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STUDY ON DYNAMICS OF TROPICAL CISK-ROSSBY WAVES AND MECHANISM OF 30-50 DAY OSCILLATIONS

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ABSTRACT: To add to the growing mature research on the tropical 30-50 day oscillations from a new prospective, the current work bases on dynamic analysis of baroclinic quasi-geostrophic models to discuss dynamic mechanisms for the generation and propagation of CISK-Rossby waves, and to understand restraints and effects of different wave structures and thermodynamic forcing on the 30-50 day oscillations in the tropical atmosphere. Some important properties of the oscillation propagation have been explained and, in detail, with respect to its meridional propagation and vertical “baroclinic” structure. The work has come up with some new opinions and viewpoints. New opinions about the propagation and energy dispersion are to be proved by more observations and study.

Key words: CISK-Rossby wave; 30-50 day oscillation; thermodynamic forcing

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1 INTRODUCTION

The 30-50 day oscillation in the tropical atmosphere is an important component of low-latitude circulation and synoptic systems. In the early 1970’s, Madden and Julian[1] are the first to discover the presence of 30-50 day oscillations in the atmospheric wind and pressure fields in the tropics and later confirm that such periodic disturbances are widely found in the atmosphere across the globe. As shown in studies[2, 3], the low-frequency oscillations in the tropical atmosphere are mainly displayed as 1 to 3 zonal waves (mostly 1 wave) in the equatorial region, which slowly propagates eastward, sometimes westward, at a speed about 10 m/s. In addition to zonal propagation, the 30-50 day oscillations also transfer meridionally by large geographical difference[2, 3]. The oscillation is also of waving along the vertical direction and significant “baroclinic” structure[2, 3, 4], the wind and geopotential fields of the latter tending to incline towards west in high and low levels of the troposphere and even have phases opposed to the original. For the mechanism of generation of low-frequency oscillations in the tropical region, Li[5] introduces the CISK mechanism into the study, the first attempt of its kind. He thinks that the moving CISK mode is an important driving force for the 30-50 day oscillations in the troughs and ridges of South Asian Monsoon. In his effort of further investigating into the feedback principles of cumulus feedback of the 30-50 day oscillations, Lau (1987) sums up the phenomenon as mobile wave-CISK and applies it in the context of slowly-eastward-moving CISK-Kelvin wave that oscillates every 30 ~ 50 days. Afterwards, Li[9] puts forward another important mechanism, the CISK-Rossby wave, to explain the eastward and

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westward movement of the oscillation.

The study of the generation and zonal propagation of the tropical 30-50 day oscillation has been more perfect than ever before, though with little address on the issues of meridional propagation, vertical waving and baroclinic features. With the foundation of the study above, the current work makes fresh attempts to discuss the mechanisms of generation and propagation of the CISK-Rossby wave and 30-50 day oscillations, especially in terms of meridional propagation and vertical structure.

2 MODEL OF KINETICS

Taking the equatorial β-plane and Boussinesq approximations, a baroclinic linear model is examined that includes thermodynamic forcing:

$$\begin{cases} \dfrac{\partial u}{\partial t} - \beta y v = -\dfrac{\partial \phi}{\partial x} \\ \dfrac{\partial v}{\partial t} + \beta y u = -\dfrac{\partial \phi}{\partial y} \\ \dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} + \dfrac{\partial w}{\partial z} = 0 \\ \dfrac{\partial}{\partial t}(\dfrac{\partial \phi}{\partial z}) + N^2 w = N^2 \eta w_B \end{cases} \tag{1}$$

where N is the Brunt-Vaisala frequency, η is the dimensionless amplitude parameter of condensation latent heat in convection and w_B is the vertical velocity at the tropopause. As the low-frequency oscillations in the tropical atmosphere are active on the planetary scale and quasi-geostrophic, as indicated in [5], baroclinic quasi-geostrophic filtering can be applied to the model to obtain a set of dynamic equations that include the β-effect and thermodynamic forcing.

$$\begin{cases} \dfrac{\partial}{\partial t}(\dfrac{\partial^2 \phi}{\partial x^2} + \dfrac{\partial^2 \phi}{\partial y^2}) + \beta \dfrac{\partial \phi}{\partial x} - \beta^2 y^2 \dfrac{\partial w}{\partial z} = 0 \\ \dfrac{\partial}{\partial t}(\dfrac{\partial \phi}{\partial z}) + N^2 w = N^2 \eta w_B \end{cases} \tag{2}$$

