Stratospheric Warmings: Observations and Theory

MARK R. SCHOEBERL

Naval Research Laboratory, Washington, D. C. 20375

Winter stratospheric warming observations and associated theories are reviewed. Historically, major warmings occur on the average every other year and may thus be considered an important climatological component of the winter stratosphere. The warming results from eddy heat transport from equatorial latitudes into the polar regions. The eddies chiefly responsible for the transport are the planetary scale waves which may attain amplitudes twice their monthly average values in the lower stratosphere prior to the warming. In the troposphere this amplitude increase is associated with the development of blocking patterns. The warming is shown to have a strong nonzonal component in the upper stratosphere, a feature not fully recognized by modelers. The critical level theory of the sudden stratospheric warming provides a simple dynamic explanation of the event. Yet mechanistic numerical models which have reproduced many features of the warming exhibit results which tend to indicate that the interaction of planetary waves and the mean flow occurs through a variety of mechanisms including transient and damping. The close connection between blocking in the troposphere and the development of the sudden warming is likely to be a result of resonance of free planetary waves in a stratospheric wind cavity.

INTRODUCTION

The discovery of the sudden stratospheric warming is credited to Scherhag [1952], who noted a sudden increase in the radiosonde 10-mbar temperature over Berlin on January 30, 1952. However, the extent of the warming phenomena was unknown until the late 1950's, when a sudden stratospheric warming took place over the American radiosonde network in January 1957. This event allowed Teweles [1958], Craig and Hering [1959], and Lowenthal [1957] to make a partial synoptic picture.

From the analysis of the 1957–1958 event by Teweles and Finger [1958] and Scherhag [1960] as well as studies of the 1956–1957 event it became evident that the stratospheric warming was a phenomenon involving the very largest zonal harmonic disturbances, the planetary waves. It is not surprising then that the more successful theoretical investigations of the sudden warming have centered on the dynamic properties of planetary waves. Charney and Drazin [1961] showed that stationary planetary waves could penetrate the stratosphere only during winter when the winds are moderate and westerly (blowing to the east). However, attempts to show that the warming might be a result of baroclinic instability with amplification of planetary scale waves have failed [Murray, 1960; McIntyre, 1972]. Matsuno [1971] suggested an alternate mechanism; the warming is generated through the interaction of the zonally averaged circulation with planetary waves along critical levels. His numerical model successfully reproduced many sudden warming features when planetary wave amplitudes were suddenly increased in the troposphere. Similar models have since confirmed Matsuno’s results [Holton, 1976].

The sudden warming must be considered in the context of the entire winter stratospheric circulation, which is qualitatively summarized below. After the fall equinox the heating at high latitudes due to ozone absorption of UV radiation decreases as the polar night expands equatorward. Temperatures over the winter pole decline, and strong westerlies develop, driven by the meridional temperature gradient between the equator and the pole and the Coriolis force. Part of the atmospheric response to the cooling of the polar regions is the development of a mean circulation cell in which air descends over the winter pole and rises over the summer pole [Leovy, 1964; Schoebert and Strobel, 1978]. These motions compensate for the radiative imbalance in the atmosphere through adiabatic processes which result in a reversal of the meridional temperature gradient in the mesosphere and weakening of the westerlies above the stratosphere. The core of strong westerly winds which thus forms in the upper stratosphere is called the 'polar night jet' or 'polar vortex.'

In addition to the radiatively forced mean circulation, cell eddies which form in the troposphere through baroclinic, orographic, and diabatic processes propagate vertically and perturb the stratospheric circulation. The most important of these eddies at mid-latitudes are large-scale quasi-stationary waves with zonal harmonics 1 and 2, commonly referred to as planetary waves [van Loon et al., 1973]. The mean circulation corresponds to zonal harmonic 0.

As the planetary waves propagate vertically, they transport heat and momentum from mid-latitudes into the polar regions. For a time harmonic planetary wave perturbation in an inviscid atmosphere the convergence of the associated eddy heat and momentum fluxes does not alter the mean circulation, since their effects exactly cancel [Charney and Drazin, 1961]. However, this cancellation in the stratosphere is to some extent negated by diabatic damping, nonlinear effects as well as the observed transience of planetary waves during winter [Hirota and Sato, 1969; van Loon et al., 1975]. Oscillations in planetary wave amplitude and the strength of the mean zonal wind in the lower stratosphere are observed to correlate well. This indicates strong planetary wave–zonal flow coupling through eddy heat transport [Madden, 1975]. The oscillation period for the mean flow–planetary wave system appears to center on 2 weeks. More recently, Madden [1978] has shown that the oscillation is a result of a free planetary wave moving westward with a 16-day period. As this free wave moves in and out of phase with the stationary planetary wave, it enhances and depletes the wave amplitude and the northward transport of heat associated with the stationary wave. This results in a fluctuation of the zonally averaged temperature gradient and a resultant oscillation in the mean zonal wind.

Occasionally, a very large planetary wave amplitude pulse is observed in the stratosphere, often associated with the depl-
Fig. 1. Development of a sudden warming at the 2-mbar pressure level [from Miller et al., 1972]. Heights are in decameters, and temperatures in degrees Celsius. Wind flags give the direction in knots, 50 kn (25 m s^{-1}) for a full flag, 10 kn (5 m s^{-1}) per line. (a) Prewarming vortex with a weak Aleutian anticyclone over Japan. (b) Intensification of the anticyclone and displacement of the polar vortex (strong growth of planetary wave number 1). (c) Full warming. Temperatures have risen 25°C at the pole; the polar low has been displaced by a weak high-pressure system; and the wind field is no longer zonal. (d) Postwarming restoration of the vortex. Temperatures have fallen to prewarming values, and the polar low is reforming.
Fig. 1. (continued)
OBSERVATIONAL ASPECTS OF SUDDEN WARMINGS

This section is concerned with the climatology of the sudden warming, classification of warming events, and details of the processes which occur during a 'typical' warming.

