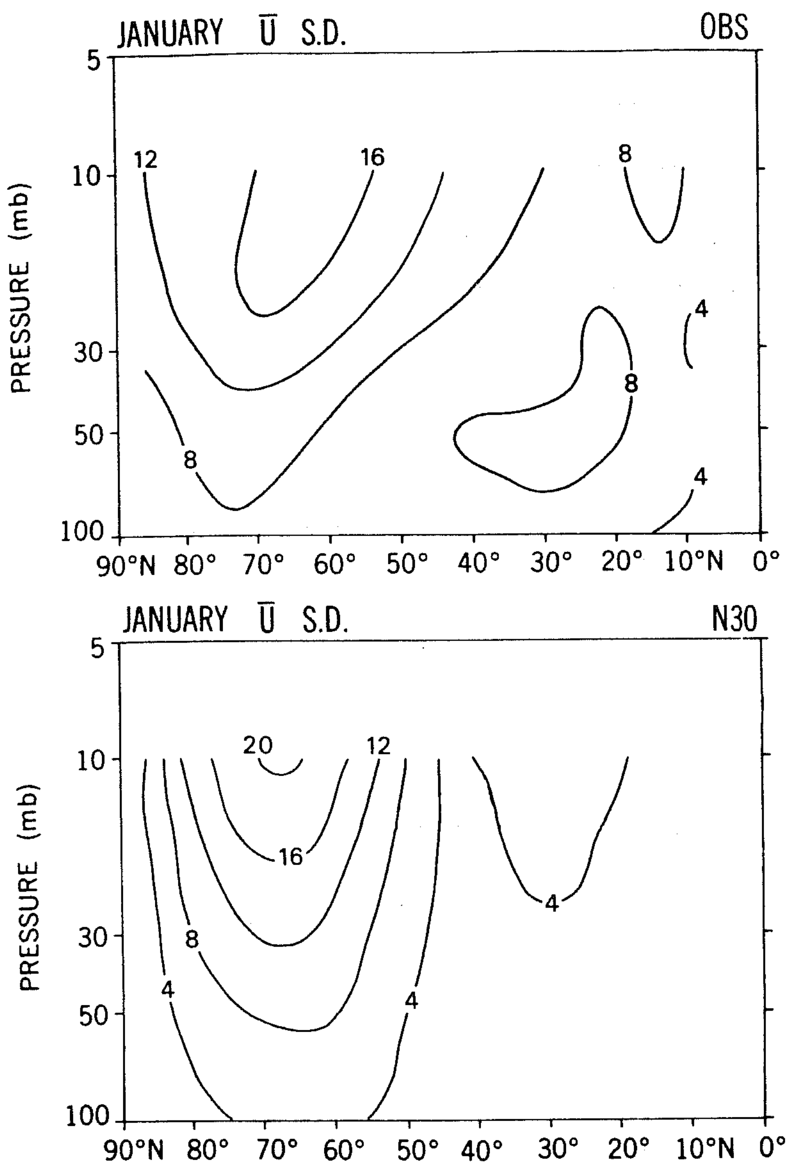

Fig. 6. The standard deviation of the January-mean, zonally-averaged zonal wind in observations and in the N30 control simulation. Contour labels are in m-s^{-1}.

on radiosonde data. Fig. 7a shows some rather undisturbed winters (such as 1982/83 or 1985/86) which are characterized by anomalously cold temperatures most of the time, interrupted only by small amplitude high frequency variability. By contrast, there are also winters that obviously were affected by major sudden warmings. The polar temperature in the strongest warming events (February 1979, February 1984, December 1984/January 1985, January, 1987) rises 35-40^{o}C in a period of 5-8 days. The polar temperature tends to remain anomalously warm for at least the next month, and the occurrence of a warming in a particular year will significantly impact even the winter mean temperature. Fig. 7b shows the same 30 mb temperature time series, but for ten consecutive years of the SKYHI control run. To first order the model results are very encouraging. In particular, about half the model winters have warmings of realistic amplitude and suddenness. On closer inspection some differences in the details of the temperature timeseries in model and observations do appear. The "cold" winters in the SKYHI simulation (e.g., "1986/87" or "1994/95") tend to be even more undisturbed than the coldest observed winters. In fact there is a general

