Numerical Simulation of the Breakdown of a Polar-Night Vortex in the Stratosphere

K. MIYAKODA, R. F. STRICKLER AND G. D. HEMBREE

Geophysical Fluid Dynamics Laboratory, ESSA, Princeton University, N. J.

(Manuscript received 27 January 1969, in revised form 6 October 1969)

ABSTRACT

With a 9-level general circulation model, an attempt was made to simulate numerically the breakdown of the circumpolar vortex in the winter stratosphere for the case of March 1965. The marching computations were started 2 and 5 days prior to the breakdown. The simulation of the vortex elongation and destruction was, to a certain extent, successful, but the split vortex in the prediction erroneously merged again after 8 days. The sudden warming was not simulated at all. The development of the Aleutian high associated with the vortex breakdown was not well computed. Studies are made on zonally averaged quantities pertaining to the tropospheric and stratospheric circulations and their coupling. The increase of eddy kinetic energy at the time of the amplification of zonal wavenumber 2 is discussed both for the numerical simulation and for the observed fields. It is reconfirmed that the eddy kinetic energy in the stratosphere is primarily supplied from below in the form of vertical flux of geopotential. The propagation of wave energy takes place through a rather narrow zonal belt at high latitude. A possible relation between the stratospheric vortex destruction and the tropospheric process of meandering westerlies is discussed in terms of vertical transmission of wave energy.

1. Introduction

In the winter stratosphere, a circumpolar vortex around the north pole elongates horizontally as the season proceeds, and then breaks down into two vortices. It quite often is accompanied by a sudden warming in the stratosphere. The reported temperature change over an observing station sometimes amounts to ~40C within two days.

This is one of the most dramatic and spectacular events found in large-scale atmospheric motion. Blocking activity in the troposphere often takes place simultaneously with strong stratospheric warming. After the final warming at the end of the season, the meridional temperature gradient in the higher latitudes of the lower stratosphere is reversed.

In the past 15 years, a great deal of attention has been focused on this problem. Knowledge on the subject has become much more abundant and more accurate, and the mechanism of the process is gradually being understood. Yet a complete solution has not been reached, and there is still controversy on some points.

In the experiments described in this paper we tried to produce the breakdown numerically with a mathematical-physical model that was developed in general circulation studies. This is perhaps the first attempt ever made along this line (in 1966) in the sense that an exact comparison is made between the computation and what actually happened. It will hopefully provide us with insight into various inferences hitherto presented on the causes and effects. [Byron-Scott (1967) attempted to produce the sudden warming numerically with a 4-level stratospheric model, and Manabe and Hunt (1968) reported a sudden-warming-like phenomenon in their general circulation experiment.]

Presumably the sudden warming and the vortex breakdown are two different phases of one phenomenon. It turns out, however, that our computations were successful, to a certain extent, in simulating the breakdown, but not in simulating the sudden warming, probably due to a mathematical drawback of the model. We are, therefore, forced to confine our subject mainly to the breakdown, although a distinct separation is practically impossible.

It often happens that a geophysical hydrodynamical phenomenon can result from several different causes. Nevertheless, the phenomenon may seem to be explained qualitatively with just one cause that is in reality less important than others. To avoid this confusion, it is necessary to have a quantitative test of the hypothesis against observation.

2. Application of the 9-level model

The simulation was made with the 9-level general circulation model developed in the Geophysical Fluid Dynamics Laboratory, ESSA (Smagorinsky *et al.*, 1965; Manabe *et al.*, 1965).

Three of the nine vertical levels which are approximately at 9, 74, and 189 mb are in the stratosphere, four levels at 336, 500, 664 and 811 mb are in the troposphere, and two levels, 926 and 991 mb, are in the Ekman and surface boundary layers. The height of the highest level (9 mb) is ~31.6 km.

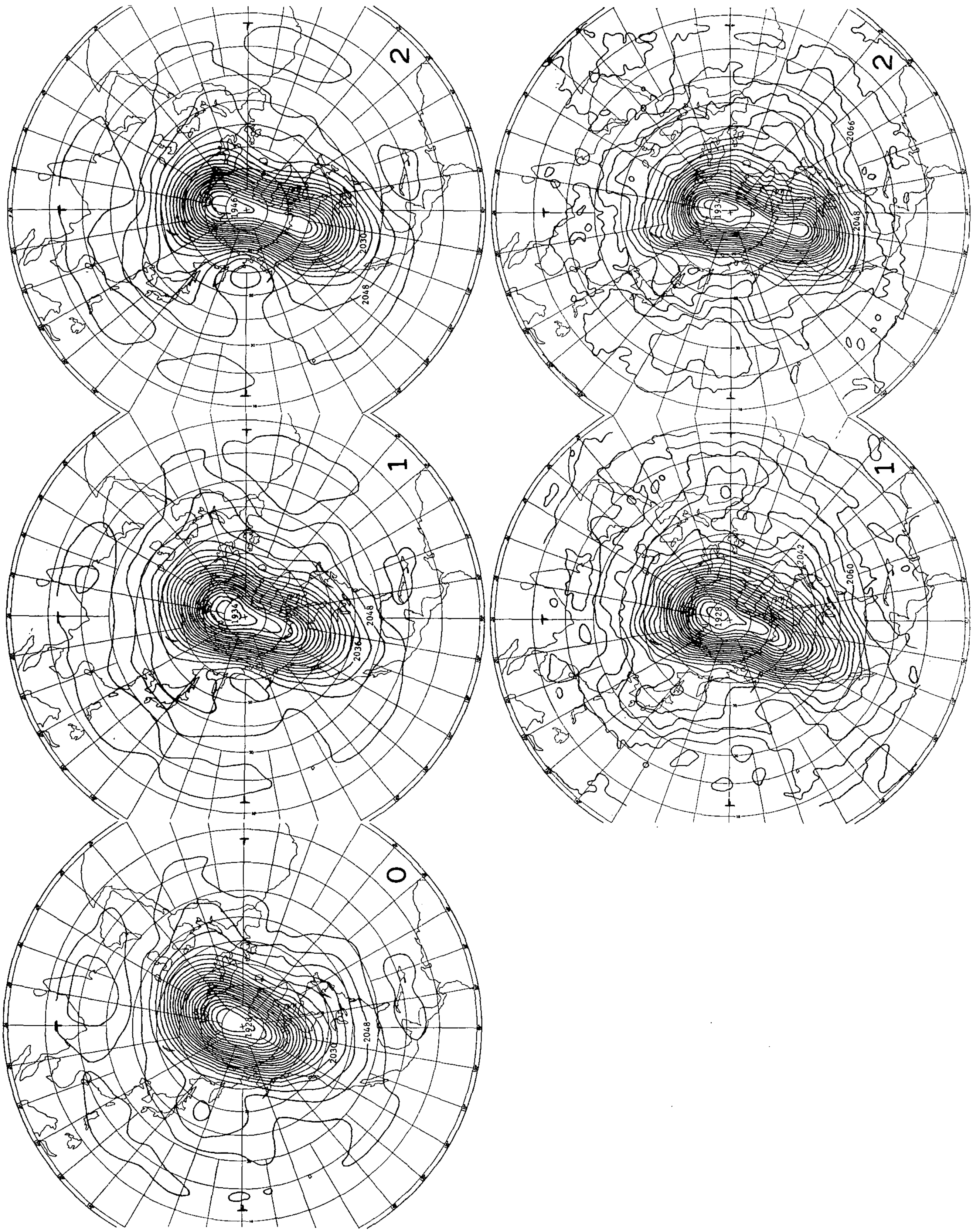


FIG. 1 The observed (upper) and Exp. A (lower) 50-mb geopotential heights for the 4-day period beginning 17 March 1965 in units of decameters.

