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# Wintertime Stratospheric Anomalies—Part I: Warm Pools

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## ABSTRACT

The stratospheric worm pools, called the 4–day wave also, are mainly the temperature anomalies in the polar regions of winter hemisphere. It will be shown that their occurrence, propagation speed and specific structure can be explained by the lower frequency coherent heating resulting from the wave interaction in the breaking layers of the stratosphere. Although their vertical phase slope is negligibly small, the warm pools cannot be considered as a barotropic anomaly.

## I. INTRODUCTION

In general, the wave spectrum in the middle and upper stratosphere is dominated by traveling waves (Leovy and Webster, 1976; Hartmann, 1976). These waves propagating eastward and westward with different wavenumbers and periods may be detected using satellite radiance data. Upon the normal circulations, there are two distinct types of anomalous circulation patterns in the winter stratosphere. One is the stratospheric sudden warmings reported originally by Scherhag (1952), and the other one is stratospheric warm poos identified initially with the 4–day wave by Venne and Stanford (1979). Since the whole processes of the anomalous circulations may last for several weeks, they may be regarded as the low frequency anomalies in the stratosphere. These anomalies occur in the winter hemisphere only. The major warmings accompanied by reversal of mean zonal circulation have been found merely in the Northern Hemisphere, while the warm pools are more sensible in the Southern Hemisphere.

Like the large scale perturbations in the troposphere, the large scale wave circulations in the stratosphere are also constrained to be hydrostatically equilibrium and geostrophic balance. So the theoretical model of geostrophic wave circulations developed by a recent study of McHall (1991a) is applicable also for the stratosphere. It has been noted (McHall, 1991c, referred to as MH hereafter) that the normal geostrophic wave circulations may be destabilized in the baroclinic regions called the breaking layers, if baroclinicity there is strong enough. Since these layers occur only when zonal mean temperature decreases poleward, they may take place at high latitudes in winter stratosphere. It is possible that these low frequency wintertime stratospheric anomalies are associated with the perturbations initiated in the breaking layers. This study will show that the main characteristics of warm pools, such as their propagation speed and specific structure, can be explained by the coherent heating resulting from the interference of the stable waves in breaking layers. The stratospheric sudden warmings will be investigated in Part II.

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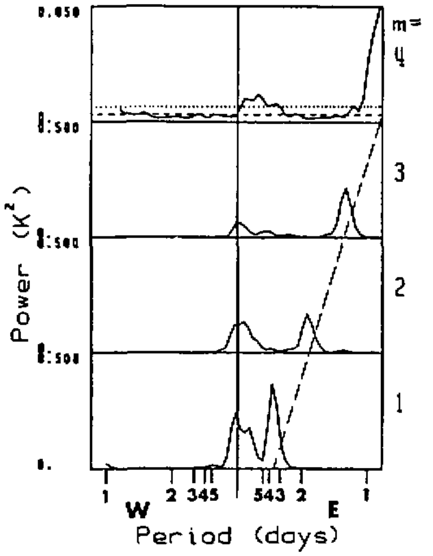

Fig.1. The brightness temperature power *vs* frequency of wave 1 through 4 for TIROS–N SSU–2 (≈ 5 hPa) in June 1979. The dotted line indicates the 99% a posteriori confidence level for wave 4. The short dashed line is the estimated background. The long dashed line corresponds to a uniform zonal phase speed. The *m* here indicates nondimensional zonal wavenumber. (After Lait and Stanford, 1988).