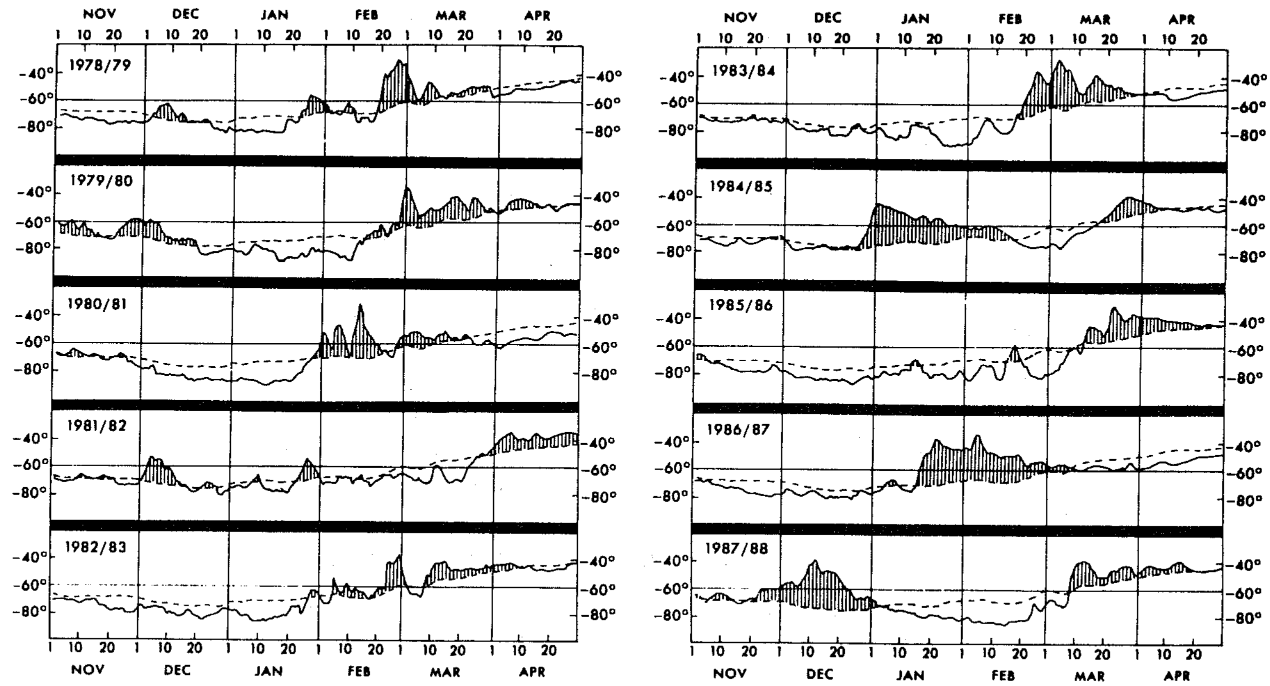

Fig. 7(a) Time series of observed daily 30 mb North Pole temperatures for November-March of ten consecutive years. The dashed lines give the long term mean values for each calendar day. Anomalously warm periods are denoted by shading. The temperature labels are in °C. Redrafted from Naujokat et al. (1988).

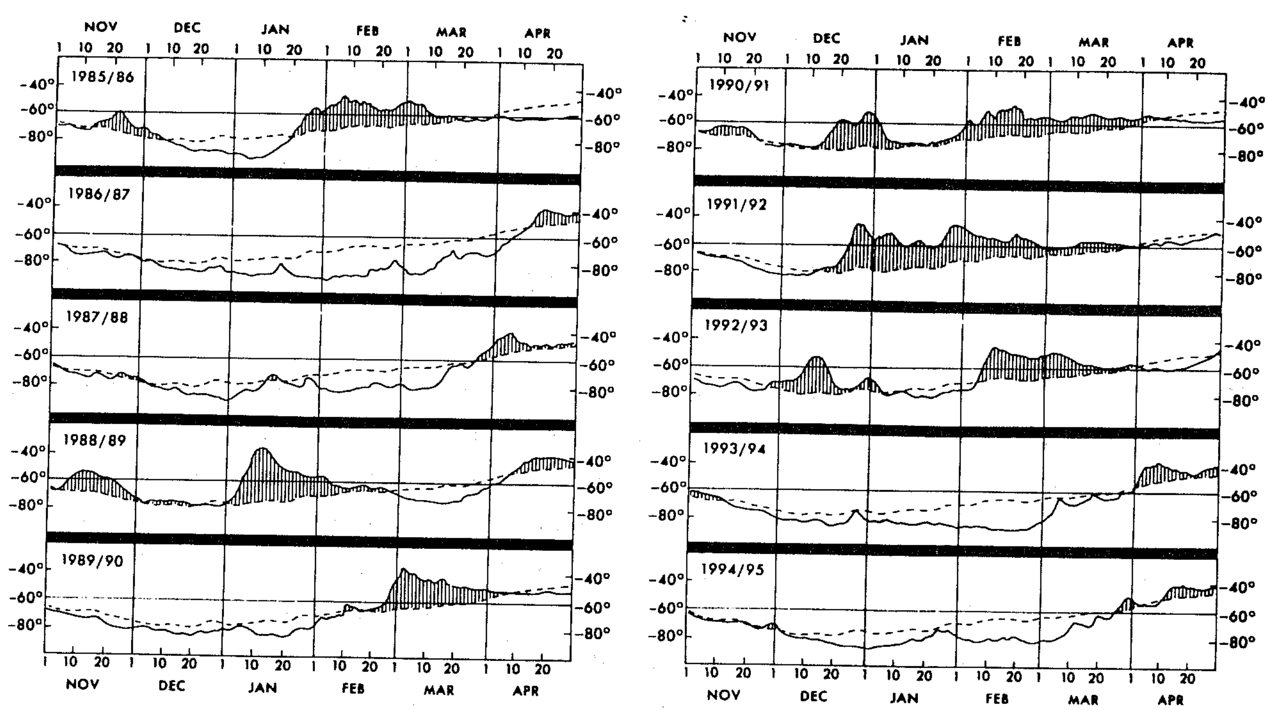

Fig. 7(b). As in (a), but for ten consecutive years of the SKYHI control integration.