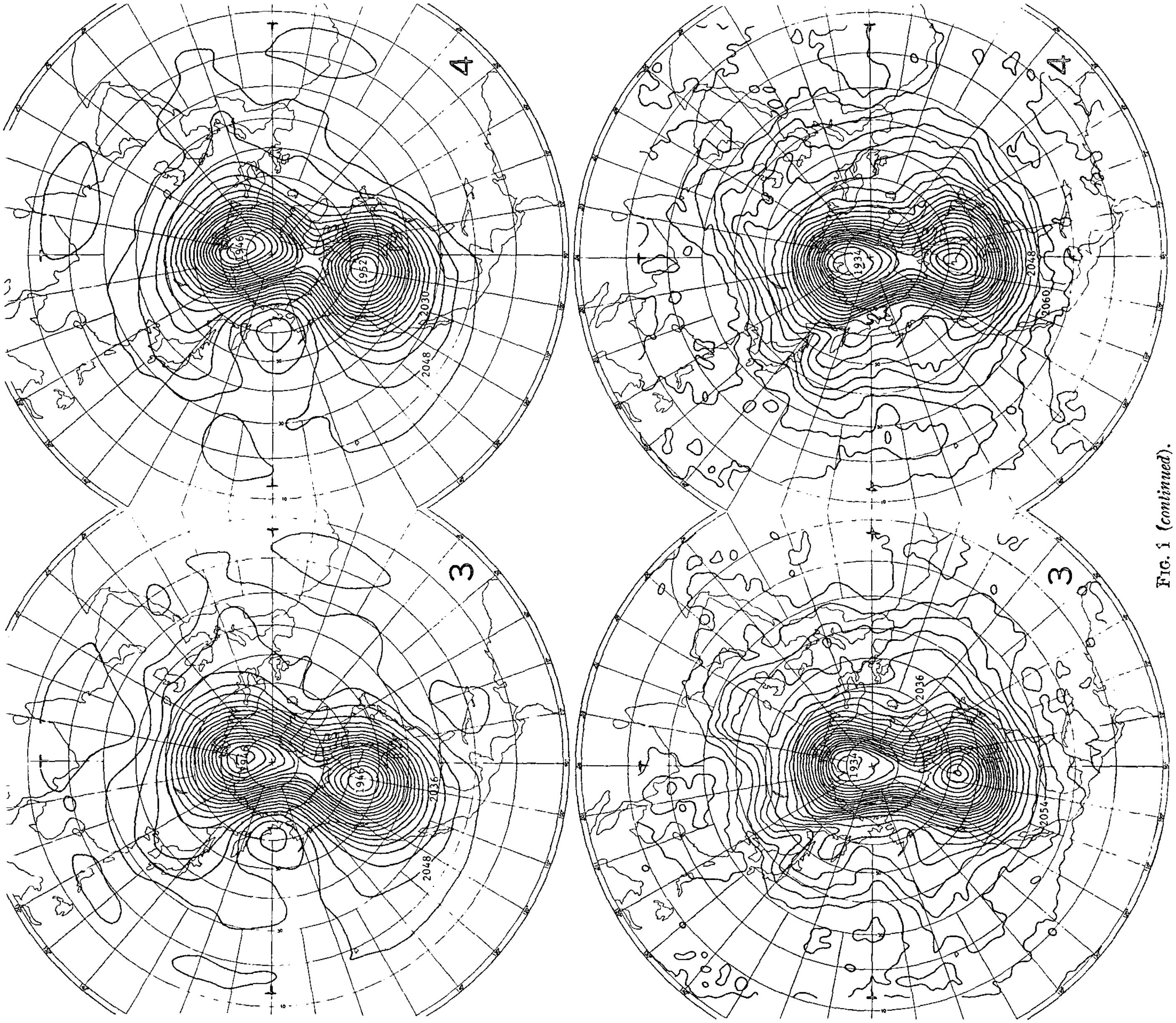


FIG. 1 (*continued*).

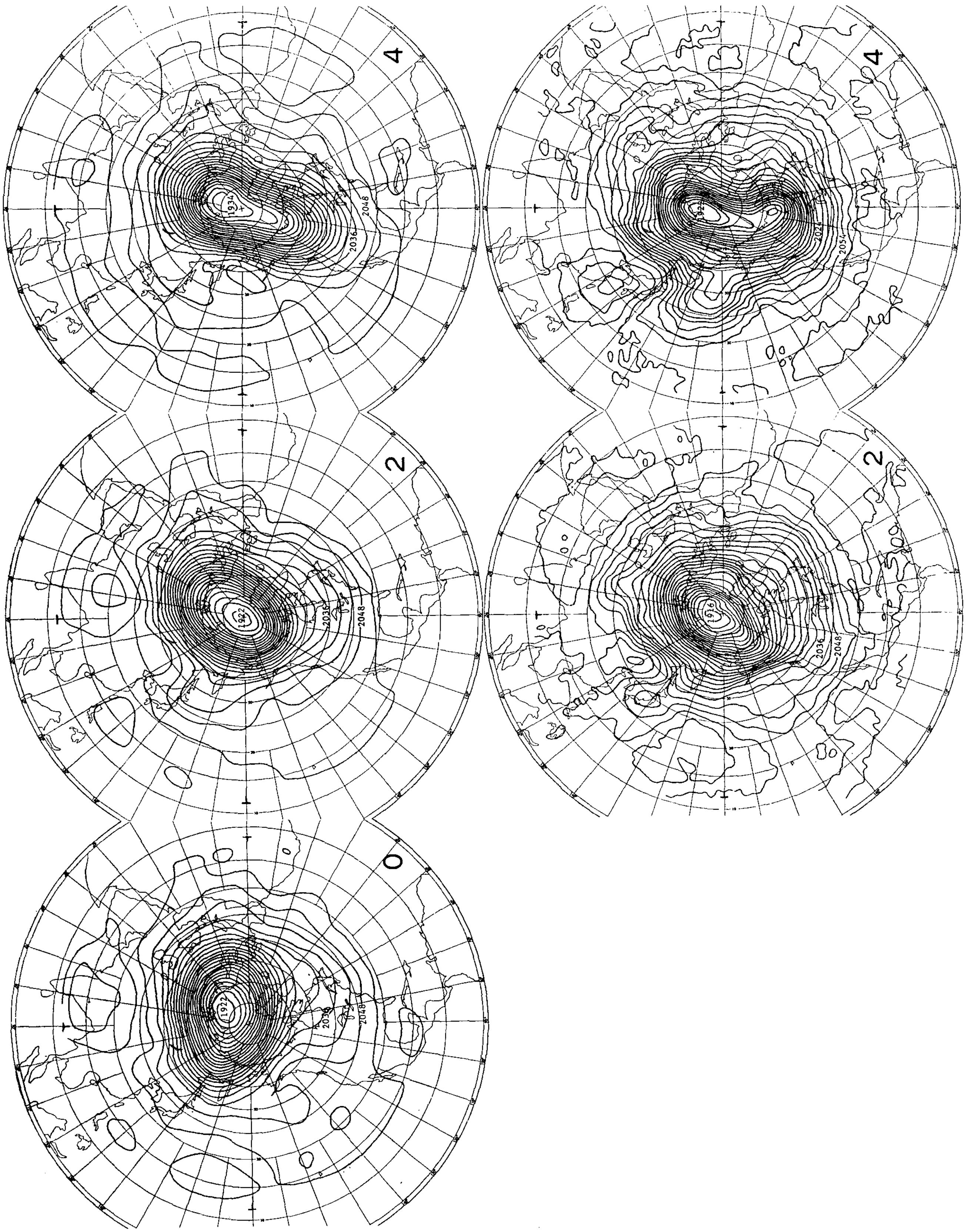


FIG. 2. The observed (upper) and Exp. B (lower) 50-mb geopotential heights at 2-day intervals for the 10-day period beginning 14 March 1965 in units of decameters. The contour interval is 60 m. The number in the lower corner is the day of prediction.

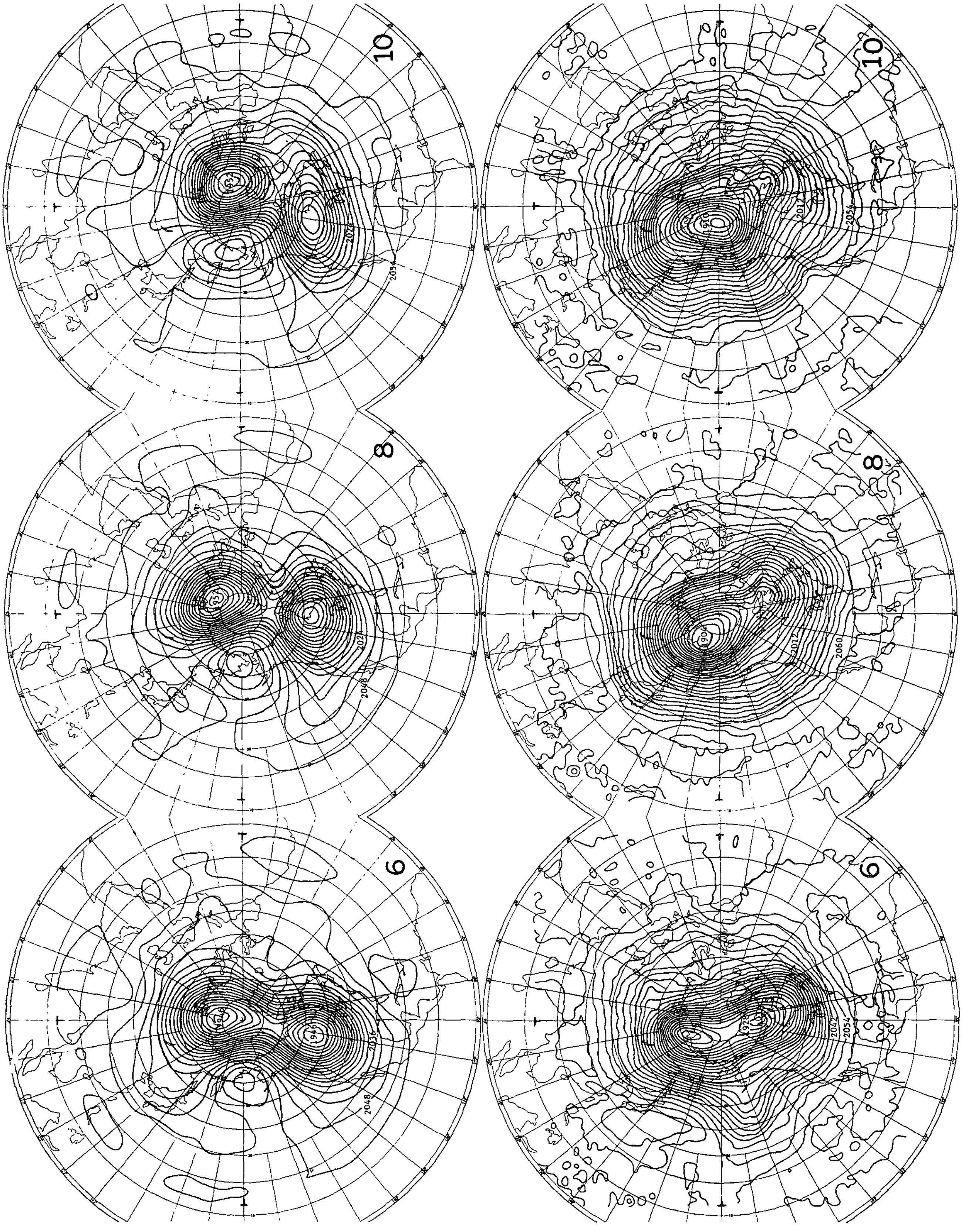


FIG. 2 (*continued*).

