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The Radiative-Photochemical Response of the Mesosphere to Fluctuations in Radiation

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ABSTRACT

The response of the mesosphere to slow fluctuations in ultraviolet and visible radiation intensity is investigated using the simplified models for photochemistry and radiative transfer developed by Lindzen and Goody (1965). Fluctuations in oxygen's ultraviolet bands, ozone's ultraviolet bands and ozone's visible band are separately considered. It is found that the mesosphere is most sensitive to fluctuations in ozone's ultraviolet bands above 35 km and to fluctuations in oxygen's ultraviolet bands above 30 km. At levels of peak sensitivity, fluctuations of about 12 per cent in either of these bands will give rise to temperature fluctuations of 2 deg K. This appears to rule out minute changes in solar ultraviolet emission as a cause for the '26-month' oscillation in the equatorial mesosphere. It is also found that the mesosphere is quite sensitive to fluctuations in visible light in the region between 20 and 35 km where fluctuations of 3–6 per cent in visible radiation can give rise to fluctuations of 2 deg K in temperature. On the average, about 26 per cent of the visible radiation in the mesosphere is received via reflection from below. Much of the reflection is from clouds and hence, variation in cloud cover forms an effective way of varying visible light in the mesosphere. In this connection it is found that the winter distribution of cloud cover in the subarctic is such as to introduce into the mesosphere a temperature disturbance whose amplitude and spatial distribution are such as to be able to trigger a sudden warming of the Northern Hemisphere winter variety.

1. Introduction

In order to make tractable the inclusion of the effects of the mesosphere's radiative and photochemical processes in hydrodynamic models, Lindzen and Goody (1965) developed highly simplified models for these processes. For temperature they obtained the following equation

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\left(\frac{\partial T}{\partial z}+\frac{g}{c_p}\right)=\eta\varphi-aT+b, \quad (1)$$

where

φ = ozone mixing ratio,
T = temperature,
a, b are constants,
$\eta=(n_m/\rho c_p)\int_\nu \alpha_3 I_{0\nu} h\nu \exp(-\alpha_3 x_3)d\nu$,
n_m = molecular number density,
ρ = density,
c_p = heat capacity at constant pressure,
α_3 = absorption cross section of ozone,
x_3 = number of O_3 molecules between the point in question and the sum,

and

$I_{0\nu}$ = intensity of incident radiation of frequency, ν.

Cooling, due mainly to CO_2's 15 μ band, is quite well approximated by Newtonian cooling as given by the terms, $-aT+b$. Heating is mainly due to absorption by ozone in its ultraviolet and visible bands, and η is the energy weighted photon density in these bands.

For ozone they found

$$\frac{\partial \varphi}{\partial t}+u\frac{\partial \varphi}{\partial x}+v\frac{\partial \varphi}{\partial y}+w\frac{\partial \varphi}{\partial z}=2\left\{\frac{n_2}{n_m}q_2(y,z)-q_3K(T)\frac{1}{n_2}\varphi^2\right\}, \quad (2)$$

where

n_2 = molecular number density of O_2.

$K(T)=E\exp(-D/T)$ is a ratio of reaction rates, and q_2 and q_3 are the photon densities of O_2 and O_3 radiation, where $q_{2,3}\doteq\int_\nu \alpha_{2,3} I_{0\nu}\exp(-\alpha_{2,3}x_{2,3})d\nu$. Eq. (2) is generally applicable when the density of O is much less than the density of O_3 which in turn is much less than the density of O_2. The density of O_2 is furthermore assumed to be sensibly independent of time, t. These conditions apply below about 55 km. The reader is referred to Lindzen and Goody (1965) for a more complete justification of these equations.

In general, time variations in incoming radiation were ignored. Instead Lindzen (1965 a, b, and c) considered the interaction of the radiative and photochemical processes with simple hydrodynamic models for the vertical propagation of long period waves in the equatorial mesosphere and for the stability of an axially symmetric zonal jet in the midlatitude mesosphere. In general, it was found that the radiative and photo-

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chemical processes are responsible for the ability of the equatorial mesosphere to propagate the "26-month" oscillation and that these processes can, furthermore, destabilize a baroclinic midlatitude zonal vortex with respect to both axially symmetric and wave disturbances. The latter result appears to be significant in connection with "sudden warming" phenomena.

As we learn more about mesospheric motions such as the "26-month" equatorial oscillation and the "sudden warmings," matters such as what drives the former and triggers the latter become important. Fluctuations in radiation are frequently proposed, and it will be the purpose of this paper to describe, in connection with such proposals, the radiative-photochemical response of the mesosphere to such fluctuations if such fluctuations exist.

2. Models for fluctuations and their effects

In the context of Eqs. (1) and (2) such variations result in variations in the factors q_2, q_3 and η, which are merely measures of photon densities at a given point in space in various portions of the solar spectrum: in particular the Schuman-Runge and Herzberg absorption bands of O_2 in the ultraviolet, the Hartley-Huggins bands of O_3 in the ultraviolet, and the Chappuis band of O_3 in the visible. The absorption coefficients in these bands as functions of wavelength are shown in Craig (1950). While more recent studies alter his data somewhat, the following conclusions of his are still approximately correct. His data is furthermore sufficient for the limited, approximate objectives of this study. Radiation near the peak of the O_2 absorption band is almost completely annihilated at altitudes above 55 km; below 55 km almost all of the O_2 absorption is in the region 1950 Å–2150 Å. Also, below 55 km almost all of the O_3 absorption involves wavelengths greater than 2200 Å. Thus, at the levels we are interested in the portions of the solar spectrum absorbed by O_2 and O_3 are well separated in wavelength, and hence it is permissible to consider these portions (and the visible) independently:

$$\int_{\text{relevant }\nu} I_{0\nu}d\nu \doteq I_{uv_1}+I_{uv_2}+I_v, \tag{3}$$

where

I_{uv_1} = intensity in O_3 ultraviolet bands,

I_{uv_2} = intensity of O_2 ultraviolet bands,

and

I_v = intensity in O_3 visible band.