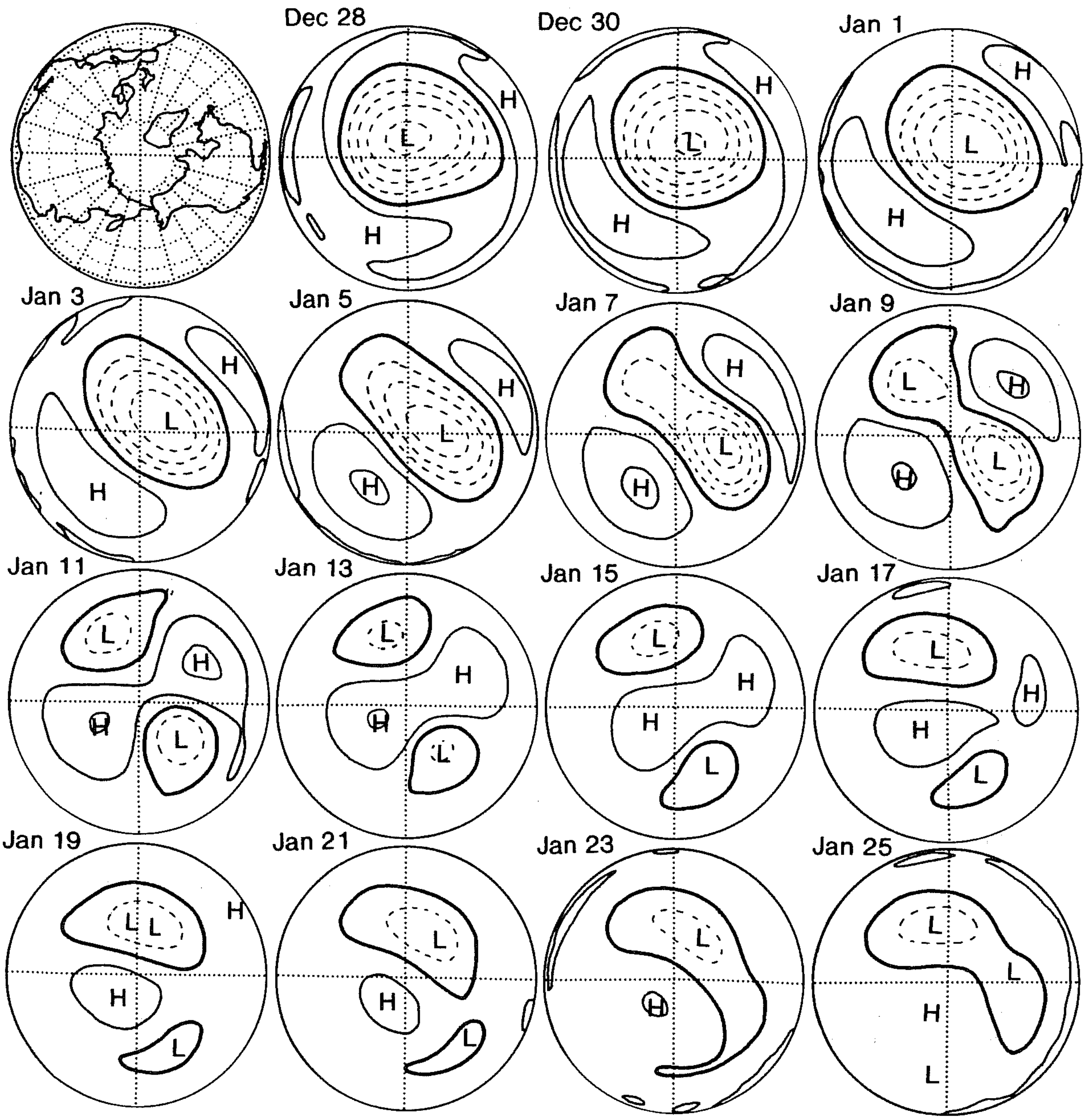

Fig. 8. Northern Hemisphere 10 mb heights at 2 day intervals from the SKYHI control integration during late "1988" and early "1989". The contour interval is 500 m and dashed contours are used for values below 30 km.

lack of high-frequency, small-amplitude warming events in the model relative to those found in the observed time series. As noted above, the major warming events are about as frequent in the simulation as in observations, but there seems to be a bias for the model to have more warmings in the early winter. In fact, Fig. 7b shows that strong warmings occurred in December "1990/91", "1991/92" and "1992/93". This is consistent with the earlier result in Fig. 5 which suggested that the model significantly overestimates the interannual variability of the December temperatures in the upper stratosphere.

The detailed model behavior in the midwinter warming events is still being investigated. Preliminary analysis suggests that the evolution of individual sudden warmings is quite realistic. As an example, Fig. 8 shows the progression of the 10 mb height field through the warming seen