The model described above is the same as the most successful of the three versions which were reported by Miyakoda *et al.* (1969). (This paper is referred to herein as [A]). At the time the present experiments were carried out, it apparently was the most realistic model we had tested.

Concerning the horizontal resolution of the model, one might suspect that a high resolution grid ($N=40$) is not really needed for treating such a large-scale phenomenon. It was shown, however, that the $N40$ grid is appreciably superior to the $N20$ grid for these experiments.

The case chosen for the experiment is the 14-day period beginning at 1200 GMT 14 March 1965. The vortex breakdown in the 1965 case was quite marked but not nearly so drastic as that in the famous case of January 1963. According to the classification of Wilson and Godson (1963), the 1965 case belongs to the *bi-polar vortex* type, in which the trough line extends from central Siberia to central Canada.

The case was suggested for this study by S. Teweles. The stratospheric data are conveniently available in digitized form for the period beginning January 1964. Objectively analyzed charts of geopotential height and temperature for the 10-, 30-, 50- and 100-mb levels were furnished by the Upper Air Branch, National Meteorological Center (Finger *et al.*, 1965).

3. Predicted patterns of geopotential height

a. Simulation starting 2 days prior to the breakdown

As a preliminary study an experiment was made starting the time integration at 1200 GMT 17 March 1965. This experiment (originally called Exp. 57A) is referred to in this paper as Exp. A. The onset of the vortex breakdown is 2 days after initial time.

As a first trial it was considered safer to try a short period of time integration, because there is a practical limit to the general predictive capability of the present model especially for the stratosphere (see [A]).

The marching computation was done for four days. Fig. 1 shows the 50-mb geopotential patterns (interpolated from levels 1 and 2, i.e, about 9 and 74 mb) for both the observed and the predicted heights for the initial day and 4 subsequent days.

Generally speaking, it can be objectively concluded that the numerical simulation was successful. The polar-night vortex continued to elongate on the 1st and 2nd days, and split into two vortices on the 3rd day.

There are, however, obvious defects. The Aleutian anticyclone was not well computed. The predicted geopotential height of the anticyclone was not high enough. The axis of the computed vortex elongation is slightly different from the observed. It is also noticed that the 50-mb geopotential pattern was contaminated by wiggling (roughness).

Encouraged by the success of this preliminary test, we next tried the same computation starting at an earlier time. Besides it was argued that the initial time in Exp. A was too close to the key day, and that the elongation of the vortex had already begun. If so, we may have missed the most important moment of the onset of the vortex destruction.

b. Simulation starting 5 days prior to the breakdown

The initial time is 3 days earlier than in the previous experiment, i.e., 1200 GMT 14 March 1965. As is seen in the observed and computed values of Fig. 2, the initial stratospheric pattern of the geopotential height is quite circular-symmetric.

The time integration was performed for 2 weeks with exactly the same model as before. This experiment (originally called Exp. 60J2) is referred to here as Exp. B.

Fig. 2 is the series of 50-mb height maps for every 2nd day, which shows how the elongated vortex develops. The initial vortex is nearly circular and centered at the pole, but gradually elongates on the 2nd day, while the trough axis rotates toward the east. On the 3rd day (not shown in the figure) the trough axis is in a different position entirely from that of the initial day. The new position is apparently the preferred location of troughs for the amplification of wavenumber 1 or 2. Further elongation proceeded on the 3rd and 4th days. These features were, to a certain extent, accurately predicted.

The onset of the vortex split occurred on the 5th or 6th day. The predicted breakdown started a little earlier than the observed. Although two vortices appeared in the prediction, the simulation of the breakdown was not as good as in Exp. A. The Aleutian high was even more poorly predicted than before. After the 8th day, the split vortices were reunited in the computed pattern, wheras the observed vortices stayed separated for a considerable time.

c. Discussion

The tendency for the stratospheric height pattern to become circular in the present model was already mentioned in [A]. It was also pointed out that the predicted temperature in mid-latitudes tends to be lower erroneously, and associated with it, the circumpolar vortex tends to be weaker and to extend farther south. All these shortcomings, which are probably interrelated, reveal themselves in the present results.

One should expect that if the simulation experiment was started as early as 8 days prior to the breakdown, the computed stratosphere would have deteriorated intolerably before reaching the time of the breakdown.

Let us next mention the development of wavenumbers 1 or 2 in the zonal direction. Since we are now concerned with the vortex breakdown, it is a part of the problem

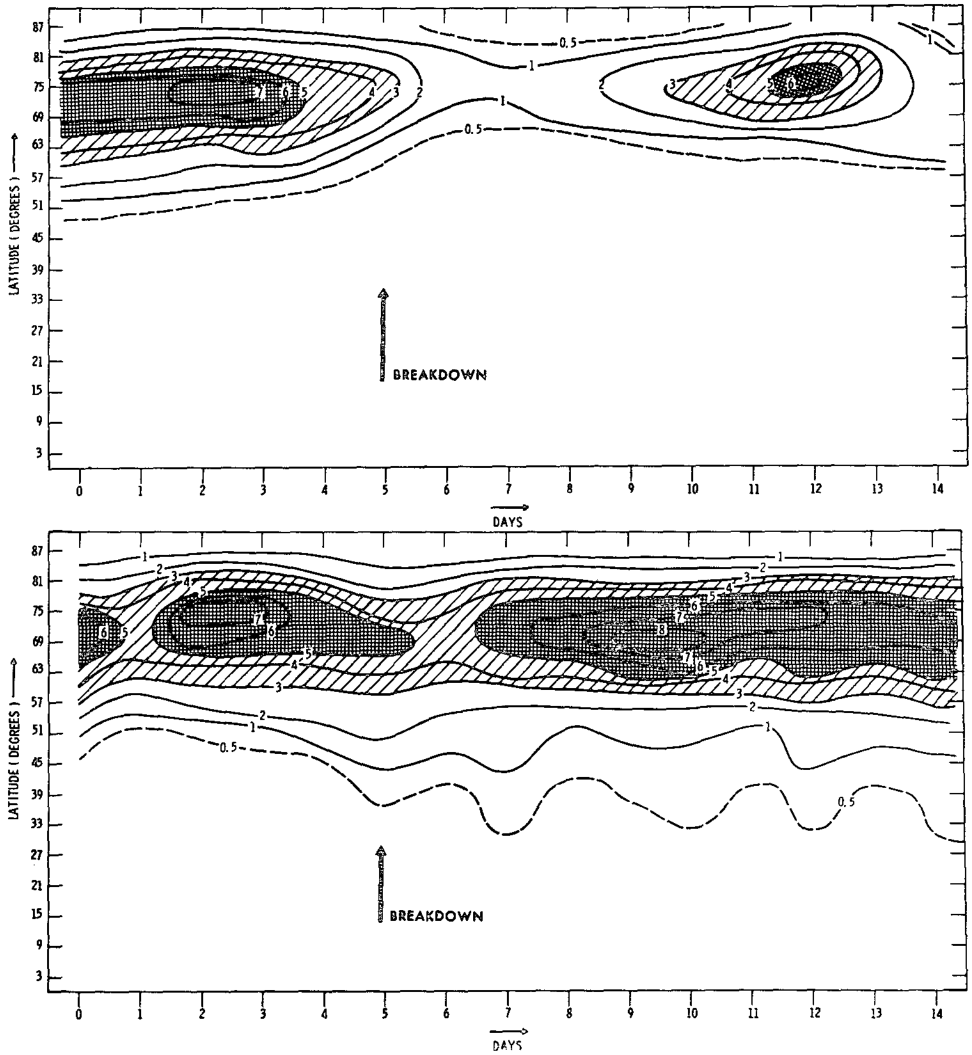


FIG. 3. The zonal kinetic energy, observed (upper) and Exp. B (lower), at level 1 in units of 10^6 cm^2 sec^{-2}. The ordinate is latitude, and the abscissa time. The onset of the vortex breakdown is indicated.

to consider the amplification of these waves. Our experiment includes the effects of mountains as well as land-sea contrast for the Northern Hemisphere, so that the contribution of these effects on the establishment or maintenance of wavenumbers 1 or 2 was definitely included. One should, however, also be aware of the fact that even without these effects wavenumber 2 can be amplified because of the dynamical properties of the stratosphere (and also of the troposphere) as was demonstrated by Manabe and Hunt (1968). They obtained, unintentionally, a sudden-warming-like phenomenon in the course of a general circulation integration (without mountain effect).

d. Vertical correspondence of flow patterns

So far as the winter westerlies are concerned, the waves aloft and the waves below (not shown) strikingly resemble each other, despite the fact that the tropospheric Ferrel jet and the stratospheric polar-night jet are distinctly different systems.