## II. OBSERVATIONAL DESCRIPTION

We may find in the winter stratosphere the various anomalous oscillations in temperature field. The most prominent one is wave one 4–day wave in wave spectrum. According to Prata (1984), the wave may be recognized most evidently in the satellite radiances of the Nimbus–5 SCR instruments, and is confined to a narrow band of latitudes with maximum amplitudes of 2 K in the Southern Hemisphere and 1 K in the Northern Hemisphere. It has been made clear recently (Lait and Stanford, 1988) that this anomaly circulation pattern is not restricted to a 4–day period of propagation. Thus, the anomaly temperature perturbations are called also the stratospheric warm pools, which have the following important properties:

i) They are a winter hemisphere phenomenon only. Attempts to find their extension into the summer hemisphere have failed.

ii) They propagate eastward at almost the same velocity. This may be seen from Fig.1, produced by Lait and Stanford (1988), which shows the brightness temperature power of wave 1 through 4 for June 1979. In this figure, the effects of atmospheric tides were filtered.

iii) Their vertical tilt is, if any, negligibly small as shown in Fig.2 which gives the vertical phase structure of 4–day wave. The horizontal tilt varies from month to month as noted by Prata (1984) and shown by Fig.3.

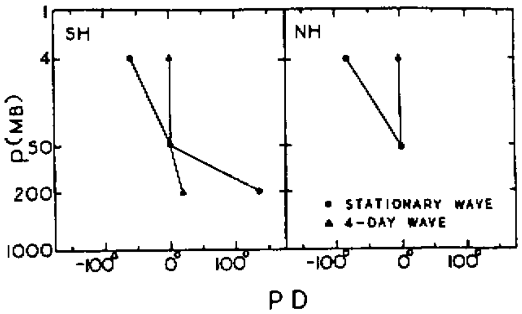

Fig.2. The vertical phase structures of 4–day wave and stationary waves depicted by phase difference PD. A negative PD indicates the westward departure from the crest at 50 hPa. (After Venne and Stanford, 1982).

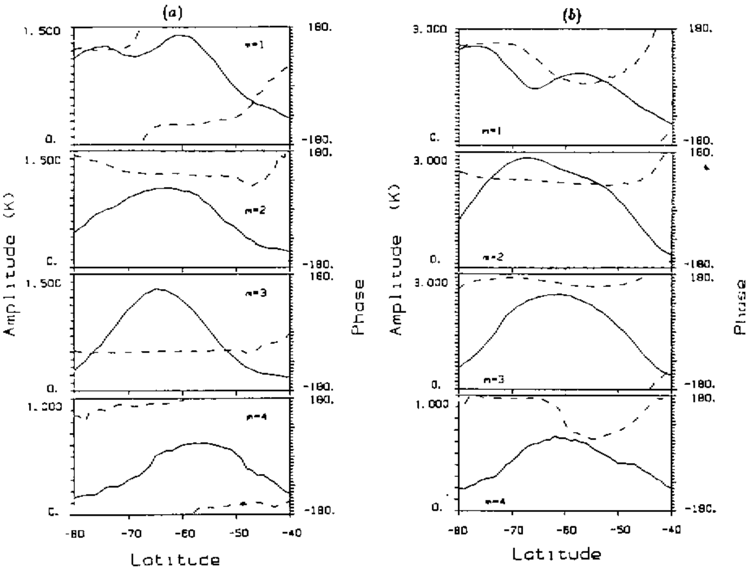

Fig.3. The latitudinal amplitude (solid) and phase (dashed) structures for (a) June 1979 SSU–2 and (b) August 1980 SSU–3, respectively. The *m* here indicates nondimensional zonal wavenumber. (After Lait and Stanford, 1988).

There have been only few theoretical and numerical studies on the warm pools. Most of them, such as the analytical study of Prata (1984) and numerical experiments of Hartmann (1983) and Young and Houben (1989),were concentrated mainly on explaining their time period. In the numerical studies, occurrence of warm pools was considered to be associated with development of wave instabilities. It is noted, however, that these anomalies may sustain stably for several weeks with limited amplitude (Lait and Stanford, 1988). The warm pools will be investigated in a different approach in the present study.