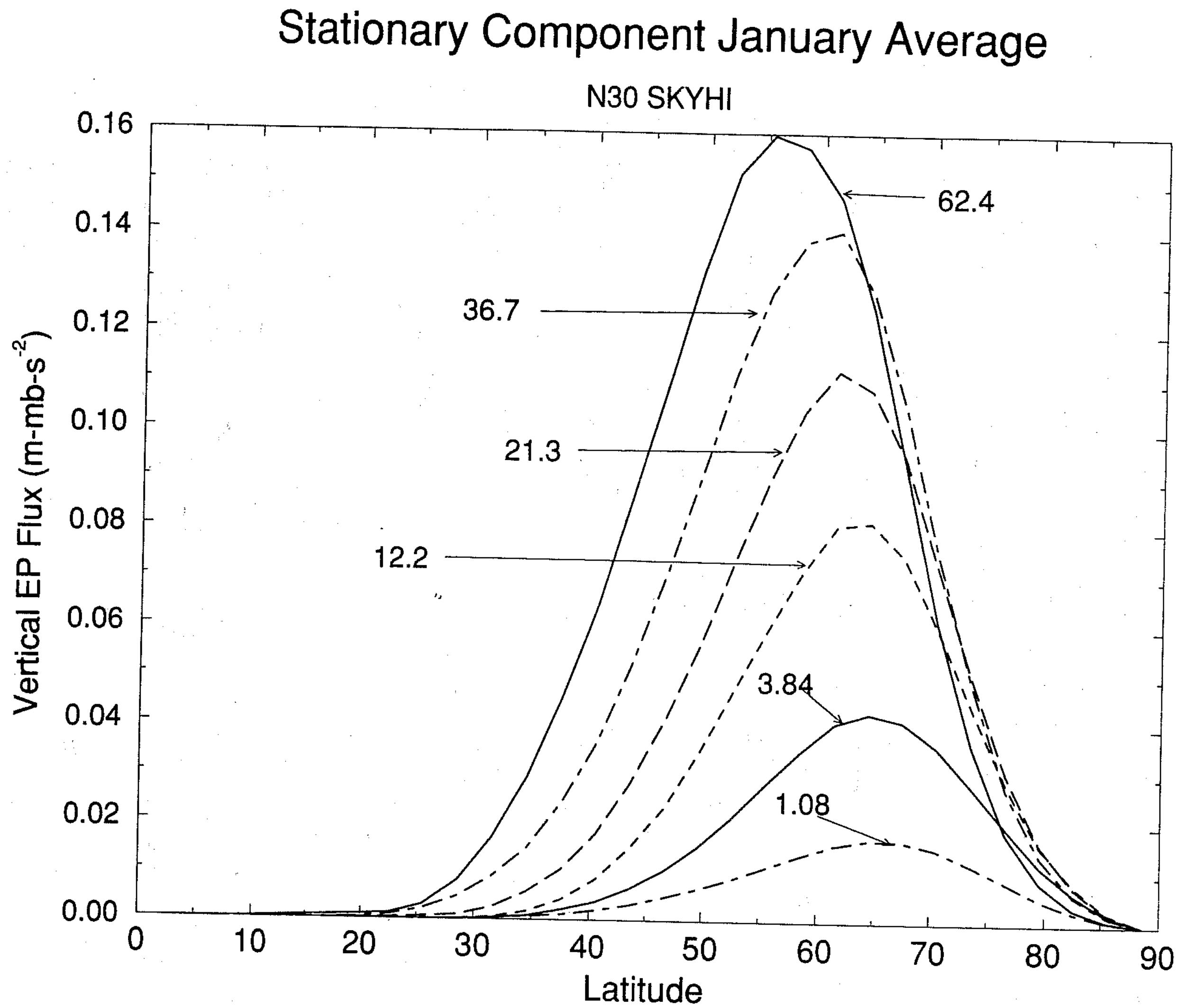

Fig. 9. Vertical component of the EP flux associated with the stationary eddies in the January-mean climatology from the N30 control run.

in early January "1989". The very strong zonal wave 2 warming is evident. The evolution of the 10 mb heights in this model warming is quite similar to that in the observed February 1979 sudden warming which has been documented in *Andrews et al.* (1987; see their Figure 6.3 showing the 10 mb heights). The February 1979 vortex breakdown was a predominantly wave 2 event, and it proceeded just as rapidly as the model warming illustrated in Fig. 8 (compare the evolution in shown in *Andrews et al.* during February 19-26 with that in the model during January 5-13). The warmings in the model also display a reasonably realistic vertical structure, with a rapid downward propagation of the zonal-mean warming generally evident.

5. DECAY OF VERTICALLY-PROPAGATING WAVES

As discussed earlier, a central issue in designing a NWP model is the placement of the top model level. The adequacy of a particular choice presumably depends on how rapidly the vertically-propagating waves in the model dissipate. Of course, there will always be some components of the spectrum of vertically-propagating waves that have such a high vertical group

