JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. D20, PAGES 23,805–23,811, OCTOBER 27, 1997

Some aspects of the sensitivity of stratospheric climate simulation to model lid height

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Abstract. Two ensembles of simulations of the middle atmosphere are compared for early northern hemisphere winter. The two ensembles differ only in the position of the model lid (80 km or 96 km). Two sets of comparisons are carried out using a primitive equation mechanistic model; the first uses Rayleigh friction in the mesosphere to mimic the effect of gravity waves, and the second uses the Hines gravity wave parameterization. Simulations which use Rayleigh friction are found to show little climatic sensitivity to the position of the lid. Simulations which use the Hines parameterization are shown to be very sensitive to the position of the lid, and this sensitivity is seen directly up to six scale heights below the lid. Indirect effects may extend throughout the middle atmosphere. This sensitivity is believed to be due to real circulation changes and not any numerical artifacts resulting from reflections from the model lid.

1. Introduction

Since the seminal work of *Lindzen* [1981], who calculated the effective force on the zonal flow in the mesosphere due to the breaking of gravity waves, there have been a number of extensions to his essentially monochromatic parameterization. The further extension of such parameterizations to include modeling the propagation of a spectrum of gravity waves has been attempted by *Fritts and Lu* [1993], *Hines* [1997a] and *Medvedev and Klaassen* [1995]. The former two schemes have been compared by *Lawrence* [1997] who found good fidelity in a comparison with observations using the Hines scheme. Nearly all the parameterization schemes in current use require careful tuning, and such tuning will be required for some time to come [*Hamilton*, 1996].

Both the validation, and the tuning, of gravity wave schemes usually involves comparison with climatology, which is always difficult in the mesosphere where some climatologies are not well based [*Lawrence and Randel*, 1996], and which is is exacerbated by the fact that many models require some sort of sponge layer at the top of the model which may lead to problems in implementing and understanding the effects of such parameterizations [*Shepherd et al.*, 1996]. (In some cases the sponge layer is intended to mimic the effect of gravity waves; for example, in previous versions of the model used here, and in others, it is included for numerical reasons, primarily to minimize the effect of waves reflecting from the model lid.)

Paper number 97JD01771.
0148-0227/97/97JD-01771$09.00

Implementations of gravity wave schemes have not always been successful, and the difficulties include both problems with tuning and the fact that the parameterization may worsen model climatology. The latter problem is usually attributed to a poor parameterization, but it can also be due to other model problems. It is the purpose of this paper to highlight one such problem: the position of the model lid.

To compare the effect of the position of the model lid, two ensembles of model runs are compared. The two ensembles differ only in the position of the model lid and are begun from four different initial conditions to provide some statistics for the comparison. Comparisons are carried out for a model formulation which includes Rayleigh friction in the mesosphere to mimic the effect of gravity wave breaking and for a formulation which includes the Hines gravity wave parameterization. In the remainder of the paper we summarize the model details, present some results, and conclude that the position of the model lid may have a significant impact on model climatology, even in the lower stratosphere some six scale heights or more below the lid.

2. Model Details

In the simulations discussed in this paper, we use a derivative of the United Kingdom Meteorological Office (UKMO) stratosphere and mesosphere model (SMM) [*Butchart et al.*, 1982]) developed by the author and compare an ensemble of simulations from two nearly identical model configurations which differ only in the position of the model lid (either 80 km or 96 km) where the vertical wind is forced to zero. In both cases the model has 5° resolution in both latitude and longitude and

2-km vertical resolution. The SMM has its lower boundary at 16 km (100 hPa) prescribed daily by UKMO geopotential height observations. For the simulations with the lid at 80 km (0.01 hPa), it has 32 free levels, and for the simulations with the lid at 96 km (0.001 hPa), it has 40 free levels.

The SMM is a primitive equation model, with a full radiative code (MIDRAD [*Shine*, 1987]). In previous versions [e.g., *Lawrence*, 1997] it has included Rayleigh friction (RF) which turned on at 50 km and increased up to 80 km (Figure 1). Most of the simulations discussed here use the Hines parameterization [*Hines*, 1997a, b] instead (i.e., there is no sponge layer). The Hines scheme is based on the Doppler spreading of an assumed spectrum of vertical wave numbers and requires a source strength and has available further "fudge" factors for tuning, the major one of which is the characteristic horizontal wave number. In the simulations discussed below a global mean for the source of 2 m/s was chosen, and the characteristic horizontal wave number was chosen to be 1/125 km. Like most implementations of this scheme the simplest possible spectral shape has been used ($s = 1$ using the notation of *Hines* [1997b]), which probably results in an overestimate of the energy at small vertical wave numbers. There is no effort to dump all of the energy in the initial spectrum before the top of the model.

