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Quasi-Biennial Variations in the Winter-Time Circulation of High Latitudes

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With 14 Figures

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Summary

In the years between 1952 and 1962 a quasi-biennial modulation became apparent in the total ozone values measured over Arosa, Switzerland, during spring. The stratospheric vortex behavior in the northern hemisphere during March of the years 1958 to 1964 also showed a biennial variation. This has led to speculations that the quasi-biennial forcing of the tropical stratosphere may extend its influence to the stratosphere and troposphere of high latitudes. It is shown in this paper that the stratosphere and troposphere of high latitudes in the northern hemisphere, indeed, are coupled by a "feedback" mechanism. The forcing from tropical latitudes, however, seems to be minimal.

Zusammenfassung

Die quasi-biennale Veränderlichkeit der Zirkulation in hohen Breiten während des Winters

Während der Jahre 1952 bis 1962 wurde in den über Arosa, Schweiz, im Frühling gemessenen Gesamtozonwerten eine quasi-biennale Modulierung entdeckt. Das Verhalten des stratosphärischen Polarwirbels im März der Jahre 1958 bis 1964 zeigte ebenfalls eine zweijährliche Veränderlichkeit. Dies verleitete zur Schlußfolgerung, daß die quasi-biennale Einwirkung der tropischen Stratosphäre sich bis in die Stratosphäre und die Troposphäre hoher Breiten erstreckt. In der vorliegenden Studie wird gezeigt, daß die Stratosphäre und Troposphäre der Nordhalbkugel in hohen Breiten tatsächlich durch einen Rückkoppelungs-Mechanismus verbunden sind. Der Einfluß tropischer Breiten auf die Zirkulationsmodulierung scheint jedoch gering zu sein.

1. Introduction

The biennial oscillation of the stratospheric wind systems in the tropics has received considerable attention during the past few years. (For a review of pertinent literature see [29, 30].) Essentially, the existence of such an oscillation could be regarded as an effect of extraterrestrial forcing, e. g. through variability in solar radiation [34], or as an internal feedback cycle in the earth-atmosphere system, possibly influenced by the 11-year sunspot cycle [33, 2]. Our present investigation proceeds on the premise that the latter is the case. The present state of knowledge of the general circulation does not permit us to derive quantitatively a closed system of cause and effect relationships that would describe such a feedback mechanism. However, the evidence compiled in recent literature lets us arrive at a qualitative and hypothetical framework of events that might be suggestive of such a feedback process within the atmosphere.

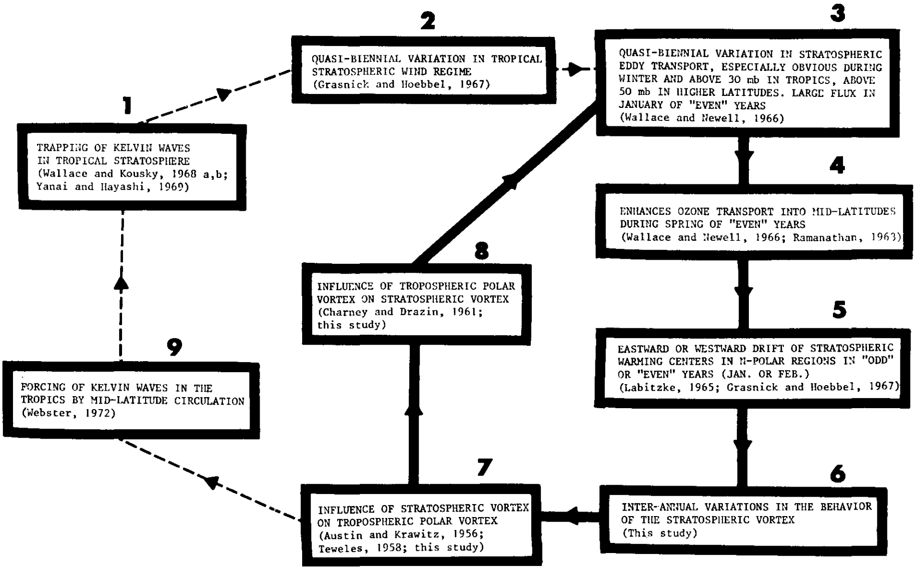

Fig. 1. Schematic flow chart depicting "quasi-biennial" forcing of the extratropical atmosphere from the tropical regions, and stratospheric-tropospheric interactions

This framework does not yet consider sea-surface temperatures, cloudiness and snow cover and their effects on albedo, etc. [9].

Fig. 1 describes schematically certain phases in the "closed loop" of the quasi-biennial forcing of the atmosphere that can be established from literature (see again [29, 30] for more details). The present study concerns itself with the possible role of the tropospheric and stratospheric circulations in middle and high latitudes during winter on the "loop" depicted in Fig. 1.

2. The Tropospheric Cold-Air Reservoir

Defant and Taba [6] described a period during January 1956, in which the circulation of the northern hemisphere changed from a strongly meridional (low index) to a predominantly zonal (high index) flow configuration. This change was characterized by a pronounced shrinking of the area circumscribed by the -25^0 C isotherm on the 500mb surface. Such an area, bounded on its edge by the polar-front jet stream, might be regarded as a crude measure of the polar cold-air reservoir in the middle troposphere.

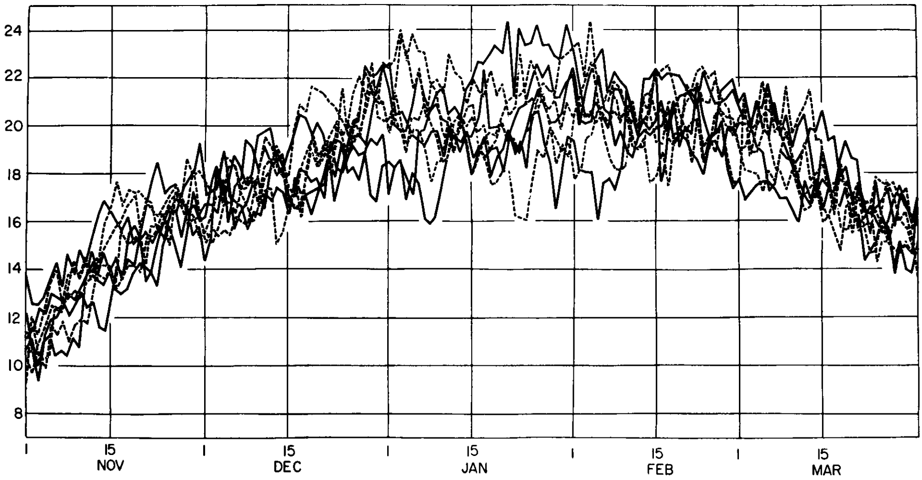

Fig. 2. Daily values of areal extent (arbitrary units along ordinate) of polar cold air, $T \leqq -30^0$ C, at 500 mb for cold seasons between 1953 and 1961. Solid lines: seasons preceding spring months with *high* total ozone at Arosa, Switzerland; dashed lines: seasons preceding spring months with *low* total ozone

