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NASA Grant NAGW–1727
"Large–scale dynamics and transport in the stratosphere"
Principal Investigator: R.A. Plumb
SEMIANNUAL REPORT 3/1/90 – 9/1/90

1) The seasonal cycle of planetary waves in the southern stratosphere.

This component of the planned research was completed during this period. Studies with a linearized hemispheric model of the southern stratosphere have failed to confirm earlier beta–plane results. Specifically, while the observed late winter amplification of quasi–stationary planetary waves is reproduced in the model, the early winter amplification is not. The latter conflict is, at present, a mystery.

This work has been reported in an M. Sc. thesis and in a paper submitted to *J. Atmos. Sci.* (see below).

2) Large–scale transport in the southern stratosphere

This component of the research is now under way again. It is intended to perform an analysis of the observed transport of ozone using general circulation and ozone data. At this stage, effort is being directed to dynamical analysis, specifically to the diagnosis of vertical motion using potential vorticity inversion. This is a necessary precursor to separating the effects of vertical and horizontal transport.

3) Theory of the mean meridional circulation in the stratosphere

Numerical experiments are being run to investigate the upward effects of tropical tropospheric heating into the stratosphere. Thus far, it has been established in the context of these experiments that the upward extension into the lower stratosphere, though weak, is enough to comprise a significant component of the poleward mass flux. This is in apprent violation of the "downward influence" principle.

4) The impact of tropospheric interannual variability on the stratospheric circulation

This component of the research is now complete. It has been shown that the characteristic patterns of low–frequency variability in the winter troposphere extend well into the stratosphere; stratospheric structures have been identified. This work has been reported in an M. Sc. thesis and a paper is in preparation.

Theses produced during this period:

Conzemius, R.J.: Stratospheric behavior during tropospheric persistent anomaly events. M.Sc. thesis, M.I.T., June 1990.

Wirth, V.: The seasonal cycle of stationary planetary waves in the southern stratosphere: a numerical study. M.Sc. thesis, M.I.T., June 1990.

Publications during this period: (copy attached)

Wirth, V.: What causes the seasonal cycle of stationary waves in the southern stratosphere? *J.Atmos.Sci.* (to appear).

(NASA-CR-187327) LARGE-SCALE DYNAMICS AND TRANSPORT IN THE STRATOSPHERE Semiannual Report, 1 Mar. - 1 Sep. 1990 (MIT) 28 p CSCL 04A
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Title:

What causes the seasonal cycle of stationary waves in the southern stratosphere?

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Abstract

Stationary planetary waves in the southern stratosphere display a characteristic seasonal cycle. Previous research based on a one-dimensional model suggests that this behavior is mainly determined by seasonally varying transmission properties of the atmosphere with respect to wave propagation. The issue is investigated with the help of a hemispheric, linear, quasigeostrophic model. It reproduces well some of the observed qualitative features and is internally consistent in the sense that its seasonal wave cycle can be explained in terms of varying wave transmission properties of the mean circulation. On the other hand, the model does not yield the observed seasonal cycle. Despite considerable sensitivity to modifications in the basic state wind and dissipation parametrization, the model could not be reasonably fit to reproduce the observed seasonal cycle. Therefore, even though suggestive, the present study is not entirely conclusive about the degree to which the observed cycle is determined by wave transmission properties alone.

1 Introduction

Stationary planetary waves in the stratosphere exhibit a characteristic seasonal behavior. For illustration, figure 1 shows the climatological seasonal cycle of the stationary wave of zonal wave number 1 at two different pressure levels. To first approximation, there is absence of wave activity in the summer hemisphere, whereas one observes strong wave activity in the winter hemisphere. As is well known, Charney and Drazin (1961) basically explained the wave behavior in the stratosphere through wave transmission properties of the underlying atmosphere, which are determined by the mean circulation.

More recently, noticeable differences in the circulation between the two hemispheres have become apparent (Hirota et al. 1983). A closer look at figure 1 shows for instance that the waves in the southern stratosphere are considerably weaker than in the northern stratosphere. They also display a distinct relative wave minimum in mid-winter (Randel 1988). Even though the data — especially in the Southern Hemisphere — have to be considered with care, Grose and O'Neill (1989) found that the basic fields like temperature and winds can be qualitatively trusted. They show that zonal mean winds as derived from LIMS (Limb Infrared Monitor of the Stratosphere) and from SSU (Stratospheric Sounding Unit), respectively, differ only by a few m s^{-1}. Therefore, we consider the *qualitative* features, which we concentrate on in this study, as real.

A simple one-dimensional, non-linear model by Plumb (1989) suggests the *hypothesis* that the different seasonal wave behavior in the two hemispheres can essentially be explained through differences in wave propagation according to the ideas of Charney and Drazin. The interhemispheric differences in Plumb's model arise from the fact that in his simulation the southern hemispheric waves stay in a linear regime, while in the Northern Hemisphere there is substantial wave mean flow interaction, which reduces the strength of the mean westerlies. Another possible source of stratospheric seasonal variation is the varying tropospheric forcing. This, however, appears to be an insufficient explanation for the substantial seasonal variation in stratospheric wave amplitude (a factor of 4.9 at the 10 mb level for the time range April through October), since the seasonal variation of the wave in the troposphere is comparatively moderate (a factor of 1.7 at the 200 mb level for the same time period).