Climatology of Warmings

In Table 1 a partial list of past winters is given with regard to the occurrence of sudden stratospheric warmings in the northern hemisphere. The table shows the type of warming, month of warming, temperature change over the pole at 10 mbar, and literature references for early events. Over the period shown in the table, major warmings occur on the average every other year, the longest interval between major warmings being 4 years. Major and minor warmings seem to exclude each other consistently, with the exception of the 1951-1952 and 1974-1975 major and minor warmings. The average temperature difference at 10 mbar between major and minor polar warmings is about 30ø, which clearly illustrates the difference in the magnitude between the two types. Canadian warmings which appear in the table have been defined by Labitzke [1977a] as minor warmings with a strong nonzonal character.

From the monthly statistics shown in Table 1 it is evident that January and February are prime months for occurrence of both major and minor warming events. Each year shows either a single major warming or a series of minor warmings (or a single minor warming). We may conclude from this evidence alone that warmings are of integral importance to winter stratospheric climate.

Prewarming Stage

Figure 2 [from Labitzke, 1977a] shows the planetary wave amplitude for zonal harmonics 1 and 2 at 60øN as well as the zonally averaged 30-mbar temperature differences between 80øN and 50øN (typically -10°C to -20°C) for 13 winters. Note that in all cases shown, there is a strong correlation between amplifying planetary waves and the occurrence of either a major or a minor warming a week or so thereafter. Major warmings and most minor warmings tend to occur only in the presence of an intense polar vortex or strong vertical shear of the zonal wind (defined by ΔT in Figure 2). A necessary condition for a major warming appears to be the presence of a wave number 1 amplitude exceeding 700 m at 30 mbar for several days. Labitzke [1977a] has noted that wave number 2 appears to be incapable of generating a major warming by itself.

Quiroz et al. [1975] have classified the prewarming behavior of planetary waves according to the zonal trajectories of local warm cells which appear in the radiance data. These warm cells, or thermal centers, are the temperature perturbations associated with the planetary waves. In the 'type I' warming, the thermal center moves zonally until it merges with a stationary thermal center associated with the Aleutian anticyclone. The warming develops as the two thermal centers amplify and move poleward. In the 'type 2' warming, stationary zonal wave number 2 amplifies and moves poleward with little phase change. The events as classified by Quiroz et al. [1975] appear in Table 1. It is interesting to note that no type 2 warmings have occurred in the last half of the measurement period given. The relatively poor data base prior to 1964-1965 is probably not sufficient to determine accurately the zonal trajectories of thermal centers and thus to classify warmings according to type.

Using Labitzke's [1977a] results from Figure 2, we may identify two types of wave amplitude behavior in the prewarming period, type A and type B. Idealized examples of these two types are shown in Figure 3. Type A is characterized by the following sequence. First, intensification of wave number 2 occurs about 2 weeks before the onset of the major warming. This is closely followed by an increase in the amplitude of wave number 1 with a subsequent weakening of wave number 2. Wave number 1 reaches a peak about 1 week prior to the warming. Following the warming, wave number 1 decreases in amplitude, and wave number 2 intensifies again.
TABLE 1. Northern Hemisphere Stratospheric Warming History

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<th>Number</th>
<th>Month</th>
<th>AT, K</th>
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<th>Number</th>
<th>Month</th>
<th>AT, K</th>
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Years prior to 1964-1965 have a low-quality data base with the possible exception of 1957-1958, which contains IGY data (K. Labitzke, personal communication, 1977). AT indicates the increase in polar temperatures at 10 mbar [McInturff, 1978].

Examples which appear to fall into the type A category are seen in Figure 2 for winters 1967-1968, 1970-1971, 1972-1973, 1976-1977, and late 1973-1974 for major warmings or final warmings. This pattern is also apparent for minor warmings which occurred in 1964-1965 and 1971-1972.

In a type B warming, planetary wave number 1 maintains a large amplitude for a long period. The 1969-1970 major warming is the best example of a type B warming. Type B minor warmings occurred in 1968-1969 and 1974-1975. Type A is the more frequent type of warming.