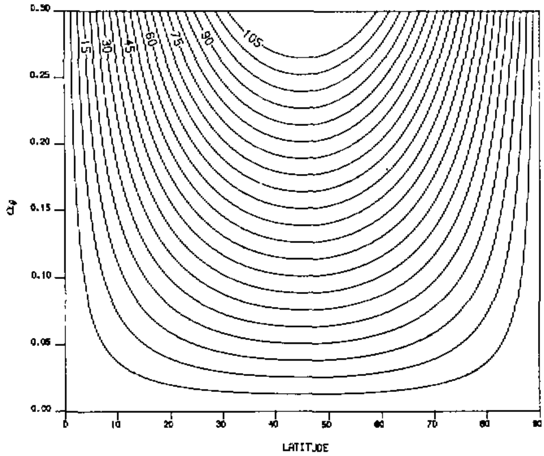

Fig.4. The breaking layers in the stratosphere denoted by the values on the lines (unit: hPa). Contour interval is 5 hPa.

## III. BREAKING LAYERS

It is noted in MH that breaking layers may occur in the troposphere at any time if baroclinity is sufficiently strong. So the associated blocking events take place in all seasons. However in the stratosphere, breaking layers may exist at middle and high latitudes only in wintertime, when zonal mean temperature decreases poleward. The mathematical expression of breaking layers cited from MH is,

$$\tilde{p} = -\frac{aC_v\sigma_y}{2C_p\sigma_z}\sin 2\varphi \ . \tag{1}$$

Here, $\varphi$ denotes latitude and

$$\sigma_y = \frac{R\partial\overline{T}}{p\partial y} = \frac{\overline{\alpha}\partial\overline{\theta}}{\overline{\theta}\partial y} \ , \qquad \sigma_z = -\frac{\overline{\alpha}}{\overline{\theta}}\frac{\partial\overline{\theta}}{\partial p} \ .$$

Their ratio gives

$$-\frac{\sigma_y}{\sigma_z} = \frac{\partial\overline{\theta}/\partial y}{\partial\overline{\theta}/\partial p} = -\left(\frac{dp}{dy}\right)_{\overline{\theta}} = \tan\alpha_\theta \ ,$$

in which, $\alpha_\theta$ measures the angle between mean potential temperature surface and isobaric surface. Inserting it into (1) yields

$$\tilde{p} = \frac{aC_v}{2C_p}\tan\alpha_\theta \sin 2\varphi \ .$$

The dependence of breaking layer on latitude and the slope of mean potential temperature surface is illustrated graphically in Fig.4. As in the troposphere, the breaking layers reach the lowest altitude at middle latitude when the other conditions are the same, and are much higher at lower and higher latitudes. If $\alpha_\theta$ is 0.015°, a breaking layer will occur around 5 hPa surface at latitude 60°.

For a stratified atmosphere with temperature lapse rate $\Gamma$, we may use

$$\sigma_y = \frac{R\partial\overline{T}}{p\partial y} , \qquad \sigma_z = \frac{R^2\overline{T}}{gp^2}\Delta\Gamma , \qquad \overline{T} = \overline{T}_s\left(\frac{p}{p_s}\right)^{\frac{R}{g}\Gamma} \tag{2}$$

in which, $\overline{T}_s$ and $p_s$ measure surface temperature and pressure, respectively; $\Delta\Gamma = g / C_p - \Gamma$. The temperature gradient in breaking layers may be estimated by

$$\frac{\partial\overline{T}}{\partial y} = -\frac{R\overline{T}}{gp}\Delta\Gamma\tan\alpha_\theta .$$

When $\overline{T} = 210$ K and $\Gamma = -0.2$ K / 100 m at 5 hPa, it gives $|\overline{T}_y| \approx 38$K / 1000 km at latitude 60°. This temperature gradient may be observed in the winter stratosphere.