Austin and Krawitz (1956), Craig and Hering (1959), Boville (1961), Julian (1961), Chen (1962), Labitzke (1962), Teweles (1963), and Sawyer (1965) have pointed out the vertical coherences of wave patterns although they are not always for the same reasons and the same purposes. Hare (1960) suggested that a strong interaction with the Ferrel wave may occur in the late winter. Perhaps this tight linkage in the vertical is a very important characteristic of the atmospheric structure, though it may now appear to be an obvious feature.

Returning to Exp. B (Fig. 2), one may see that, for the 6th day, the computed 50-mb trough over Canada is different in position from the observed. Apparently

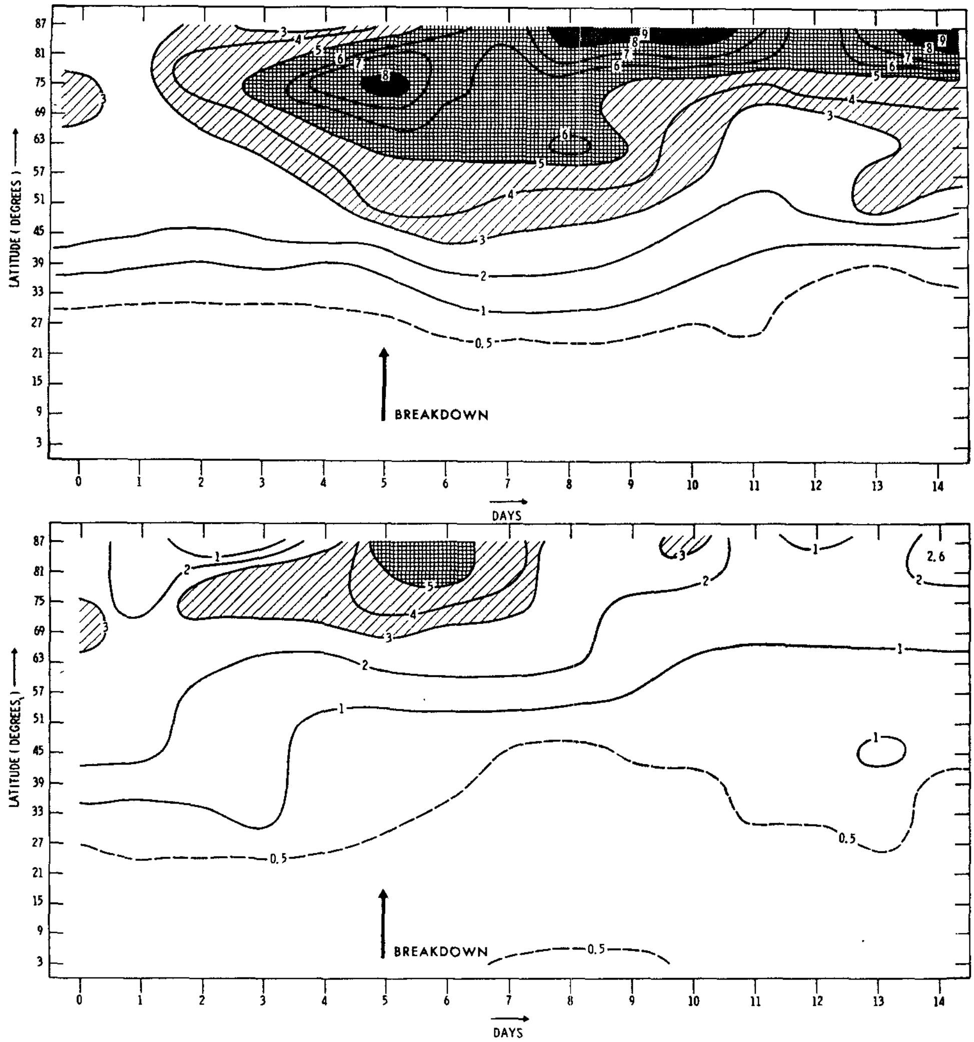


FIG. 4. The zonal average of eddy kinetic energy, observed (upper) and Exp. B (lower), at level 1 in units of 10^6 cm^2 sec^{-2}. See Fig. 3 for other details.

this is related to the erroneously predicted trough in the lower atmosphere.

The predicted pattern in the troposphere (not shown) is not particularly good. Especially a ridge over the eastern Pacific ocean at the 300-mb level is incorrectly predicted. It is interesting to note, associated with this ill-defined ridge in the troposphere, that the Aleutian anticyclone at 50 mb is not well predicted either. A similar phase error in the stratospheric wave is also seen on the 4th day in Exp. A (see Fig. 1). A question may arise as to why the computed trough position in the lower atmosphere was wrong, but a simple, clear-cut answer is not known.

Boville (1960) called attention to the dominant feature of the Aleutian-Alaskan anticyclone in the winter stratosphere, and mentioned that, "the origin of the anticyclone should be expected in the troposphere."

4. Zonal means of kinetic energy and temperature

Let us next look at the time evolution of kinetic energy and temperature for the predicted and the observed field for Exp. B. For convenience, the kinetic energy is divided into zonal kinetic energy K_Z and eddy kinetic energy K_E from the definitions, $K_Z = (\bar{u}^2+\bar{v}^2)/2$, and $K_E = \overline{(u'^2+v'^2)}/2$, where $u'=u-\bar{u}$, $v'=v-\bar{v}$, and the bar indicates the zonal average.

a. *Kinetic energy*

Fig. 3 and 4 are latitude-time charts of the zonal kinetic and eddy kinetic energies, K_Z and K_E, respectively, at level 1 ($\sim$9 mb). K_Z decreases by a considerable amount before the breakdown, and at the same time K_E increases explosively. This is a typical feature observed with sudden warmings (Teweles, 1963). Quali-

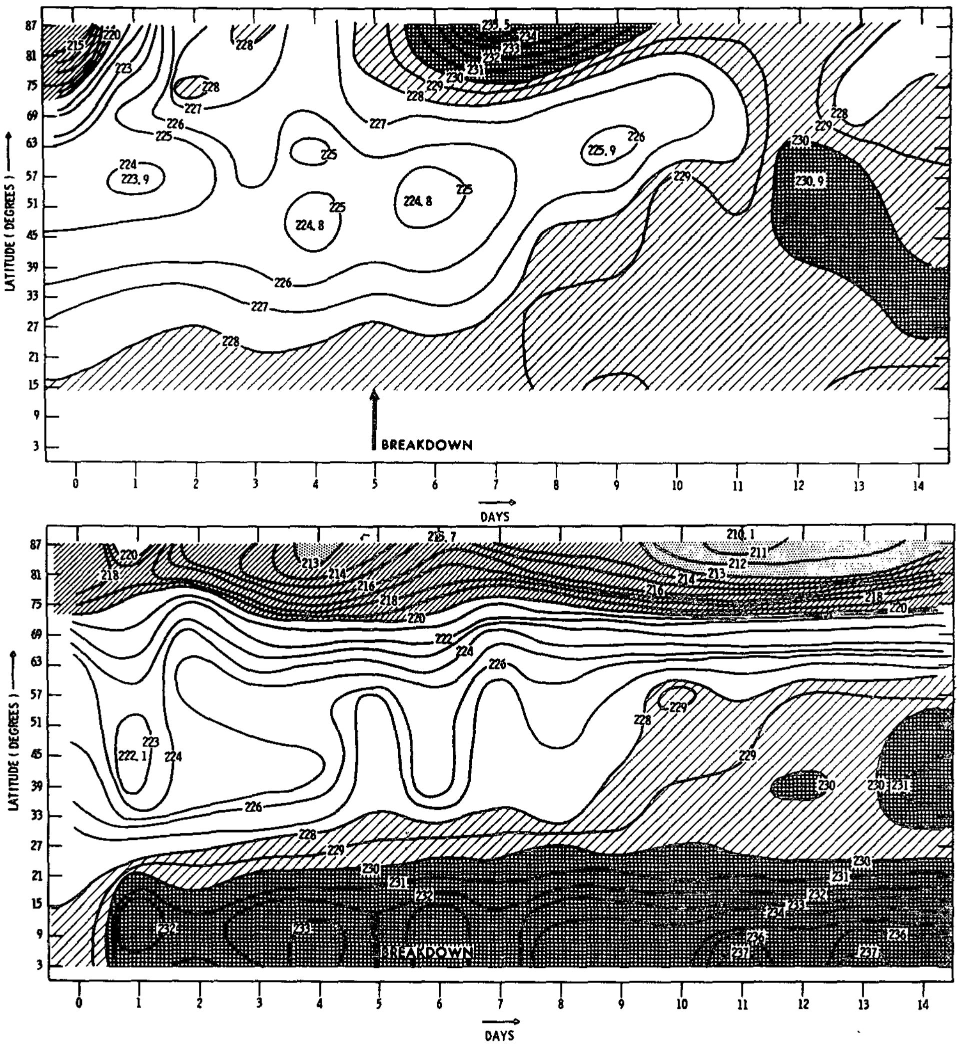


FIG. 5. The zonal average of temperature, observed (upper) and Exp. B (lower), at level 1 in °K. See Fig. 3 for other details.

tatively, these features were simulated well by the present experiment. Quantitatively, however, the prediction is poor. The decrease of K_Z is not well computed, and the predicted K_E is much smaller than the observed.