A cursory examination of the Daily Series Synoptic Weather Maps revealed that during the winter months the strongest meridional temperature gradients — indicative of the intersection of the polar front with the 500mb surface — were usually concentrated between the -20^0 and -35^0C isotherms. We, therefore, chose the -30^0C isotherm on the 500mb surface as an indicator of the areal extent of the polar cold air mass. The area contained within this isotherm was planimetered for each day, using the 1500 GMT or 1200 GMT

Daily Synoptic 500 mb charts, as applicable, for each day between 1 November and 31 March and for "cold seasons" between 1953 and 1961. Unfortunately publications of these weather maps were not available for a longer time period.

Relatively small pools of cold air that split off from the main body of polar air were not any longer counted in the planimetered area if they remained separated. If, however, a portion of cold air split off and later rejoined the main body of polar air we continued to count its areal extent. The results are shown in Fig. 2. According

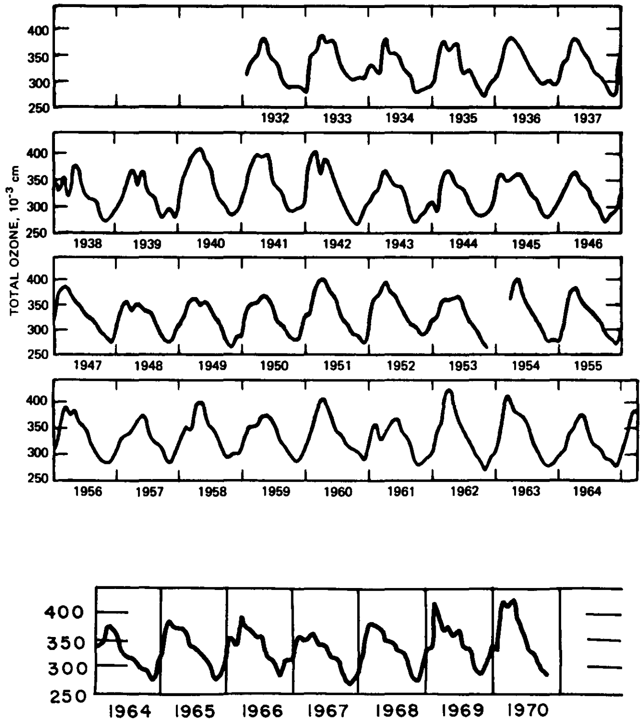

Fig. 3. Monthly mean total ozone amounts at Arosa, Switzerland (46.5° N, 9.4° E). [Top part of diagram from J. M. Wallace and R. E. Newell, Quarterly Journal of the Royal Meteorological Society, 92; 487 (1966); bottom part of diagram: Data courtesy of Dr. J. London]

to Wallace and Newell [37] the eight years included in our investigation revealed a well-established biennial oscillation in the total ozone amounts at Arosa, Switzerland (Fig. 3). We, therefore, proceeded to mark the curves for cold seasons preceding "high" and "low" ozone springs with solid and dashed lines, respectively, in Fig. 2.

Several features of interest in Fig. 2 should be pointed out briefly:

a) Quasi-periodic fluctuations in the size of the polar cold-air pool indicate the transition from low to high index periods. As an