Following a way similar to [6], an equation that contains only one variable w is obtained by eliminating ϕ from Eq.(2):

$$\frac{\partial}{\partial t}(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\beta^2 y^2}{N^2}\frac{\partial^2 w}{\partial z^2}) + \beta \frac{\partial w}{\partial x} = \eta \frac{\partial^3 w_B}{\partial t \partial x^2} + \eta \frac{\partial^3 w_B}{\partial t \partial y^2} + \beta \eta \frac{\partial w_B}{\partial x} \tag{3}$$

For emphasized discussion of the low-frequency oscillation associated with longwave, the η term on the right hand side of Eq.(3), which is with β, is retained while neglecting the rest[6]. The equation is then reduced to:

$$\frac{\partial}{\partial t}(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\beta^2 y^2}{N^2}\frac{\partial^2 w}{\partial z^2}) + \beta \frac{\partial w}{\partial x} = \beta \eta \frac{\partial w_B}{\partial x} \tag{4}$$

3 CONDITIONS FOR GENERATION OF WAVES AND VERTICAL PROPAGATION

As the vertical velocity at the tropopause, w_B, can be approximated[7] to be $w_B = b \cdot w$ ($b \leqslant 1$), we can get the following equation by substituting $w = W(z) \cdot \mathrm{e}^{i(kx+ly-st)}$ into Eq.(4):

$$\frac{d^2W}{dz^2} + QW = 0 \tag{5}$$

in which the analytical solution of $Q = -\frac{N^2}{f^2}[(k^2+l^2) + \frac{kb}{s}(1-bh)]$ can be derived from Eq.(5):

$$W(z) = c_1 \mathrm{e}^{-\sqrt{-Q}\cdot Z} + c_2 \mathrm{e}^{\sqrt{-Q}\cdot Z}$$

Usually, the lateral conditions can be specified in this way: $W(z)$ is bounded when $z \longrightarrow \infty$ and $c_2 = 0$ is thus obtained. Therefore, we have $W(z) = c_1 \mathrm{e}^{-\sqrt{-Q}\cdot Z}$ and by substituting this solution back to the set solution set above, we get:

$$w = W(z) \cdot \mathrm{e}^{i(kx+ly-st)} = c_1 \mathrm{e}^{-\sqrt{-Q}\cdot Z} \cdot \mathrm{e}^{i(kx+ly-st)} \tag{6}$$

If Q is the slowly varying function of z, then m, the local vertical wavenumber, can be introduced:

$$Q = m^2 = -\frac{N^2}{f^2}[(k^2+l^2) + \frac{kb}{s}(1-bh)] \tag{7}$$

When $Q = m^2 > 0$, $w = c_1 \mathrm{e}^{-\sqrt{-Q}\cdot Z} \cdot \mathrm{e}^{i(kx+ly-st)} = c_1 \mathrm{e}^{\pm miz} . \mathrm{e}^{i(kx+ly-st)} = c_1 \mathrm{e}^{i(kx+ly\pm mz-st)}$.

In this expression, k and I are respectively the zonal and meridional wavenumber. If the local vertical wavenumber $m = \frac{np}{H}$ is taken (H is the eigenvector height at the tropopause and n is the integral number), it is then obvious that w displays itself in the state of wave in the direction of z, which propagates vertically. The wave is stable due to constant amplitude c_1 for the whole wave though there is activity in both horizontal and vertical directions.

As the CISK-Rossby wave is closely associate with the 30-50 day oscillation in the tropical region, the features of the vertical wave can be used to explain the baroclinic structure of the latter. Such "baroclinic" structure shows itself as well-defined inclination towards the west in its primary disturbance, i.e. zonal wavenumber 1, which is in company with out-of-phase distribution between the upper and lower level of the troposphere. The 30-50 day oscillations of zonal wavenumber 2 ~ 4 are also slanting westward vertically, though stop short of having opposed phases between the two levels[2, 4]. If $n = 1$ is assumed, then the vertical structure of the CISK-Rossby wave can be generally viewed as a westward-inclining disturbance at lower levels of the 30-50 day oscillation (Fig.1a). If $n = 2$ is taken, however, the out-of-phase characteristic is normally shown to exist from low to high levels of the troposphere (Fig.1b).