The above hypothesis of varying transmission properties is based on a beta-plane model, which allows only for vertical wave propagation. Yet, since the work of Charney and Drazin (1961), numerous studies (e.g. Matsuno 1970, Karoly and Hoskins 1982, Lin 1982, Nigam and Lindzen 1989) have shown that hemispheric geometry, basic state wind field curvature, and meridional in addition to vertical wave propagation play an essential role for the propagation of waves. In these studies, the refractive index is introduced as a quantity of key importance and as a useful diagnostic for wave propagation in the meridional plane. If the hypothesis holds true, the refractive index, too, should display a seasonal cycle corresponding to the observed wave cycle. The latter proposition, however, is challenged by observations: even though the mean *winds* vary substantially, the *refractive index* displays no substantial overall variation throughout the winter season (Randel 1988). This behavior is plausible, since the refractive index is essentially the ratio of the quasigeostrophic potential vorticity gradient and the mean wind. Months with stronger mean winds turn out to have stronger potential vorticity gradient, and hence the two effects tend to cancel each other.

The discrepancy between the hypothesis and the observed behavior of the refractive index motivated us to re-examine planetary wave propagation with special attention to the seasonal cycle of wave propagation in the Southern Hemisphere. The present note gives a brief overview. A more detailed description of the model used and its results can be found in Wirth (1990).

2 The model

To investigate the issue, we use a linear, quasigeostrophic, hemispheric model for stationary waves, essentially following Matsuno (1970). The model prescribes a zonally symmetric basic state, simulates forcing by specifying the wave at the lower boundary, and solves for the wave in the whole domain under consideration. Matsuno and subsequent investigators (Simmons 1974, Schoeberl and Geller 1977, see also Schoeberl et al. 1979, Lin 1982, Karoly and Hoskins 1982; part of these studies use primitive equations instead of quasigeostrophic theory) have shown that this type of model is able to qualitatively simulate essential features of northern hemispheric winter-time stationary waves. On the other hand, a more detailed comparison between such models and relevant data reveals quantitative discrepancies and further limitations (Austin 1982, 1983). We therefore do not aim for a quantitatively correct simulation. Yet, we hope to include enough realism such as to reproduce the essential features of planetary wave propagation, especially the seasonal cycle. The decisive improvement over Plumb's one-dimensional model (Plumb 1989) is that we allow for meridional in addition to vertical wave propagation and include realistic wind shear.

The quasigeostrophic potential vorticity equation is linearized about a purely zonal basic state flow, for which we use climatological monthly mean zonal mean winds from Randel (1987). Since the stationary waves in the southern stratosphere are dominated by the lowest wave number (Randel 1988), we restrict our study to zonal wave number 1. In order to model the seasonal behavior of the Southern Hemisphere winter, we consider subsequent months, ranging from April through October. For each month, the problem is treated as stationary. This is a reasonable approximation to the extent that the basic state varies slowly as compared with the time required to establish a stationary wave. The latter should be satisfied to a good approximation in the present situation. Similarly, since the wave amplitudes are smaller and show less interannual variability in the Southern Hemisphere as compared with the Northern Hemisphere, the use of a linear model and the use of climatological monthly mean data is expected to be a fair approximation for a qualitative simulation of the wave propagation behavior. In particular, interannual variability as a likely error source can be excluded, since there is no apparent correlation between months with comparatively large interannual variability (Mechoso et al. 1985) and months which are reproduced less successfully by our model.

With the above approximations, the model dynamics reduces to one single elliptic partial differential equation for the wave behavior:

$$\mathcal{L}\Psi + \nu_s \Psi = 0 , \tag{1}$$

where Ψ is proportional to the perturbation stream function, $\mathcal{L}$ is an elliptic, second order differential operator in latitude and altitude (similar to the operator of Matsuno 1970), and ν_s is the refractive index square (simply called the "refractive index" in the following). Dissipation is implemented as Rayleigh friction and Newtonian cooling, using the same damping coefficient α for both. Guided by estimates for the Newtonian cooling coefficient (Leovy

1984), α is chosen to be $\alpha = 0.05\ \mathrm{day}^{-1}$ below 48 mb, $\alpha = 0.2\ \mathrm{day}^{-1}$ above 0.7 mb, and linear and continuous in between. With this form of dissipation the refractive index is complex, which prevents the singularity of the equation at critical levels, i.e. where the basic state velocity vanishes. The domain under consideration extends in altitude from 200 mb up to 1 mb and in latitude from the South Pole up to 10° southern latitude (denoted as 10°S or −10° in the following). At the lower boundary, we prescribe the solution for Ψ as derived from Randel's (1987) data. The natural boundary condition at the South Pole is $\Psi = 0$. Since the overall propagation of the waves is upward and equatorward, for the upper and equatorward boundary some radiation condition would seem to be the best choice. However, in order to circumvent related technical difficulties, we instead use sponge layers and zero Dirichlet boundary conditions beyond the sponges. The model results are both qualitatively and quantitatively insensitive to the precise treatment of critical levels and boundary conditions (Wirth 1990).

For numerical implementation, the equation is discretized on a 5° by 5 km grid (latitude by altitude) using finite differences. Interpolation of the data from Randel's data set onto the present grid uses bicubic splines. The resulting algebraic system of equations is solved with the help of a direct solver (based on Lindzen and Kuo 1969). To test the sensitivity of the model results with respect to the numerical resolution, the gridspacing was considerably increased in both altitude and latitude. The differences in the results turned out to be negligible.