## IV. COHERENT HEATING

The fact that warm pools occur only at high latitudes of winter stratosphere implies that they are perhaps the anomalies taking place in the breaking layers. The superposition of the perturbations with wavenumbers $k_1$ and $k_2$ in breaking layers are represented by (referring to MH)

$$\phi' = i\left(\Phi_1 e^{i(\nu_1 t - k_1 + my + lp)} + \Phi_2 e^{i(\nu_2 - k_2 + my + lp)}\right) ,$$

$$u' = \frac{m}{f}\left(\Phi_1 e^{i(\nu_1 t - k_1 + my + lp)} + \Phi_2 e^{i(\nu_2 - k_2 + my + lp)}\right) ,$$

$$v' = V_1 e^{i(\nu_1 t - k_1 + my + lp)} + V_2 e^{i(\nu_2 - k_2 + my + lp)} ,$$

$$\omega' = W_1 e^{i(\nu_1 t - k_1 + my + lp)} + W_2 e^{i(\nu_2 - k_2 + my + lp)} ,$$

$$\alpha' = -\delta\frac{\sigma_z}{\sigma_y} m\left(\Phi_1 e^{i(\nu_1 t - k_1 + my + lp)} + \Phi_2 e^{i(\nu_2 - k_2 + my + lp)}\right) ,$$

in which,

$$V_j = \frac{k_j}{f}\Phi_j , \qquad W_j = \left((1+\delta)\frac{\sigma_y k_j}{f\sigma_z} + i\delta\frac{fM_j}{\sigma_y k_j} m\right)\Phi_j ;$$

$$M_j = \frac{\beta + \frac{f^2}{\alpha^2\beta}}{f(k_j^2 + k_T^2)} k^2 \qquad (j = 1,2) ;$$

$$l = -\frac{\delta\sigma_z}{(1+\delta)\sigma_y} m , \qquad k_T^2 = \frac{\delta^2 f^2 \sigma_z m^2}{(1+\delta)^3 \sigma_y^2} .$$

Here, $\nu_j$ is simalar to the $\nu$ given in the study of McHall (1991a) using $k_i$ instead of $k$.

As occurrence of the thermal anomalies must have some effect on heat balance in the stratosphere, we discuss now the heat balance in breaking layers by inserting the superposition perturbations into the remainder equation of heat (McHall, 1991b):

$$\dot{T} = -u'\frac{\partial\alpha'}{\partial x} - v'\frac{\partial\alpha'}{\partial y} - \omega'\left(\frac{\partial\alpha'}{\partial p} + \frac{C_v\alpha'}{C_p p}\right) - \sigma_y\overline{v} + \sigma_z\overline{\omega} + \frac{R}{C_p p}H ,$$

giving

$$\dot{T} = \overline{DT_1} + \overline{DT_2} + DT'_1 + DT'_2 + DT_c - \frac{p}{R}(\sigma_y \bar{v} - \sigma_z \bar{\omega}) + \frac{H}{C_p} \ . \tag{3}$$

Here,

$$\overline{DT_j} = \frac{\delta k_j m}{2fR}\left[\frac{\sigma_z p(k_j^2 - k_T^2)}{f\sigma_y (k_j^2 + k_T^2)}\left(\beta + \frac{f^2}{\alpha^2\beta}\right) + \frac{C_v}{C_p}\right]\Phi_j^2$$

are the rates of zonal mean heatings produced respectively by the wave components, and

$$DT'_j = C_{1j}\cos\Psi + C_{2j}\sin\Psi + D_{1j}\cos2\Psi + D_{2j}\sin2\Psi$$

tells the zonally asymmetric heating produced by wavemean–flow and wave–wave interactions, where

$$C_{1j} = \frac{\delta\sigma_z k_j^2 m\bar{v}p}{fR\sigma_y(k_j^2 + k_T^2)}\left(\beta + \frac{f^2}{\alpha^2\beta}\right)\Phi_j \ ,$$

$$C_{2j} = -\frac{\delta\sigma_z p}{R\sigma_y} m^2\left(\bar{v} + \delta\frac{\sigma_z}{\sigma_y}\bar{\omega}\right)\Phi_j \ ,$$

$$D_{1j} = \frac{\delta k_j m}{2fR}\left[\frac{\sigma_z p}{f\sigma_y}\left(\beta + \frac{f^2}{a^2\beta}\right) + \frac{C_v}{C_p}\right]\Phi_j^2 \ ,$$

$$D_{2j} = -\frac{C_v k_T^2 k_j}{2C_p R f^2 (k_j^2 + k_T^2)}\left(\beta + \frac{f^2}{a^2\beta}\right)\Phi_j^2 \ .$$

These asymmetric heating coefficients are similar to whose shown in a previous study of McHall (1991b).