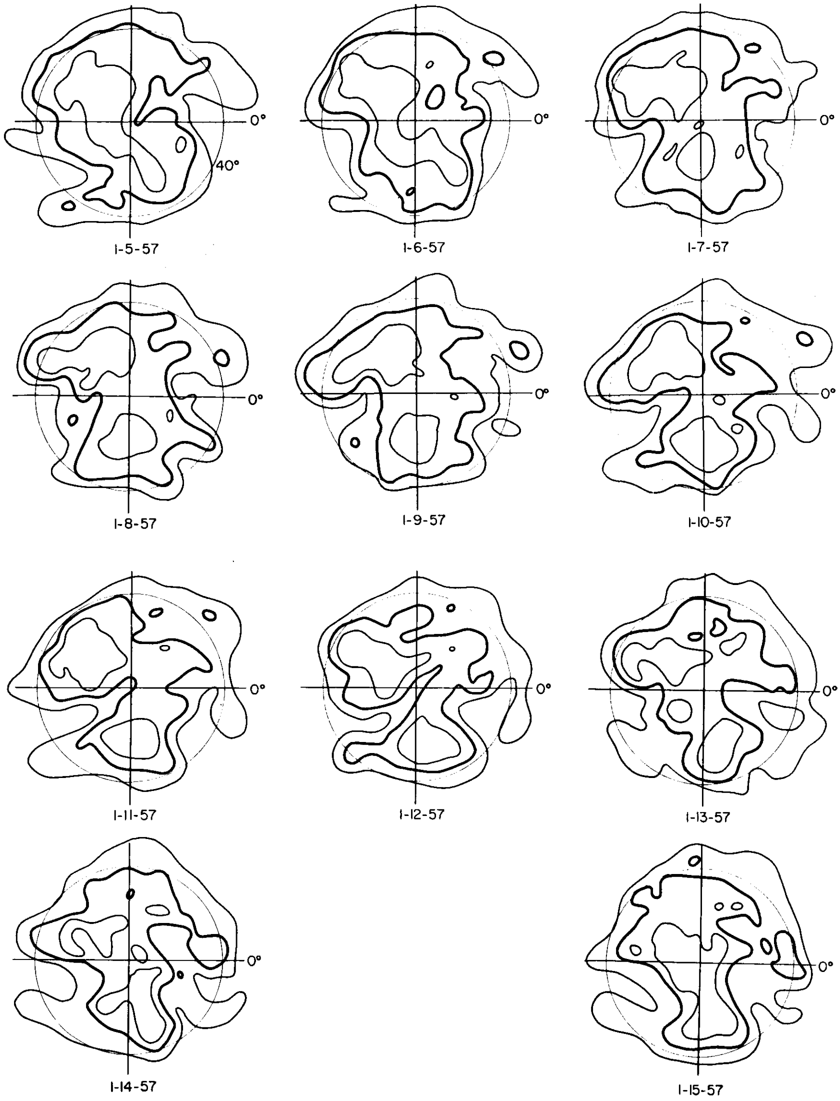

Fig. 4. Daily configuration of the -20^0 C, -30^0 C, and -40^0 C isotherms on the 500 mb surface for dates as indicated. 40^0 N latitude circle and 0^0, 90^0 E, 180^0 E and 90^0 W meridians are given for reference. (From U. S. Dept. of Commerce, Weather Bureau, Daily Series Synoptic Weather Maps)

example, Fig. 4 shows the changes in the configuration of cold air revealed by the -20^0, -30^0, and -40^0 C isotherms, between January 5 and 15, 1957, one of the most conspicuous contractions of the cold area on record. The area inside the -30^0 C isotherm shrank by approximately 1/3 of its original size during this relatively short time period. On January 12 the area of cold air almost managed to split into two. Contrary to the findings by Defant and Taba [6], the beginning of the time period shown in Fig. 4 resembles more a high-index, zonal flow situation, than the end of the period when the cold-air mass was drastically reduced in size.

b) The interannual variability of the areal extent of cold air, expressed by the scatter of curves in Fig. 2, remains relatively small until the middle of December. Then, however, until the middle of March, the variability is considerably higher. This is also revealed in Fig. 5 which gives the standard deviations of the whole 8-year ensemble of data from the daily means, as well as the standard deviations for the cold seasons preceding *high* and *low* ozone spring seasons, from the respective 4-year averages. There does not seem to be any significant difference in the standard deviations of these two sub-sets of data, that would suggest a biennial variability in the *relative* expansions and contractions of the cold-air pool. From Fig. 2 it also would appear that the rate of production of cold air during fall bears no obvious correlation with the size of the Arctic cold-air pool during the middle of winter.

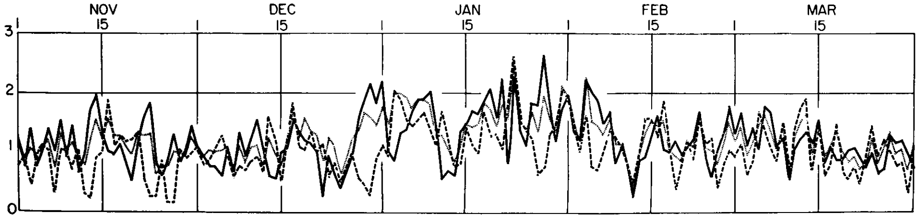

Fig. 5. Standard deviations of areal extent of polar cold air ($T \leqq -30^0$ C) at 500mb surface from daily mean values (same arbitrary units as in Fig. 2). Dotted line: Deviations from 8-year ensemble of data, 1953 to 1961. Solid line: Deviations from 4-year ensemble preceding spring seasons with *high* total ozone. Dashed line: Deviations from 4-year ensemble preceding spring seasons with *low* total ozone at Arosa, Switzerland

c) There is an indication that during winters preceding high ozone springs the size of the cold-air reservoir is smaller than during winters preceding low-ozone spring seasons. This is expressed more clearly in Fig. 6 which shows the daily values of areal extent of Fig.2 now averaged over all 8 years of data, and over the seasons preceding high and low ozone years (according to Fig. 3). A significant departure between the latter two curves occurs between 18 December and 9 January. An analysis of variances [3, 23] reveals a high

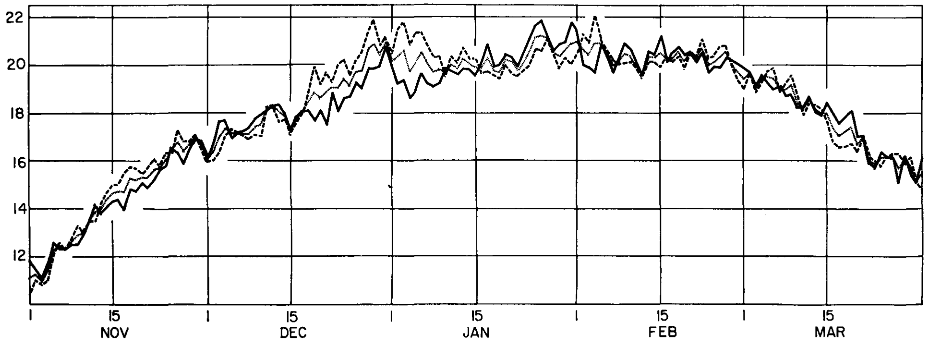

Fig. 6. Daily mean values of areal extent (same arbitrary units as in Fig. 2) of polar cold air ($T \leqq -30^0$ C), averaged over the 8-year ensemble 1953 to 1961 (dotted line), over the 4 years preceding spring seasons with *high* total ozone at Arosa, Switzerland (solid line), and over the 4 years preceding spring seasons with *low* total ozone (dashed line)

degree of significance at the $1^0/_0$ level in the spread between low- and high-ozone years for this particular time period. In comparison, the time periods from 16 January to 13 February, and 19 November to 17 December showed little or no significance of a difference in behavior between high- or low-ozone years.

Fig. 6 sheds additional light on a statistical investigation undertaken by Landsberg *et al.* [15]. They found a quasi-biennial temperature variation at a number of stations in both hemispheres. The variations, according to their study, tended to be 180^0 out of phase between equatorial and mid-latitude stations, especially those of the northern hemisphere. The quasi-biennial temperature variations also revealed some phase shifts with longitude during part of the sampling period. In the northern hemisphere there was a preference for the maxima of the quasi-biennial variation to occur during the winter months. Fig. 6 certainly confirms the significance of the oscillation during early winter. It would appear from this figure that the temperature record of mid-latitude stations located underneath the mean jet-stream position would be particularly sensitive to expansions or contractions of the polar cold-air reservoir. Since these changes in area occur mainly in the wake of the development of cyclonic and anticyclonic disturbances one should not expect the surface temperatures at a given latitude to respond uniformly in all longitude sectors to these expansions and contractions. Miller et al. [21] may be quoted in support of this statement. For the period 1955–1964 they find *maximum* northward transport of momentum on the 500mb surface in mid-latitudes during winters preceding low total ozone spring saesons (odd years) in wave numbers 1 and 3. Wave number 2 shows maximum transport in *even* years (preceding high-ozone spring seasons). Cyclone waves behave more erratic, apparently undergoing a shift with time in their phase relationship. From this it is obvious that superposition of the transport effects from all planetary waves would yield different amplitudes of the quasi-biennial oscillation effects at different longitudes.