3 Model results and interpretation

The model wave amplitude for different months is presented in figure 2, while the corresponding observed wave amplitude is shown in figure 3. Comparison of the two figures indicates that our model simulates well the qualitative features of the observed wave for the later winter months (August through October). In both observations and model, the wave amplitude increases with altitude in the lower and middle stratosphere, and the so-called polar night jet descends and shifts poleward. As for the latter feature, the wave amplitude mimics the basic state zonal wind field (cf. Simmons 1974). This mimicking behavior turns out to be a rather robust property in the present model. The phase behavior of the model wave and the direction of the Eliassen-Palm flux (no figures shown here) indicate overall upward and equatorward wave propagation, which is in qualitative agreement with observations.

However, in earlier winter months the agreement between model and observations is rather poor. For instance, the observed wave amplitude in April increases with altitude, but it is approximately constant with height in the model. Similarly, the model wave in June exhibits qualitative differences in comparison with the observed amplitudes. Correspondingly, the seasonal cycle of the model wave amplitude (figure 4) is qualitatively different from the observed cycle (figure 1). The model does not yield the observed relative minimum in mid-winter. Instead, it shows a continuous increase in wave amplitude until late winter. Since the simulation is better in late than in early winter, it appears that the main deficiency of the model is the "missing" relative wave maximum in early winter.

Despite the discrepancies in early winter, the overall model performance encourages a closer analysis to address the questions raised in the introduction. We find that the model results can be consistently interpreted on the basis of refractive index diagnostics, i.e. in terms of wave transmission. For illustration, figure 5 shows the basic state wind field and the refractive index for the two months April and October. The main features of the refractive index are negative values toward the pole and equatorward beyond the critical lines, a ridge-like structure in higher latitudes, a local low altitude minimum in midlatitudes and an overall increase toward the equator. In spite of the overall similarity of the refractive index for different months (as pointed out by Randel 1988), the following more detailed structures turn out to be of key importance: for easy upward wave propagation, and hence for large stratospheric wave amplitude, the higher latitude ridge (acting as a wave guide, see Karoly and Hoskins 1982, Lin 1982) should reach down all the way to the forcing level; the low-level midlatitude minimum (inhibiting wave propagation) should be weak and located more towards the equator; and the refractive index should display a strong poleward gradient. The importance of the low-level refractive index can be illustrated in a plot of its seasonal cycle (figure 6). The figure considers only latitudes between 80°S and 40° S, where the main forcing is located. The similarity with the seasonal cycle of the model wave amplitude (figure 4) is apparent. In connection with a sensitivity study (see below), we modified the basic states for the different months in such a way that the low-level refractive index had a two-peaked structure with a minimum in mid-winter. The resulting wave response showed the same qualitative two-peaked structure, which demonstrates the key importance of the low-level refractive index. Another feature of presumable importance is the cavity-like structure in late winter, which is created through the negative values of refractive index in the higher stratosphere and which might result in resonance and therefore increased amplitudes (Matsuno 1970).

In summary, accepting the above suggested key features in the refractive index, the seasonal cycle of the model's wave appears plausible in the light of the observed seasonal cycle of the basic state. On the other hand, these results draw into question Plumb's explanation of the seasonal cycle. Note e.g. that, in both April and October, the wind maximum in the considered domain is about 50 m s^{-1}. The dramatic differences in wave response between April and October (see figure 2) thus cannot be explained by a one-dimensional consideration of wave propagation relying only on the mean wind.

Since there is considerable sensitivity of the model response with respect to variations in the basic state (cf. Schoeberl and Geller 1977), it is important to check the robustness of our results with respect to such variations. We considered a great variety of basic state modifications and examined the modified response. Particular sensitivity was found with respect to modifications which affect the low-level winds and the jet-structure of the wind field. Modifying the basic state wind in the middle and upper stratosphere resulted in less dramatic changes, and often the response could be rationalized in terms of the mimicking tendency mentioned above. For the low-level modifications, weaker winds generally result in higher low-level refractive index and hence, according to our consistent interpretation, in increased wave amplitudes.

The sensitivity to low-level basic state wind modifications was used for an interesting experiment. We decreased the low-level winds in May and June by 10 m s^{-1}, in April by 5 m s^{-1}, increased them in August by 10 m s^{-1}, and left them unmodified in July, September and October. As a result, the wave amplitude in the middle stratosphere showed a double-peaked structure with a minimum in mid-winter, quite similar to the observed one. However, not all qualitative features of the model wave were in agreement with observations after these sizable and rather arbitrary modifications; the wave amplitude in April and May still did not show the observed growth with height.

To check the sensitivity of our results with respect to the exact treatment of forcing, we replaced our "realistic" lower boundary condition by a constant boundary condition with no seasonal cycle and with no variation in latitude. The qualitative wave behavior turns out to be unchanged. This means that the comparatively weak seasonal cycle in the original lower boundary condition (± 25% during the period April through October) plays a minor role in determining the strong seasonal cycle of the model response.