In addition, $DT_c$ measures the heating rate produced by interaction between the waves of different wavenumbers. It is referred to as the coherent heating and is represented by

$$DT_c = C_{c1}\cos(\Delta\nu t - \Delta k x) + C_{c2}\sin(\Delta\nu t - \Delta k x)$$
$$+ D_{c1}\cos2(\bar{\nu}t - \bar{k}x + my + lp) + D_{c2}\sin2(\bar{\nu}t - \bar{k}x + my + lp) \ ,$$

in which,

$$C_{c1} = \frac{\delta C_v \bar{k} m}{fC_p R}\Phi_1\Phi_2 \ ,$$

$$C_{c2} = \frac{\delta\sigma_z m^2 \Delta k p}{(1+\delta)fR\sigma_y}\Phi_1\Phi_2 \ ,$$

$$D_{c1} = \frac{\delta m}{fR}\left[\frac{k_T^2\sigma_z p}{f\sigma_y \bar{k}}\left(\beta + \frac{f^2}{\alpha^2\beta}\right) + \frac{C_v}{C_p}\bar{k}\right]\Phi_1\Phi_2 \ ,$$

$$D_{c2} = -(1+\delta)\frac{C_v k_T^2}{2C_p R f^2 \bar{k}}\left(\beta + \frac{f^2}{\alpha^2\beta}\right)\Phi_1\Phi_2 \ .$$

Here,

$$\Delta\nu = \nu_2 - \nu_1 \ , \qquad \Delta k = k_2 - k_1 \ ;$$

$$\bar{\nu}=\frac{\nu_2+\nu_1}{2}\ ,\qquad \bar{k}=\frac{k_2+k_1}{2}\ .$$

This coherent heating may be rewritten as

$$DT_c=H_{cl}\cos(\Delta\nu t-\Delta kx+\rho_{cl})+H_{ch}\cos2(\bar{\nu}t-\bar{k}x+my+lp+\rho_{ch})\ , \tag{4}$$

where

$$H_{cl}^2=C_{c1}^2+C_{c2}^2\ ,\qquad H_{ch}^2=D_{c1}^2+D_{c2}^2$$

and

$$\cos\rho_{cl}=\frac{C_{c1}}{H_{cl}}\ ,\qquad \sin\rho_{ch}=\frac{C_{c2}}{H_{ch}}\ , \tag{5}$$

$$\cos\rho_{ch}=\frac{D_{c1}}{H_{cl}}\ ,\qquad \sin\rho_{ch}=\frac{D_{c2}}{H_{ch}}\ ,$$

It possesses higher and lower frequency components, and is zonally asymmetric.

From (3), the zonally symmetric heating gives

$$\dot{\bar{T}}=\overline{DT_1}+\overline{DT_2}-\frac{p}{R}(\sigma_y\bar{v}-\sigma_z\bar{\omega})+\frac{\bar{H}}{C_p}\ , \tag{6}$$

in which, $\bar{H}$ indicates zonal mean external heating rate. When balance of zonally symmetric heating is established, $\dot{T}=0$, and so there remains only the asymmetric heating

$$\dot{T}'=DT'_1+DT'_2+DT_c+\frac{H'}{C_p}\ ,$$

which may produce the thermal perturbations of variant periods and wavelengths. For the study of warm pools, however, only the lower frequency coherent heating will be considered.