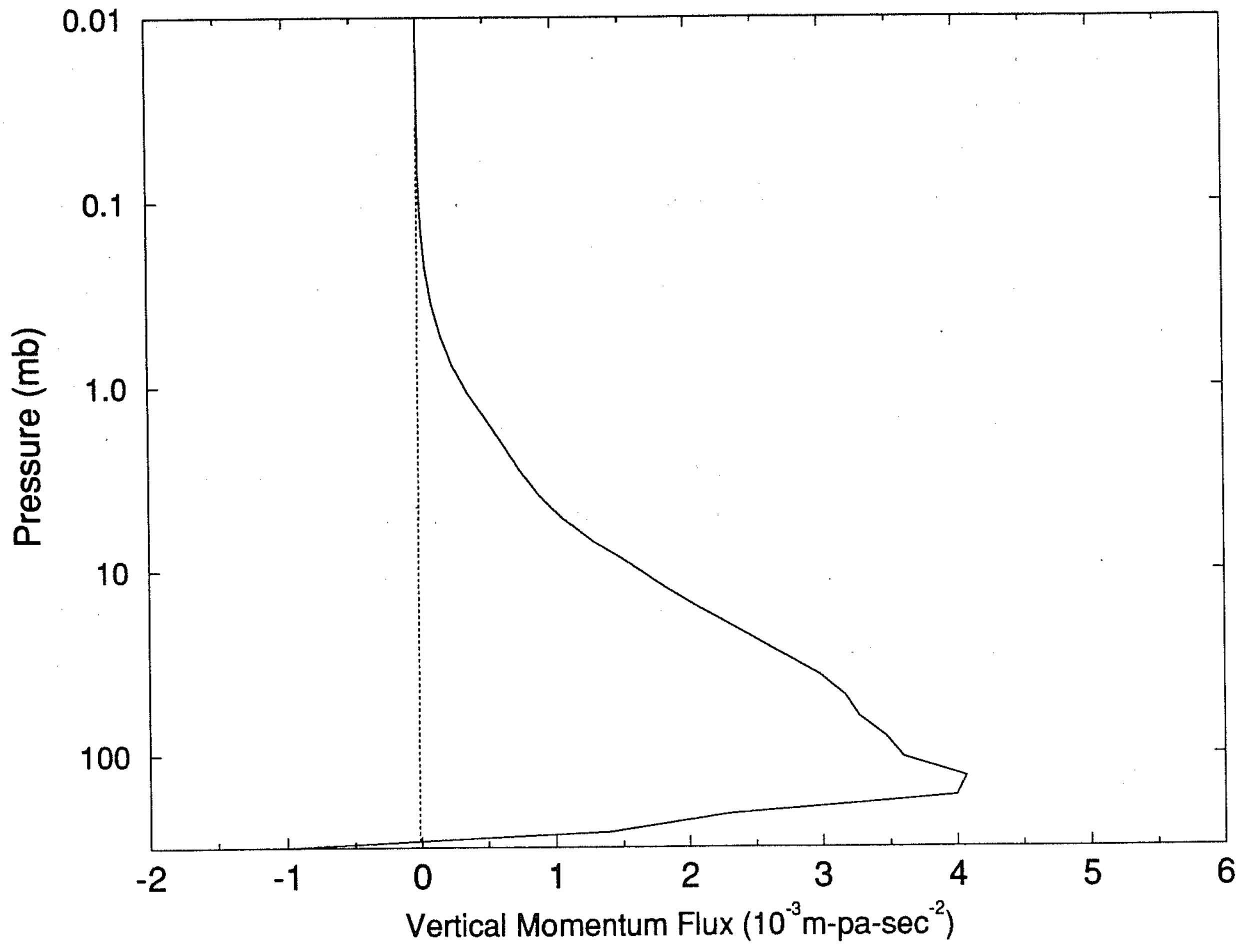

Fig. 10. Vertical momentum flux in an imposed monchromatic equatorial Kelvin wave averaged over the latitude band 35°S-35°N. See text for details.

velocity that they will strongly reflect from the upper boundary. Such components typically have high frequency and short horizontal scales, and in an actual numerical prediction such motions should be suppressed by the initialization procedure. The real concern is the effect of the upper boundary on the large-scale motions that are resolvable in observations, particularly quasi-stationary planetary waves in the extratropics and global-scale equatorial waves in low latitudes. In linear wave models such as that of *Kirkwood and Derome* (1977) the decay of the upward wave fluxes depends on the (somewhat arbitrary) dissipation employed. In a full GCM like SKYHI the waves are dissipated in a self-consistent manner that involves radiation, subgrid-scale mixing parameterizations and the resolved dynamical nonlinearity. Fig. 9 shows the vertical component of the Eliassen-Palm (EP) flux (defined in isobaric coordinates, see *Andrews et al.*, 1983) associated with the standing waves in the January climatological mean of the N30 control integration. Results are shown as a function of latitude in the NH. The rather rapid saturation of the wave amplitudes in the stratosphere appears here as a marked decrease of EP flux with height. The reduction in wave activity with height appears to be somewhat more pronounced in these results than in the simple model of *Kirkwood and Derome* (1977), perhaps indicating the importance of nonlinear wave saturation in the full model.

The determination of the analogous vertical structure for the equatorial waves is a little more difficult, since the EP flux associated with such waves is spread out over a broad space-time spectrum. To examine this issue, a special experiment was run with the N30 SKYHI model. This was initialized from a June 1 snapshot of the control run, and then was integrated with an arbitrary heat source added in the tropical upper troposphere. This added perturbation took the form of a eastward-travelling zonal wave 1 heating with period 8 days modulated by an equatorially-trapped meridional structure. This forced a monochromatic vertically-propagating equatorial Kelvin wave. The amplitude of the forcing was sufficiently weak that the forced wave is fairly linear. The experiment was run for 160 days and the last 112 (14 wave periods) were analyzed. Fig. 10 shows a measure of the upward momentum flux in this wave (very nearly equal to the vertical EP flux, since the meridional winds associated with the wave are very small). There is a drop in the flux throughout the stratosphere almost as great as that seen in the extratropical stationary wave fields. The dissipation of the imposed wave in this case comes not from resolved nonlinearities, but rather from a combination of radiative thermal damping and subgrid scale mechanical damping associated with the Richardson number-dependent vertical mixing activated by the "background" eddies present in the model. This mechanical dissipation turns out to be more important than the radiative effect, suggesting that simple models with only radiative damping may overestimate the