Therefore, the seasonal cycle of the model can essentially be attributed to a corresponding cycle in wave transmission properties. Also the sensitivity of the model with respect to variation in the damping coefficient was extensively examined. Even though there is some sensitivity (cf. again Schoeberl and Geller 1977, and Schoeberl et al. 1979), the seasonal wave cycle always turns out to have only one peak in late winter.

In summary, the modifications studied here do not suggest that the discrepancies between model and observations can entirely be explained in terms of model sensitivity to dissipation parametrization, to the basic zonal wind, or to the lower boundary condition.

4 Summary and conclusions

The present work studies the seasonal cycle of stationary planetary waves in the southern stratosphere, using a linear, hemispheric model for wave propagation. The model simulates well the qualitative features of the wave dynamics for late winter months. In the higher stratosphere, the wave amplitude displays a strong tendency to mimic the basic state zonal wind field. The model wave can consistently be interpreted with the help of the refractive index, i.e. in terms of the transmission properties of the underlying atmosphere. Specific features in the refractive index turn out to be of key importance, in particular its behavior in the lower stratosphere.

The pronounced seasonal cycle of the model wave is mostly determined through varying transmission properties; the weak tropospheric cycle plays hardly any role. The present model draws into question a qualitative explanation for the seasonal cycle which relies on the one-dimensional Charney-Drazin model.

However, in early winter, there are qualitative discrepancies between the model results and observations. As a consequence, the observed seasonal cycle is not captured by the model. Since the model assumptions seem reasonable at least for a qualitative simulation of the wave behavior, one might question the accuracy of the winds derived from satellite data. In particular for the latitude band between 40°S and 60°S, there are few ground-based data. In fact, the model results show considerable sensitivity to modifications of the lower stratospheric wind in middle latitudes. However, no set of modified basic states was found which was able to reproduce the observed qualitative features of the waves including their seasonal cycle. A more systematic, albeit more cumbersome, approach would be solving the nonlinear, inverse problem. Because of the discrepancies, the present study is not entirely conclusive about the cause of the observed seasonal cycle, even though it strongly suggests that the variation in transmission properties plays a major role.

Acknowledgements

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Figure captions

Figure 1: Seasonal cycle (latitude-time section) of stationary wave amplitude (in m) for zonal wave number 1 at 10 mb (left panel) and 1 mb (right panel). Contour interval: 100 m. Data used are climatological monthly means. The figure is taken from Randel (1987).

Figure 2: Model wave amplitude (in m) for zonal wave number 1 in meridional sections for every other month. Contour interval: 60 m. Note that the lower boundary is at 200 mb.

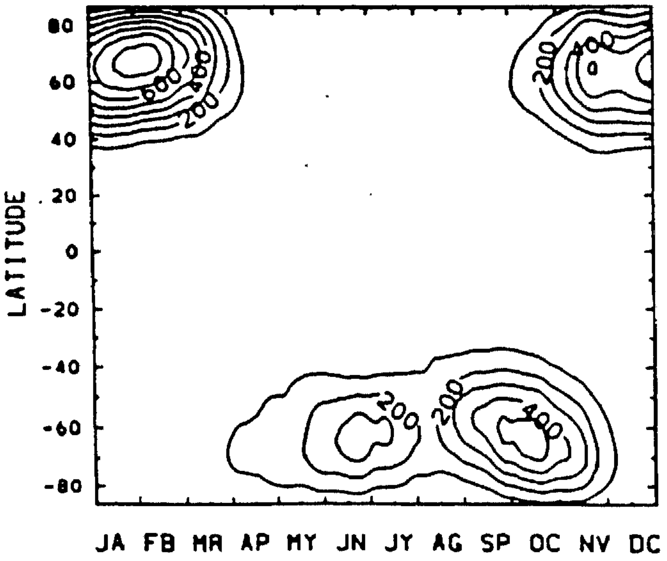
Figure 3: Observed wave amplitude (in m) for zonal wave number 1 in meridional sections for every other month. Contour interval: 60 m above 100 mb, 20 m below 100 mb. Note that the lower boundary of the data is at 1000 mb. The figures are taken from Randel (1987).

Figure 4: Seasonal cycle (latitude-time section) of the model stationary wave 1 amplitude (in m) at 10 mb (left panel) and 1 mb (right panel). Contour interval: 100 m.

Figure 5: Basic state zonal wind (in m s^{-1}; left row) and refractive index (dimensionless; right row) for April and October, meridional sections. Contour interval: 10 m s^{-1} for the zonal wind, 5 for the refractive index. For the refractive index only contours between 0 and 60 are drawn.

Figure 6: Seasonal cycle (latitude-time section) of the refractive index (dimensionless) at 100 mb in the latitude range between 80°S and

40°S. Contour interval: 5. No negative contours are drawn.