**Vertical Structure of the Sudden Warming**

One of the well-known characteristics of a sudden warming event is the downward propagation of a warm layer from about 45 km into the lower stratosphere as seen by single-station rocket measurements and satellite radiance data [Scott, 1972; Quiroz, 1969, 1971]. It is generally assumed that this downward propagating warm layer is attributed to changes in zonally averaged thermal structure [Matsumo, 1971], but recent evidence indicates that the warming may be highly nonzonal, as was first suggested by Hirota [1968]. Figure 4a [from McInturff, 1978] shows a synoptic description of the 1973-1974 major warming. The warming reaches its maximum intensity (AT = 70 K) near 65°N and 110°E, and the presence of a strong thermal planetary wave imbedded in the flow is clearly indicated. The eastward motion of the thermal center shown by the arrow in Figure 4a is motion in the postwarming period. In the prewarming phase the thermal center tends to move westward. Hirota [1968] noted that a westward tilted thermal wave, slowly drifting westward (which is consistent with the type 1 description given by Quiroz et al. [1975]) will produce a downward propagating warming, as single stations observe. Barnett et al. [1971] has noted exactly this process during satellite monitoring of the 1970-1971 major warming. Figure 4b [from Labitzke, 1977b] tends to confirm the importance of nonzonal thermal waves in the warming structure. It is also apparent from Figures 4a and 4b that an important zonal mean temperature increase is associated with the warm-
Fig. 2. Values of the zonally averaged 30-mbar temperature difference $\Delta T$ between 80°N and 50°N (dashed lines) and daily values of the amplitude $m$ of zonal harmonics 1 (heavy line) and 2 (light line) at 60°N for the years 1964–1977 [after Labitzke, 1977a].
conversion processes were generally larger during winter. Oort [1971] for 1964. Their results showed that the energy eddies increase the zonal available potential energy $\Delta L$, while calculated by Oort [1964] for the IGY (1957-1958) and Doppl- found that in the 100- to 30-mbar layer the planetary scale transport momentum and exchange of kinetic energy, $C$. A similar analogy can be made for the energy lessens, and $C_A$ points from $A_L$ to $A_E$, increasing wave temperature gradient, then the wave acts as a refrigerator, increasing the temperature gradient and the zonal available potential energy $A_L$, while losing eddy available potential energy $A_E$ in the process. In this case, $C_A$ points from $A_E$ to $A_L$. The reverse situation occurs when the wave transports heat along a negative mean poleward temperature gradient: The mean temperature gradient is reduced, so the zonal available potential energy lessens, and $C_A$ points from $A_E$ to $A_L$, increasing wave energy in the process. A similar analogy can be made for the transport momentum and exchange of kinetic energy, $C_E$.

The annual energy cycles for the stratosphere have been calculated by Oort [1964] for the IGY (1957-1958) and Dopplick [1971] for 1964. Their results showed that the energy conversion processes were generally larger during winter. Oort found that in the 100- to 30-mbar layer the planetary scale eddies increase the zonal available potential energy $A_L$, while Dopplick found that in the 100- to 10-mbar layer the eddies reduce $A_L$. The differences in these calculations may be due in part to the contribution of the 30- to 10-mbar layer, but it is also interesting to note that 1957-1958 was the year of a major warming, while 1964 contained only minor events. Van Loon et al. [1973] have shown that for five Januarys from 1965 to 1969 the planetary waves 1 and 2 dominate the eddies above 100 mbar and transport heat northward (tilt westward with height) on a monthly mean. Thus Oort's calculation suggests that the temperature increases poleward, presuming that the eddies transport heat northward on the average. This is exactly the condition which is observed following a major warming [Julian and Labitzke, 1965]. Dopplick's calculation indicates that zonal mean temperature decreases northward throughout most of the winter, again presuming that the eddies transport heat northward. This is consistent with the warming history of 1964.

In the study by Julian and Labitzke [1965] of the 1962-1963 event shown in Figure 5 the prewarming energy conversions are generally similar to the Dopplick annual cycle: Planetary waves gain energy in the stratosphere at the expense of the zonally averaged temperature gradient. Note also the large amount of eddy energy flowing from the troposphere, indicating that the troposphere plays a significant role in driving the stratospheric eddies in the prewarming phase. In the post-warming period the troposphere still drives the stratospheric eddies, but the waves transport heat against the now reversed poleward temperature gradient and lose energy to the zonal mean flow.

Another interesting aspect of the energy calculations shown in Figure 5 is the term $C_n$, which indicates the direction of the zonally averaged vertical motion field. In Dopplick's annual cycle, $C_n$ increases $A_n$, which implies that the zonally averaged flow is upward at the pole and downward at middle and low latitudes when the zonally averaged temperature decreases toward the pole. This type of motion field is consistent with Mahlman's [1969] analysis. Physically, the zonally averaged vertical flow increases the mean temperature gradient by adiabatic cooling of rising air and heating of subsiding air. In the prewarming phase shown in Figure 5, there is definitely rising motion over the poles and generation of $A_n$, but in the post-warming phase the sign of the conversion term reverses, so $A_n$ is destroyed. The motion field has not changed in the post-

Fig. 3. Two idealized warming sequences constructed after data presented in Figure 2.
warming phase, but instead, the temperature gradient has reversed. The zonally averaged motion field thus tends to cool the warm polar region and heat the cooler mid-latitudes, destroying $A_z$.

The energy cycle of Julian and Labitzke [1965] shown in Figure 5 is generally consistent with the other studies mentioned in previous paragraphs, although the magnitude and sign of some of the other conversion terms vary. Overall, however, while energy studies like this are useful diagnostic tools, they provide little information on the mechanism responsible for the sudden warming.

**Southern Hemisphere Warmings**

For many years it was believed that major midwinter stratospheric warmings were confined only to the northern hemisphere, probably because so little radiosonde and rocketsonde data were available for the southern hemisphere. With the advent of satellite coverage of the southern hemisphere, Barnett [1975] was the first to report a major midwinter warming in the Antarctic stratosphere, during July 1974. From radiance data the temperature rise in the stratosphere appeared to be at least as large as the 1970–1971 and 1974–1975 events in the northern hemisphere at 10 mbar. Nevertheless, radiosonde
measurements did not show the circulation reversal [Quiroz, 1974] required by the WMO definition of a major warming.