When $Q = m^2 < 0$, $w = c_1 \mathrm{e}^{-\sqrt{-Q}\cdot Z} \cdot \mathrm{e}^{i(kx+ly-st)} = c_1 \mathrm{e}^{-mz} . \mathrm{e}^{i(kx+ly-st)}$. At the time there is only the horizontal wave while the vertical wave is blocked. The amplitude is now $c_1 \mathrm{e}^{-mz}$ that

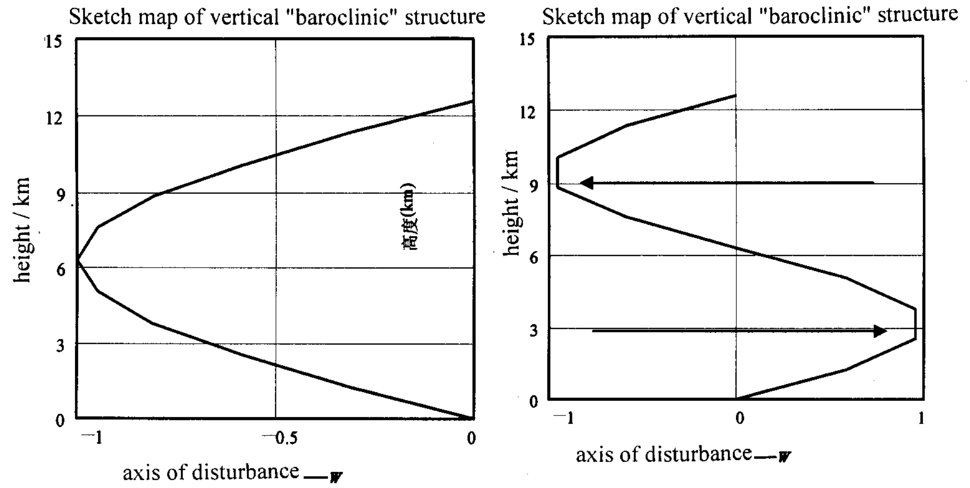

Fig.1 The sketch map of vertical structure of the CISK-Rossby wave when *n*=1 (a) and *n*=2 (b)

decays exponentially with height. The horizontal wave is significant at lower levels but quite weak at high levels.

Following the discussions above, we know that the conditions for vertical waves or vertical propagation of waves to appear can be summed up as $m^2 > 0$.

From $m^2 = Q = -\frac{N^2}{f^2}[(k^2+l^2)+\frac{kb}{s}(1-bh)] > 0$, we have $\frac{N^2}{f^2}[(k^2+l^2)+\frac{kb}{s}(1-bh)] < 0$.

It shows that the thermodynamic forcing (η) has to be very strong to enable the wave to travel vertically whenever $h > h_c = \frac{1}{b}[\frac{s(k^2+l^2)}{kb}+1]$ (the critical value). In other words, the strong thermodynamic action is one of the important conditions for vertical inducement or propagation of the CISK-Rossby wave.

From $m^2 > 0$, another form of the conditions for vertical wave propagation is obtained here: $s < \frac{-kb(1-bh)}{k^2+l^2}$ or $C_x < -\frac{b(1-bh)}{k^2+l^2}$ (C_x is the phase speed in the zonal direction). It is shown that when the heating η is weak with $(1-bh) > 0$, only the west-moving CISK-Rossby wave can propagate upward; when η is intense with $(1-bh) < 0$, both the west-going and quasi-stationary CISK-Rossby waves can propagate upward and so can the slow-traveling CISK-Rossby wave. To put it in another way, when the heating effect η is weak, only the westward-traveling CISK-Rossby wave may be baroclinically structured in the vertical direction; when it is intense, the westward-going, quasi-stationary waves and slowly moving 30-50 day oscillations can all be of such structure.

For the wave to be blocked vertically, the condition has to be $m^2 < 0$. Likewise, when thermodynamic forcing is below the critical value ($h < h_c$), only the horizontal CISK-Rossby wave can be excited. It is inferred that barotropic structures occur in the 30-50 day oscillations that meet this condition.