We now allow the radiation in each of these spectral regions to fluctuate as follows:

$$\begin{aligned} I_{uv_1} &\doteq I_{uv_{10}}(1+P_a e^{i\omega_a t}), \\ I_{uv_2} &= I_{uv_{20}}(1+P_b e^{i\omega_b t}), \\ \text{and} \qquad I_v &= I_{v_0}(1+P_c e^{i\omega_c t}). \end{aligned} \tag{4}$$

Furthermore, for mathematical simplicity we will restrict ourselves to small P's which in turn will allow linearization; i.e.,

$$\begin{Bmatrix} P_a \\ P_b \\ P_c \end{Bmatrix} = \epsilon \begin{Bmatrix} N_a \\ N_b \\ N_c \end{Bmatrix}; \quad \epsilon \ll 1, \quad \begin{Bmatrix} N_a \\ N_b \\ N_c \end{Bmatrix} \sim O(1). \tag{5}$$

Having partitioned the relevant spectral regions, we may also partition η, q_2, and q_3:

$$\begin{aligned} \eta &= \eta_{uv}+\eta_v, \\ q_2 &= q_{2_{uv}}, \\ \text{and} \qquad q_3 &= q_{3_{uv}}+q_{3_v}. \end{aligned} \tag{6}$$

In addition we introduce the following approximations:

$$\begin{aligned} \eta_{uv} &\doteq \hat{\eta} I_{uv_1}, \quad q_{3_{uv}} \doteq \hat{q}_3 I_{uv_1}, \\ \eta_v &\doteq \tilde{\eta} I_v, \qquad q_{3_v} \doteq \tilde{q}_3 I_v, \\ \text{and} \qquad q_2 &\doteq \hat{q}_2 I_{uv_2}, \end{aligned} \tag{7}$$

where $\hat{\eta}$, $\tilde{\eta}$, $\hat{q}_3$, $\tilde{q}_3$ and $\hat{q}_2$ are assumed to be independent of I_0. It is because of this assumption that Eqs. (7) are approximate. The assumption is completely justified for $\tilde{\eta}$ and $\tilde{q}_3$, because visible light is negligibly depleted by ozone; absorption in the visible is important only because there is a lot of ozone in the ozone layer, and I_v is very large. It is also approximately justified for $\hat{q}_2$ because n_2 is almost independent of time, and because at the levels we are dealing with the overlap between oxygen and ozone bands is comparatively unimportant. Finally, above 45 km, the assumption is also justified for $\hat{q}_3$ and $\hat{\eta}$ because there is insufficient ozone above this level to significantly deplete the radiation in ozone's ultraviolet bands. Between 43 km and 34 km almost all ultraviolet radiation in ozone's bands is depleted (see Fig. 2, Lindzen and Goody, 1965), and hence, below 43 km $\hat{q}_3$ and $\hat{\eta}$ depend on the amount of ozone above the level in question which in turn depends on I_{uv_1} and I_{uv_2}. Fortunately, below 34 km the effects of $\hat{q}_3$ and $\hat{\eta}$ are relatively unimportant anyway, and between 43 km and 34 km these effects turn out to be considerably smaller than those retained in (7)—at least in situations where linearization is permissible. Note that $\hat{q}_3$, $\tilde{q}_3$, $\hat{\eta}$, $\tilde{\eta}$ and $\hat{q}_2$ vary with height. The distributions of these functions as well as the values of $I_{uv_{10}}$, $I_{uv_{20}}$, and I_{v_0} are obtained from the data in Craig (1950).

3. Equations

Our equations for the response of our system to fluctuations in radiation are obtained by introducing the expressions for η, q_2, and q_3 obtained from Eqs. (4), (5), (6) and (7) into Eqs. (1) and (2); expanding all our fields in powers of ϵ; and separating terms according to their order in ϵ. Assuming our zero order radiation influx is axially symmetric and steady and our motion is geostrophic and hence zonal, there will be no advection

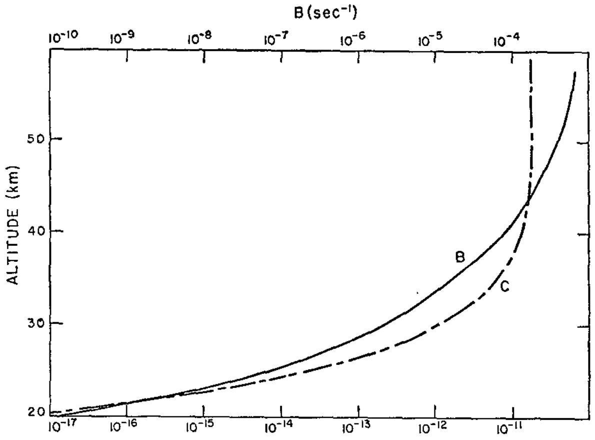

FIG. 1. B, the photochemical relaxation rate, and C, the rate factor for the thermal destruction of ozone, as functions of altitude in neighborhood of the equator.

terms in the zero order equations for ozone and temperature; i.e., the zero order state will consist in radiative-photochemical equilibrium (Leovy, 1964, Lindzen and Goody, 1965). The first order equations in ϵ are then merely the linearized equations for responses to radiation fluctuations:

$$\frac{\partial T'}{\partial t}+\text{advection of }\bar{T}$$

$$=\bar{\eta}\varphi'-aT'+\bar{\eta}\bar{\varphi}\left(\frac{\bar{\eta}_{uv}}{\bar{\eta}}P_a e^{i\omega_a t}+\frac{\bar{\eta}_v}{\bar{\eta}}P_c e^{i\omega_c t}\right), \quad (8)$$

and

$$\frac{\partial \varphi'}{\partial t}+\text{advection of }\bar{\varphi}$$

$$=-B\varphi'-CT'$$

$$+\tfrac{1}{2}B\bar{\varphi}\left(P_b e^{i\omega_b t}-\frac{\bar{q}_{3uv}}{\bar{q}_3}P_a e^{i\omega_a t}-\frac{\bar{q}_{3v}}{\bar{q}_3}P_c e^{i\omega_c t}\right), \quad (9)$$

where primes refer to fluctuating fields, overbars to zero order fields and where B and C are functions of the zero fields:

$$B=4\bar{q}_3K(\bar{T})\frac{1}{\bar{n}_2}\bar{\varphi}, \quad (10)$$

and

$$C=\tfrac{1}{2}B\bar{\varphi}\left[\left(\frac{1}{K}\frac{dK}{dT}\right)_{T=\bar{T}}+\frac{1}{\bar{T}}\right]. \quad (11)$$

η and a have already been described. B is the well-known photochemical relaxation rate; C represents the effect of temperature on relaxation—in essence, increasing T decreases the photochemical equilibrium value of ozone density, and hence causes the ozone to approach the new, lower equilibrium value. B and C vary strongly with altitude as shown in Fig. 1. Additional details concerning these parameters may be found in Lindzen and Goody. Fluctuations in I_0, result in the driving terms in Eqs. (8) and (9)—terms omitted in previous work.