Table 2 gives a short history of stratospheric warming events for the southern hemisphere. No major warming (by the WMO definition) has been observed for the southern hemisphere, but temperature increases as large as those associated with northern hemisphere warmings have occurred. There are other important climatological differences between the hemispheres. Observations indicate that the polar night jet is stronger and the polar stratosphere colder in the winter in the southern hemisphere. The polar night jet winds, for example, have been observed to exceed 100 m s$^{-1}$ at the stratopause in July and August [Hartmann, 1977]. Standing planetary wave numbers 1-3 have also been observed in the southern hemisphere stratosphere with amplitudes comparable to northern hemisphere values [Hartmann, 1977; van Loon and Jenne, 1972]. In addition, wave number 2 has a significant eastward traveling component during winter [Hartmann, 1976; Leovy and Webster, 1976].

The nonreversal of the polar vortex in the southern hemisphere during a strong warming appears to be simply due to the fact that the prewarming vortex is much stronger in winter [Quiroz, 1974]. In other words, there appears to be an upper bound on the maximum temperature increase which occurs over the pole in either hemisphere during a warming. For the colder southern hemisphere stratosphere the warming appears to be insufficient to reverse the poleward temperature gradient over a layer deep enough to cause a breakdown in the polar vortex. This result also implies that the formation of easterlies is not critical to the development of a major warming.

**Theory**

Theoretical models of sudden stratospheric warmings fall into three broad categories: (1) stability models, (2) dynamic-mechanistic models, and (3) general circulation models. While none of the models has completely illuminated all of the physical processes that generate the sudden warming event, the dynamic-mechanistic models have certainly been the most successful.

**Stability Models**

Early investigators thought that the development of the sudden warming might be similar to the rapid development of mid-latitude synoptic systems due to baroclinic instability. Murray [1960] checked to see if the polar vortex in the stratosphere met the necessary condition for instability, using a simple one-dimensional model of the lower stratospheric wind shear. While the wind shear profile used by Murray turned out to be unstable, McIntyre [1972] has shown that the unstable modes do not have the correct vertical scale or growth rate to account for the sudden warming. Charney and Stern [1962] examined a realistic profile of the polar night jet in the lower stratosphere, using the Rayleigh integral theorem to check for...

<table>
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<th>Month</th>
<th>Minor Number</th>
<th>Month</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>0</td>
<td>July, Oct.</td>
<td>0</td>
<td></td>
<td>Quiroz [1974]</td>
</tr>
<tr>
<td>1971</td>
<td>0</td>
<td>Sept.</td>
<td>0</td>
<td></td>
<td>Barnett [1975]</td>
</tr>
<tr>
<td>1972</td>
<td>0</td>
<td>July–Aug.</td>
<td>0</td>
<td></td>
<td>Barnett [1975]</td>
</tr>
<tr>
<td>1973</td>
<td>0</td>
<td>Aug.</td>
<td>0</td>
<td></td>
<td>Barnett [1975]</td>
</tr>
<tr>
<td>1974</td>
<td>1</td>
<td>July</td>
<td>0</td>
<td></td>
<td>Barnett [1975]</td>
</tr>
<tr>
<td>1975</td>
<td>1</td>
<td>July</td>
<td>0</td>
<td></td>
<td>R.S. Quiroz (private communication, 1978)</td>
</tr>
<tr>
<td>1976</td>
<td>no data</td>
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<td>0</td>
<td></td>
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</tr>
<tr>
<td>1977</td>
<td>0</td>
<td>Sept.–Oct.</td>
<td>0</td>
<td></td>
<td>R.S. Quiroz (private communication, 1978)</td>
</tr>
</tbody>
</table>

Major indicates an increase in zonally averaged temperature comparable to a northern hemisphere warming. No circulation reversal is indicated in any of the events listed, so they cannot be considered major warmings by the WMO definition.

stability. They concluded that the jet was stable to infinitesimal disturbances. More recently, Leovy and Webster [1976] have found that the upper stratosphere can become barotropically unstable during midwinter but this instability may not be explicitly connected with the sudden warming.

The stability of the polar night jet in the mesosphere has been examined by Dickinson [1973a] and Simmons [1974b] who concluded that while instabilities can develop in that region, the growth rate for the most unstable modes is too small to account for the sudden warming. Matsuno and Hirota [1966] studied the stability of a distorted polar vortex (i.e., wave number 0 plus a planetary wave) and concluded that barotropic instability is possible in this case. However, energy studies of the warming indicated in Figure 5 suggest strong baroclinicity in the prewarming stage as indicated by the large value of $C_m$, the barotropic conversion term $C_k$ being smaller.

Overall, the stability models tend to rule out baroclinic or barotropic instability as the principal driving mechanism for the sudden warming. Nevertheless, Geisler and Garcia [1977] have shown that some unstable transient modes, which they referred to as 'Green modes' after their discovery by Green [1960], with large vertical and horizontal scales have growth rates of the order of 2–3 weeks.

Dynamic-Mechanistic Models

In a mechanistic model, the troposphere is treated as a known and prescribed source of planetary waves, and the mean zonal winds are specified from data. Matsuno [1971] was the first to use a mechanistic model to study stratospheric warmings. Starting at $t = 0$, Matsuno increased the wave amplitude at 300 mbar between 30°N and the pole to simulate the observed increased planetary wave strength prior to the warming. The transient wave pulse generated by the switch on forcing propagated vertically and produced an easterly wind region in the upper mesosphere. The easterly wind region then rapidly descended into the lower stratosphere, where the temperature rose, simulating a major warming. For wave number 1 the easterly wind region reached the lower stratosphere in 15 days after the initial forcing, while for wave number 2 the easterly wind region descended in 20 days. The resulting temperature increase in the stratosphere was 40 K for $m = 1$ and 80 K for $m = 2$ at the 10-mbar level (30 km), most of the rise occurring over the last 10 days of the integration.