To summarize the discussions above, we come up with the mechanism through which the CISK-Rossby wave propagates vertically. When η is within the h_c, the critical value ($Q = m^2 < 0$), the thermodynamic forcing is such that horizontal CISK-Rossby waves are generated (as the amplitude decreases with height index). As η increases steadily, the amplitude of horizontal waves with the same stratification grows; when η goes to and past the critical point h_c (so that $Q = m^2 > 0$), the amplitude reaches its maximum c_1 and stabilizes and waving starts to appear in the vertical direction. It is therefore concluded that the thermodynamic forcing is an important physical factor in strengthening the horizontal wave and generating the vertical wave.

Let's now apply the mechanism in the vertical structure of the 30-50 day oscillation. It can be inferred that the "baroclinic" structure found in the oscillation is conditional — when the thermodynamic forcing is large, it is more likely for the oscillation to be "baroclinically" structured than any other time; when the forcing is relatively weak, it is not necessarily to have such structure in the oscillation.

4 PROPAGATION AND THERMAL CONSTRAINTS OF CISK-ROSSBY WAVES

From σ, the wave frequency, we have the oscillatory period of the horizontal wave:

$$T = \left|\frac{2p}{s}\right| = \left|\frac{2p\,[(k^2+l^2)+\dfrac{m^2f^2}{N^2}]}{kb\,(1-bh)}\right|$$

From Eq.(7), the frequency σ is derived and then the horizontal phase and group velocities are computed on the basis of it:

$$s = -\frac{kb(1-bh)}{(k^2+l^2)+\dfrac{m^2f^2}{N^2}} \qquad \text{phase velocity}\begin{cases} C_x = \dfrac{s}{k} = -\dfrac{b(1-bh)}{(k^2+l^2)+\dfrac{m^2f^2}{N^2}} \\[2ex] C_y = \dfrac{s}{l} = -\dfrac{b(1-bh)\cdot\dfrac{k}{l}}{(k^2+l^2)+\dfrac{m^2f^2}{N^2}} \end{cases}$$

The group velocity of the CISK-Rossby can be expressed by:

$$\begin{cases} C_{gx} = \dfrac{¶s}{¶k} = -\dfrac{b(1-bh)}{(k^2+l^2)+\dfrac{m^2f^2}{N^2}} + \dfrac{2k^2b(1-bh)}{[(k^2+l^2)+\dfrac{m^2f^2}{N^2}]^2} = \dfrac{b(1-bh)[(k^2-l^2)-\dfrac{m^2f^2}{N^2}]}{[(k^2+l^2)+\dfrac{m^2f^2}{N^2}]^2} \\[3ex] C_{gy} = \dfrac{¶s}{¶l} = \dfrac{2klb(1-bh)}{[(k^2+l^2)+\dfrac{m^2f^2}{N^2}]^2} \end{cases}$$

The angle between the directions x and y, α, can be written as the following to express the horizontal propagation of wavetrains:

$$\tan(a) = \frac{C_{gy}}{C_{gx}} = \frac{2kl}{[(k^2 - l^2) - {m^2 f^2}/{N^2}]}$$

Specifically, $k = \frac{2p}{L_x}$ is the zonal wavenumber, $l = \frac{2p}{L_y}$ the meridional wavenumber, $m = \frac{np}{H}$ the local vertical wavenumber, H the characteristic altitude of tropopause and n an integral number, which takes 0, 1, 2, ⋯, representing the wave structure in the vertical direction. During the computation, we take $H = 1.1\times10^4$ m, $f = 0.25\times10^{-4}$ /s, $b = 2.25\times10^{-11}$ / ms (being equivalent to about 10°N), b = 0.4, and $N^2 = 1.0\times10^{-4}$ /s^2.