It is fluctuations in temperature that drives motions in the atmosphere. In order to find the temperature variations that result from radiation fluctuations, we must eliminate φ' between Eqs. (8) and (9). Doing so we obtain the following equation for T':

$$\frac{\partial^2 T'}{\partial t^2}+(a+B)\frac{\partial T'}{\partial t}+(aB+\eta C)T'$$

$$+\left(\frac{\partial}{\partial t}+B\right)(\text{Advection of }\bar{T})$$

$$+\eta(\text{Advection of }\bar{\varphi})$$

$$=\bar{\eta}\bar{\varphi}\left\{\frac{\bar{\eta}_{uv}}{\bar{\eta}}(B+i\omega_a)-\tfrac{1}{2}B\frac{\bar{q}_{3uv}}{\bar{q}_3}\right\}P_a e^{i\omega_a t}$$

$$+\tfrac{1}{2}\bar{\eta}B\bar{\varphi}P_b e^{i\omega_b t}$$

$$+\bar{\eta}\bar{\varphi}\left\{\frac{\bar{\eta}_v}{\bar{\eta}}(B+i\omega_c)-\tfrac{1}{2}B\frac{\bar{q}_{3v}}{\bar{q}_3}\right\}P_c e^{i\omega_c t}. \quad (12)$$

Now this temperature equation is second order in t as opposed to the usual temperature equation and hence, it becomes a little difficult to interpret the driving terms as heat sources. What has been done instead has been to calculate the thermal response to these drives in the absence of motion. This gives some measure of the non-dynamic heating against which advections must act. Doing this one obtains the following:

$$T'\text{ non-dynamic}=\text{transient}+F_aP_a e^{i\omega_a t}$$
$$+F_bP_b e^{i\omega_b t}+F_cP_c e^{i\omega_c t}, \quad (13)$$

where

$$F_a=\frac{\bar{\eta}\bar{\varphi}\left\{\frac{\bar{\eta}_{uv}}{\bar{\eta}}(B+i\omega_a)-\tfrac{1}{2}B\frac{\bar{q}_{3uv}}{\bar{q}_3}\right\}}{\{-\omega_a^2+i\omega_a(a+B)+(aB+\eta c)\}}, \quad (14a)$$

$$F_b=\frac{\tfrac{1}{2}\bar{\eta}\bar{\varphi}B}{\{-\omega_b^2+i\omega_b(a+B)+(aB+\eta c)\}}, \quad (14b)$$

and

$$F_c=\frac{\bar{\eta}\bar{\varphi}\left\{\frac{\bar{\eta}_v}{\bar{\eta}}(B+i\omega_c)-\tfrac{1}{2}B\frac{\bar{q}_{3v}}{\bar{q}_3}\right\}}{\{-\omega_c^2+i\omega_c(a+B)+(aB+\eta c)\}}. \quad (14c)$$

The properties of the transient response are described in Lindzen and Goody. We will, in this paper, concern ourselves with the direct responses to radiation fluctuations as given by the response functions F_a, F_b, and F_c. Note that the response functions are complex. In

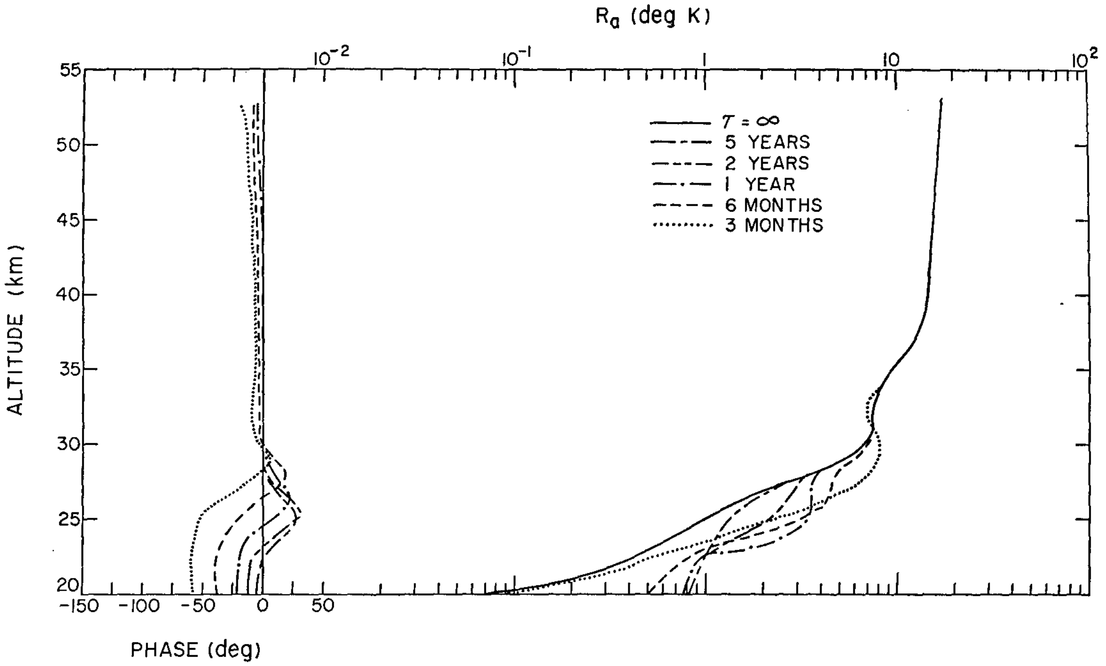

FIG. 2. The amplitude, R_a, and phase, φ_a, of the thermal response of the mesosphere to fluctuations, of various periods, in the radiation in the ultraviolet bands of ozone as a function of altitude.

particular, they may be rewritten as:

$$F_a = R_a e^{i\varphi_a},$$
$$F_b = R_b e^{i\varphi_b}, \qquad (15)$$
$$F_c = R_c e^{i\varphi_c},$$

where R is a real amplitude and φ is a real phase. Furthermore, the R's and φ's depend both on altitude and frequency of fluctuation.