Matsuno [1971] explained the results produced by his numerical model in terms of critical level effects. A critical level forms whenever the phase speed of a wave in a fluid is equal and opposite to the mean flow speed. For planetary waves on a β plane we may write the linearized form of the potential vorticity equation

$$\left(\frac{\partial}{\partial t} + k + im(\omega)\right)q_m + i m \frac{\partial q_m}{\partial y} \psi_m = 0$$

(1)

where

$$\frac{\partial q_m}{\partial y} = \beta - \frac{\partial (q_m' w)}{\partial y} - \frac{\partial \psi_m}{\partial (q_m')} = \psi_0 \frac{\partial}{\partial z} \left( \frac{\partial \psi_m}{\partial (q_m') w} \right)$$

and

$$z = H \ln (p_0/p)$$

$p$ pressure;

$p_0$ reference pressure;

$H$ constant scale height;

$m$ zonal wave number;

$N$ Brunt-Väisälä frequency;

$\rho_0 = \rho_0 \exp (-z/H)$;

$\psi_0$ atmospheric density at $p_0$;

$f$ Coriolis parameter, equal to $f_o + \beta y$;

$y$ the northward distance;

$\beta = (2f/a) \cos \theta$;

$\omega$ mean zonal wind;

$k$ constant damping coefficient (both Newtonian cooling and Rayleigh friction);

$q_m$ potential vorticity of wave number $m$, equal to $q_m$ for $m = 0$;

$\psi$ stream function for planetary wave, equal to $\psi_m e^{imx}$;

$q$ total potential vorticity of the atmosphere.

An equation for the mean flow can be written as

$$\left(\frac{\partial}{\partial t} + k\right) q_o = -\frac{m}{2} \frac{\partial}{\partial y} \left[\text{Im} (\psi_m q_m)\right] + K \frac{f_o^2}{H \rho_0} \frac{\partial}{\partial z} \left( \frac{1}{\rho_0} \frac{\partial \psi_m}{\partial (q_m') \partial w} \right)$$

(2)

where $J$ is the heating rate per unit mass, $K = R/c_p$, and the asterisk denotes a complex conjugate. Both equations (1) and (2) are derived by linearizing the potential vorticity equation...
and assuming disturbances of the form $e^{imx}$, where $x$ is in the zonal direction. The eddy flux convergence term in (2) combines both zonal momentum flux and heat flux in a compact form:

$$\frac{1}{2} \frac{\partial}{\partial y} \left[ \text{Im} \left( \psi_m^* q_m \right) \right] = - \frac{\partial}{\partial y} \left( \psi_m^* \frac{\partial \psi_m}{\partial x} \right) = \int_0^1 \frac{\partial}{\partial y} \left( \frac{1}{m} \frac{\partial (u'^n)}{\partial y} - \frac{R}{H \rho_0} \frac{\partial \theta}{\partial z} \frac{\rho_0}{N^2} (v'^T) \right)_m$$

where $u'$ and $v'$ are the eastward and northward winds associated with wave number $m$. $T'$ is the temperature perturbation. The angle brackets indicate the zonal average. For a thorough discussion of these equations, see Holton [1972, 1975].

Equations (1) and (2) can be related to Laplace's tidal equation which describes shallow fluid motion on a rotating sphere [Longuet-Higgins, 1968]. The solutions to (1) resemble the type 2 solutions to the tidal equation which describes Rossby type waves as opposed to gravity waves. The solutions to (2) resemble the type 7 solutions to the tidal equation which were first investigated by Leovy [1964]. A more recent discussion of the simplified forms of Laplace's tidal equation has been given by Moura [1976].

A dispersion relation can be derived from (1) by assuming $\psi_m = A \sin \beta \exp (s + 1/2H)z - \text{Im} \psi_m$ where $l = \pi n/L$ and $L$ is the width of the $\beta$ channel. Taking $N^2$ and $(\omega)$ to be constant and solving for $s$, we obtain

$$s = \left( \frac{1}{4H^2} - \frac{imgN^2/4H^2}{(im\omega + k - m\gamma)} + \frac{(P + m^2)N^2}{4H^2} \right)^{1/2}$$

This equation is really a generalized form of the Rossby wave equation which can be obtained if $s = -H/2$ and $k = 0$. Note that $s^{-1}$ vanishes when $c = -(\omega)$ and $k = 0$. This situation occurs in the vicinity of a critical layer.

The northward heat transport by the eddies associated with these wave solutions to (1) is given by

$$\langle v'^T \rangle = \frac{1}{2} \left( \frac{m}{R \beta} \right)^{1/2} \left[ \text{Im} \left( \psi_m \frac{\partial \psi}{\partial z} \right) \right]$$

which can be simply obtained from the definition of $v'$ and $T'$ on a $\beta$ plane [Dickinson, 1969]. In order for $(v'^T)$ to be nonzero, $s$ must be complex. In the absence of damping ($k = 0$) this condition can be derived from (3) for a stationary wave ($c = 0$) if

$$0 < (\omega) < \beta \left[ \int_0^1 \left( \frac{f_0^2}{4N^2H^2} + (P + m^2) \right) \right]^{-1}$$

Thus for a westerly zonal wind decreasing with height the wave is propagating below the $\omega = 0$ line (critical level) and evanescent above. If a small amount of damping is introduced, then the solutions to (1) give a discontinuity for $(v'^T)$ at the critical level [Dickinson, 1968]. In other words, the eddies transport heat northward below the critical level but not above it. This imbalance in heating with height causes a deceleration of the mean flow by a superposition of a secondary circulation pattern on the zonally averaged flow. Figure 6 shows a schematic diagram of the effect. Note that the pattern of temperature changes at high and low altitudes is exactly that observed by Labitzke [1972].