The two ensembles of simulations each consist of four simulations begun on November 7, 1991, with the same lower boundary prescribed daily throughout. The four initial conditions were generated by first producing four individual temperature fields by merging observed stratospheric temperatures from 1991, 1992, 1993 and 1994 respectively with COSPAR International Reference Atmosphere (CIRA) temperatures [*Barnett and Corney*, 1985] from 48 to 80 km (and extrapolating isothermally above for the 96-km simulations). These fields were stacked on top of the geopotential field at 16 km, and balanced winds [*Randel*, 1987] for the initial conditions were produced from the resulting geopotential fields. Each simulation was run out to the end of January 1992, but average results are only presented here for December. This procedure was followed, as four full years of simulation for each ensemble would have been prohibitively expensive in terms of computation time.

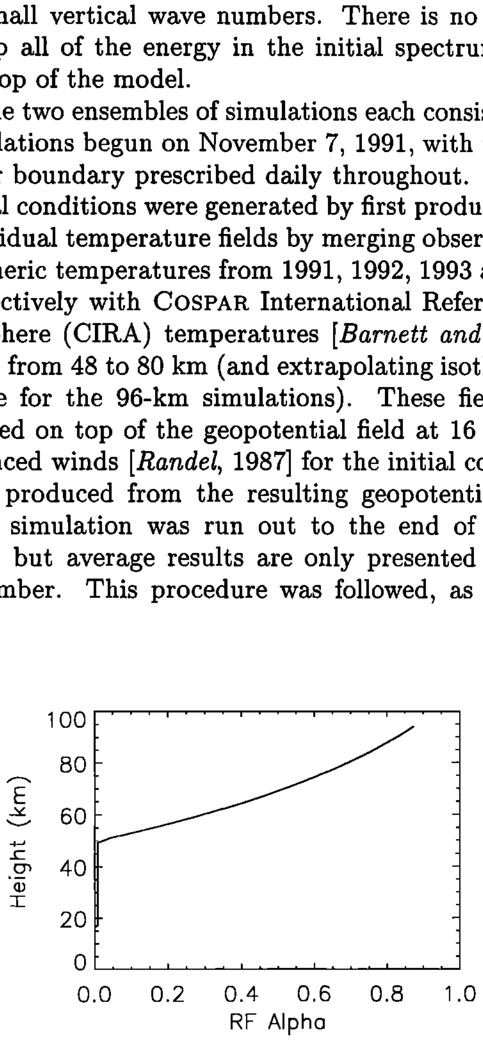

Figure 1. Standard Rayleigh friction profile (days^{-1})

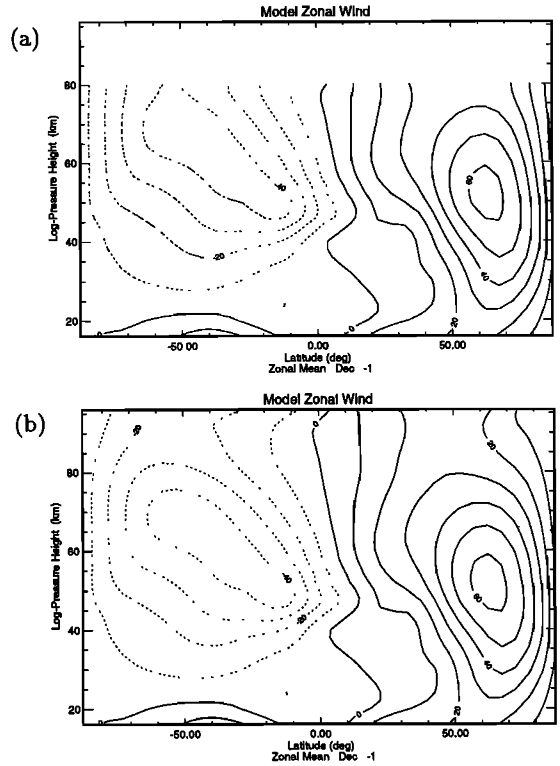

Figure 2. Ensemble mean zonal mean wind ($\overline{u}$) from the two sets of simulations using Rayleigh friction (m/s): (a) 80-km lid and (b) 96-km lid.