Before going on to a detailed study of the response functions, it should be observed that F_a and F_c are $O(1/\omega)$ and F_b is $O(1/\omega^2)$. While we may not take the limit of $\omega \rightarrow \infty$ since we have averaged over diurnal variations in obtaining (1) and (2), the asymptotic dependence on ω suggests that the thermal response to high frequency radiational fluctuations is small. This is in agreement with Leovy's result that the maximum thermal variation caused by the radiative-photochemical response to diurnal fluctuations is about 4.5 deg C.

4. Response functions

Our main concern in this paper is not with fluctuations as rapid as the diurnal fluctuations mentioned in the preceding section, but with longer period fluctuations. Expressions (14) have been evaluated in order to obtain the R's and φ's as functions of altitude for $\tau(2\pi/\omega) = 3$ mo, 6 mo, 1 yr, 2 yr, 5 yr, and ∞.

In Fig. 2 we have plotted R_a and φ_a. The fact that φ differs from zero indicates that the temperature does not respond "instantaneously" to fluctuations in radiation. We notice, however, that the mesosphere is most responsive, for all τ's, to fluctuations in ozone's ultraviolet bands above 35 km and in this region φ_a is, in fact, small. R_a reaches a peak value of about 17 deg K. This means that at least a 12% fluctuation in the integrated intensity in ozone's Hartley-Huggins Bands would be necessary to produce a 2 deg K temperature fluctuation in the regions of efficient response. Below 30 km, R_a is less than 8C for all frequencies. It should be pointed out that the estimate obtained here for the sensitivity of the mesosphere to fluctuations in ozone band ultraviolet radiation is much less than that obtained by others such as Staley (1963). They argued that a small increase in radiation could give rise to a small increase in heating which over long periods could give rise to a comparatively large temperature increase. They neglected to note that temperature changes in excess of those computed here would also result in reduced ozone and increased infrared cooling—the sum of which would result in an increase in the cooling rate greater than the increased heating.

In Fig. 3, R_b and φ_b are shown. We see that the mesosphere is most responsive to fluctuations in oxygen's ultraviolet bands above about 30 km. Furthermore, R_b also has a peak of about 17 deg C in this region.[2] Above 35 km the thermal response is almost in phase with the radiation fluctuation. Thus, if there are simultaneous fluctuations in radiation in both ozone's and oxygen's ultraviolet bands then only half the

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[2] It is worth noting that while fluctuations in O_2 band radiation contribute negligibly to direct heating they cause significant thermal fluctuations because of their importance in ozone's photochemistry.

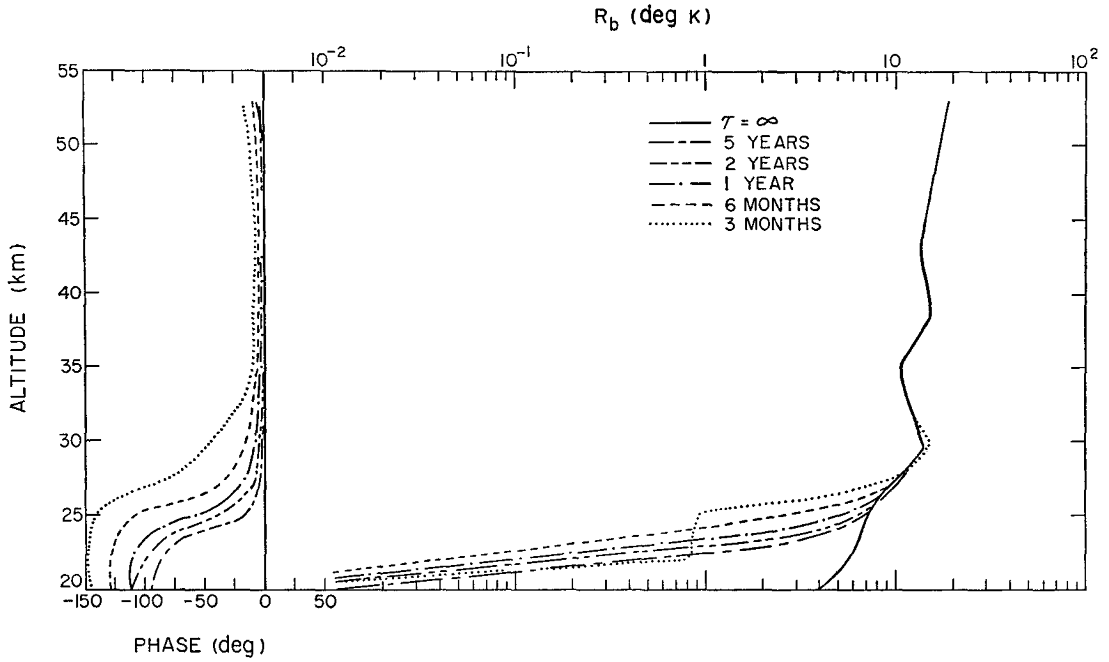

FIG. 3. The amplitude, R_b, and phase, φ_b, of the thermal response of the mesosphere to fluctuations, of various periods, in the radiation in the ultraviolet bands of oxygen as a function of altitude.

estimated fluctuation of 12% in radiation would comprise the minimum fluctuation necessary for a 2 deg K temperature fluctuation in this upper region. Below 35 km, a significant phase lag arises in the thermal response which increases both with frequency of fluctuation and decreasing altitude. However, for most frequencies the response becomes reasonably inefficient below 28 km, and hence the large phase lags in the lower region are unlikely to be of practical importance.