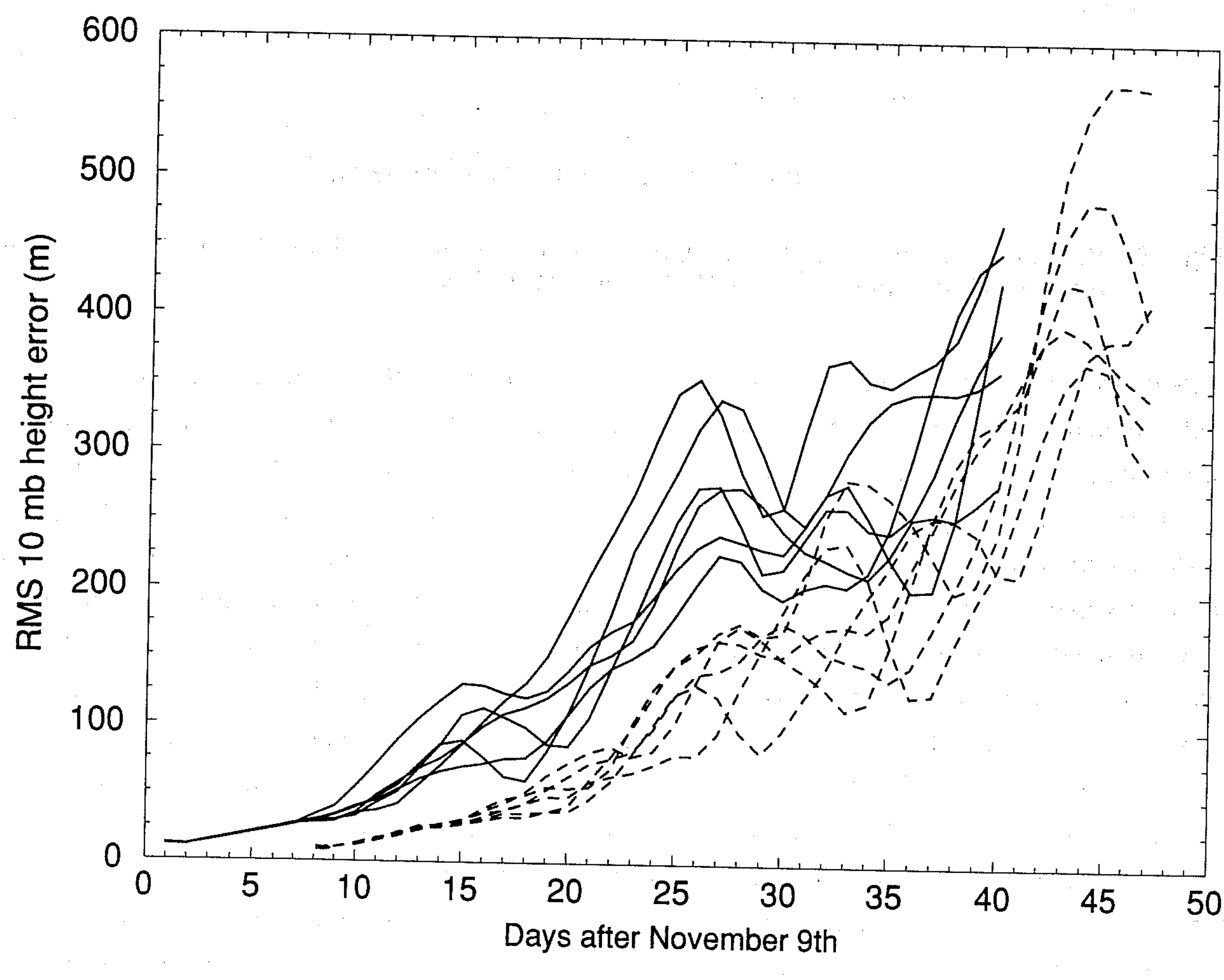

Fig. 11. The RMS deviation over the NH of the 10 mb height in perturbed integrations versus the control. The results are for 6 integrations starting from perturbed initial conditions on November 9 (solid curves) and 6 starting from initial condirions perturbed on November 16 (dashed curves).

