A Further Study of the Annual Cycle of the Zonal Mean Circulation in the Middle Atmosphere[1]

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ABSTRACT

The influence on the stratospheric mean circulation of planetary wavenumber 2 disturbances excited by steady forcing at the 100 mb level is investigated using a global semi-spectral primitive equation model. There exists a critical forcing amplitude below which the waves have little effect on the mean flow, while above which the waves produce subseasonal time scale vacillations in the winter hemisphere, including both major and minor warmings. Wave transience induced by the evolving mean flow distribution is responsible for generating the vacillations, while thermal damping serves to reduce the wave-driven changes in the mean flow.

1. Introduction

The mechanistic model proposed by Matsuno (1971) is generally believed to provide at least a qualitatively correct description of the dynamics of sudden stratospheric warmings [for a review see Holton (1980)]. In Matsuno's model the warming is generated by wave-mean flow interactions associated with vertically propagating planetary waves forced in the troposphere. According to the so-called "non-acceleration theorem" (Andrews and McIntyre, 1976; Boyd, 1976) such wave-driven mean flow changes can occur only in the presence of wave transience (time rate of change of wave amplitude) or wave dissipation. In Matsuno's model, mean flow deceleration results primarily from wave transience imposed by the initial switch-on of the wave forcing. However, if the mean flow in the stratosphere is time varying, then vertically propagating waves with steady forcing will have transient components because the refractive index governing vertical propagation is a function of the mean wind (Charney and Drazin, 1961) and hence will be time varying. Thus, it is not clear whether the generation of stratospheric warmings *requires* time varying wave forcing in the troposphere,[2] or whether wave transience associated with mean wind variations in the stratosphere might produce sudden warmings in the presence of steady forcing.

The latter possibility, which Plumb (1981) has interpreted as a finite-amplitude instability, was first investigated by Holton and Mass (1976) in the context of a β-plane channel model. They found that there was a critical amplitude of the wave forcing below which the mean flow always evolved toward a radiative equilibrium state, and above which the mean flow underwent repeated sudden warming sequences which Holton and Mass called "stratospheric vacillations." In a subsequent note Holton and Dunkerton (1978) showed that the critical wave-forcing amplitude in the Holton and Mass model depended sensitively on the mean wind profile throughout the stratosphere, with weak mean westerlies providing the lowest values of the critical forcing.

The Holton-Mass model is a highly idealized β-plane channel model in which only a single cross channel wave mode is retained. In this model the flux of wave activity, as measured by the Eliassen-Palm flux (Edmon *et al.*, 1980), is directed purely vertically; while in the atmosphere the flux of wave activity in the winter stratosphere normally has an equatorward component (Dunkerton *et al.*, 1981; Palmer, 1981). Therefore the wave-driven mean flow acceleration at high latitudes, as measured by the convergence of the Eliassen-Palm flux, tends to be exaggerated in the Holton-Mass model. However, Schoeberl and Strobel (1980a,b) have shown that vacillations can occur in a quasi-geostrophic model which permits lateral wave propagation. In this note, similar stratospheric vacillations are investigated using a primitive equation model with an annual cycle.

Holton and Wehrbein (1980a, hereafter referred to as HW) reported an annual cycle integration of a global primitive equation model of the middle atmosphere in which a single forced wave disturbance of zonal harmonic wavenumber 1 was permitted to interact with the zonal mean flow. In HW the wave forcing amplitude at the lower boundary (100 mb) was held constant in time and had a specified latitudinal profile symmetric about the equator. Thus, wave-driven mean flow accelerations were determined only by dissipation and by transience due

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[2] Observed sudden warmings often seem to be associated with planetary wave anomalies in the troposphere but no simple relationship between tropospheric forcing and stratospheric warmings has been observationally established.

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to the time dependence of the mean flow forced by the annual cycle in diabatic heating. In the HW wavenumber 1 simulation no midwinter sudden warmings occurred. However, final warmings appeared in the spring in both hemispheres. These final warmings were produced by transience and dissipation associated with large increases in the wave amplitude as the waves adjusted to the weakening westerlies of the spring season. Thus, the simulation of HW did not provide conclusive evidence that the Holton-Mass vacillation process could occur in a global primitive equation model—much less in the atmosphere.