Finally, in Fig. 4 we see the response of the meso-

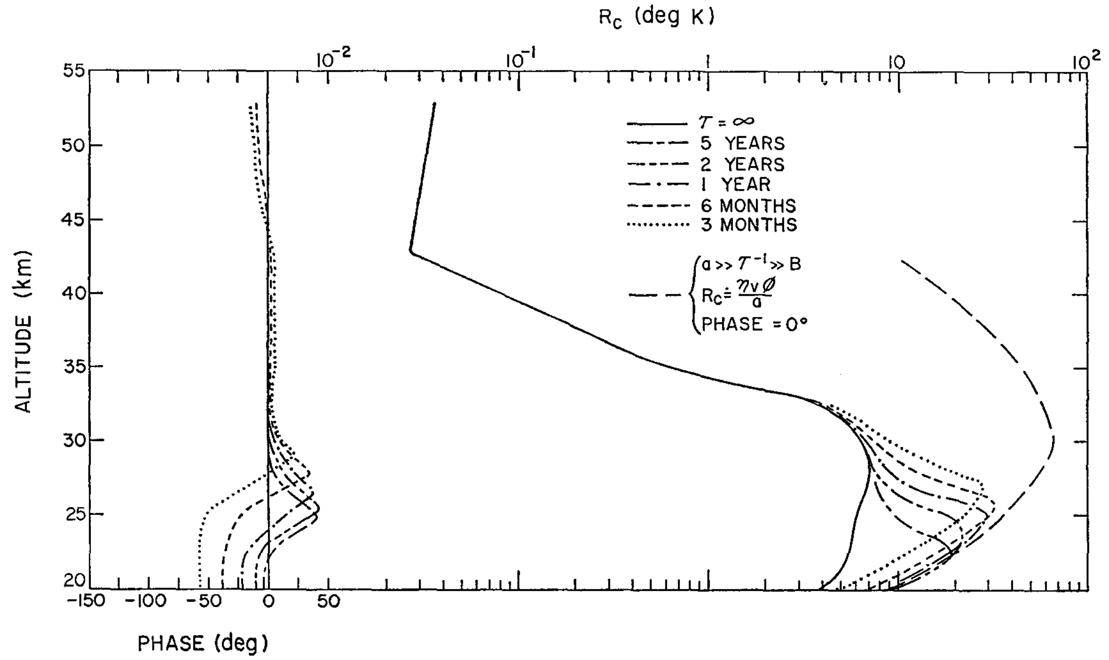

FIG. 4. The amplitude, R_c, and phase, φ_c, of the thermal response of the mesosphere to fluctuations, of various periods, the radiation in the visible band of ozone as a function of altitude. Also shown is $R_c=\eta_v\bar{\varphi}/a\equiv R_c^*$, the response function when either $a\gg\omega\gg B$, or φ is held fixed.

sphere to fluctuations in visible light. Not surprisingly, the response, R_c, is significantly large primarily below 32 km. Depending on the frequency of the fluctuation, the response remains significant to some altitude between 20 and 22.5 km. The peak value of R_c in the intermediate region varies from about 20 deg K to 35 deg K depending on frequency. Thus fluctuations in visible light on the order of 5% could effect 2 deg K temperature fluctuations. Note also, that significant phase shifts occur at altitudes of peak response amplitude. In this connection it might be well to mention that Lindzen (1965a) in a study of the propagation of a "26-month" wave at the equator predicted that the wave should be attenuated even more rapidly than is observed as it penetrates below 25 km. One suggestion, therefore, was that the oscillation is directly driven below 25 km. The question, however, remained as to why the oscillation still appeared to propagate at these lower levels. If the direct drive is due to fluctuations in visible light, an answer is provided in Fig. 7 where we see that the phase shift in the response below 25 km for a 2-year fluctuation is such as to make it appear that the fluctuation is propagating downward at approximately 1 km mo^{-1}.

Finally, a curve, $R_c = \bar{\eta}_v \bar{\varphi}/a$, is shown in Fig. 7. This is the asymptotic form of the response when $a \gg \omega \gg B$. More important, this would be the response curve if one could somehow keep φ fixed at a given level. In Lindzen (1965a) it was shown that the dynamics associated with the "26-month" oscillation are such as to hold φ fixed at some level in the neighborhood of 30 km. Under these conditions, R_c would be approximately 70 deg K at this level, and only a 2–3% fluctuation in visible light would be needed to produce a 2 deg K temperature fluctuation.

5. Sources of radiation fluctuations

In Section 4 no mention was made of the possible origin of the radiation fluctuations, the response to which we had calculated. The absence of long term measurements of solar emission in all parts of its spectrum makes it impossible to say very much. In particular, no measurements in the near ultraviolet (1800–3000 A) have been made. However, a few comments are in order. First, the order of magnitude of the fluctuations in ultraviolet radiation required to produce dynamically significant thermal fluctuations is such as to leave variations in solar emission as the only likely source of such radiation fluctuations. This is not to say that such fluctuations do, in fact, exist. In this connection Lindsay (1963) reports that fluctuations of at least 7% have been observed in Lyman α ($\sim$1250 A) emission. The connection between Lyman α and fluctuations elsewhere in the ultraviolet is, unfortunately, unknown; however the observation is suggestive. Dütsch (1964) reports large variations in ozone in the upper stratosphere, where solar *u-v* emission is a dominant control factor. This too at least suggests the possibility of fluctuations in solar emission in the near *u-v*.