In summary, thus, we can state that *high-ozone* spring seasons, indicative of enhanced meridional transport in the stratosphere, are preceded by winters with a relatively contracted pool of cold air in the troposphere and a below-average momentum transport at 500 mb in wave-numbers 1 and 3, above-average transport in wave number 2.

3. The Stratospheric Vortex

During years with high total ozone (1958, 1960, 1962, 1963, according to Fig. 3), the polar vortex at 10 mb tends to be more circular and centered closer to the north pole during March than is the case during years with low total ozone (1959, 1961, 1964). Mean maps analyzed at the Freie Universität Berlin [8] show these differences rather strikingly (Fig. 7). (A mean map for March 1958 was not readily available for reproduction. However an inspection of daily 10mb maps confirmed the similarity with the mean patterns for March 1960 or 1962.)

Wave no. 1 measuring the excentricity of the vortex certainly appears to be more prominent in the stratospheric vortex of the low-ozone years, than during the high-ozone years. Thus, Fig. 7 indicates a quasi-biennial behavior of stratospheric transport processes at planetary-wave scales similar to the one found by Miller *et al.* on the 500mb surface. During the low-ozone years the center of the polar vortex at 10 mb in March is removed by about 10^0 of latitude into the eastern hemisphere (70^0 to 90^0 E). Simultaneously, a strong high pressure region appears in the western hemisphere, leading to a pronounced jet stream over the north pole blowing from the West Pacific into the Atlantic region. During high-ozone years the vortex at 10 mb is centered closer to the pole, the high pressure region is less pronounced, and the polar-night jet stream does not flow over the North Pole.

From Fig. 7 we see, furthermore, that during low-ozone years the ozone observing stations of Tateno, Japan, and Arosa, Switzerland, are under the influence of the same low-pressure region in the upper stratosphere (10 mb ~ 31 km). During ozone-rich spring seasons, on the other hand, as exemplified by March 1960, Tateno is under the influence of a high-pressure ridge at 10 mb, whereas Arosa lies closer to a trough. From Fig. 8 we see that, as a consequence, the ozone peak at these two stations does not occur during the same month. The 1958 cold season had a similar effect on the ozone distributions shown in Fig. 8.

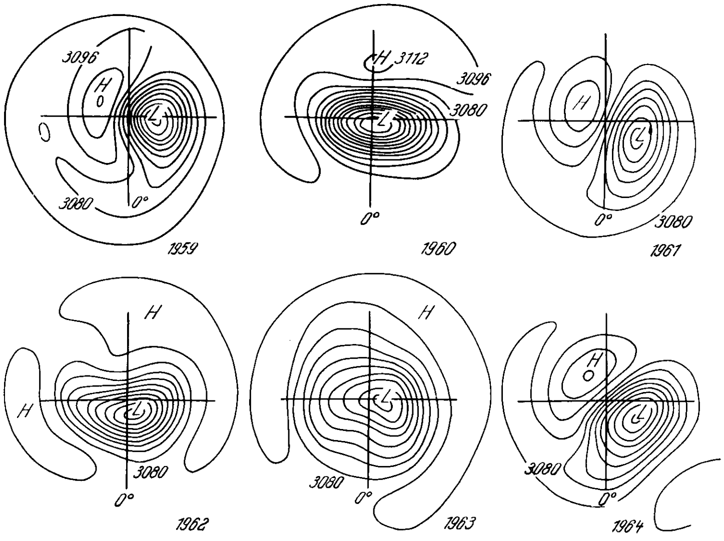

Fig. 7. Mean contour heights (dynamic deca-meters) of 10mb surface during March of years as indicated. (From [8])

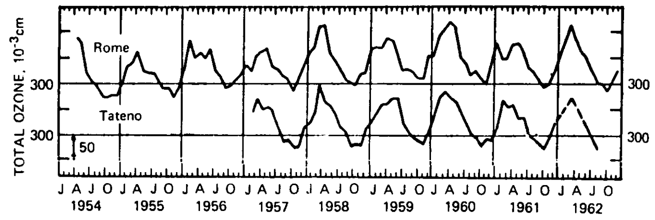

Fig. 8. Monthly mean total ozone amounts at Rome, Italy, and Tateno, Japan. (From [24])

The temporary breakdown of the quasi-biennial oscillation has been discussed by several authors [12, 13, 17, 18, 25]. The disruption of the cycle is evident from the ozone data (Fig. 3) as well as from the behavior of the stratospheric vortex at 10 mb. From 1964 to 1966 there was a gradual build-up of the ozone peak of spring in midlatitudes. A breakdown in the pattern occurred in 1967, when a minimum was reached. A build-up, again, was observed until 1969. The stratospheric vortex of March 1964 shows a pronounced off-center configuration that appears to be characteristic of low-ozone years (Fig. 9). March 1965 still shows an off-center configuration, with the low center displaced approximately 5⁰ southward along the Greenwich meridian. During March 1966 the vortex was more nearly circumpolar, as befits a high-ozone year, except for the fact that the contour gradients were rather weak.