The conditions on the deceleration of the mean zonal flow by planetary waves is described mathematically by the Charney-Drazin theorem, which has been recently generalized to include nongeostrophic disturbances by Boyd [1976] and Andrews and McIntyre [1976a, b]. More recently, F. Bretherton (unpublished work, 1977) has shown that this theorem is really
Schoeberl: Stratospheric Warmings

The mean zonal winds are decelerated by the transient pulse, but only when the pulse reaches the very low density regions near the mesopause is the deceleration strong enough to convert the westerlies to easterlies.

The band of easterlies which forms at the mesopause now becomes a critical level for the stationary planetary waves. Further deceleration of the mean zonal wind occurs along the zero wind line as more heat is transferred to the mean circulation by the eddies until the band of easterlies reaches the lower stratosphere where the sudden warming is observed. The rate at which the critical level descends depends upon the atmospheric density, since more heat is required to decelerate the mean flow at low altitudes than at high ones.

Figure 7 shows some of the numerical results obtained by Matsuno [1971] for $m = 1$ and $m = 2$ integrations. The timing and amplitude of the warming both agree qualitatively with observations. Matsuno's results thus clearly establish the connection between vertically propagating planetary waves and the sudden warming.

From a theoretical viewpoint, probably the most questionable aspect of Matsuno's numerical model of the sudden warming concerns the role of frictional and radiative damping. Damping has two important aspects: (1) it provides a mechanism by which the decelerated mean zonal flow may relax to the unperturbed state after eddy forcing ceases; (2) when a critical level no longer descends, that is, when it becomes stationary, then the wave will numerically reflect from the critical level if no damping is present. For the integrations shown in Figure 7, no damping was used, so that changes in the zonal flow which occurred are irreversible. Matsuno used damping equivalent to (15 days)$^{-1}$ in another integration, obtaining little difference in results; however, Dickinson [1973] and Schoeberl and Strobel [1978] have noted that the damping time scale should be much shorter than this for the upper stratosphere and mesosphere.

There are also a few discrepancies between Matsuno's [1971] calculations and observations. For the $m = 1$ integration, Matsuno found that the warming formed at two widely separated altitudes simultaneously, which is generally not observed. In addition, the existence of downward propagating critical levels is not clearly supported by observations of the mesosphere [Quiroz, 1969]. The ability of the $m = 2$ planetary wave to generate a sudden warming as Matsuno [1971] produced is not supported by data [Labitzke, 1977a], and furthermore, from Table 1 it is apparent that a $m = 2$ warming as intense as that obtained by Matsuno [1971] has not occurred.

Holton [1976] has also used a mechanistic model of the stratosphere and mesosphere to simulate a warming event. Using Matsuno's [1971] wind model and a similar forcing function, Holton solved the perturbation forms of the primitive equations for both the waves and the zonal mean flow.

The structure of the warming generated by Holton's numerical study was considerably different from that generated by Matsuno. First, the double-layered warming that Matsuno obtained for $m = 1$ (Figure 7a) did not develop, and there appeared to be no evidence of a downward propagating critical level. Instead, after an initial weakening of the mean winds by the transient wave a region of easterlies appeared simultaneously in the height region 30–80 km. Holton's simulation also showed more eddy deceleration of tropical mean zonal winds than Matsuno's; however, this is understandable, since Matsuno's model was quasi-geostrophic.

In order to compare better the results obtained by Holton...
with Matsuno's [1971] calculation the wave amplitudes for $m = 2$ from both models and $m = 1$ from Holton's model at a constant altitude have been plotted as a function of time in Figure 8a. Aside from the inclusion of some nonlinear terms in the equations for the mean zonal flow and numerical filtering of gravity waves the major difference in the dynamics of the models at mid-latitudes is the more realistic damping used by Holton. The wave amplitude response of both models is quite similar up to day 20; however, after that time the $m = 2$ results are not in good agreement. It is interesting to note the weak oscillations superimposed on the linearly increasing amplitude curves for all wave numbers. At higher altitudes these oscillations are much stronger in Holton's model for $m = 1$. The zonal mean temperature progression curves shown in Figure 8b indicate considerable differences. After 22 days of integration, Matsuno [1971] obtained a greater than 80 K temperature increase at 28 km, while Holton obtained only a 34 K increase. The source of the disparity between the two calculations is not apparent.

While Matsuno's [1971] model explained much of the dynamics of a sudden warming, it provided no explanation for the anomalous wave amplitude increases observed prior to the warming event. A process suggested by R. S. Lindzen which provides such an explanation to the anomalous wave amplitude increase observed before the warming as well as the sudden warming was quantified by Clark [1974]. The basic idea is that under certain flow conditions, free Rossby waves which are normally transient in the stratosphere become stationary as the polar vortex intensifies during early winter. Since the free modes are normal modes of the flow field, small amounts of forcing for these modes produces a resonant response in wave amplitude. For traveling waves the forcing is normally near zero, but for stationary planetary waves the orographic and thermal forcing is relatively large. Thus if a free mode became stationary, it would amplify explosively. The sudden amplification of the wave then decelerates the mean zonal flow by the Charney-Drazin mechanism and perhaps produces a sudden warming.