As to visible light we are reasonably certain that solar emission does not fluctuate any more than one per cent. However, on the average about 26 per cent of the visible light in the mesosphere is received via reflection from below. The largest contributor to the earth's albedo is cloud cover and this is subject to large spatial and temporal variations. Thus, we have a possible terrestrial source for fluctuations in visible light intensity in the mesosphere.[3]

6. Applications

As mentioned in Section 1, our purpose in this investigation has been to evaluate the possibilities of fluctuations in radiation as drives for the "26-month" equatorial wave and triggers for "sudden warmings." For a description of the first phenomenon the reader is referred to Reed (1964, 1965). Briefly, an oscillation in the zonal wind with an approximate period of 26 months has been observed between 15 and 55 km in the tropical mesosphere. The oscillation propagates downward with a phase speed varying from 2 km per month above 30 km to 1 km per month below 30 km. The oscillation has a peak wind amplitude at about 24 km and appears to be symmetric about the equator. Furthermore, the wind appears to be in geostrophic balance with an associated oscillation in temperature whose peak amplitude is approximately 2 deg K. The observed distribution of the amplitude of the temperature oscillation at the equator is shown in Fig. 5. Also shown are R_a, R_b, R_c and $R_c{}^*(\bar{\eta}_v \bar{\varphi}/a)$ for $\tau = 2$ yr. As far as anyone has been able to determine, there is no resonance in the mesosphere at 26 months; as a result it is reasonable to assume the need for a drive capable of producing the observed amplitudes. From Fig. 5 we see that fluctuations of about 10% in ultraviolet radiation are needed to produce the observed temperature oscillation. This seems to rule out mechanisms calling for extremely small fluctuations in solar emission. The vertical distribution of R_a and R_b does not appear to be such as to give rise to $|T'|$. This, however, does not completely rule out a direct ultraviolet drive. As shown in a previous paper (Lindzen, 1965a) the mesosphere effectively propagates such disturbances at heights above 25 km. Consequently, at any point above 25 km energy may be received both from direct drive and through propagation from above. In such a situation, the peak energy might be found at the bottom of the region of direct drive.

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[3] In this work we have neglected cooling in the O_3 9.6 μ band as being small compared to that due to CO_2's 15 μ band. However, 9.6 μ cooling is strongly dependent on cloud cover and temperature, and in particular, the presence of clouds whose tops are colder than the ground gives rise to increased 9.6 μ cooling. This effect is opposite to the effect of clouds as reflectors wherein the reflected light gives rise to increased heating, and in certain circumstances may be significant. However, the conditions for clouds being good reflectors differs from the conditions for them to increase 9.6 μ cooling, and hence, considering one in the absence of the other is still consistent. Furthermore, at high latitudes the temperature differences between cloud tops and ground is sufficiently small to render the effect of clouds on 9.6 μ cooling negligible at those latitudes.

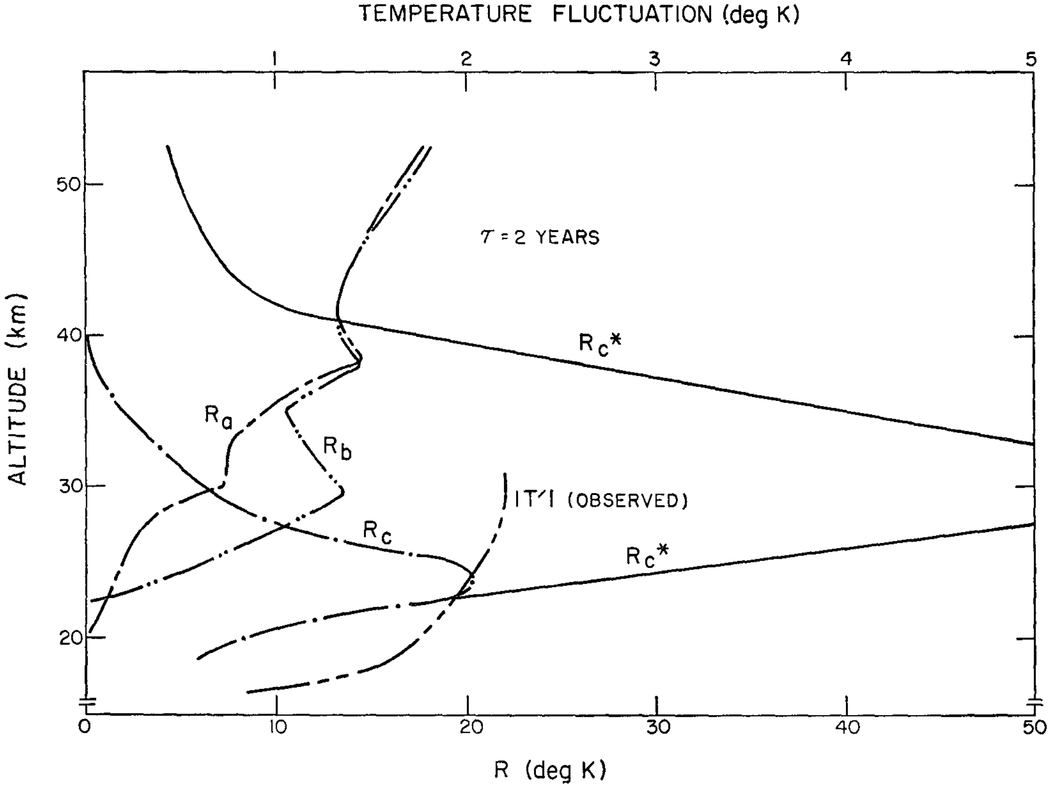

FIG. 5. $|T'|$, the amplitude of the 26-month temperature oscillation at the equator as a function of altitude. Also shown are R_a, R_b and R_c for $\tau=2$ yr, and R_c*.

Below 25 km, it is believed that the medium itself will tatenuate the wave. Looking at R_c, it would appear that fluctuations of 10% in visible light would be necessary to produce the observed oscillation. However, the distribution of R_c does not appear to be capable of producing the distribution of $|T'|$. On the other hand, as was pointed out in section 4, there are reasons for believing that at certain altitudes R_c* is the appropriate function. If this is correct, then only 3% fluctuations in visible light would be necessary, and furthermore, the distribution of R_c* seems essentially consistent with that of $|T'|$. In addition, a drive due to fluctuations in visible light appears better able to account for the continued appearance of a propagating wave at lower altitudes (see Section 4). Unfortunately, we do not know whether there is a "26-month" oscillation in cloud cover over the equator—or what would cause such an oscillation if it does exist. In brief, this study does not tell us what causes the "26-month" oscillation. It does, however, tell us that if fluctuations in radiation are responsible, these fluctuations must be of a certain measurable magnitude—involving fluctuations of this magnitude in solar emission and/or cloud cover.