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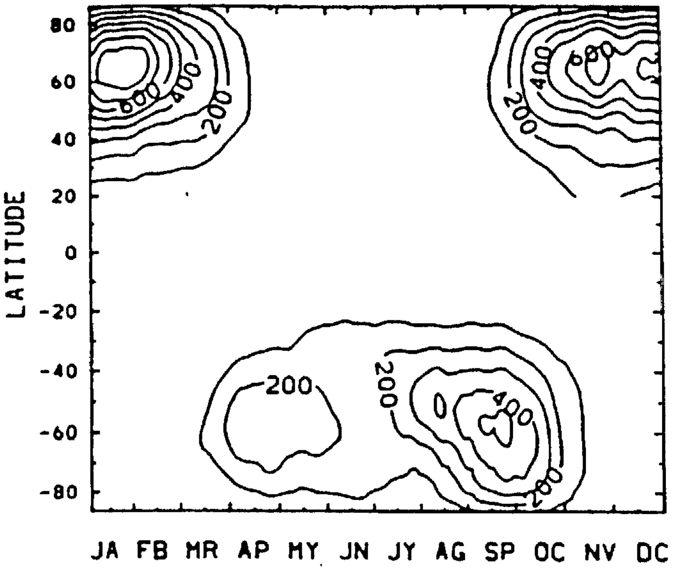

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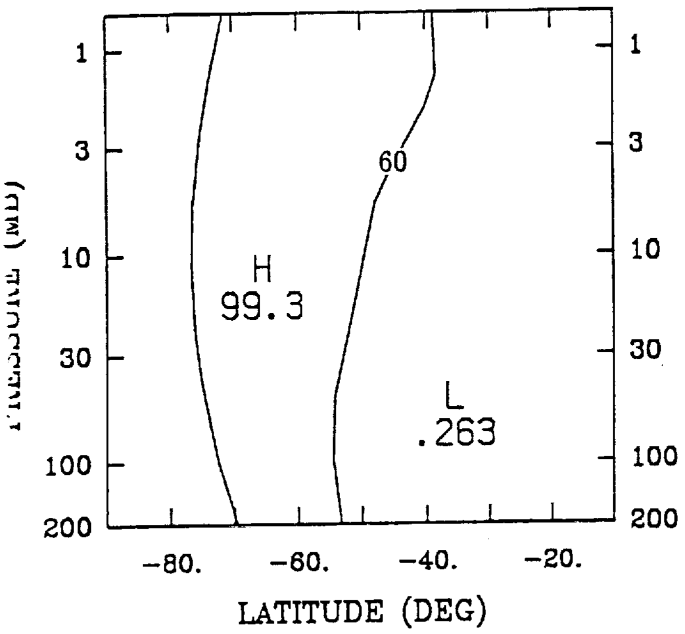

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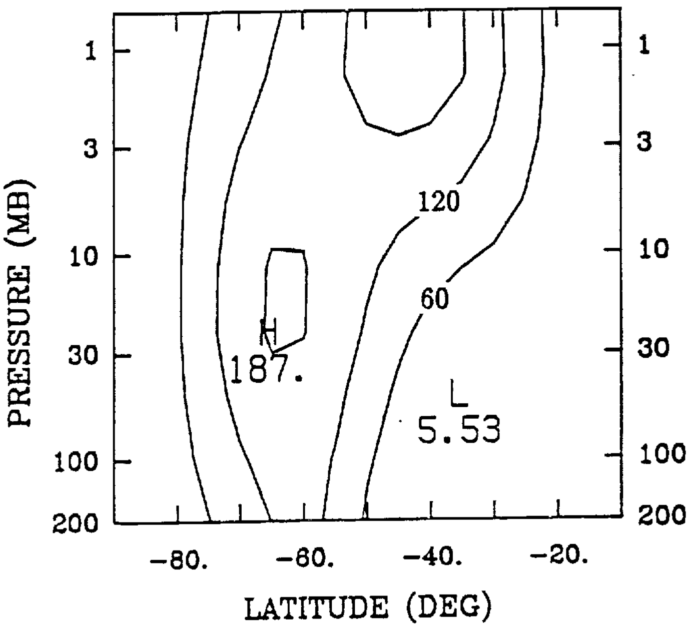

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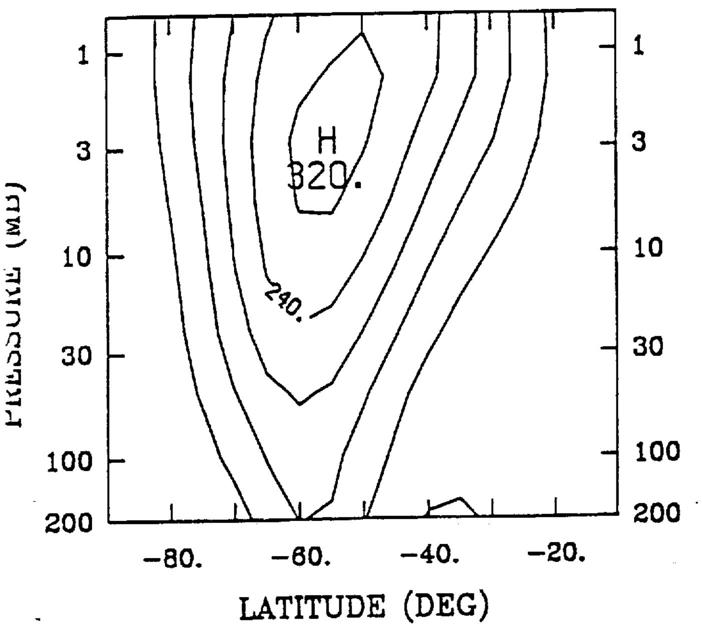