It is noted that there is a compensating tendency between the two quantities; that is, roughly speaking, K_Z decreases as K_E increases. This may be one of the factors which led to the hypothesis of barotropic instability as the cause of the breakdown in the past.

b. Temperature

The zonal mean of temperature at level 1 is shown in Fig. 5. The sudden warming which starts on the 5th day culminates on the 7th day. However, in the prediction (also in Exp. A), there was almost a *complete failure in the simulation of the sudden warming*. The only consolation is that a slight increase of temperature is noticed at days 5–7 of the prediction.

In the observed temperature chart of Fig. 5, the 228K isotherm, initially at low latitude, moves northward with time, indicating the overall warming of the entire Northern Hemisphere. Interestingly, this feature was simulated well by the experiment, despite the fact that the seasonal change of insolation is not included in the model. This was evidently achieved by the eddy flux of temperature associated with the vortex breakdown, even though the predicted breakdown was not as intense as the observed one.

The predicted temperature near the north pole is much lower than the observed.

Fig. 6 is the zonal mean of temperature at the 50-mb level and, in fact, represents the temperature distribution in the lower stratosphere. The usual marked mid-

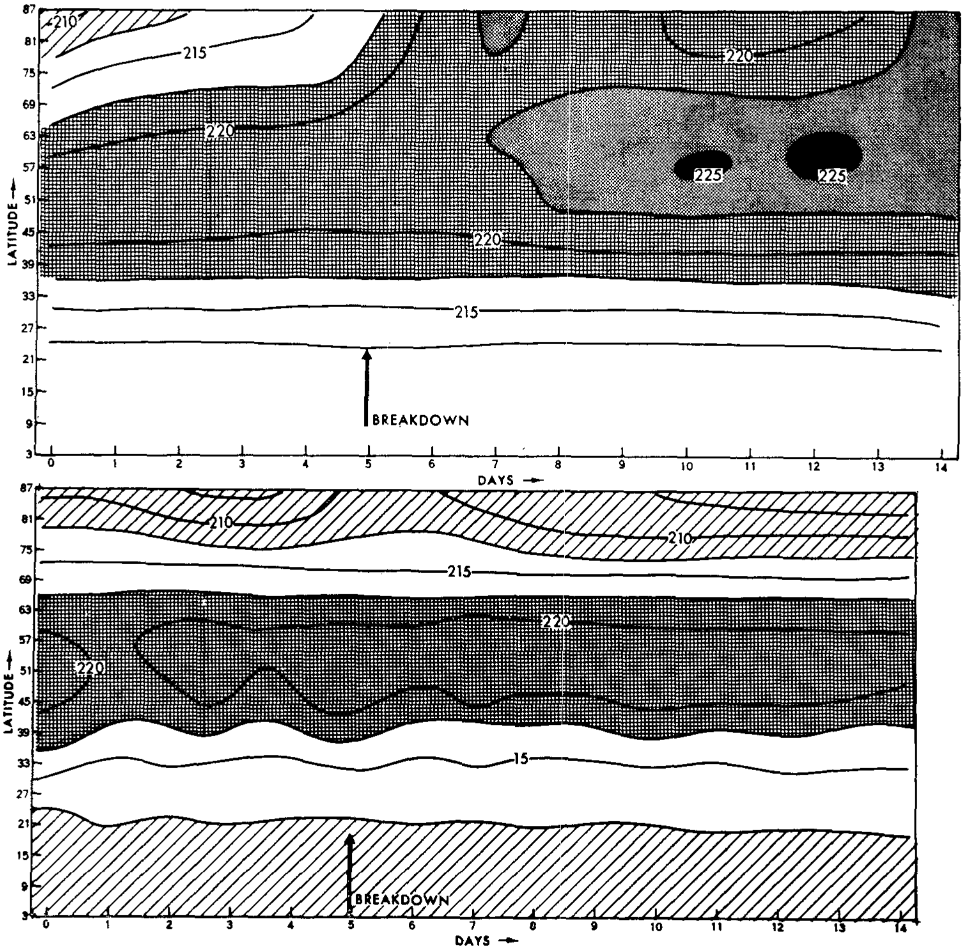


FIG. 6. The zonal average of temperature, observed (upper) and Exp. B (lower), at the 50-mb level in °K.

latitude temperature maximum is shown in the observation. But the maximum in the prediction becomes less pronounced as time goes on. This is apparently a defective characteristic of the model.

A. J. Miller and F. G. Finger (personal communication) have commented that the failure to simulate the warming might be due to the lack of higher levels in the model. Their experience with the analyses of 5-, 2- and 0.4-mb patterns indicates that "these regions undergo warmings that are never observed at the lower levels."

5. Energy conversion before and after the vortex breakdown

Since the amplification of wavenumbers 1 or 2 is a key point in the vortex breakdown, it is necessary to discuss the change of eddy kinetic energy. Especially it is important to know by what processes the disturbance energy in the stratosphere changes with time and how the increase in K_E is achieved at the time of the vortex destruction.

Using the notation of Phillips (1956), we find three major terms in the mechanical energy equation for K_E, i.e.,

$$-\partial(\overline{\omega'\phi'})/\partial p,$$

$$-\overline{\omega'\alpha'}=\langle P_E\cdot K_E\rangle,$$

$$-\overline{u'v'}\cdot(\cos\varphi)\frac{\partial}{a\partial\varphi}\left(\frac{\bar{u}}{\cos\varphi}\right)=\langle K_Z\cdot K_E\rangle.$$

It is now widely accepted that the *first term is the most important one* in the energetics of the middle and low stratosphere.

Charney and Drazin (1961) and Dickinson (1968) threw important light on the significance of the first term.

Actual assessments of $-\overline{\omega'\phi'}$ with observed data were carried out by Jensen (1961), Barnes (1962), Miyakoda (1963), Oort (1964), Lateef (1964), Murakaimi (1965), Julian and Labitzke (1965), Muench (1965), Perry

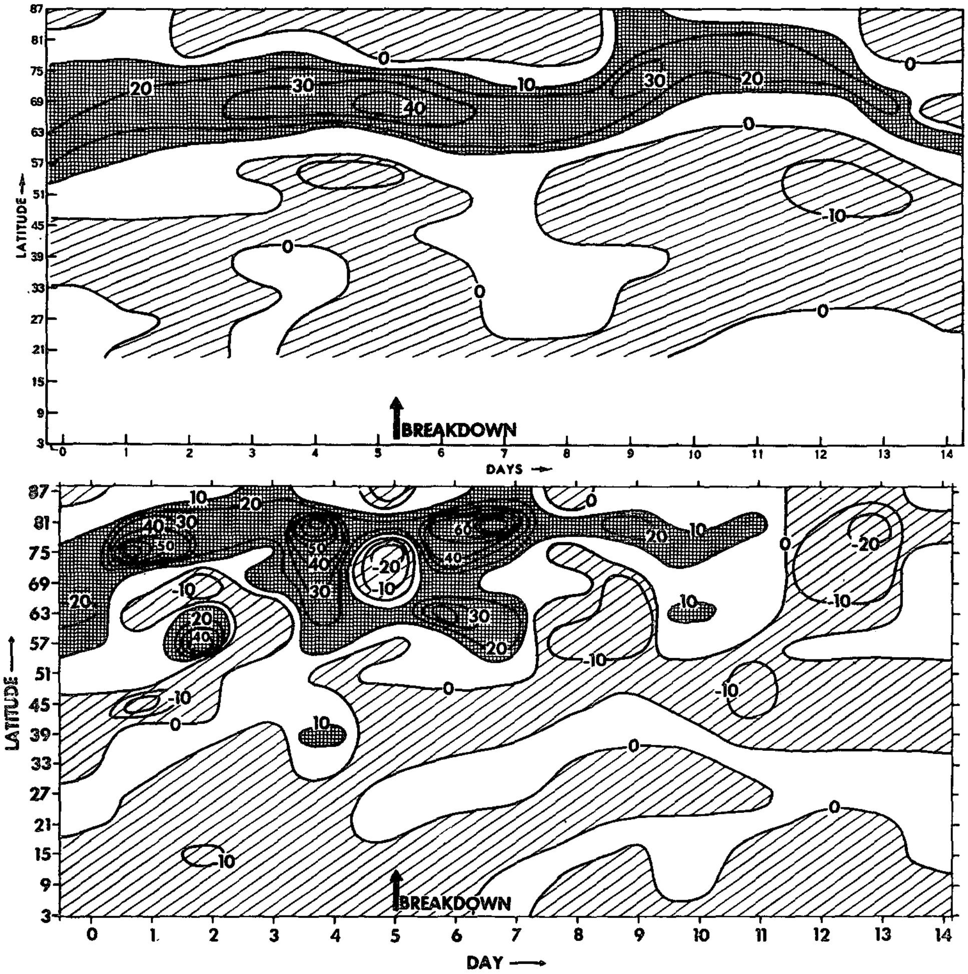


FIG. 7. Latitude-time diagram for divergence of the vertical eddy flux of geopotential, $-\partial\overline{\omega'\phi'}/\partial p$, in the layer from 0–34 mb in units of cm^2 sec^{-3} for the result from the ω equation and the observed geopotential (upper), and from Exp. B (lower).