## V. LOWER FREQUENCY COHERENT HEATING

The observed warm pools are the anomalous temperature field mainly. The raw power spectra of geopotential wave 1 at high latitudes did not manifest the significant peaks of the same period (Venne and Stanford, 1982). A case study of Prata (1984) showed that the worm pool represented by satellite radiances did not travel uniformly and appears to distort in shape from day to day. He suggested that this temperature anomaly might be a kind of nonlinear disturbances. According to their typical scale and structure, the warm pools are discussed below in terms of nonlinear mechanics of the lower frequency coherent heating.

The lower frequency coherent heating separated from (4) may be written as

$$DT_{cl}=H_{cl}\cos(\Delta\nu t-\Delta kx+\rho_{cl})$$

with

$$H_{cl}=\frac{\delta m}{fR}A\Phi_1\Phi_2\ ,\qquad A\sqrt{\left(\frac{C_v}{C_p}\bar{k}\right)^2+\left(\frac{\sigma_z\Delta kmp}{(1+\delta)\sigma_y}\right)^2}\ . \tag{7}$$

Its wavelength and period is given by $\Delta k$ and $\Delta\nu$, respectively, which are generally different from those of the superposition geostrophic perturbations in breaking layers (MH). Thus, if warm pools are produced by the coherent heating, the disturbances of the same structure need not occur simultaneously in geoptential field.

The temperature variation produced by the low frequency heating is estimated by integrating (7), gaining

$$\Delta T_{cl} = \frac{H_{cl}}{\Delta v} \sin(\Delta vt - \Delta kx + \rho_{cl}) \ . \qquad (8)$$

In general, the stratospheric waves possess the similar amplitudes in both hemispheres between 10–1 hPa (Leovy and Webster, 1976). But the horizontal temperature gradient between latitudes 60° to 80° is weaker in the southern upper stratosphere than in the northern (Labitzke, 1973). Thus, from the expression of $A$, the temperature anomaly produced by the coherent heating may be stronger in the Southern Hemisphere. As noted by Prata (1984), the warm pools in the Northern Hermisphere may only be detected using filtered data.

## VI. PROPAGATION VELOCITY

Fig.1 shows that the warm pools of different periods propagate at almost the same velocity eastward. This fact implies that their traveling periods depend on wavenumber only, that is

$$\tau = \frac{2a\pi}{cN_x} \cos\varphi \ ,$$

where, $N_x = ak\cos\varphi$ indicates nondimensional zonal wavenumber. For $\tau = 4$ days as $N_x = 1$, there is

$$c = \frac{a}{2} \pi\cos\varphi \qquad (\mathrm{m} / \mathrm{day}) \ .$$

Applying it yields

$$\tau = \frac{4}{N_x} \qquad (\mathrm{day}) \ .$$

For example, the wave 2 warm pools possess two days period, and the wave 4 warm pools have one day period (referring to Fig.1). Therefore, the more substantial problem related to the specific wave periods of warm pools is to explain their propagation velocity.

It has been noted already that the period and wavenumber of lower frequency coherent heating are both different from those of the superposition waves and their envelope in breaking layers. The coherent heating propagates at the dispersive velocity of the superposition waves as well. If the wave components which form the superposition waves have the same amplitudes, the dispersive velocity will be equivalent to the velocity of mean zonal flow (MH). In the winter stratosphere where mean temperature decreases poleward, the warm pools always propagate eastward. Fig.5 gives the time period for the zonal wind to encircle a latitude in the Southern Hemisphere in July 1973. The dashed line is drawn for the duration of a warm pool with 3.88 days period centred near 70° S. This diagram tells clearly that the thermal anomaly propagated nearly at the velocity of mean zonal flow. This, however, did not mean that the warm pool was advected around by the mean flow.

It is noted that the mean zonal wind in this theoretical model is presented on spheres but not on $f$–plane. Since the direct survey of upper atmospheric wind is not available till now, the velocity field in the upper stratosphere is calculated from satellite radiance measurements by successive application of hydrostatic and geostrophic approximations (Geller et al., 1983; Mechoso et al., 1985). As the wind speed in the upper atmosphere is generally large, the geostrophic wind estimated on $f$–plane may be significantly different from the mean wind on spheres, especially at high latitudes.