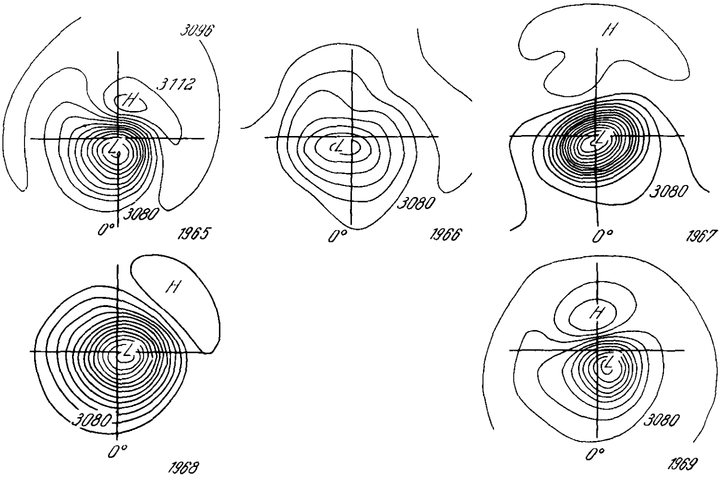

Fig. 9. Same as Fig. 7, except for different years

The mean 10 mb charts for March 1967, 1968 and 1969 do not at all reflect the symptoms of the vortex described above. During 1967 and 1968, when total ozone was relatively low, the stratospheric vortex during March appeared to be well centered. In 1969, when ozone was high, the 10 mb vortex during March was off-center. The *mean* configuration of the polar stratospheric vortex, while showing great interannual variation in both *shape* and *intensity,* does not relate well, therefore, to the total ozone amounts in middle latitudes, hence to the meridional transport processes in the lower stratosphere. The fallacy of establishing periodicities from records that are too short, pointed out by London and Haurwitz [16] (see also [17]) becomes quite apparent.

In order to study the behavior of the stratospheric vortex during low- and high-ozone years in more detail we computed for every day of the "cold season" the mean latitude, $\bar{\Phi}$, at which the 30640 m contour line of the 10 mb surface intersected every 30 degrees of longitude. This value gives a very crude measure of the areal extent of the stratospheric polar vortex, not taking into account its intensity. As we may expect from Figs. 7 and 9, there are wide variations between individual years in this quantity, partly due to the varying central pressure of the vortex. In order to reduce the effects of this variability we plotted the quantity

$$100 \sum_{t=1}^{t} (90-\bar{\Phi})^2 / \sum_{t=1}^{T} (90-\bar{\Phi})^2 \qquad (1)$$

on a daily basis for the time period 1 November through 31 March. t signifies the time within this period counted by days, and T is the total length of the period. Results are shown in Fig. 10 in terms of a cumulative percent distribution of $(90-\bar{\Phi})^2$. The "cold seasons" preceding high-ozone years are characterized by a reduction of the area circumscribed by the 30640 m contour line somewhere between early January and late February. This is indicated by the reduction in slope of the *solid* curves in Fig. 10. One exception is the 1964/65 season which lies closer to the characteristics of winters preceding a low-ozone year. Such an ill-defined character of this particular season was also evident from Fig. 9. The 1968/69 cold season, which precedes a high-ozone year also does not reveal the shrinkage of the stratospheric vortex during mid-winter. From this it appears, that the *size* of the stratospheric vortex bears no lasting correlation with the eddy transport processes that affect the mid-latitude ozone distribution.

A crude measure of the zonality or meridionality of the flow was obtained by considering the quantity

$$\sigma_t^2 = \overline{(\Phi-\bar{\Phi})^2} \qquad (2)$$

which expresses the variance of the colatitude values at which the 30640 m contour at 10 mb intersects every 30^0 of longitude on each day t. Fig. 11 shows the cumulative percent distribution of this quantity for the time-period $t = 1$ (1 November) to $t = T$ (31 March), i. e. the values of

$$100\left(\sum_{t=1}^{t} \sigma_t\right) / \left(\sum_{t=1}^{T} \sigma_t\right) \tag{3}$$

for each cold season 1957 to 1969.

The difference between winters before high- and low-ozone years is quite drastic. It starts to appear during January, when a steeper slope in the curves characteristic of high-ozone years brings them above the curves for low-ozone years. The steeper slope indicates a period in which the variance values σ_t^2 are large, i. e. in which the

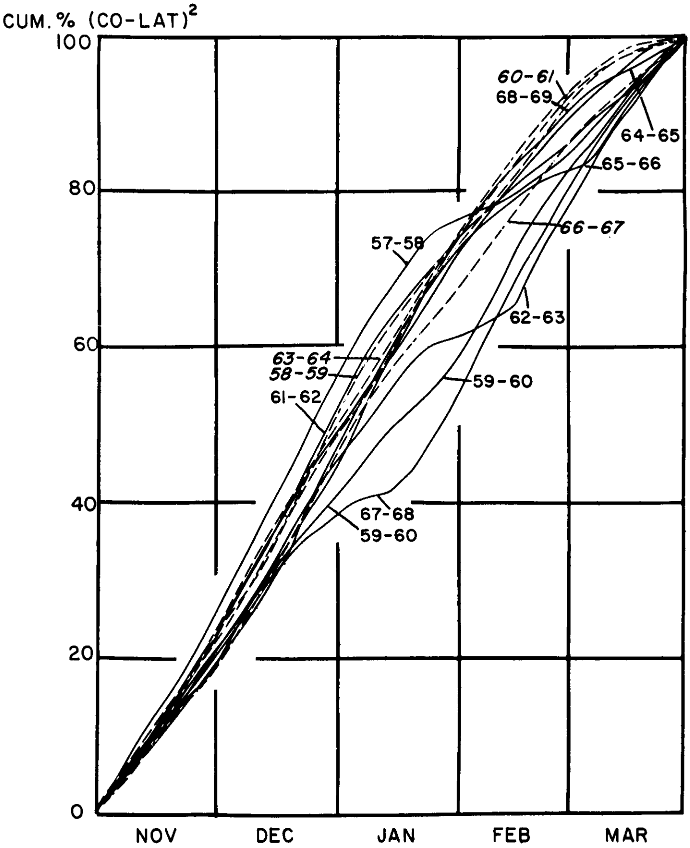

Fig. 10. Cumulative percent distribution of quantity expressed by Eq. (1). Solid lines and upright numbers represent cold seasons preceding springs with high total ozone, dashed lines and slanting numbers represent seasons preceding low-ozone springs

relatively zonal stratospheric vortex undergoes strong meridional disturbances. Such behavior is characteristic of the breakdown of the stratospheric vortex which is usually associated with "sudden warming" events, but also of the appearance of a pronounced trough-ridge pattern that need not necessarily lead to a complete vortex breakdown. Such a trough-ridge pattern is caused by baroclinic disturbances in the troposphere that also bring about the shrinking of the tropospheric cold-air pool.