(1967) and Paulin (1968), based upon diagnostically computed ω, where methods of the estimation of ω were not always the same. They all concluded that the term $-\partial(\overline{\omega'\phi'})/\partial p$ is the largest contribution in the budget of K_E.

Different and important approaches were made by Peng (1965), Smagorinsky *et al.* (1965), and Manabe and Hunt (1968), who conducted numerical experiments on the general circulation including the stratosphere, using 4-, 9- and 18-level models, respectively. They also concluded that $-\partial(\overline{\omega'\phi'})/\partial p$ is the most important term. Manabe and Hunt, especially, who used the most elaborate model for stratospheric simulation, concluded that the magnitude of $-\partial(\overline{\omega'\phi'})/\partial p$ is six and two times larger in the middle and lower stratosphere, respectively, than that of the second largest term $-\overline{\omega'\ \alpha'}$ at the time of the horizontal elongation of the vortex. (The simulation was for the annual mean conditions but the result included a stratospheric vortex elongation.) Let us now consider how these factors change at the time of the vortex breakdown in Exp. B (see K_E in Fig. 4).

Fig. 7 shows the latitude time variation of the vertical eddy flux of geopotential, $-\partial(\overline{\omega'\phi'})/\partial p$, in the layer between 0 and 34 mb. The upper figure is based on ω computed with the ω equation from the observed geopotential height which does not include the friction nor the heating terms. The lower figure is the result of Exp. B.

Both in the prediction and observation, there are regions of upward transmission of energy (positive) from below, which are confined to *a narrow belt at high latitudes* throughout most of the period. This tendency is especially pronounced in the observation, probably because the polar-night jet is well retained in high latitudes. At the time of the vortex breakdown the propagation has increased appreciably, and later

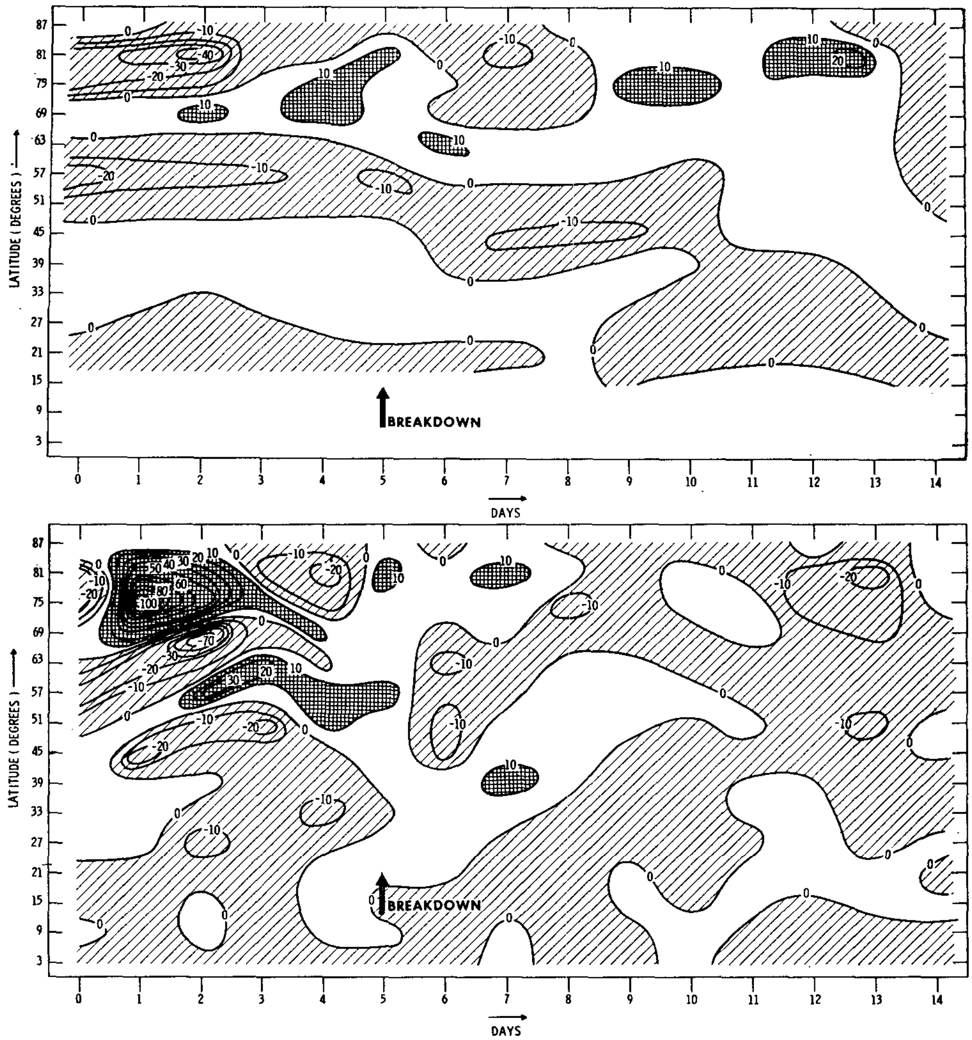


FIG. 8. The same as Fig. 7 except for the conversion from eddy available potential to eddy kinetic energy, $-\overline{\omega'\alpha'}$.

weakened considerably. However, this important change did not occur as suddenly as expected.

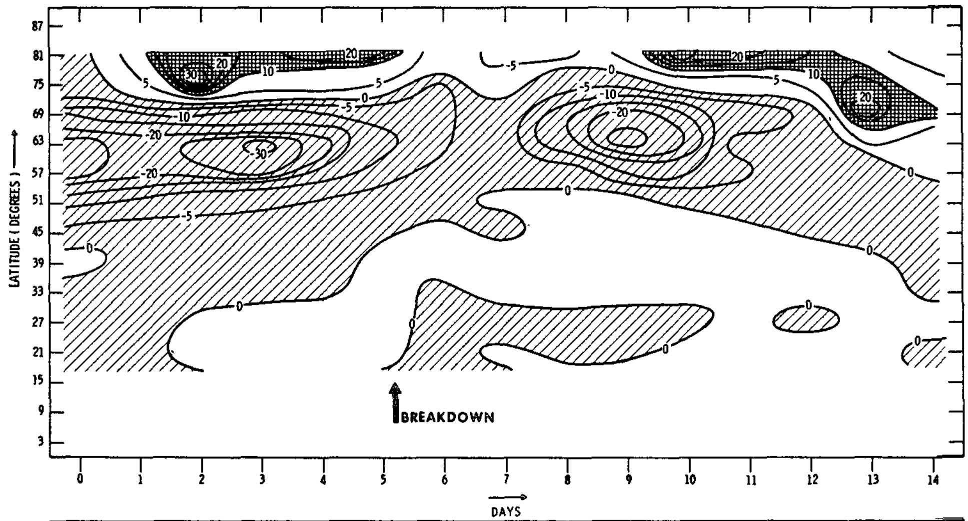
The values of $-\overline{\omega'\,\alpha'}$, the conversion from eddy available potential energy to eddy kinetic energy, at level 1 (Fig. 8) appear to have a positive belt at high latitudes, though large negative values are juxtaposed.

Fig. 9 shows the conversion from zonal kinetic energy to eddy kinetic energy, $-\overline{u'v'}(\cos\varphi)\,\partial(\bar{u}/\cos\varphi)/a\partial\varphi$, at level 1. The positive region exists only at very high latitudes, and large negative regions are located between 45 and 75N both in the prediction and the observation. This means that the kinetic energy transformation is mostly of the type $K_E \rightarrow K_Z$, which is the same as in the troposphere.

a. Comparison with preceding research

Reed *et al.* (1963) and Sekiguchi (1963) computed rates of various conversions for the cases of the sudden warming in January 1957 and 1958, respectively, using 50-mb data. Both results showed that before the warming $\langle P_E \cdot K_E \rangle$ is positive, but after the warming it is completely reversed. While $\langle K_E \cdot K_Z \rangle$ was always positive in Reed's result, it was slightly negative before the warming in Sekiguchi's.

Miyakoda (1963), Julian and Labitzke (1965) and Muench (1965) also evaluated the conversions for the cases of January 1958, 1963 and 1958, using the data for both the troposphere and stratosphere. They concluded that $-\overline{\omega'\phi'}$ was large at the time of the warming.