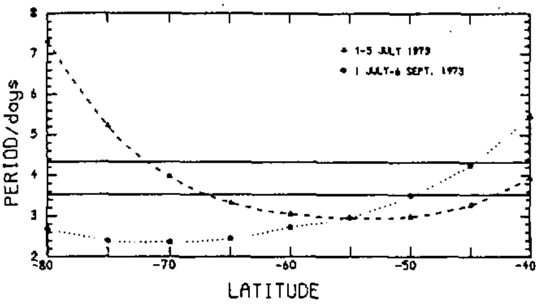

Fig.5. The time period of the geostrophic zonal wind to encircle a latitude in the Southern Hemisphere. The dashed line is for 1–5 July, 1973; the dotted line for 1 July–6 September. The horizontal lines are the upper and lower bounds for the period of the period of the 4–day wave observed in July 1973. (After Prata 1984).

The mean zonal flow on spheres calculated from a mean state equation of McHall (1991a) gives

$$\bar{u} = \frac{a}{2} f\ \mathrm{ctan}\varphi \left( \sqrt{1 - \frac{4\bar{\varphi}_y}{af^2} \tan\varphi} - 1 \right) .$$

Applying geostrophic wind $\bar{u}_g = -\bar{\varphi}_y / f$ yields

$$\bar{u} = a\Omega\cos\varphi \left( \sqrt{1 + \frac{2\bar{u}_g}{a\Omega\cos\varphi}} - 1 \right) . \tag{9}$$

If we use the Taylor expansion

$$\sqrt{1 + \frac{2\bar{u}_g}{a\Omega\cos\varphi}} \approx 1 + \frac{\bar{u}_g}{a\Omega\cos\varphi} - \frac{\bar{u}_g^2}{2a^2\Omega^2\cos^2\varphi}$$

the difference between these two velocities reads

$$\bar{u}_g - \bar{u} \approx \frac{\bar{u}_g^2}{2a\Omega\cos\varphi} .$$

Thus, the geostrophic wind velocity estimated on $f$–plane is larger than on spheres. Provided that $\bar{u}_g = 60$ met / s at latitude 70°, we see $\bar{u}_g - \bar{u} \approx 11.3$ met / s. This difference cannot be ignored.

For example, a warm pool observed at about 2 hPa height in August 1980 was centred at 70°S and had the mean period of 3.75 days (Lait and Stanford, 1988). It is equivalent to the propagation speed $c_g = 42.3$ met / s. While the geostrophic wind estimated by Mechoso et al. (1985) was about 54 met / s there, which is considerably higher than the propagation speed. However, the zonal mean wind evaluated from (9) shows $\bar{u} = 47$ met / s, and is only 4.7 met / s different from the estimated propagation speed.

As warm pools propagate approximately at the velocity of mean zonal flow, we may expect that propagation velocity of warm pools increases with intensity of mean westerly. This was confirmed by the study of Venne and Stanford (1982). They found that the period of

4–day wave decreases as circumpolar vortex increases its angular speed. Also, as the mean westerly wind in the Southern Hemisphere is stronger than in the northern (Leovy and Webster, 1976), the periods of warm pools there are generally shorter as reported by (Venne and Stanford, 1979).

## VII. THERMAL STRUCTURE

Equation (8) shows that phase tilt of the lower frequency coherent heating depends on variations of $\rho_{cl}$. According to MH, there is $\Delta k > 0$ in the Northern Hemisphere but $\Delta k < 0$ in the Southern Hemisphere during winter season. Since momentum flux is poleward at high latitudes in the winter stratosphere, $m$ is positive in the Northern Hemisphere but negative in the Southern Hemisphere (McHall, 1991a). For convenience, we set $\Delta k^* = -\Delta k$ and $\Delta v^* = -\Delta v$. So, (8) is rewritten, in the Southern Hemisphere, as

$$\Delta T_{cl}^* = -\frac{H_{cl}}{\Delta v}\sin(\Delta v^* t - \Delta k^* x + \rho_{cl}^*) ,$$

where, from (5),

$$\cos\rho_{cl}^* = \frac{C_v \bar{k}}{C_p A} , \qquad \sin\rho_{cl}^* = -\frac{\sigma_z m \Delta k^* p}{(1+\delta)\sigma_y A} .$$