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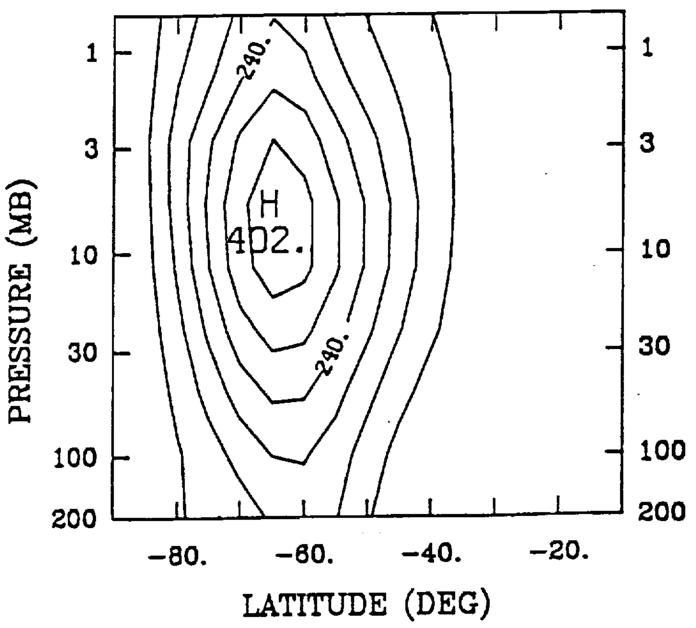

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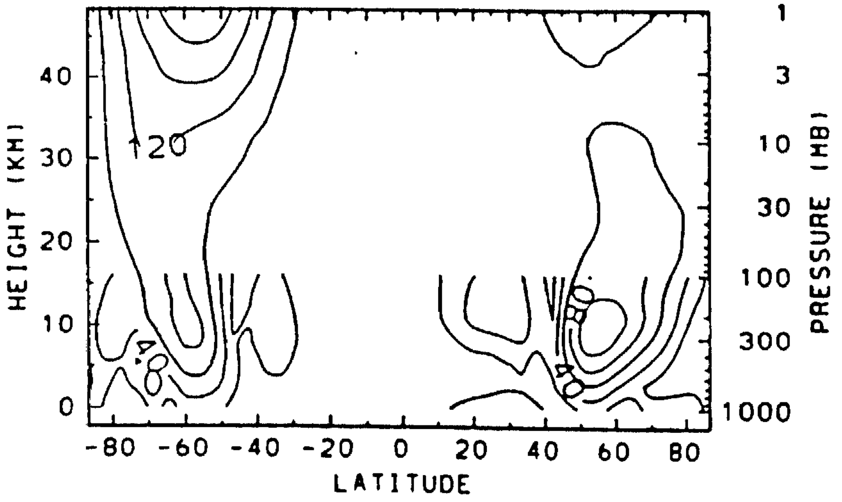

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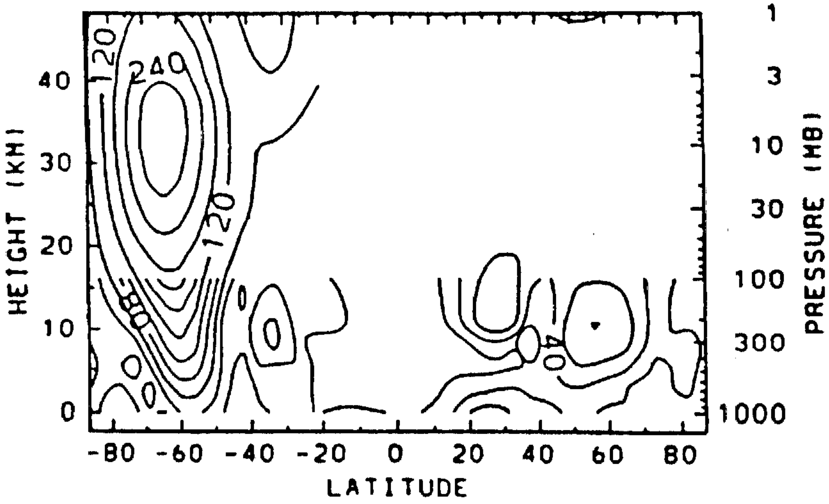

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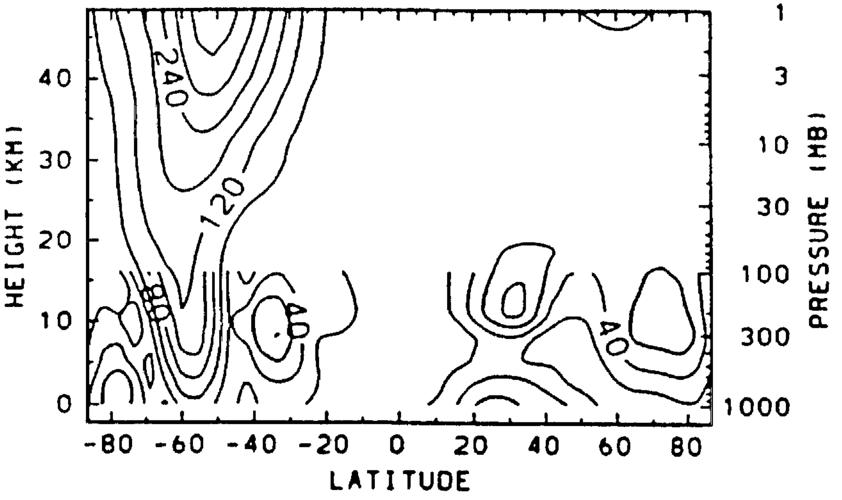