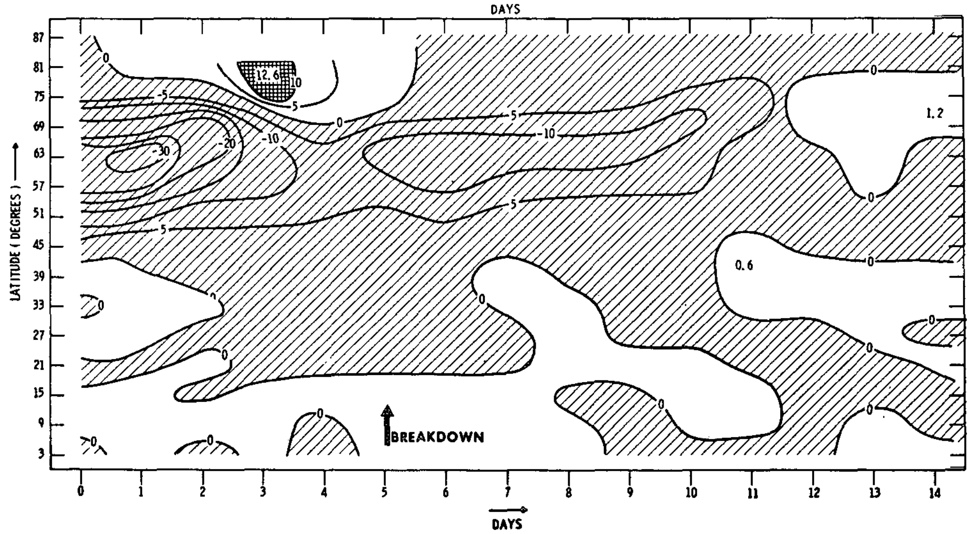


FIG. 9. The same as Fig. 7 except for the conversion from zonal kinetic to eddy kinetic energy, $-(1/a)(\cos\varphi)\cdot\overline{u'v'}(\partial/\partial\varphi)(\bar{u}/\cos\varphi)$.

The results for $\langle P_E \cdot K_E \rangle$ was the same as those of Reed *et al.*

Murakami (1965) computed $\langle K_E \cdot K_Z \rangle$ and $\langle P_E \cdot K_E \rangle$ with three month's data at 50 mb for the period including the sudden warming of January 1958. He concluded that a vast amount of energy must be supplied from below.

Perry (1967) dealt with the sudden warming of January 1963. This was the extraordinary warming with a dramatic vortex destruction. According to his calculation, for zonal wavenumber 2, the terms $-\partial(\overline{\omega'\phi'})/\partial p$, $\langle P_E \cdot K_E \rangle$, and $\langle K_E \cdot K_Z \rangle$ are all of comparable magnitude, and $\langle P_E \cdot K_E \rangle$ and $\langle K_E \cdot K_Z \rangle$ are both positive. This means that even for the case of the most drastic breakdown, the kinetic energy transformation is of the type $K_E \rightarrow K_Z$.

6. The relation with the troposphere

The relationship between the stratospheric vortex destruction (or sudden warming) and the blocking process in the troposphere has been observed by a number of authors: Teweles (1958, 1963), Wexler and Moreland (1958), Craig and Hering (1959), Hare (1960), Wexler (1961), Boville (1961, 1963), Julian (1961), Labitzke (1962, 1965), Miyakoda (1963), Wada (1964), Muench (1965), Murakami (1965), Julian and Labitzke (1965) and Paulin (1968). The term "blocking" was not always used explicitly and the status of the troposphere was sometimes referred to as "low index cycle." The interpretation of the evidence was not the same in each paper, and the point of emphasis was often different.

Some of the investigators mentioned that sudden

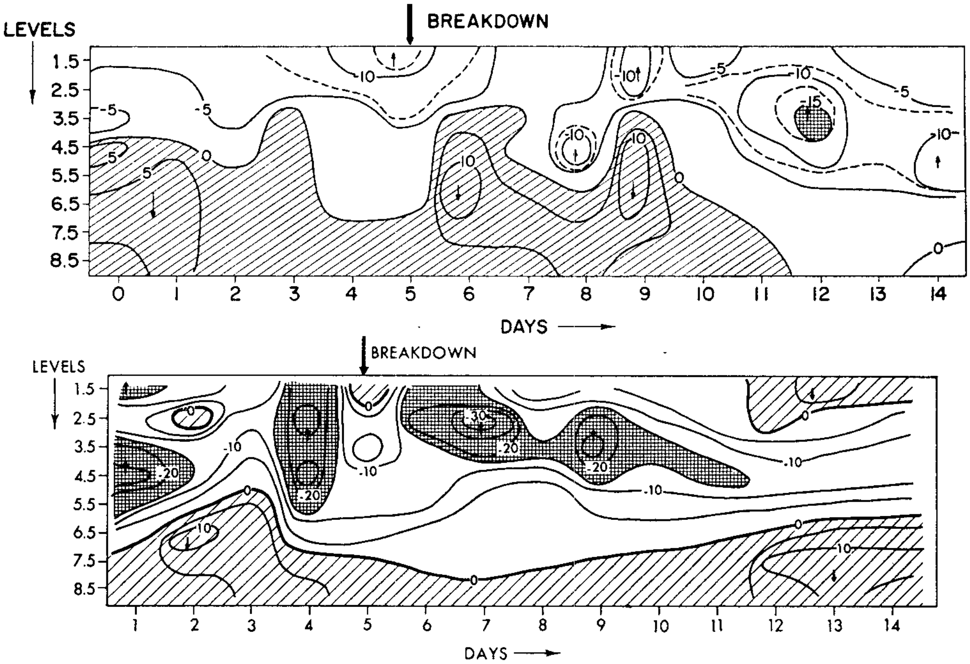


FIG. 10. Height-time diagram for the vertical eddy flux of geopotential $\overline{\omega'\phi'}$ at a high latitude belt in units of 10^2 gm sec^{-3}, from the ω-equation (upper) and from Exp. B (lower). The areas of the downward flux are hatched, and the areas where the intensity of upward flux is greater than 15×10^2 gm sec^{-3} are cross-hatched.

warmings might be the consequence of an extraterrestrial cause or the chemical reaction of gases in the upper atmosphere. According to this interpretation, the coincidence of blocking at the time of the sudden warming suggested that an extraterrestrial cause or an activity of the stratosphere or mesosphere was influencing a tropospheric process. In addition, since the warming begins at great height and then propagates downward, the ultimate origin was sometimes thought to exist in the stratosphere, or mesosphere, or in space. If true, these ideas are fascinating. But the present authors tend to believe that an approach along a thermodynamical line still holds the promise for understanding the sudden warming.

Although there has long been an awareness of the possible linkage between the vortex breakdown and blocking, it is also true (Finger, Wada, Miller and Johnson, personal communication) that one-to-one correspondence is not always guaranteed. Miyakoda (1963) showed the correspondence between the warming in the stratosphere and the cooling in the troposphere for the case of January 1958. But this agreement is not always observed. The linkage is still being debated, and part of the reason may be a semantic difference or the lack of a clear-cut definition of the blocking process.

a. Propagation of energy from the troposphere

Murakami and Tomatsu (1965) reported, based on an analysis of the actual atmosphere, that $-\overline{\omega'\phi'}$ at the 50-mb level increased at a certain time during the blocking process for January 1958.

Expecting a similar effect in our experiment, we computed the time-height distribution of $-\overline{\omega'\phi'}$ in the latitudinal belt from 66–79N for the solutions of the ω equation and from 72–84N for Exp. B (see Fig. 10). The latitude belts were chosen to include the maximum values of $-\overline{\omega'\phi'}$. We had hoped to find a marked upward transmission of energy with an explosive increase in flux just prior to the breakdown, but the diagram failed to show it in a convincing way. Perhaps the 14-day period may be too brief to prove this trend.

Teweles (1958) pointed out that "sudden warming is especially intense when the trough is stationary or retrogressing."

Another relevant fact was reported by Sugimoto (1968). He took a three month period from December 1965 to March 1966 and showed a parallel trend between the pressure height of the Aleutian high and $\overline{v'T'}$ for wavenumber 1 at 60N at the 30-mb level.

b. Downward propagation of the warming phase

Finger and Teweles (1964) said there is "evidence of a maximum intensity of circulation change and sudden warming in the layer near 45 km (the portion of the ozone layer heated most strongly by solar radiation)," and that "the circulation changes appear to begin in this layer and then spread both downward and upward."

Why then does the warming propagate downward, despite the aforementioned possibility that the influence of the troposphere is initiating the phenomenon? In this connection, Bryon-Scott's numerical experiment is instructive. He used a 3-level (from 70 to ~0.4 mb) stratospheric model, in which temperature is determined by the usual thermal equation. The equations of motion was highly simplified; i.e., he used the quasi-stationary vorticity equation, included the photochemistry of ozone, and specified an external forcing at the lowest boundary of 163.3 mb, the latter being such that an upward flux of eddy geopotential across the lower boundary is permitted. In the experiment, the warming started about the 0.9-mb level, in spite of the fact that the initial energy flux was given at 163.3 mb. Then the warming propagated downward.

As mentioned earlier, the failure in simulating the sudden warming in our experiment may be due to the coarse vertical resolution in the model, or due to the absence of a higher level such as the 0.9-mb level. It is also possible that our failure may be attributed to the fact that the model does not include the photochemical process (Lindzen, 1966) or does not properly consider the refractive characteristics at higher levels.

Let us, however, mention another aspect that does not necessarily contradict the concept described above and certainly deserves attention. Hirota (1967) claimed that the downward propagation of warming just appears to be so in the time-height section of temperature of one observing station. This is, so to speak, the "Eulerian" view. If one traces the phase in a "Lagrangian" way, he will find that the real warming tendency starts at about the 50-mb level and propagates upward. Byron-Scott also explained that the westward slanting waves are responsible for the downward progression of the warming in his model. This point needs more study.

In any event the suddeness of the phenomenon has not yet been fully understood.

7. Conclusions

The simulation of the vortex breakdown was successful although it was not wholly satisfactory. The time variation of the zonal mean of computed eddy kinetic energy compared well qualitatively with the observed for the two week period, but quantitatively it was very poor.