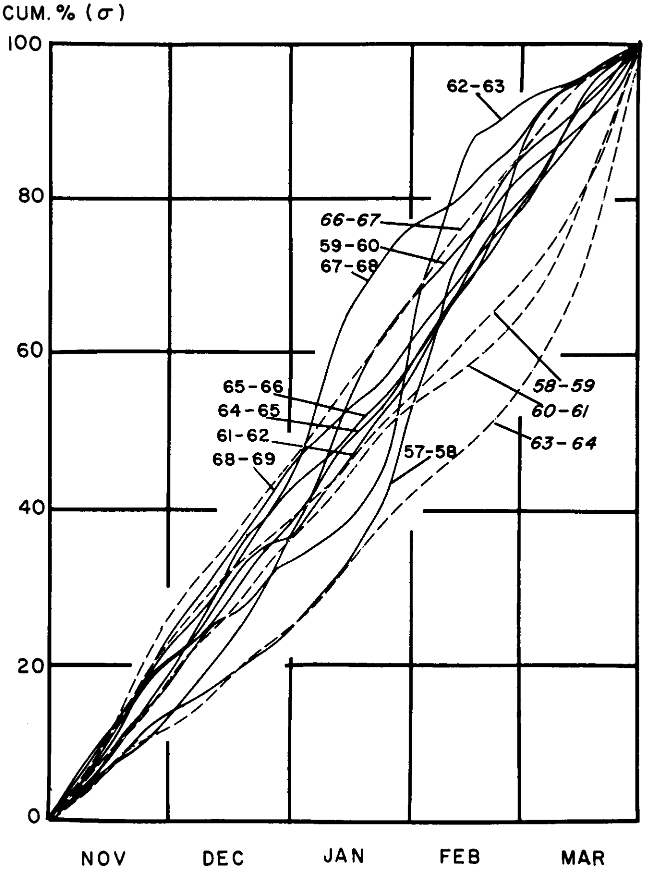

Fig. 11. Cumulative precent distribution of quantity expressed by Eq. (2) for cold seasons preceding springs with high (solid lines) and low (dashed lines) total ozone

In Fig. 11 we note two exceptional seasons that do not fit the general pattern very well: The 1964/65 season marks the lower limit of the spread of "high-ozone" curves during March, again in linie with the ambiguous character of this year. The curve for the "low ozone" season 1966/67 also fits the pattern poorly. We note however, that this is mainly due to high values of σ_t accumulating during November 1966. The pronounced meridionality of flow during the early part of the cold season apparently has no effect on the ozone distribution during the subsequent spring months. From Fig. 3 we see, however, that this meridionality caused relatively high ozone levels during December of 1966.

The largest differences in the meridionality of the stratospheric vortex between high- and low-ozone years occur towards the end of February. Tab. 1 summarizes these values. We may conclude, therefore, that the magnitude of stratospheric eddy transport processes during January and February critically influences the total ozone amounts in mid-latitudes observed during the subsequent spring maximum. In this context we recall earlier statements from the literature, which identify the winter months as those responding most strongly to the quasi-biennial variation of the circulation in middle latitudes.

Table 1

Season	Percent Contribution to $\sum_{t=1}^{T} \sigma_t$ on February 28	Total ozone
1957—58	84.9	High
1958—59	68.5	Low
1959—60	82.3	High
1960—61	64.2	Low
1961—62	79.4	High
1962—63	92.1	High
1963—64	54.8	Low
1964—65	78.2	High
1965—66	85.2	High
1966—67	85.1	Low
1967—68	87.0	High
1968—69	78.1	High

It has been shown by Reiter and Lovill [32] that *traveling* disturbances with the nature of baroclinic waves in the troposphere strongly modulate the distribution of total ozone in middle latitudes, and also have a pronounced effect on the meridional ozone transport. This is in agreement with findings by Hirota and Sato [11]. Their computation of the *transient-wave* transport of angular momentum agrees qualitatively well with the ozone distribution during spring in middle latitudes (Fig. 3), more so than the interannual variability of the transport by *standing waves*. In a rather crude analogy to small-scale flow we may, perhaps, regard the planetary standing eddies as the quasi-laminar component of large-scale transport processes, and the transient eddies as the irreversible turbulent mixing aspects that move ozone poleward and downward, especially in jet-stream maxima associated with deeping cyclone waves [19, 27, 28].

4. Stratospheric-Tropospheric Interaction

Unfortunately the time periods of the tropospheric and stratospheric data samples discussed in the foregoing sections are not congruent. Daily 10mb maps were not available before the International Geophysical Year 1957/58, and the publication of the Daily Synoptic 500 mb charts in a carefully analysed and easily manageable form stopped after 1961. This leaves us with four "cold seasons" of overlapping tropospheric and stratospheric data.

The discrepancy in the two time periods of data samples prohibits us from comparing Figs. 6 with Fig. 11, without detailed scrutiny. The 1959/60 "cold season", for instance, which preceded a high-ozone year, showed a marked dip in the areal extent of the 500mb pool of cold air on 17 December, 1959 (Fig. 2), and below-average values thereafter, thus contributing significantly to the behavior of the curve for "high-ozone years" between 17 December and 10 January shown in Fig. 6. Correspondingly, Fig. 11 reveals a steepening of the slope of the 1959/60 curve, starting in late November and continuing well into January 1960. This indicates an increasing meridional perturbation in the stratosphere that leads to an early vortex breakdown and "stratospheric warming" event. Since in this case the stratospheric events seem to precede the breaking-up of the tropospheric cold-air reservoir, one might be inclined to argue that the eddy processes involved in the stratospheric warming controlled to a certain extent the development and fate of the tropospheric vortex.

The 1957/58 cold season also preceded a high-ozone year. According to Fig. 2 the areal extent of the cold-air pool dropped significantly after 1 January 1958, assuming below-average values thereafter, thus contributing to the behavior of the appropriate curve in Fig. 6. According to Fig. 11, however, the stratospheric vortex did not begin to break down *before,* but *after* this date, namely after January 10. From this evidence one would be inclined to hold tropospheric forcing responsible for the breakdown of the stratospheric vortex.