Numerous studies (e.g., Matsuno, 1971; Holton, 1976; Schoeberl and Strobel, 1980a) have demonstrated that when only a single zonal harmonic wave is allowed to interact with the mean flow, wavenumber 2 forcing produces warmings more readily than wavenumber 1 forcing. Thus, it is not clear whether the absence of midwinter warmings in the HW model is due to a lack of time variations in the forcing or whether for the conditions of that model the forcing was subcritical, despite its rather large amplitude (300 m geopotential perturbation at 60° latitude at the 100 mb level).

The purpose of this contribution is to briefly present results from two additional annual cycle runs of the HW model which examine the role of wavenumber 2 forcing.

2. A comparison of the annual cycle for subcritical and supercritical wave forcings

The model used here for the annual cycle simulations was identical to that of HW except that the forced wave has zonal wavenumber 2 instead of 1. Two cases were run. In case A the forcing amplitude at the lower boundary was 200 m, in case B it was 250 m. In both cases the forcing was held constant in time after a transient switch-on period of ~5 days. As in HW, the meridional profile of the forcing was symmetric about the equator with maxima at ±60° latitude.

The model was initialized with barotropic mean zonal winds corresponding to the 100 mb mean zonal winds at the Northern Hemisphere autumnal equinox and run with annually varying diabatic forcing for 530 days in case A and 570 days in case B. The results are displayed in Figs. 1–3 in the form of latitude-time sections for zonal mean temperature at the 33.5 km level, mean zonal wind at the 51 km level, and quasi-geostrophic potential vorticity flux[3] at the 51 km level. It is easily seen that case B exhibits far greater variance on the subseasonal time scale than does case A. In fact, the temperature and wind fields of case A are remarkably similar to those of the zonally symmetric model of Holton and Wehrbein (1980b), especially in the Southern Hemisphere.

The quasi-geostrophic potential vorticity flux exhibits strong asymmetries between the two hemispheres in both cases. In the low-amplitude forcing case (Fig. 3a) the forced waves are unable to propagate vertically in the presence of the strong westerly jet of the Southern Hemisphere winter. Thus, significant potential vorticity fluxes are limited to a brief period during the spring when the mean winds are weak and westerly. In the high-amplitude forcing case (Fig. 3b) mean wind deceleration equatorward of ~45°S latitude due to wave transience during the autumn retards the development of westerly mean flow. Consequently, the polar night jet is restricted to a narrower latitude band than in case A. This apparently changes the index of refraction for wave propagation sufficiently so that the waves are able to propagate vertically for the entire winter. However, even in this case the waves have relatively little effect on the polar temperature field until after the spring equinox when a strong transient wave pulse produces a "final warming."

In the Northern Hemisphere, there is a dramatic difference between cases A and B. Although the waves propagate vertically throughout both the first and second simulated winters of case A, the potential vorticity flux remains weak and positive at high latitudes (except for a brief period at the spring equinox) and the zonal mean temperature field evolves much like that of the Holton and Wehrbein (1980b) zonally symmetric model. Apparently, in case A the wave-mean flow nonacceleration theorem is approximately valid for most of the winter season. Wave transience is weak and the large vertical scale of the waves renders thermal damping rather ineffective. In case B, however, the flow undergoes substantial transient subseasonal oscillations, including both major and minor stratospheric warmings. This behavior somewhat resembles the vacillation regime in the Holton and Mass (1976) β-plane channel model, although in the present model the vacillations lack the regularity of those on the β-plane. Thus, we conclude that there is a critical wave-forcing amplitude, dependent on the mean wind profile, above which midwinter sudden warmings occur spontaneously in the model without the presence of transience due to a switch-on of the wave forcing. These results are in accord with the conclusions of Schoeberl and Strobel (1980a) who found that their quasi-geostrophic model produced vacillations for wavenumber 2 forcing amplitude of 300 m, but not for forcing amplitude of 200 m.

It might be argued that the vacillations in the pres-

[3] The term "potential vorticity flux" as used here actually denotes the *magnitude* of the meridional component of the flux of quasi-geostrophic potential vorticity. It is approximately proportional to the divergence of the Eliassen-Palm flux (Dunkerton *et al.*, 1981) and is therefore an excellent measure of the effect of the waves on the mean flow.