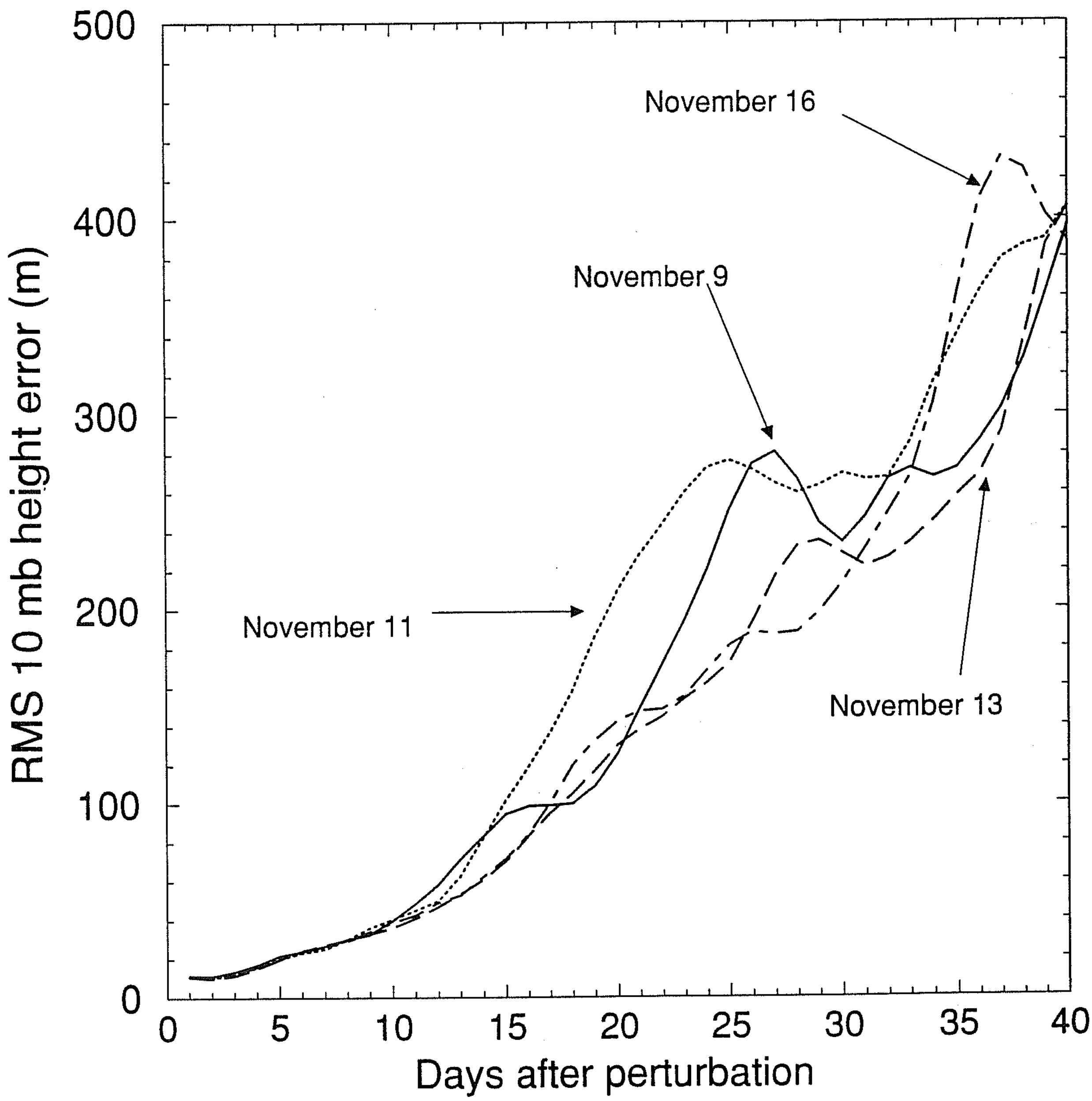

Fig. 12. The RMS deviation over the NH of the 10 mb height in perturbed integrations versus the control, with each curve representing the mean value for 6 seperate integrations. The Labels refer to the date at which the perturbation was introduced.

upward fluxes of large-scale equatorial waves.

The dropoff of wave flux through the stratosphere in both Figs. 9 and 10 is very impressive. It certainly seems that locating an upper boundary near 1 mb would be more than adequate for any practical NWP application.

6. AN EXPERIMENT TO INVESTIGATE ATMOSPHERIC PREDICTABILITY DURING A SUDDEN WARMING

As noted earlier, it is reasonable to speculate that any stratospheric effect on atmospheric predictability is most important during midwinter sudden warmings. In this section some simple predictability experiments for a sudden warming case using the SKYHI model will be reported.

The experiments relate to the sudden warming that occurred in December "1990" of the N30