In all the simulations, 11,360 particles were initialized on eight different pressure heights and distributed throughout latitude and longitude so as to have an equal distribution with area. The particle locations were tracked throughout the simulation and dumped at 5-day intervals.

3. Results and Discussion

Figure 2 shows the climatologies for the RF simulations with lids at 80 and 96 km. It can be seen that there are few differences; the strength of the polar night jet and the summer mesospheric jets are identical, as are the shape and position. The minor differences in the height at which the jet closed could easily be within the climatological variance. No further results from the RF simulations are presented.

In contrast with the RF simulations, the simulations using the Hines gravity wave scheme shown in Figure 3 show significant differences in the polar night between the simulations with lids at 80 and 96 km. The polar night jet splits in the lower mesosphere in the simulation with the lid at 96 km, a result more in tune with climatological expectation [e.g., *McLandress and McFarlane*, 1993; *Rosier et al.*, 1994] and, more important, from a stratospheric point of view, the height of the jet maximum has been lowered and there is a smaller region

(a)

(b)

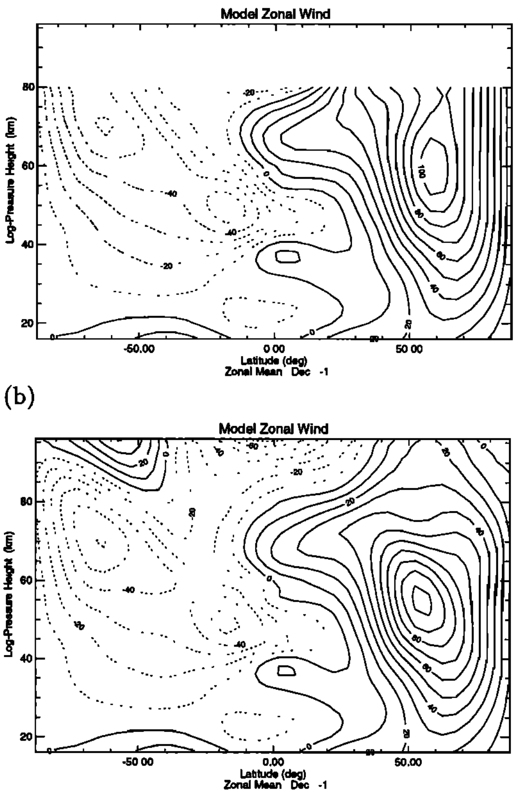

Figure 3. Ensemble mean December zonal mean wind ($\overline{u}$) from the two sets of simulations using the Hines gravity wave scheme (m/s): (a) 80-km lid and (b) 96-km lid.

where the jet peak is greater than 90 m/s. The summer jet structure has not been significantly affected by the change in the lid position.

Evidence that the difference between the Hines ensembles is statistically valid can be seen by considering the standard deviation of the zonal means for each set of four simulations. Figure 4 shows these and clearly demonstrates the differing nature of the simulations; in the case where the lid is at 80 km, most of the variability is concentrated around the single polar night jet maximum and the tropics (as can be seen in the top panel). With the lid at 96 km, the clear presence of two northern polar night jet structures and variability in each is much more prominent in these fields of standard deviation. These climatological results are born out in a study of the individual simulations. In none of the simulations with the lid at 96 km does the polar night jet tilt noticeably toward the pole, whereas in the 80-km simulations, two of the four simulations have polar jets dominated by obvious poleward tilts while the other two are more nearly vertical in orientation.

Much of the difference in the polar night jet structure between these two ensembles is due to the enhanced descent into the polar night upper stratosphere in the simulations with a lid at 96 km (Figure 5a). This leads to much warmer polar mesospheric temperatures in the northern hemisphere (NH) (Figure 5b) and hence a reduced meridional temperature gradient and weaker jet. Figure 6 shows the difference in direct gravity wave driving. Although not obvious without difference plots (omitted for brevity), the ensemble with the higher lid has maximum wave drag in the NH polar night lower (by around 10 km) than the ensemble with the lower lid (essentially, in the latter case the wave drag increases up to the top of the model, whereas the clear peak in the driving is well resolved in the higher lid ensemble). Since much of the meridional momentum balance in the mesosphere is between the Coriolis torque on the meridional flow ($f\overline{v}$) and the zonal gravity wave driving, Figure 6 also shows that the simulations with lids at 96 km will also resolve a considerable amount of meridional transport not possible in the 80-km-lid model. This, and the fact that the peak in driving is lower, both lead to a greater northward mass flux, which implies via continuity greater vertical motion in polar latitudes (which for this season and hemisphere means greater descent).