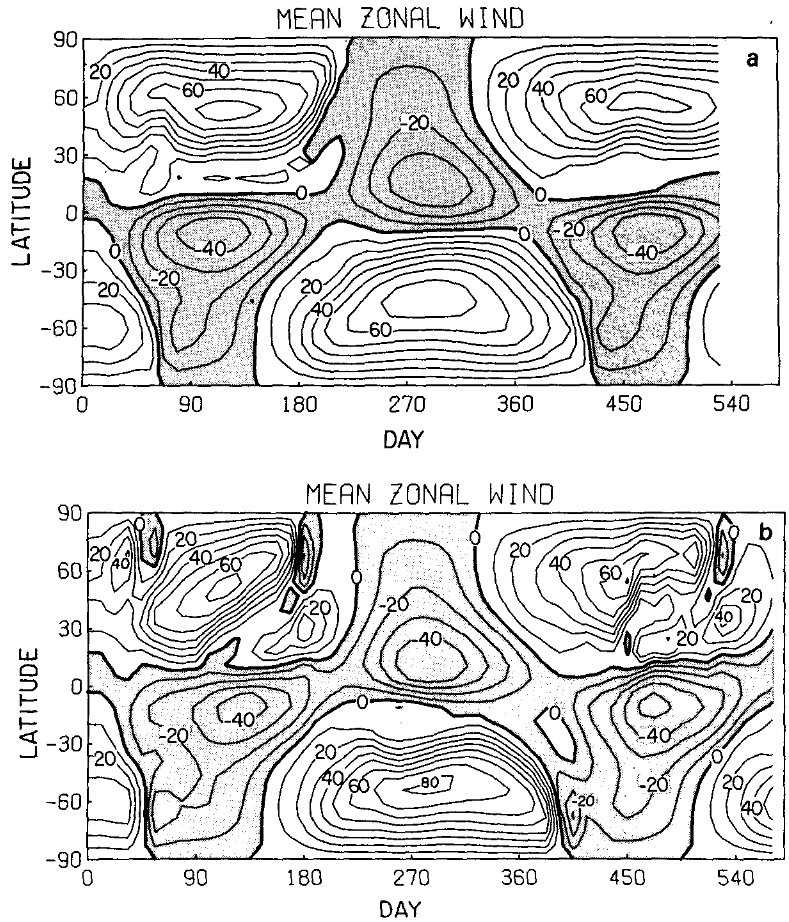

FIG. 1. Time-latitude sections of the mean zonal wind (m s^{-1}) at the 51 km level for (a) subcritical forcing and (b) supercritical forcing. Easterlies are shaded. A 360-day year is used for simplicity. Day 0 corresponds to the Northern Hemisphere autumn equinox.

ent model are somehow excited by the annual cycle. To demonstrate that this is not the case we did a control run in which the solar heating field was held constant from day 90 onward (i.e., perpetual Northern Hemisphere winter solstice). For forcing conditions corresponding to case B vacillations still occurred, although their development was delayed ~10 days.

These results highlight the importance of understanding the processes responsible for variations of the stationary wave amplitude near the tropopause. Resolution of this problem apparently will require a much better observational and theoretical understanding of tropospheric planetary waves than currently exists.

3. The Northern Hemisphere winter warmings

In case B there are sudden warmings in both of the simulated Northern Hemisphere winters. Three major warmings may be identified in Fig. 2b. These occur near days 45, 180 and 530. The latter two may be considered final warmings because the westerly polar jet stream is not reestablished following the warmings. The early winter warming at day 45 is clearly a response to the transient switch-on of the wave forcing, and is thus analogous to warmings simulated in several previous studies (e.g., Matsuno, 1971; Holton, 1976). Note that no such warming occurs in the second year of the simulation.

In addition to these major warmings there is a minor warming around day 450. This warming is initiated by a large increase in the wave potential vorticity flux which modifies the mean flow sufficiently so that the waves can continue to propagate with enhanced amplitude until the time of the final warming at day 540.

Fig. 3b indicates that during both Northern Hemisphere winters the wave potential vorticity flux field during the prewarming stage is split into a positive region near the pole and a negative region in middle latitudes. Since the potential vorticity flux is ap-