The 1958/59 cold season shows a behavior similar to the 1957/58 season in Fig. 2, yet it preceded a low-ozone year. The stratospheric vortex also became disturbed and shifted off the pole during the middle of January but recovered towards the end of the month. Such a recovery did not take place in 1958 until the end of March. In 1959, on the other hand, the final breakdown occurred at the beginning of March. This difference in behavior has already been pointed out in Fig. 7, and is also noticeable in Fig. 11. As has been mentioned earlier, it appears to be the degree of meridionality of the stratospheric flow during January and February that influences critically the spring maximum of total ozone in middle and high latitudes.

From the limited data sample discussed above it would be difficult to decide whether the stratospheric vortex exercises a steering influence upon the tropospheric cold-air reservoir, or the other way around. To examine this issue we used the superposed epoch method [23] on 31 "tropospheric warming" events during the cold seasons between 1957 and 1961. Such an event is defined as a de-

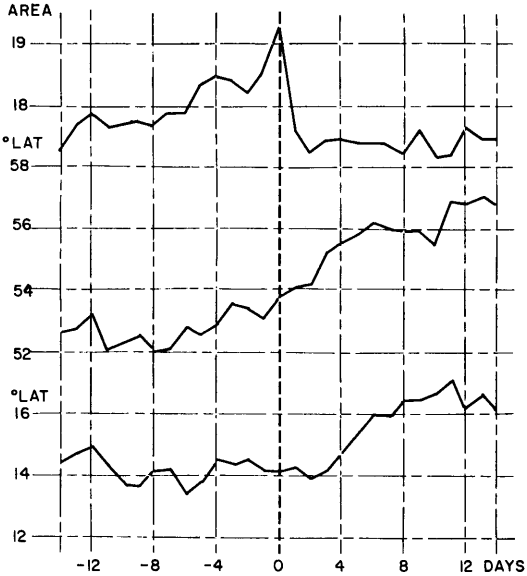

Fig. 12. Superposed epoch averages of 31 cases of tropospheric warming indicated by shrinkage of cold area ($T \leqq -30^0$ C) at 500 mb (top diagram), of changes in the mean latitude of the 30640 m contour line at 10 mb (middle diagram), and of "meridionality" of 10 mb flow expressed by Eq. (2) (lower diagram)

crease by at least 2 area units in Fig. 2 over a period of either one or two days. $t = 0$ marks the day preceding this shrinkage in the polar cold area. The mean behavior of the cold pool for 14 days on either side of this warming event has been plotted in Fig. 12, together with the mean latitude of the 30640 contour on the 10mb surface, also averaged over the 31 cases. We find that 8 days prior to the contraction of the tropospheric cold-air reservoir the stratospheric polar vortex starts to contract, too. This contraction continues at an almost linear rate until, on the average, 6 days after the "tropospheric warming".

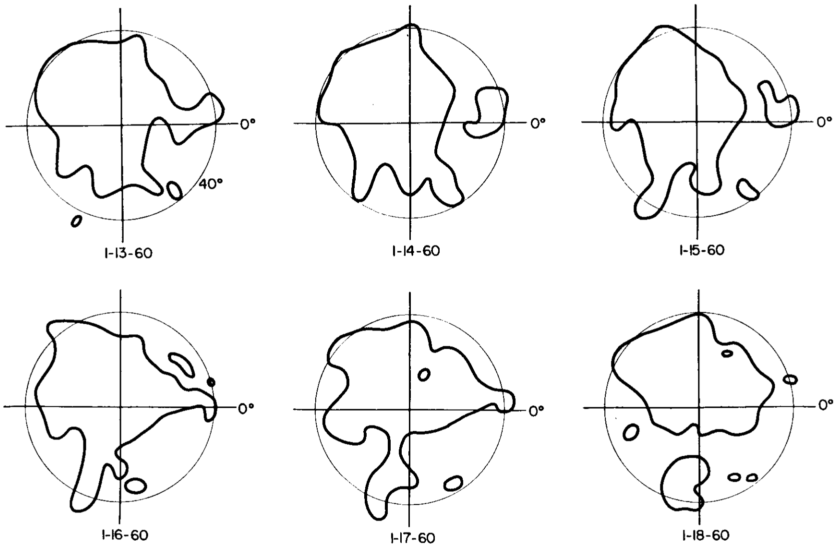

Fig. 13. Development of cut-off cyclone portrayed by behavior of -30^0 C isotherm at 500 mb during successive days. (See also legend to Fig. 4)

The same superposed epoch method was applied to the $\sigma_T{}^2$ values defined by Eq. (2). Results ar plotted in the lower part of Fig. 12. There is no significant increase in the "meridionality" of the flow prior to the onset of tropospheric warming. Only 2 to 11 days, on the average, *after* the tropospheric warming event does the stratospheric vortex increase the amplitude of its wave disturbances.

Part of the "tropospheric warming" is due to the formation of cut-off lows that separate portions of cold air ($T \leqq -30^0$C at 500mb) from the main body of the polar air mass. It was mentioned in Section 2, that such cut-off bodies of air were not included in the planimetered areal extent of the polar air, if they remained separated and did not rejoin the main air mass. Examples of such a cut-off at 500 mb are shown in Fig. 13. A planimetered area estimate of these separated small bodies of cold air reveals, however, that the bulk of the "tropospheric warming" phenomena included in Fig. 12 is due to an actual reduction in the size of the area, even if one includes the air contained in cut-off lows. As a matter of fact, in only 5 of the 31 cases considered in Fig. 12 did the inclusion of the cold air within cut-off lows reduce the shrinkage of the total cold-air area below the arbitrarily chosen threshold value of two units.