One way of examining the descent is by examining the Lagrangian descent of a number of particles which are advected by the model winds. The extra descent in the 96-km-lid ensemble is seen in Figure 7, which shows the mean height of those particles north of 60°N which were initialized on the 74-km surface. It can be seen that the northward mass flux is well captured: Of the

(a)

(b)

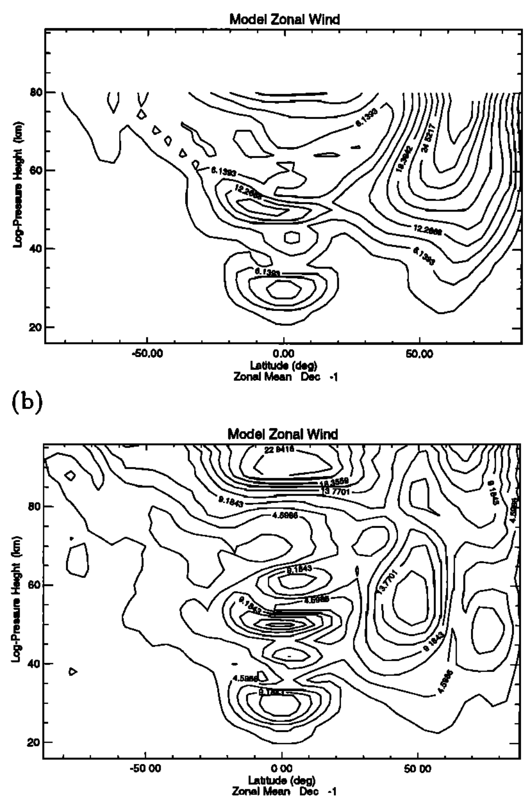

Figure 4. Standard deviation of the December zonal mean wind within each set of four Hines simulations (m/s): (a) 80-km lid and (b) 96-km lid.

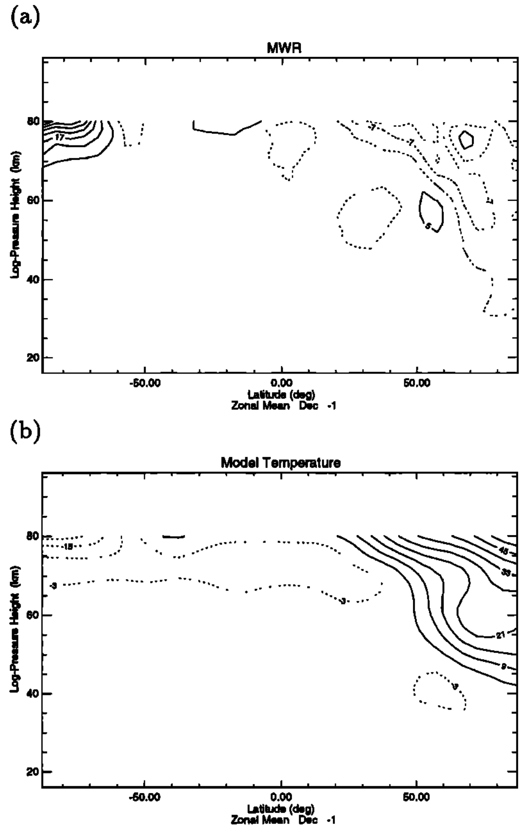

Figure 5. Differences between the December ensemble mean simulations (96-km minus 80-km): (a) Residual mean vertical velocity (mm/s), and (b) temperature (K).

1420 particles originally on the 74-km surface throughout the globe, over 400 have moved north of 60°N after 10 weeks of simulation. The obvious downward mass flux is also clearly seen, a result first reported by *Fisher et al.* [1993] using an earlier variant of this model with RF. What is new here is the clear increase in both northward and downward movement seen in each year between the simulations when the model lid is raised. The year 1993 is included independently in Figure 7 to make this clearer (it is in no way untypical of the four comparisons); both the downward and northward movements are more obvious when only one year is shown. The amount of descent is greater than indicated, since the final mean height will be biased by the mesospheric air arriving over the pole at greater alitudes.