The temperature disturbance in the Northern Hemisphere is represented by (8). We may find that $0 < \rho_{cl}, \rho_{cl}^* < \pi / 2$. If intensity of mean temperature gradient at high latitudes decreases poleward from middle latitudes, magnitudes of $\rho_{c1}$ and $\rho_{c1}^*$ will increase poleward for provided wavenumbers. It means that the phases of warm pools will tilt westward and equatorward in both hemispheres. This result is supported by the study of Prata (1984). The opposite phase tilt may be produced if the zonal mean baroclinity increases poleward. For the temperature gradient varies from time to time, the phase tilt tends to be quite variable, as noted by Prata and shown in the study of Lait and Stanford (1988).

Furthermore, if (5) is rewritten as

$$\tan\rho_{cl} = -\frac{C_p \sigma_z m \Delta k p'}{(1+\delta) C_v \sigma_y \bar{k}} ,$$

we find that $\rho_{cl}$ may decrease with height. Thus from (8), the produced temperature deviation may tilt westward with increasing height. In the stratified atmosphere, we may use (2) and obtain

$$\tan\rho_{cl} = -\frac{C_p R \bar{T} m \Delta\Gamma \Delta k}{(1+\delta) C_v \bar{T}_y \bar{k}} .$$

It tells that $\rho_{cl}$ is almost independent of height, and so its vertical variation is generally small. Therefore, the lower frequency coherent heating tilts slightly in vertical direction like observed warm pools.

The small vertical tilt of warm pools need not suggest that they are a barotropic disturbance. It would be suspected that the numerical experiments using barotropic models may reveal much of the basic structure of warm pools. For example, in the experiments of Hartmann (1983) with a barotropic model, appearance of unstable waves 1 and 2 which had periods 3.7 and 1.9 days, respectively, required mean zonal wind of 150 m / s. This speed is much greater than that observed at the levels of worm pools. The simulated disturbances did not show the specific structure of warm pools. Also, the produced $e$—folding tmes in the numerical model were 6.8 days for wave 1 and 10 days for wave 2. However, the observed warm pools usually exhibit little changes in their amplitudes during several weeks.

## VIII. CONCLUSIONS AND DISCUSSIONS

Stratospheric warm pools are an anomalous circulation pattern that occurs mainly in temperature field at high latitudes of winter hemisphere. Their occurrence, propagation velocity and thermal structure may be explained by the lower frequency coherent heating resulting from interference of gostrophic waves initiated in breaking layers. In the stratosphere, the breaking layers may take place in the winter polar regions only. This coherent heating may happen on a planetary scale, and produce the relatively stable anomalies predominantly in temperature field but not in geopotential field. It propagates at the velocity similar to the velocity of mean zonal flow, which may be considerably different from the geostrophic wind velocity estimated from the thermal wind equation on $f$—plane at high latitudes. However, this does not suggest that the dynamics of warm pools is simply related to advection of mean zonal flow.

Although the anomaly perturbations which produce the warm pools are generated in a highly baroclinic breaking layer, the lower frequency coherent heating tilts negligibly westward. Their borizontal phase tilt depends on meridional variations in baroclinicity, and may vary significantly from case to case. When intensity of baroclinicity decreases poleward, the horizontal phase tilt is in the same direction as that of the planetary geopotential waves in both hemispheres. An observed warm pool of this structure was analysed by Prata (1984). The statistic study of Venne and Stanford (1979) showed that horizontal phase tilts of warm pools are opposite in the Northern and Southern Hemisphere. This difference is probably due to the fact noted by Prata (1984) that the wave considered by Venne and Stanford represented a time averaged perturbation over 2—3 months and incorporating two different years.

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