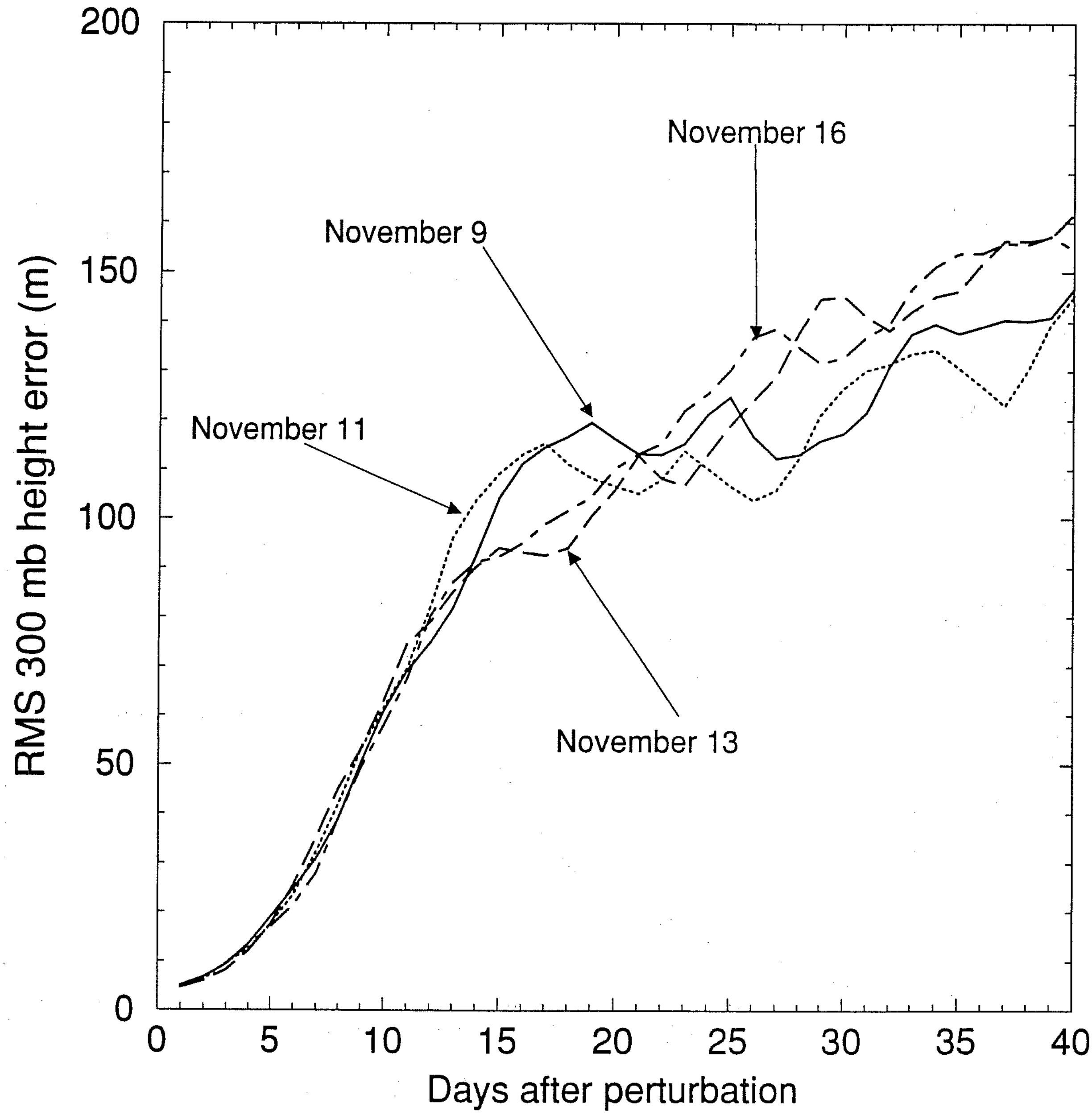

Fig. 13. As in Fig. 12, but for the 300 mb height.

control run (see Fig. 7b). Each integration was started from initial conditions that were taken from this control run and then randomly perturbed in the temperature field. The perturbation introduced was a randomly chosen value (i.e. no coherence in either the vertical or horizontal) between +1.5^{o}C. and -1.5^{o}C, and was added to the temperature at each grid point and level at and below 103 mb. A total of 24 of these perturbation experiments were conducted (each integrated 40 days), 6 starting from each of November 9, November 11, November 13 and November 16. It is interesting that those integrations perturbed on November 13 and 16 all produce strong warming events in December, while those perturbed on November 9 and 11 fail to develop significant warmings.

Fig. 11 shows the time series of the NH RMS difference between the 10 mb height field in each of the individual perturbation experiments and in the control. For clarity of presentation only results for the November 9 and November 16 experiments are shown. The perturbation initially introduces about a 10 m RMS "error" in the 10 mb heights, and this error grows to several hundred m over the period considered. Even from this rather complicated figure one can discern the somewhat slower error growth in the experiments perturbed on November 16. Fig. 12 shows the same measure of error in the 10 mb height, but now averaged over each set of 6 experiments (and plotted as a function of the time after the perturbation). The error growth in the November 13 and November 16 experiments is clearly slower than that in the experiments perturbed earlier, at least for about the first 30 days of integration. The difference between these cases during the period from about days 15-25 can amount to the equivalent of about 5-10 days on the time axis. Fig. 13 shows the same statistics, but now for the 300 mb height field. The differences in the error growth among the different cases is much less pronounced than in the 10 mb results shown in Fig. 12, but there is a period between about 12 and 20 days into the integrations where the November 13 and 16 experiments have considerably less error than those perturbed earlier.

The results discussed here are for just a single case, and obviously need to be regarded with caution. The results do suggest the presence of a well-defined boundary in the stratospheric predictability, so that if random tropospheric perturbations are made after a certain date, the occurrence of a stratospheric warming is virtually certain. In terms of the 10 mb RMS error verification, this boundary also corresponds to a sudden increase in the predictability horizon of the order of 5-10 days. There is a suggestion that there may also be a similar jump in tropospheric predictability at this boundary as well.

7. CONCLUSION

The simulation of the stratospheric circulation by the SKYHI model has been shown to have a number of promising features, as well as some clear deficiencies. The long-term mean NH winter circulation in the model is of realistic intensity, and the deformation of the time-mean polar vortex by stationary waves in the model is also quite similar to that observed. The model displays a realistic degree of both interannual and day-to-day variability in the NH winter stratosphere. The simulation of midwinter sudden warmings of realistic intensity and frequency is a particularly encouraging result. This feature of the control integration allows the use of the model in predictability studies of practical interest (such as those discussed in Section 6 of this paper).

Heading the list of remaining problems with SKYHI is the very unrealistic simulation of the SH winter circulation. The polar vortex in the SH upper stratosphere is much too intense in the model. This deficiency improves with resolution, but even at N90 it is still very severe. Further work on subgrid scale parameterization will likely be required to alleviate this problem.

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