At extratropical latitudes, the amount of vertical motion $w_G(z_0)$ due to the gravity wave parameterization at height z_0 can be calculated using the downward control integral *Haynes et al.* [1991]:

$$w_F(z_0) = \frac{-1}{\rho_s(z_0) a \cos\phi} \frac{\partial}{\partial \phi} \left[\frac{\cos\phi}{f} \int_{z_0}^{z_T} \rho_s(z)\, F(z)\, dz \right],$$

where ϕ is the latitude, ρ_s is a standard density, f is the Coriolis parameter, a is the radius of the Earth, and F is the body force per unit mass due to the parameterization (and any other tendencies due to numerical truncation, etc.). Strictly, the integration should proceed up to $z_T = \infty$; however the model lid puts a maximum height on the integration. It can be shown that if F is solely due to gravity waves, then w_F is controlled only by the net momentum flux carried by the gravity waves through z_0.

Figure 8a demonstrates the effect of changing the upper limit of integration from $z_T = 80$ km to $z_t = 96$ km in the 96-km ensemble. It can be seen that the descent rates in the polar night are underestimated mainly in the mesosphere; there is little difference in the stratosphere. This means that the gravity wave-driving occurring above 80 km is not impacting on the northern stratospheric temperatures in this ensemble. However, the total gravity wave driving is very different between the ensembles, as expressed previously, because the upward propagating spectrum is meeting a very different environment. This means there is a further feedback between the changes in the mean flow, which change the actual net momentum fluxes propagating through any given level (and hence change the vertical motion arising from the deposition of such fluxes above). Figure 8b shows the ratio of w_F in the 80-km-lid ensemble to w_F in the 90-km ensemble. The clear impact of the lack of the upper mesosphere is apparent in the poles of both hemispheres and extends throughout the vertical extent of the model; the descent into the polar night is underestimated by about 40% right down to the model bottom.

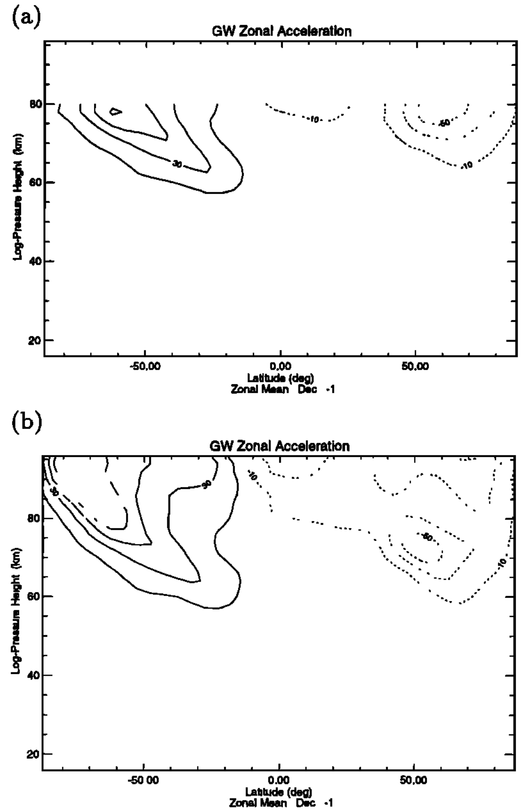

Figure 6. Ensemble mean December zonal mean zonal tendencies due to the Hines gravity wave parameterization (m s^{-1} d^{-1}): (a) 80-km lid and (b) 96-km lid.