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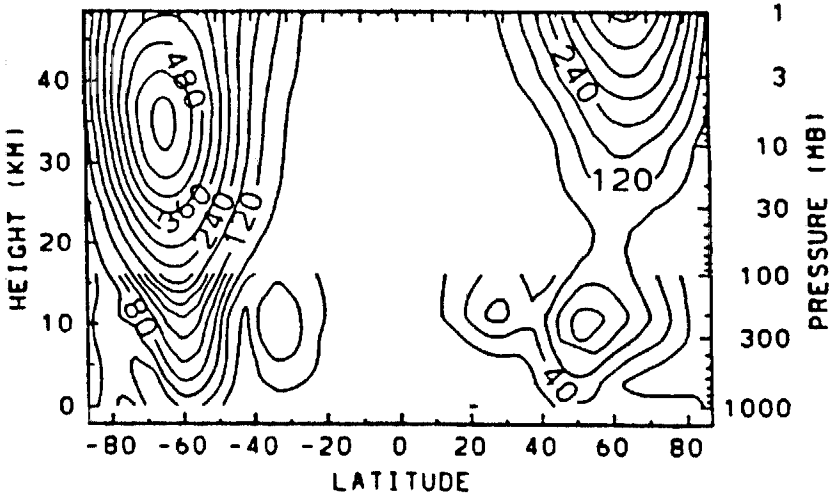

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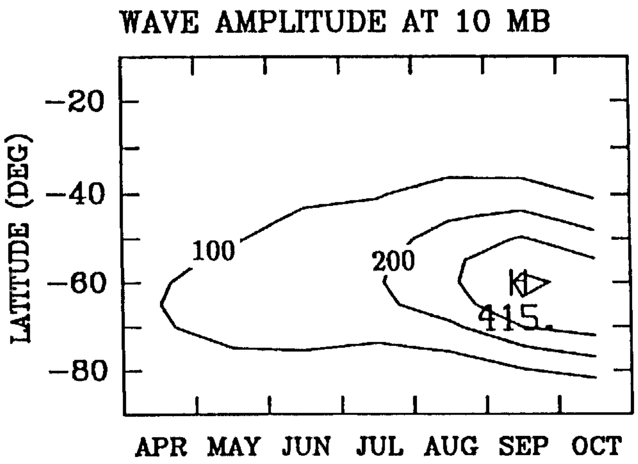

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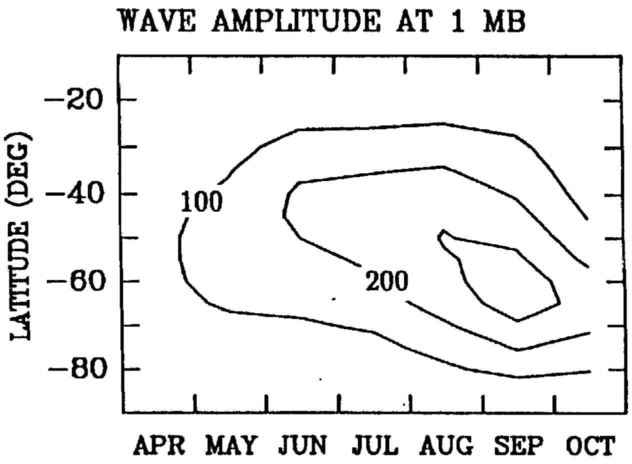

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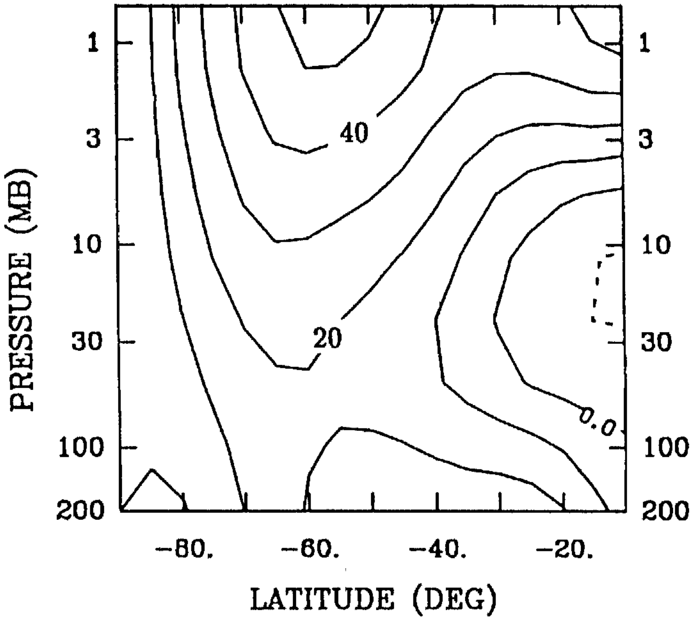