The sudden warming was not predicted at all. In the prediction the split vortex erroneously began to merge again after about 8 days, and then the computed vortex became circular with its center at the pole. The defects in the stratospheric simulation may be partly due to insufficient vertical resolution of the model, and partly due to the model's weak capability of producing large-scale meanders of the westerlies. This study showed that the vertical propagation of energy from the troposphere, expressed by the term $-\overline{\omega'\phi'}$, is overwhelmingly important for the vortex breakdown. Among other effects this vertical transmission of energy takes place in a narrow latitudinal belt at high latitudes (~50–80N) associated with the polar-night jet. It is likely that $-\overline{\omega'\phi'}$ may become rather large during the simultaneous occurrence of blocking in the troposphere and the presence of reasonably strong stratospheric westerlies.

Acknowledgments. The authors are indebted to several staff members for programming and technical assistance and wish to thank Messrs. Merlin L. Neff, Irving I. Shulman, Lemuel W. Reed, Jr., Terry L. Mauk, Philip G. Tunison and Howard H. Engelbrecht.

Special gratitude is expressed for important suggestions and encouragement by Drs. Joseph Smagorinsky and Syukuro Manabe. We wish to thank Prof. N. A. Phillips for the special review and Dr. S. Teweles, and many colleagues who gave valuable suggestions.

REFERENCES

Austin, J. M., and L. Krawitz, 1956: 50-millibar patterns and their relationship to tropospheric changes. *J. Meteor.*, **13**, 152–159.

Barnes, A. A., 1962: Kinetic and potential energy between 100 mb and 10 mb during the first six months of the IGY studies of the stratospheric general circulation. Rept. AFCRL-63-435, Dept. of Meteor., Massachusetts Institute of Technology, 138 pp.

Boville, B. W., 1960: The Aleutian stratospheric anticyclone. *J. Meteor.*, **17**, 329–336.

——, 1961: A dynamical study of the 1958–59 stratospheric polar vortex. *Publ. Meteor.*, No. 36, Arctic Meteor. Res. Group, McGill Univ., Montreal, 134 pp.

——, 1963: What are the causes of the Aleutian anticyclones? *Meteor. Abhandl., Inst. Meteor. Geophys., Frei. Univ., Berlin*, **36**, No. 107–119.

Byron-Scott, R., 1967: A stratospheric general circulation experiment incorporating diabatic heating and ozone chemistry. *Publ. Meteor.*, No. 87, Arctic Meteor. Res. Group, McGill Univ., Montreal, 201 pp.

Charney, J. G., and P. G. Drazin, 1961: Propagation of planetary-scale disturbances from the lower into the upper atmosphere. *J. Geophys. Res.*, **66**, 83–110.

Chen, L. S., 1962: The vertical propagation of disturbances of various scale in atmosphere in a non-geostropic model. *Collected Papers on the General Circulation in the Stratosphere*, Institute Geophys. and Meteor., Academia Sinica, 18–26.

Craig, R. A., and W. S. Hering, 1959: The stratospheric warming of January–February, 1957. *J. Meteor.*, **16**, 91–107.

Dickinson, R. E., 1968: On the exact and approximate linear theory of vertically propagating planetary waves forced at a spherical lower boundary. *Mon. Wea. Rev.*, **96**, 405–415.

Finger, F. G., and S. Teweles, 1964: The mid-winter 1963 stratospheric warming and circulation change. *J. Appl. Meteor.*, **3**, 1–15.

——, H. M. Woolf and C. E. Anderson, 1965: A method for objective analysis of stratospheric constant-pressure charts. *Mon. Wea. Rev.*, **93**, 619–638.

Hare, F. K., 1960: The disturbed circulation of the arctic stratosphere. *J. Meteor.*, **17**, 36–51.

Hirota, I., 1967: The vertical structure of the stratospheric sudden warming. *J. Meteor. Soc. Japan*, **45**, 422–435.

Jensen, C. E., 1961: Energy transformation and vertical flux processes over the Northern Hemisphere. *J. Geophys. Res.*, **66**, 1145–1156.

Julian, P. R., 1961: Remarks on the disturbed circulation of the arctic stratosphere. *J. Meteor.*, **18**, 119–121.

——, and K. B. Labitzke, 1965: A study of atmosphere energetics during the January-February 1963 stratospheric warming. *J. Atmos. Sci.*, **22**, 597–610.

Labitzke, K., 1962: Beitrage zur Synoptik der Hochstratosphäre. *Meteor. Abhandl., Inst. Meteor. Geophys. Frei. Univ., Berlin*, **28**, No. 1, 1–93.

——, 1965: On the mutual relation between stratosphere and troposphere during periods of stratospheric warmings in winter. *J. Appl. Meteor.*, **4**, 91–99.

Lateef, J. A., 1964: The energy budget of the stratosphere over North America during the warming of 1957. *J. Geophys. Res.*, **69**, 1481–1495.

Lindzen, R. S., 1966: Radiative and photochemical processes in mesospheric dynamics: Part IV. Stability of zonal vortex at mid-latitudes to baroclinic waves. *J. Atmos. Sci.*, **23**, 350–359.

Manabe, S., and B. G. Hunt, 1968: Experiments with a stratospheric general circulation model: I. Radiative and dynamic aspects. *Mon. Wea. Rev.*, **96**, 477–502.

——, J. Smagorinsky and R. F. Strickler, 1965: Simulated climatology of a general circulation model with a hydrologic cycle. *Mon. Wea. Rev.*, **93**, 769–798.

Miyakoda, K., 1963: Some characteristic features of winter circulation in the troposphere and lower stratosphere. Tech. Rept. No. 14, Grant NSF-GP-471, Dept. of Geophys. Sci., The University of Chicago, 93 pp.

——, J. Smagorinsky, R. F. Strickler and G. D. Hambree, 1969: Experimental extended predictions with a nine level hemispheric model. *Mon. Wea. Rev.*, **97**, 1–76.

Muench, H. S., 1965: On the dynamics of the wintertime stratospheric circulation. *J. Atmos. Sci.*, **22**, 349–360.

Murakami, T., 1965: Energy cycle of the stratospheric warming in early 1958. *J. Meteor. Soc. Japan*, **43**, 262–283.

——, and K. Tomatsu, 1965: Energy cycle in the lower atmosphere. *J. Meteor. Soc. Japan*, **43**, 73–89.

Newell, R. E., 1966: The energy and momentum budget of the atmosphere above the tropopause. *Problems of Atmospheric Circulations*, Washington, D. C., Spartan Books, 106–126.

Oort, A. H., 1964: On the energetics of the mean and eddy circulations in the lower stratosphere. *Tellus*, **16**, 309–327.

Paulin, G., 1968: Spectral atmospheric energetics during January 1959. *Publ. Meteor.*, No. 91, Arctic Meteor. Res. Group, McGill Univ., Montreal, 256 pp.

Peng, L., 1965: A simple numerical experiment concerning the general circulation in the lower stratosphere. *Pure Appl. Geophys.*, **61**, 191–218.

Perry, J. S., 1967: Long-wave energy processes in the 1963 sudden stratospheric warming. *J. Atmos Sci.*, **24**, 539–550.

Phillips, N. A., 1956: The general circulation of the atmosphere: A numerical experiment. *Quart. J. Roy. Meteor. Soc.*, **82**, 123–164.

Reed, R. J., J. L. Wolfe and H. Nishimoto, 1963: A special analysis of the stratospheric sudden warming of early 1957. *J. Atmos. Sci.*, **20**, 256–275.

Sawyer, J. S., 1965: The dynamical problems of the lower stratosphere. *Quart. J. Roy. Meteor. Soc.*, **91**, 407–416.

Sekiguchi, Y., 1963: Energy variation in the stratosphere during the winter season and its relation to dynamic stability of the polar winter. Rept. ARL-1277-3, Res. Inst., Univ. of Oklahoma, 46 pp.

Smagorinsky, J., S. Manabe and J. L. Holloway, Jr., 1965: Numerical results from a nine level general circulation model of the atmosphere. *Mon. Wea. Rev.*, **93**, 727–798.

Sugimoto, Y., 1968: Effect of ultra-long wave on temperature variation in the stratosphere. *J. Meteor. Soc. of Japan*, **15**, 511–518.

Teweles, S., 1958: Anamalous warming of the stratosphere over North America in early 1957. *Mon. Wea. Rev.*, **86**, 377–396.

——, 1963: A spectral study of the warming epoch of January–February 1958. *Mon. Wea. Rev.*, **91**, 505–519.

Wada, H., 1964: Some aspects of the general circulation of the atmosphere in winter to summer. *Geophys. Mag.*, **32**, No. 1, Japan Meteor. Agency, Tokyo, 77–106.

Wexler, H., 1961: Some aspects of stratospheric and mesospheric temperature and wind patterns. *Space Research II*, Amsterdam, North-Holland Publ. Co., 1083–1093.

——, and W. B. Moreland, 1958: Winds and temperatures in the arctic stratosphere. *Polar Atmosphere Symposium*, Part I, New York, Pergamon Press, 71–84.

Wilson, C. V., and W. L. Godson, 1963: The structure of the arctic winter stratosphere over a 10 year period. *Quart. J. Roy. Meteor. Soc.*, **89**, 205–224.