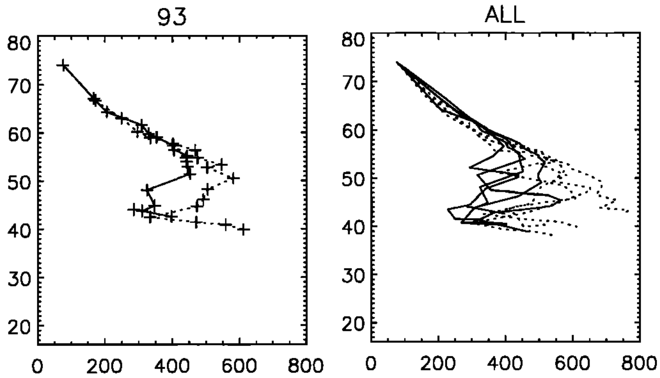

Figure 7. Lagrangian descent: The left-hand panel is from the 1993 simulations and the right-hand panel presents the results from all the members of both ensembles. The X axis is the number of particles north of 60°that were originally on the 74-km surface. The Y axis is the mean height of those particles. The lines show the evolution through the simulation, with every five days marked with a cross. The solid line connects the particles from the 80-km-lid runs and the dotted line connects the particles from the 96-km-lid runs.

Along with the changes in the zonal mean are concomitant changes in the propagation of planetary waves which themselves lead to nontrivial changes in the background flow. The effect of these can be seen in Figure 9, which compares the stationary Eliassen-Palm (EP) flux divergence for the two ensemble climatologies. Although there is a complicated nonlinear interaction between the mean flow and the planetary wave propagation, a distinct difference between the ensembles can be seen. An examination of the ensemble members (not shown) reinforces the impression of a clear difference between the two ensembles.

Both the direct effect of the meridional circulation being enhanced and the indirect effect of the changes in planetary wave propagation will lead to changes in the lower stratosphere. However, it is somewhat harder in the lower stratosphere to identify ensemble differences within the large variability known in the northern stratospheric winter, particularly given the small number of ensemble members. Nonetheless, it is clearly possible given the changes in planetary wave structure for there to be systematic differences in the vortex structure and thus upon the potential for accurate simulation of ozone destruction in the northern winter (see, for example, *Taylor et al.* [1994], who highlight the importance of the structure upon polar stratospheric cloud formation).

The complete lack of any sponge layer in the model with Hines parameterization could, in principle, cause errors associated with reflections from the model lid; however, an examination of instantaneous model fields suggests that the high-frequency variability in the strength and direction of the gravity wave driving would itself damp any downward propagating waves before they could penetrate deep into the model domain. It is certainly contended that such errors would be smaller than the effects discussed in the body of this paper. If such a layer were found to be required, it should, in principle, be placed above the region where gravity wave driving dominates [*Shepherd et al.*, 1996], which would lead to a model lid nearer 110 km.

4. Conclusions

If one had been trying to tune the Hines gravity wave parameterization toward climatology with the model lid at 80 km, and allowing oneself only to molest the "fudge" factors available, the aim would have been to lower the peak in wave driving and somehow adjust the sources to give a split jet. However, in this case it appears that this can be achieved simply by raising the model lid. This complicated interplay between existing model characteristics and new parameterization could lead to great difficulty in the effective imposition of any physically based gravity wave parameterization.

The direct effect of lifting the lid in the simulations led to increased penetration of downwelling from the mesosphere (which for the 2 months of integration was

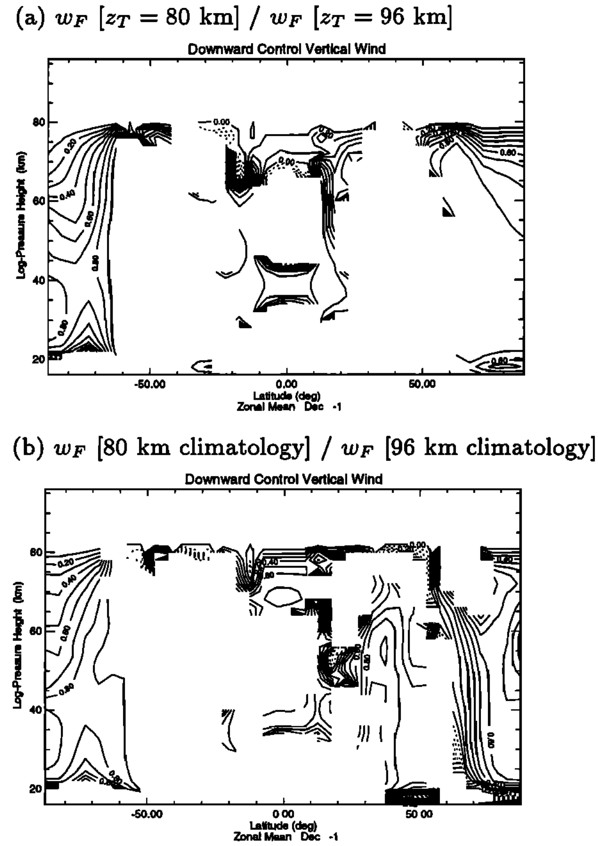

Figure 8. A comparison of w_F ratios using downward control and (a) different values of z_T and the 96-km ensemble and (b) z_T = model lid and the two different ensembles. (Much of the detail is tropical noise where the downward control approximation is not valid; the systematic differences are in the polar regions.)