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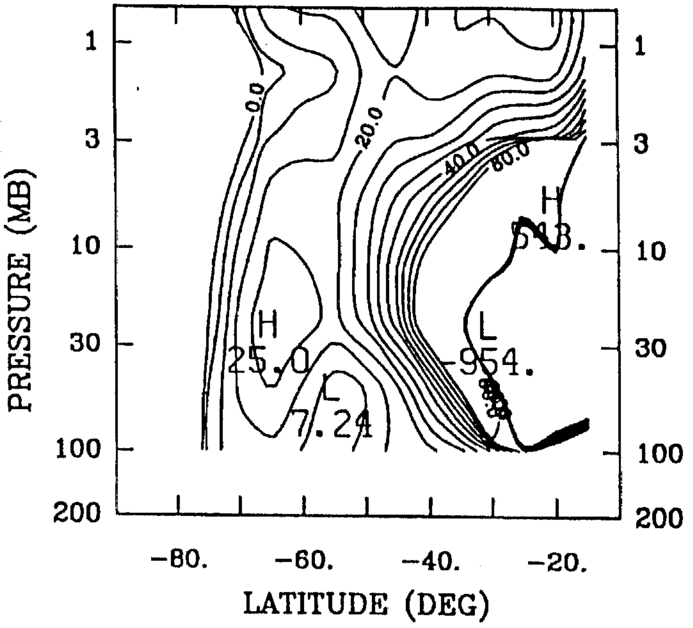

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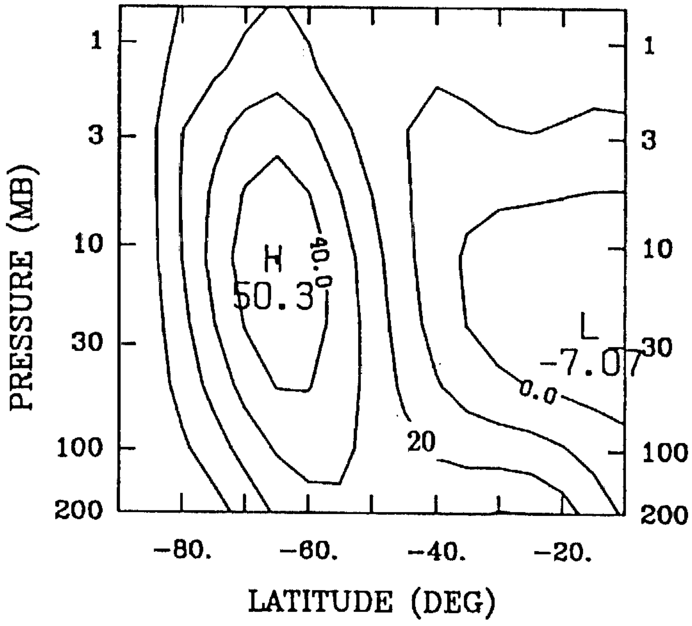

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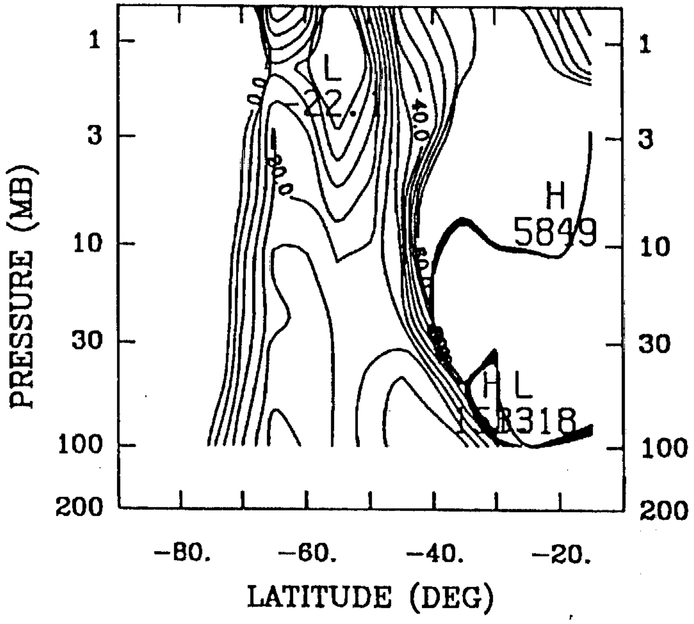

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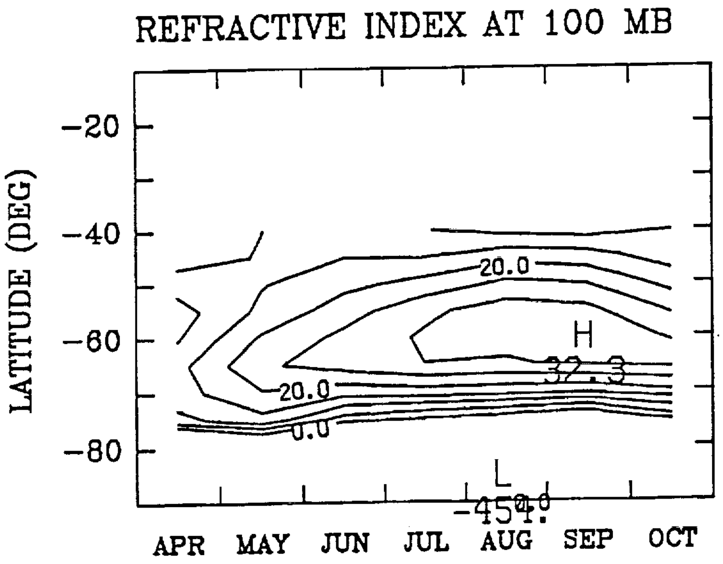
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