Clark [1974] tested this theory, using a one-dimensional two-layer model of the polar night jet. Free modes developed by reflecting off the strong westerlies associated with the jet. Even with realistic damping he found that resonant interaction was capable of producing a sudden warming in a time scale of about 2 weeks. Unfortunately, Clark's model did not allow for north-south energy flow. Under normal winter conditions a band of easterly winds exists near the equator. Dickinson [1968] suggested that the critical level formed by such easterlies should completely absorb wave energy generated at mid-latitudes. Thus it would appear that a stratospheric resonant cavity could never be attained if easterlies existed near the
Geisler [1974] presented a one-dimensional model of the sudden warming and produced results similar to those generated by Matsuno [1971]. While Geisler's model was not as detailed as Matsuno's, it illustrated much more clearly the vertical structure of the warming as well as critical level effects. Geisler also found that wave amplitude forcing must be sustained for at least 13 days before a warming could occur, a result which is observationally consistent with the type B warming discussed in the previous section. During the integrations, Geisler discovered that downward propagation of the critical level was often hampered by distortion of the flow ahead of the critical level. The distortion effect was first discovered by Geisler and Dickinson [1974] for barotropic flow and occurs when momentum deposition by the waves ahead of the critical level alters the flow so that \( \partial q / \partial y \) changes sign. This causes the wave to be partially reflected from the distortion before it reaches the critical level and reduces the energy input into the critical region thus slowing the descent of the easterly wind region.

In addition to studying the sudden warming, Geisler [1974] also looked for the free modes in his model in order to test the results obtained by Clark [1974]. He found that for a given amplitude forcing, there was no evidence that a warming would occur earlier if the mean zonal flow had a resonant configuration. In other words, the time scale for the resonant growth rate appeared to be too slow to compete with the critical level effects. Tung [1977], however, has noted that the observed development of a type 1 warming [Quiroz et al., 1975] is much like that predicted by resonance theory. The slowly westward drifting thermal planetary wave observed before the warming is the transient free wave which has not yet become stationary. When the free wave matches phase with the Aleutian anticyclone, resonance occurs with a subsequent increase in the strength of the planetary wave. The meridional motion of the thermal center after resonance is a result of the amplification of wave number 0, due to the increased northward heat transport associated with the planetary waves.

Tung [1977], using analytic models of the stratosphere, has shown that when nonlinear effects and damping are both considered, the equatorial critical levels will partially reflect wave energy so that near-resonant states can be achieved. Instead of the resonance generating the warming, as was suggested by Clark [1974], Tung noted that resonant growth need only produce the prewarming planetary wave amplification required by Matsuno [1971] to produce a sudden warming. The tropospheric blocking which appears to be coincident with many major warming events [Miyakoda et al., 1970; Labitzke, 1965] would be a manifestation of the resonant planetary wave at low altitudes.

A recent model which suggests a connection between the climatology of the stratosphere and the sudden warming has been presented by Holton and Mass [1976]. Using a one-dimensional formulation of planetary waves on a \( \beta \) plane similar to that given by Simmons [1974a] they showed that the interaction of planetary waves with the mean flow at mid-latitudes was analogous to the interaction of equatorial waves with the mean flow at the equator which produces the quasi-biennial oscillation in the stratosphere [Holton and Lindzen, 1972; Lindzen and Holton, 1968]. During a long time integration, Holton and Mass [1976] found that continuous forcing of planetary waves produces descending easterlies which block planetary waves from the upper stratosphere and mesosphere. Since wave forcing is eliminated from the upper regions, the easterlies switch back to westerlies through damping. The thin layer of easterlies continues to move downward until the wave forcing is insufficient to counteract damping and the easterlies vanish. The cycle then begins to repeat itself.

Holton and Mass [1976] referred to this process as a vacillation of the stratosphere, and Figure 9 shows their results for planetary wave number 1. The minimum forcing to set up the vacillations was found to be about 150 m at 300 mbar for wave numbers 1 and 2; however, a smaller minimum may be more realistic [Schoeberl and Strobel, 1978]. However, no vacillations of the stratosphere on the time scale of 50 days suggested by Holton and Mass [1976] are clearly evidenced by Table 1 or in studies by Labitzke [1977a]. This may be due to the fact that actual planetary wave forcing during winter is not steady.

**General Circulation Models**

Since global general circulation models (GCM's) have only recently begun to include levels in the stratosphere, few attempts have been made to simulate sudden stratospheric warmings. Simple stratospheric GCM's developed by Bryon-Scott [1967] and Clark [1970] relied upon very large inputs of wave energy to produce warmings. Trenberth [1973] generated minor warmings in his spectral model of the stratosphere. More recently, Newson [1974] was able to obtain a stratospheric warming after 70 days of 'perpetual January' conditions. Prior to the warming, however, a very intense polar night jet appears with a magnitude of 120 m s\(^{-1}\) at 45 km which may have become barotropically or baroclinically unstable in Newson's model.