From the expression of phase velocity, we know that when the thermodynamic action η is small so that $(1 - bh) > 0$, there is $C_x < 0$. At the time, the CISK-Rossby wave propagates westward, which is consistent with but slower than the typical Rossby wave in low-latitude atmosphere; when η increases till $(1 - bh) = 0$, the phase velocity in both meridional and zonal directions of the CISK-Rossby wave becomes zero and the wave itself is quasi-stationary; when η keeps growing until $(1 - bh) < 0$, the wave would propagate to the east and north. Without considering the meridional structure, such characteristics of the zonal propagation agree with the typical mode and a number of other findings[6], which is different from the Rossby wave in free atmosphere. The Rossby wave in question is propagating not only zonally but meridionally and it is just why it can be used to describe the meridional propagation of the 30-50 day oscillation. On the other hand, what is different from the typical mode[9] is that the CISK-Rossby wave discussed above is of dispersion in y as well as x direction, which is hoped to depict the dispersion phenomenon present in the 2-dimensional wavetrains of the wave and some low-frequency tropical systems[10, 11]. As expanded vertical property of the CISK-Rossby wave is introduced, we are able to have a full interpretation of some of the low-frequency disturbances that contain the baroclinic structure.

For the critical thermodynamic point during the vertical propagation of the CISK-Rossby wave

$$h_c = \frac{1}{b}\left[\frac{s\,(k^2 + l^2)}{kb} + 1\right] = \frac{1}{b}\left[\frac{c_x (k^2 + l^2)}{b} + 1\right]$$

computation is done as follows:

(1) Taking the zonal wavelength at $L_x = 1.0\times10^7$ m and meridional wavelength at $L_y = 3.5\times10^6$ m, h_c = 0.5 for the zonally westward propagation of the Rossby wave (c_x = –5 m/s) and h_c = 4.5 for the meridionally eastward propagation of the Rossby wave (c_x = 5 m/s);

(2) Taking the zonal wavelength at $L_x = 4\times10^7$ m and meridional wavelength at $L_y = 5.0\times10^6$ m, h_c = 1.61 for the westward propagation of the Rossby wave (c_x = –5 m/s) and h_c = 3.39 for the meridionally eastward propagation of the Rossby wave (c_x = 5 m/s);

(3) h_c = 2.5 for stationary Rossby waves, regardless of the wavelength in zonal or meridional direction.

As shown in the results above, the west-going CISK-Rossby wave requires just a little heating while the east-going CISK-Rossby wave requires relatively strong one, and the stationary CISK-Rossby wave needs a critical heating rate between the two to have vertical propagation. It is conceived that such thermodynamic structure is favorable for vertical propagation of the Rossby wave moving westward. In contrast, the stationary and slow eastward-moving Rossby will not propagate vertically unless relatively strong thermodynamic conditions are satisfied.

5 OBSERVATIONAL FACTS AND INTERPRETATION OF TROPICAL 30-50 DAY OSCILLATIONS

As the observation reveals, the 30-50 day oscillation with wavenumber 1 is mainly propagating along the equator at a speed of about 10 m/s, though it may travel to the west. The westward movement is quite common in tropical areas outside the equator[2, 3]. Apart from zonal propagation, the oscillation is also pronounced for its meridional transfer. Krishnamurti (1982) points out that the 30-50 day oscillation in the monsoon troughs and ridges of South Asia can be moving northward slowly at a speed of about 0.75 latitude / day. Chen long-xun (1982) discovers that the oscillation in the East Asian summer monsoon is slowly propagating northward at an average speed of 0.5 ~ 0.82 latitude / day. Another important feature of the meridional propagation is the significant geographical features, which are marked by consistent northward propagation in the region of South Asia (south of the point 80°E, 30°N, Fig.2a) and generally southward propagation south of 30°N in winter against northward propagation south of 15°N but southward propagation north of it