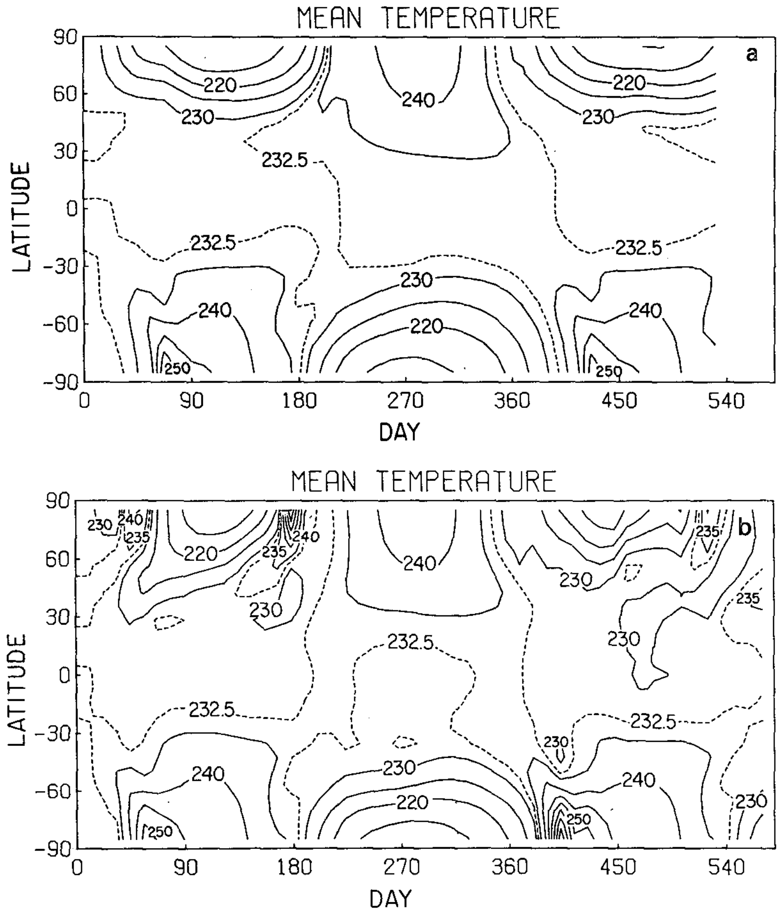

FIG. 2. Time-latitude sections of the zonal mean temperature field (K) of the 33.5 km level for (a) subcritical forcing and (b) supercritical forcing.

proximately equal to the wave forcing of the mean zonal wind (Andrews and McIntyre, 1976; Holton, 1980; Dunkerton *et al.*, 1981), the waves tend to accelerate the mean wind in the polar region and decelerate it in midlatitudes. As the prewarming stage progresses the region of positive potential vorticity flux gradually contracts and finally disappears with the onset of the polar warming. Comparison of Figs. 1b and 3b indicates that the zero contour of potential vorticity flux coincides closely with the latitude of maximum mean zonal wind during the prewarming periods of both winters. However, this holds only near the 51 km level, and probably does not reflect any fundamental physics.

The occurrence of a region of positive quasi-geostrophic potential vorticity flux (e.g., Eliassen-Palm flux divergence) in the polar stratosphere during the winter season is not unique to this model but occurs in stratospheric general circulation models (Mahlman, personal communication) and in observational data (Edmon *et al.*, 1980). In our model this flux divergence is not directly related to thermal damping or wave transience. However, we have been unable to determine the physical processes responsible for this peculiar upgradient potential vorticity flux.

Andrews and McIntyre (1976) have stressed the roles of dissipation and transience in wave-driven mean flow acceleration, and have shown that the two processes can be formally separated in an expression for the mean flow forcing. A similar separation of transience and dissipation was given by Holton and Dunkerton (1978) for a quasi-geostrophic β-plane model. In an attempt to elucidate the relative roles of transience and damping in the present model we have utilized the spherical coordinate form of Holton and Dunkerton's formula. The results (not shown) indicate that in the present model transience and damping appear to contribute almost equally although the transience contribution is rather noisy and hence difficult to evaluate without time averaging. However, the formal separation of transience and damping may be somewhat misleading. Through reduction in wave amplitude, damping will itself tend to reduce the role of transience (which depends on the time rate of change of the wave-amplitude