With respect to "sudden warmings," there are numerous descriptions in the literature (Craig and Hering, 1959; Reed *et al.*, 1963; Finger and Teweles, 1964; and others for the Northern Hemisphere; Palmer and Taylor, 1960 for the Southern Hemisphere). The designation "sudden warming" appears to have been applied to all disruptions of the basic winter polar vortex. In the Southern Hemisphere (where data are available for winters from 1957 to 1962 (Finger and Teweles, 1964)), the warmings have, so far, been observed only after the end of local winter, and have been of zonal wave number one. In the Northern Hemisphere, however, many of the warmings have occured during local winter, and most examples of these have involved disturbances primarily in zonal wave number two. An example of the Northern Hemisphere winter disturbance was the warming of January–February 1957. This well documented case involved much of the temperate and arctic Northern Hemisphere mesosphere. According to Finger and Teweles the involvement of much of the stratosphere outside the polar night region is typical. The disturbance was of wave number two, with warm anomalies over the Pacific and Iceland. The temperature difference between cold and warm portions of the disturbance was of the order of 30 deg K, and the disturbance took over a week to develop. The temperature disturbance was observed to originate over the United States. The origination of these Northern Hemisphere winter disturbances south of the polar night region is, according to Finger and Teweles, also typical. Noting the absence of this type of winter, wave number two disturbance in the Southern Hemisphere, Wexler (1959) suggested that surface topography (the main source of difference between

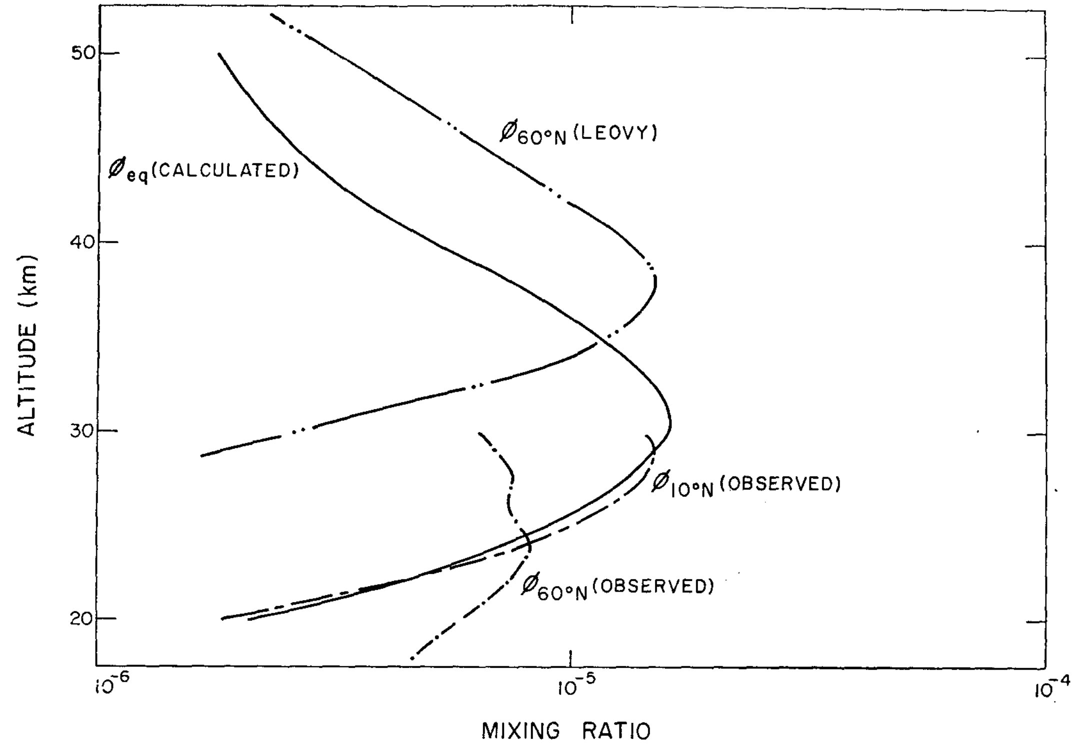

FIG. 6. The radiative-photochemical equilibrium distributions of ozone mixing ratio at the equator in spring (Lindzen and Goody, 1965) and at 60N in winter (Leovy, 1964). Also shown are observed distributions of ozone mixing ratio at 10N in May 1963 and at 60N in January-February 1963 (Hering and Borden, 1964).

Northern and Southern Hemispheres) must introduce an appropriate large amplitude disturbance into the mesosphere which in turn triggers the warming—the warming being, presumably, the unstable response of the medium to the imposed disturbance (Lindzen, 1965c). In the years following this suggestion, however, no effective mechanism was suggested for introducing such a disturbance into the mesosphere. Our calculations suggest that the distribution of tropospheric cloud cover in the winter is such as to cause the proper distribution of visible light in the mesosphere for producing such a disturbance.

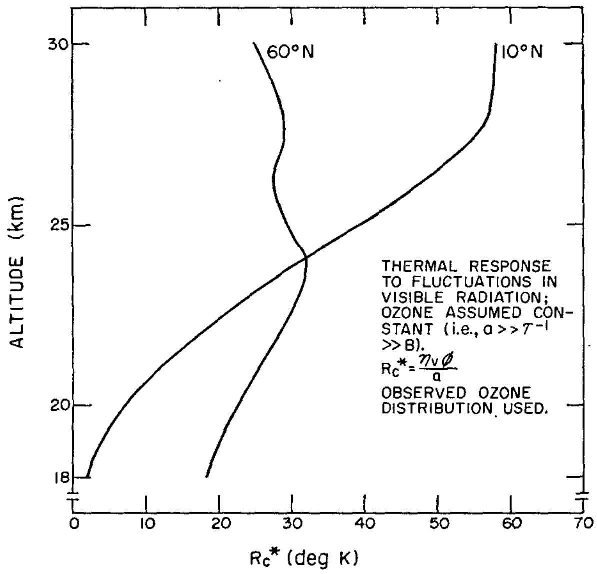

FIG. 7. R_c^* at 10N and 60N based on the observed distribution of φ.