The superposed epoch method was also applied to 4 episodes of *stratospheric* vortex breakdown as key dates. As a criterion for the vortex breakdown we used an increase in the mean latitude of the 30640m contour at 10 mb of at least 10^0 lat in $\leqq 3$ days. Fig. 14 shows that, on the average of the 4 cases which fulfilled this criterion (26 January 1958, 21 March 1959, 11 January 1960 and 16 March 1961), there is a slight increase in the mean latitude of the vortex already one day before the required magnitude of this in-

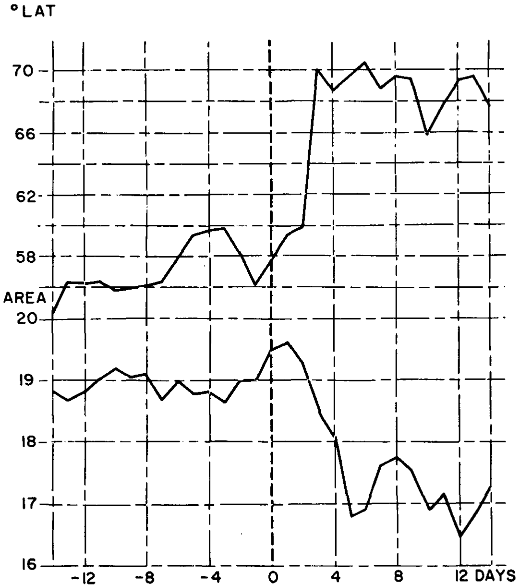

Fig. 14. Superposed epoch averages of 4 cases of stratospheric vortex breakdown measured by an increase in the mean latitude of the 30640 m contour at 10 mb (top diagram), and the mean area (arbitrary units) of the cold air ($T \leqq -30^0$ C) at 500mb (lower diagram)

crease was reached. The tropospheric pool of cold air responded strongly one to two days after the events in the stratosphere. The shrinkage of the cold-air area amounts to more than 2.5 arbitrary units, or 12.5 % of the total area. This, again, suggests a stratospheric triggering mechanism for the tropospheric baroclinic disturbances which consumed part of the available potential energy stored in the polar cold air.

From the foregoing discussion, and from Fig. 12 we can develop the following qualitative scheme of stratospheric/tropospheric interaction:

a) Shrinkage of the area within the 30640m contour line at 10 mb (i. e. an increase in its mean latitude) implies a stratospheric mass flow into the polar regions and a pressure rise in the stratosphere in middle latitudes. This mass flow enhances the ozone transport from low to high latitudes. With Mahlman [20], Teweles [36] and Walts [40] we may assume that sinking motion in the stratosphere is associated with this mass convergence.

b) Sinking motion in the middle troposphere and release of available potential energy can be held responsible for the observed warming phenomenon. We assume the mean frontal slope $\tan\alpha = \delta z/\delta y$ to be 1/110 [22]. The mean vertical velocity, $\overline{w}$, of the cold air underneath the polar front, that results in a hemispheric contraction of the front, may be estimated as

$$\overline{w} = \frac{\delta z}{\delta t} = \frac{\delta \bar{r}}{\delta t} \cdot \tan\alpha \qquad (4)$$

where $\bar{r}$ is the mean radial distance of the front from the pole measured along a meridian.

The area change determined by planimetry is

$$\delta A' = 2\pi r' \delta r' = 2\pi m^2 r \delta r = m^2 \delta A$$

where the "primes" indicate quantities measured on the map, "unprimed" quantities are measured on the earth and m is the scale factor of the map. $(1/A')\,(\delta A'/\delta t)$, according to Fig. 12, is 10 % or 0.1 in 2 days. We may write, therefore

$$-0.1 A' = 2\pi r' \delta r' \quad \text{or} \quad \delta r' = -0.05\, r'. \qquad (6)$$

The radius r' from the pole is measured in degrees of co-latitude, ψ. The average position of the polar front is found near $\Phi = 50^0$ or

$\psi = 40^0$. With $r = 1.11 \cdot 10^7 \cdot \psi\,\text{cm}$, the observed reduction of the radius of the cold area is $\delta r = -2.22 \cdot 10^7\,\text{cm}$.

From Eq. (4) we obtained for $\delta t = 2$ days and $\tan\alpha = 1/110$

$$\overline{w} = -1.16\,\text{cm/sec} \tag{7}$$

This *net* sinking motion has to be considered as the residual between ascending and descending motions that are found near the polar front. Furthermore, this motion is observed near the level of non-divergence, hence of maximum vertical motions.

If we assume this net vertical motion to be characteristic for a band B approximately 5^0 lat. wide and extending parallel to the polar front, the mass flux caused by $\overline{w}$ is

$$M = \overline{w} \cdot \varrho \cdot B \text{ or } 1.2 \cdot 10^{14}\,\text{g/sec.}$$

In comparison, the total hemispheric mass flux from the stratosphere to the troposphere is of the order of $8 \cdot 10^{19}$ g/year or $2.5 \cdot 10^{12}$ g/sec (for references see [31], p. 102 and 111). We may conclude, therefore, that the direct involvement of stratospheric air in the tropospheric sinking and warming processes is only minor, even though such processes, coupled with cyclogenesis, constitute the major stratospheric/tropospheric exchange mechanism in mid-latitudes [5, 19, 26, 27, 28].

c) A contraction of the stratospheric vortex, as evident from the 10mb charts precedes, on the average, the major tropospheric warming events during the winter season. This suggests at least a modest stratospheric steering effect upon major re-adjustments in the tropospheric polar vortex. On the other hand, baroclinic disturbances, responsible for the tropospheric sinking and warming events, cause a re-adjustment of the stratospheric polar vortex and its "meridionality". These events are associated with transient waves which appear to accomplish the bulk of the meridional ozone transport.

5. Conclusions

The foregoing study confirms the hypothesis that interannual variations of the eddy fluxes in the stratosphere exercise a certain steering effect on the tropospheric polar vortex. The baroclinic disturbances which, to a certain extent, may be triggered by adjustments in the stratospheric polar vortex, themselves exercise a strong influence on the stratospheric vortex. In the schematic flow diagrams of Fig. 1 this is expressed as the heavily drawn "feedback loop" between boxes No. 7 and 3. In view of the relatively weak biennial response of the tropospheric vortex revealed in Fig. 6 we can conclude that this "feedback loop" shunts most of the quasi-biennial response of the polar atmosphere, so that only little, if any, quasi-biennial forcing of the tropical atmosphere from extratropical latitudes should be expected (dashed line between boxes 7 and 3 in Fig. 6). This would place the main responsibility for the existence of a quasi-biennial oscillation on the tropical atmosphere with its vertical momentum transports executed by Kelvin waves. The rest of the atmosphere, especially the polar troposphere, appears to act as a sink into which the eddy energies in the frequency band of the quasi-biennial modulation are leaking, rather than as a resonant response system.

Admittedly, these conclusions are rather speculative in nature. Numerical models of the global circulation, together with additional data analyses, will help to confirm or reject the framework of hypotheses.

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