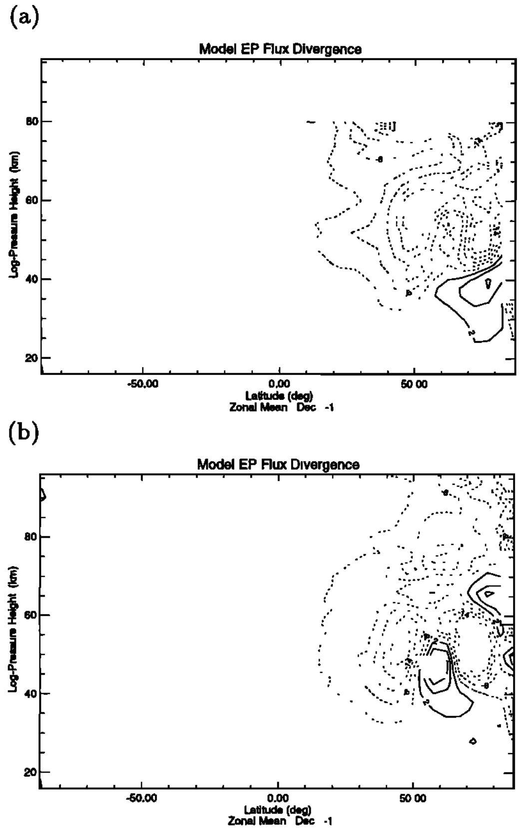

Figure 9. Ensemble mean December stationary Eliassen-Palm flux divergence (m/s/day): (a) 80-km lid and (b) 96-km lid.

down to around 40 km, approximately six scale heights below the original model lid position). Comparisons of the amount of descent due to the gravity wave parameterization show that in the northern polar region the descent was increased throughout the vertical extent of the model. Lower in the stratosphere this increase was not apparent in the residual mean circulation, partly because the actual amount of descent is so much smaller in the lower stratosphere and partly because some of the gravity wave induced descent must have been offset by the observed changes in planetary wave driving. These indirect effects upon Rossby wave propagation will themselves lead to significant changes in the lower stratosphere although it is not yet clear whether this would lead to a systematic difference in, for example, minimum temperatures in the northern polar night (and thus the potential for accurate simulations of ozone depletion).

Although these results were based on a comparison of simulations which used one gravity wave parameterization, the effects of changing the model lid height were very similar to the changes seen when simulations are performed with and without a gravity wave parameteriztion [e.g., *Garcia and Boville*, 1994], which leads one to conclude that these effects would be seen with any physical gravity wave parameterization (as opposed to unphysical parameterizations like RF) and are dependent on the amount of parameterized gravity wave flux (as would be expected from downward control) rather than the details of the implementation.

With a physical gravity wave parameterization, we expect there to be some height at which there is no longer any significant momentum carried by the gravity waves. The results presented in this paper suggest that model lids should not be below this height, as one needs to consider not only the direct effect of the gravity waves on the residual mean circulation, but alos the indirect effect of these waves which induce changes in resolved planetary waves. The actual height of importance is a moot point: the work carried out here used a parameter ($s = 1$) which probably overestimated the long-wave part of the spectrum and hence overestimated the height to which significant amounts of gravity wave flux are carried.

Acknowledgments. The model simulations described in this work were carried out at the Rutherford Appleton Laboratory and at Oxford University while the author was an Atlas Research Fellow supported by the U.K. Natural Environment Research Council. I am grateful for useful conversations with David Andrews, Colin Hines, Richard Kennaugh, and Lesley Gray and an excellent suggestion from one of the reviewers.

References

Barnett, J., and M. Corney, Middle atmosphere reference model derived from satellite data, in *Atmospheric Structure and Its Variation in the Region 20 to 120 km*, edited by K. Labitzke, J. Barnett, and B. Edwards, vol. 16 of *Handbook for MAP*, pp. 47–85. Univ. of Ill., Urbana, 1985.