Before proceeding to a description of these calculations, it must be mentioned that the calculations in the preceding sections were based on the presence of a basic state of radiative-photochemical equilibrium in the neighborhood of the equator. As may be seen in Fig. 6, the distribution of ozone so obtained does not differ greatly from the observed distribution at 10N. On the other hand, as we go to higher latitudes, B, the photochemical relaxation rate, becomes much smaller, and consequently the observed distribution of ozone at high latitudes differs substantially from the equilibrium distribution. This too may be seen in Fig. 6. Clearly, at 60N it is no longer permissible to base our response calculations on the equilibrium distribution of ozone. Instead, since B is very small below about 35 km at 60N, the appropriate response function to fluctuations in visible light becomes R_c^*, where $\bar{\varphi}$ is replaced by the observed φ. R_c^*, so calculated, is shown in Fig. 7. Note that it varies from 20 to 30 deg K in the region between 18 and 30 km. In Fig. 8 the mean February cloud cover distribution for the Arctic and subarctic is shown. The

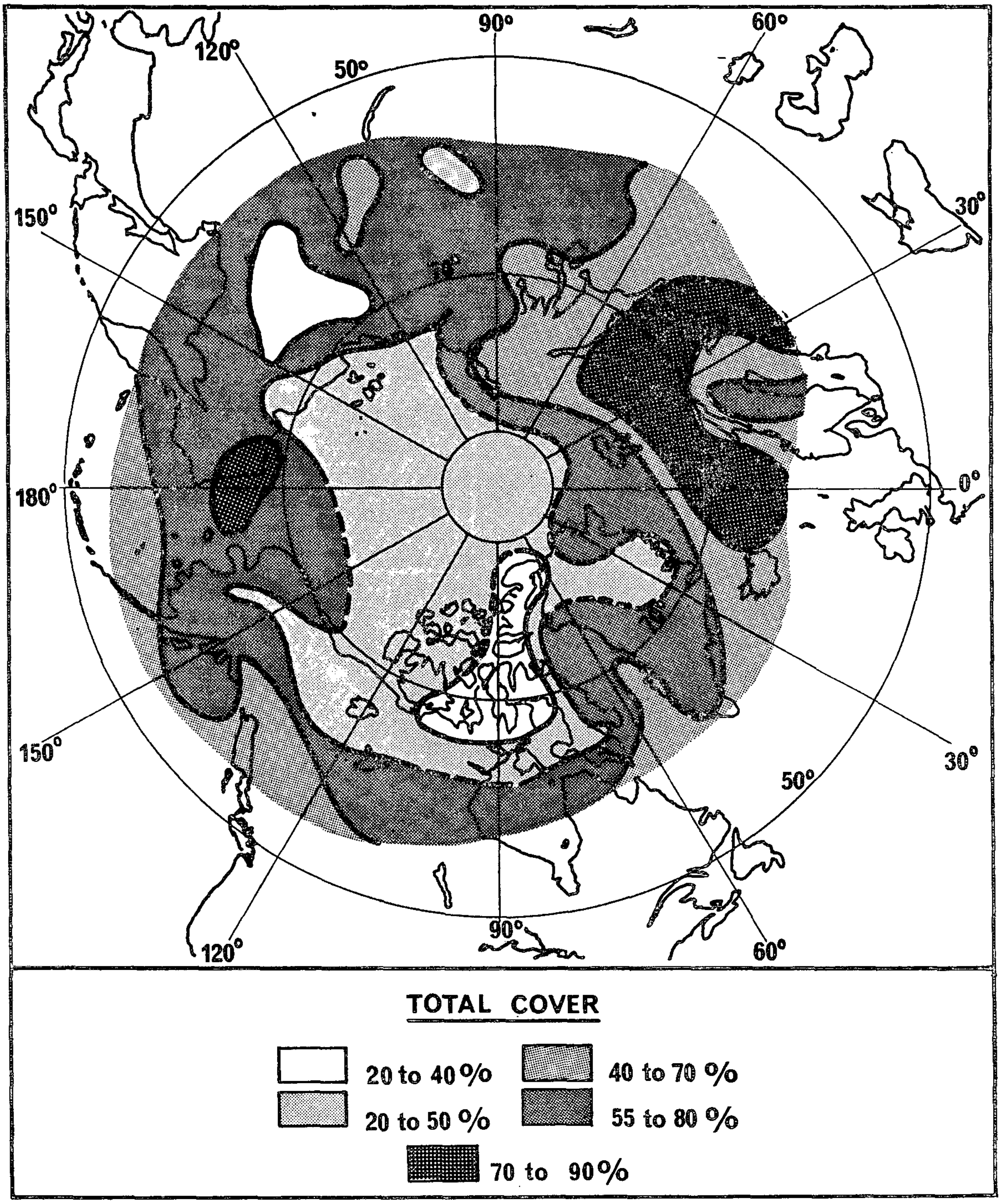

FIG. 8. Mean cloudiness over the arctic and subarctic during February. From Pettersen *et al.*, 1956.

distribution displays with impressive accuracy the wave number 2 form typical of the sudden warmings, with high cloud cover coinciding in position with warm temperature anomalies in the mesospheric sudden warming pattern. Referring back to the raw data in Pettersen, Jacobs and Haynes (1956), it appears that the cloud cover varies from as low as 20 per cent in the low cloud density regions to as high as 87 per cent in the high cloud density regions. The information and knowledge available do not permit us to associate albedos in a quantitatively precise manner with the different percentage cloud covers. However, it does seem reasonable to estimate that there might be as much as 35 per cent more visible light in the mesosphere over the high cloud density regions than over the low cloud density regions. The results in Fig. 7 then suggest that associated with the cloud distribution of Fig. 8 there will be a temperature disturbance in the mesosphere of approximate wave number 2 with warm regions about 10 deg K warmer than cold regions. Such a disturbance could constitute an appropriate trigger for a Northern Hemisphere winter warming.

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