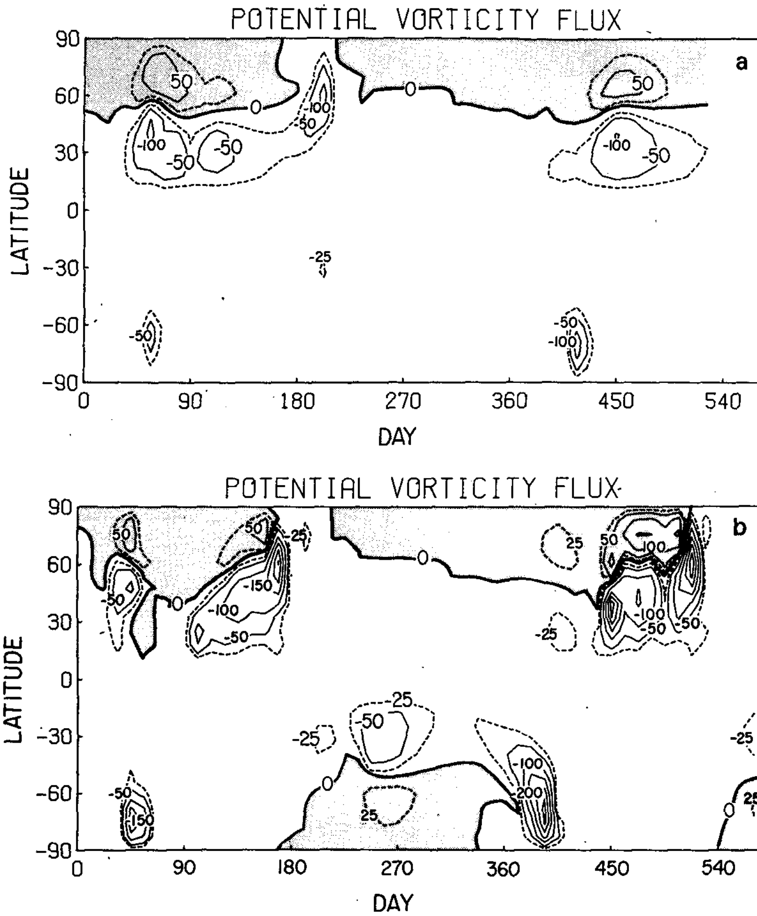

FIG. 3. Time-latitude sections of the zonal mean quasi-geostrophic potential vorticity flux (10^{-6} m s^{-2}) at the 51 km level for (a) subcritical forcing and (b) supercritical forcing. Regions of positive flux are shaded.

squared). Therefore, damping might indirectly serve to reduce the wave-driven mean flow acceleration by modifying the transience term! We have verified that this is indeed the case in the present model by performing an additional 140-day integration identical to case B except that the thermal dissipation of the waves was set to zero.[4] In this case the warming caused by the initial switch-on occurred ~5 days earlier than in case B and the polar temperature change at the 38.5 km level more than doubled from ~13 to 32°C. Perhaps more significantly the second warming occurred not as a final warming near the spring equinox as in case B, but at day 135 (i.e., early February). Again, the amplitude of the warming more than doubled compared to that in case B (~72°C vs ~33°C at 38.5 km and 85°N). These results seem to confirm that wave transience is the crucial physical driving mechanism for the sudden warmings and that dissipation, in fact, may tend to reduce the magnitude and frequency of warming events, at least in this model.

Schoeberl and Strobel (1980a), on the other hand, have emphasized the role of meridionally propagating zero mean wind lines (critical lines) which seem to be associated with wavenumber 2 warmings in most simulations (e.g., Matsuno, 1971; Holton, 1976; Hsu, 1981). The dynamical role of critical lines during strongly transient events is not yet understood. However, it does seem clear from both observational studies (O'Neill and Taylor, 1979; Palmer, 1981) and the above cited theoretical studies, that lateral propagation associated with horizontal momentum fluxes is crucial to the evolution of wavenumber 2 warmings.

4. Conclusions

We have shown that for steady wave forcing at the 100 mb level greater than some critical amplitude, wave transience induced by seasonal variations

[4] Frictional damping was maintained, but it had a very long time scale below 50 km.

in the mean wind profile leads to strong vacillations in the mean flow including both major and minor model stratospheric warmings. The model used in this study is quasi-linear in the sense that only a single wave mode is allowed. This wave interacts with the mean flow, but wave-wave interactions are neglected. The studies of Hsu (1981) and Lordi *et al.* (1980) indicate that interactions between zonal wavenumbers 1 and 2 are quantitatively important for the evolution of sudden warmings.

It seems likely that a model with better spectral resolution might exhibit behavior similar to that reported here, but that the forcing amplitude necessary to produce vacillating behavior would be lower than in the present model. In particular, wavenumber 1 forcing should be much more effective in producing warming events in a model which allowed the development of wavenumber 2 by the self interaction of the forced wavenumber 1.

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