The most important attempts to simulate sudden warmings have been made by Miyakoda et al. [1970] and Manabe and Mahmman [1976], using versions of the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model. Miyakoda et al. [1970] used the nine-level version of the model with levels at 9, 74, and 124 mbar in the stratosphere. Starting with initial data 2 and 5 days before the warming and integrating over 4 and 10 days, respectively, they compared numerical results with observations taken for the final warming in March 1965 (not indicated in Table 1). Figure 10 shows their results for the 10-day experiment at 50 mbar for days 2, 6, and 10. In this period the polar vortex at 50 mbar was observed to split into two separate systems (\( m = 2 \)) which re-

![Stratospheric vacillations for m = 1 produced by Holton and Mass [1976].](image)
Fig. 10. Results of the general circulation simulation of the March 1965 final warming by Miyakoda et al. [1970] showing (top row) the height of the 50-mbar surface from observations and (bottom row) the numerical simulations obtained with the nine-level GFDL model. Large numerals indicate days.
phere (300 mbar) also appeared after 6 days.

The authors indicated that lack of resolution in the model stratosphere was the most likely cause for the poor reproduction of the warming, although significant errors in the forecast troposphere (300 mbar) also appeared after 6 days.

Manabe and Mahlman [1976] have reported general simulations of the winter stratosphere, using an 11-level improved version of the GFDL model discussed by Miyakoda et al. [1970], the highest level of the model being 31 km (10 mbar) with four levels in the stratosphere. Overall, this model was able to reproduce many of the gross features of the stratospheric circulation in winter including the polar night and the Aleutian anticyclone. But the jet was computed to be twice as strong as that observed. Furthermore, the model failed to produce any midwinter sudden warming. Again, the discrepancy between observations and predictions can probably be attributed to limited stratospheric resolution and upper boundary effects.

Given the validity of the critical level and resonance theories of warmings discussed in the last section it is not surprising that GCM's have had limited success in simulating a major warming. For example, if the critical level theory is correct, then a GCM would require good resolution above 50 km as well as proper radiation algorithms for ozone heating and IR cooling to simulate the polar night jet. If resonance theories for the generation of the prewarming planetary wave amplification are correct, then GCM's must be able to simulate partially reflecting critical levels in order to produce the planetary wave resonant cavity.

**SUMMARY AND CONCLUSIONS**

The major stratospheric warming is defined by an observational event sequence beginning with the rise in the amplitude of planetary wave number 1 at mid-latitudes in the winter stratosphere followed by the breakdown of the polar vortex and a simultaneous rapid temperature rise over the polar regions. The sequence can be subdivided into the two categories illustrated in Figure 3. Type A, the more frequently observed, clearly shows the involvement of both planetary wave numbers 1 and 2, while type B involves only wave number 1. Minor warmings have the same basic character as major warmings but lack the intensity; as a result the polar vortex does not completely break down as it does with the major warming. Both major and minor warmings appear to be integral components of the winter stratospheric climate in that they occur nearly every year in the northern hemisphere. For the southern hemisphere warming, similar thermal pulsations have been observed in the stratosphere. The intensities of these events are the same as those associated with major warmings in the northern hemisphere, but a mean circulation reversal has never been observed.

Single-station observations show that a stratospheric warming begins at high altitudes and descends into the lower stratosphere and troposphere. This behavior seems to be partly due to the nonzonal character of the warming. The planetary scale temperature wave has a strong westward tilt and thus gives the appearance of a downward progressing thermal system which drifts westward prior to the warming [Hirota, 1968; Quiroz et al., 1975]. The ultimate source of heat for the zonally averaged temperature increase is the tropical troposphere and stratosphere; the large-amplitude planetary waves appear to pump heat northward during the warming, depositing it in the polar regions [Mahlman, 1969], and energy studies confirm the importance of baroclinic transfer of heat from eddies to the zonal mean circulation during the warming.

Dynamic instability of the polar vortex has all but been ruled out as the mechanism behind the sudden warming [McIntyre, 1972]. More plausible is a variant on theories presented by Matsuno [1971] and Clark [1974], recently linked together by Tung [1977]. The combined theory is described as follows. At the start of the prewarming period the mean zonal flow obtains a configuration in which one of the free planetary wave modes becomes resonant. The free modes exist trapped between the polar night jet and the earth's surface and between the partially reflecting critical layer near the equator and the pole. When the free mode matches phase with the stationary planetary wave forcing it, it grows explosively. The resonance excites a transient planetary wave pulse which propagates vertically through the jet into low-density regions of the upper atmosphere, decelerating the westerlies by transporting heat northward along the wave front [Uryu, 1974]. Easterlies eventually form at some high level and halt further vertical flow of wave energy at the critical surface. Continued deposition of stationary wave energy along the critical surfaces causes the easterlies to descend to the lower stratosphere, precipitating the warming.

No numerical model has tested the resonance theory concerning the initial development of the sudden stratospheric warming, but numerical models given by Matsuno [1971], Geisler [1974], and Holton [1976] have attempted to model the development of a warming triggered by a transient wave pulse. The results of the models have not been entirely consistent with the simple critical level theory presented by Matsuno [1971]. Critical level descent was found by Geisler [1974] to be partially hampered by flow distortion ahead of the level and was not seen at all in Holton's [1976] simulation. Matsuno's [1971] integration for m = 1 produced double (two level) warmings, also not observed, and the m = 2 warming appeared to be too intense. The existence of downward propagating critical levels has still not been observationally confirmed for the mesosphere.

While the simulation of a sudden warming in mechanistic models seems to follow directly from the artificial amplification of a single wave number planetary wave in the troposphere, the results of these models have not yet quantitatively explained the entire dynamics of the warming event. Many important questions still remain unanswered. For example, what is the role of wave-wave interaction? What is the source of interwinter variability in the stratosphere? And how do minor warmings differ from major warmings in generation and development?

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