Butchart, N., S. Clough, T. Palmer, and P. Trevelyan, Simulations of an observed stratospheric warming with quasi-geostrophic refractive index used as a model diagnostic, *Q. J. R. Meteorol. Soc.*, *108*, 475–502, 1982.

Fisher, M., A. O'Neill, and R. Sutton, Rapid descent of mesospheric air into the stratospheric polar vortex, *Geophys. Res. Lett.*, *20*, 1267–1270, 1993.

Fritts, D. C., and W. Lu, Spectral estimates of gravity wave energy and momentum fluxes. Part II: Parameterization of wave forcing and variability, *J. Atmos. Sci.*, *50*, 3695–3713, 1993.

Garcia, R. R., and B. A. Boville, "Downward Control" of the mean meridional circulation and temperature distribution of the polar winter stratosphere, *J. Atmos. Sci.*, *51*, 2238–2245, 1994.

Hamilton, K., Comprehensive meteorological modelling of the middle atmosphere: A tutorial review, *J. Atmos. Terr. Phys.*, *58*, 1591–1627, 1996.

Haynes, P., C. Marks, M. McIntyre, T. Shepherd, and K. Shine, On the "Downward Control" of extratropical diabatic circulations by eddy-induced mean zonal forces, *J. Atmos. Sci.*, *48*, 651–678, 1991.

Hines, C. O., Doppler-spread parameterization of gravity-wave momentum deposition in the middle atmosphere. 1: Basic formulation, *J. Atmos. Terr. Phys.*, *59*, 371–386, 1997a.

Hines, C. O., Doppler-spread parameterization of gravity-wave momentum deposition in the middle atmosphere. 2: Broad and quasi-monochromatic spectra, and implementation, *J. Atmos. Terr. Phys.*, *59*, 387–400, 1997b.

Lawrence, B. N., The effect of parameterized gravity wave drag on simulations of the middle atmosphere during northern winter 1991/1992 - General evolution, in *Gravity Wave Processes and Their Parameterization in Global Climate Models*, edited by K. Hamilton, vol. 50 of *NATO ASI Ser. I*, pp. 291–307. Springer-Verlag, New York, 1997.

Lawrence, B. N., and W. J. Randel, Variability in the mesosphere observed by the Nimbus 6 pressure modulator radiometer, *J. Geophys. Res.*, *101*, 23,475–23,490, 1996.

Lindzen, R. S., Turbulence and stress owing to gravity wave and tidal breakdown, *J. Geophys. Res.*, *86*, 9707–9714, 1981.

McLandress, C., and N. A. McFarlane, Interactions between orographic gravity wave drag and forced stationary planetary waves in the winter northern hemisphere middle atmosphere, *J. Atmos. Sci.*, *50*, 1966–1990, 1993.

Medvedev, A. S., and G. P. Klaassen, Vertical evolution of gravity wave spectra and the parameterization of associated wave drag, *J. Geophys. Res.*, *100*, 25,841–25,853, 1995.

Randel, W. J., The evaluation of winds from geopotential height data in the stratosphere, *J. Atmos. Sci.*, *44*, 3097–3120, 1987.

Rosier, S., B. Lawrence, D. Andrews, and F. Taylor, Dynamical evolution of the northern stratosphere in early winter 1991/92, as observed by the improved stratospheric and mesospheric sounder, *J. Atmos. Sci.*, *51*, 2783–2799, 1994.

Shepherd, T., K. Semeniuk, and J. Koshyk, Sponge-layer feedbacks in middle atmosphere models, *J. Geophys. Res.*, *101*, 23,447-23,464, 1996.

Shine, K., The middle atmosphere in the absence of dynamical heat fluxes, *Q. J. R. Meteorol. Soc.*, *113*, 603–633, 1987.

Taylor, F. W., A. Lambert, R. G. Grainger, C. D. Rodgers, and J. J. Remedios, Properties of northern hemisphere polar stratospheric clouds and volcanic aerosol in 1991/92 from UARS/ISAMS satellite measurements, *J. Atmos. Sci.*, *51*, 3019–3026, 1994.

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(Received February 12, 1997; revised May 22, 1997; accepted June 16, 1997.)