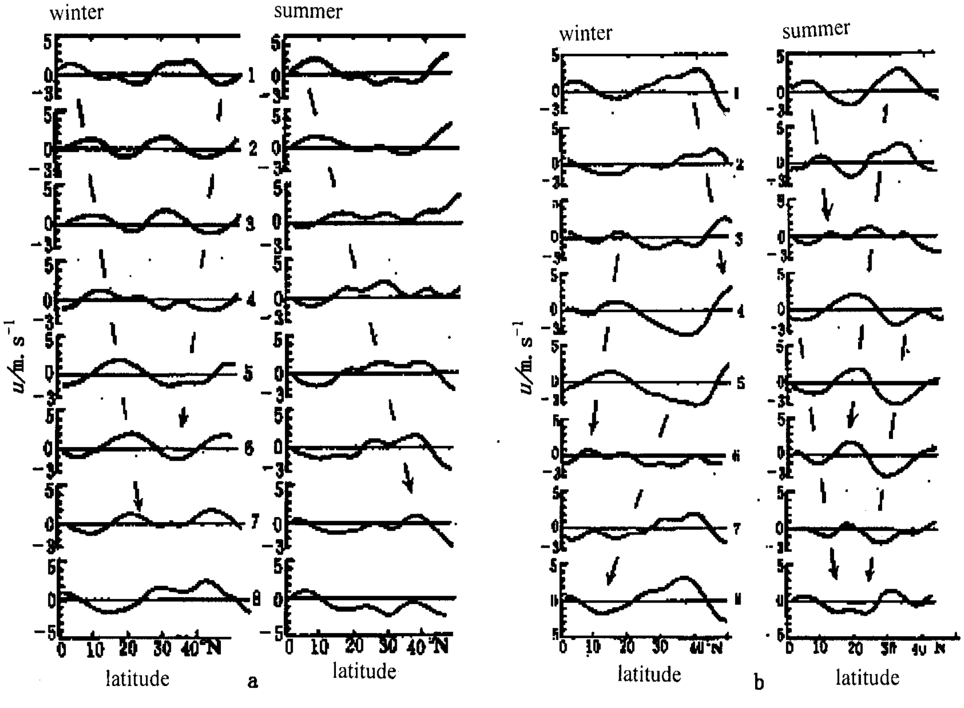

Fig.2 The meridional pattern along 80°E (a) and 130°E (b) of zonal wind oscillation phase through 30～60 days band-pass filter on the 500 hPa level

in summer (Fig.2b).

The propagating characteristics and regional differences in the 30-50 day oscillation can be interpreted by dynamic propagation of the CISK-Rossby wave. Low-frequency oscillations in the tropics are displayed as zonal wavenumber 1 ~ 4 and zonal wavenumber 1 is the most frequently seen 30-50 day oscillation in the equatorial region. We therefore focus the computation on the wavenumber 1 (with corresponding meridional scale at 5000 km and the unit takes m/s for the velocity of phase and group phase). Some computation and brief discussions are also conducted for the tropical 30-50 day oscillations with wavenumber 3 ~ 4.

(1) By taking $L_x = 4.0\times10^7$ m (wavenumber 1 near the equator) and wavenumber 1 in the vertical direction in the tropical troposphere (n = 2), we can have 30-50 day periodic oscillations (T = 46.2 ~ 55.9 days) within the thermodynamic domain η = 0.2 ~ 0.6 (weak) and η = 4.4 ~ 4.8 (strong). Specifically, the zonal velocity produced during weak heating, C_x = –10.03 ~ –8.29, is comparable to and in the same direction as the zonal group velocity, C_{gx} = –9.79 ~ –8.09, heading towards west or dispersing (Type I). When the thermodynamic action is large with C_x = 8.29 ~ 10.03 and C_{gx} = 8.09 ~ 9.79, the 30-50 day oscillation will propagate and disperse eastward at comparable speed (Type II).

(2) By taking into account the wavenumber 1 and meridional wave at wavelength of $L_y = 5\times10^6$ m, we can have 30-50 day periodic oscillations (T = 35.87 ~ 55 days) within the thermodynamic domain η = 0.2 ~ 1 (weak) and η = 4 ~ 4.8 (strong). Specifically, the zonal velocity produced during weak heating, C_x = –12.91 ~ –8.42, and the meridional velocity, C_y = –1.61 ~ –1.05, are separately heading towards west and south, with zonal and meridional group velocity at C_{gx} = –12.51 ~ –8.16 and C_{gy} =3.18 ~ 2.07, respectively (Type III). With the 30-50 day oscillation produced during the heating is strong, the zonal and meridional velocity are C_x = 8.42 ~ 12.91 and C_y = 1.05 ~ 1.61, and propagating towards east and north, respectively. In the meantime, the zonal and meridional group velocity are C_{gx} = 8.16 ~ 12.51 and C_{gy} = –2.07 ~ –3.18, respectively and traveling towards southeast (Type IV).

Under the joint actions by the β effect and thermodynamics, as shown in the discussion above, disturbances in either meridional or vertical direction can produce 30-50 day oscillation within a domain of comparable thermodynamic forcing. They have generally the same attributes for the zonal propagation: When the thermodynamics is weak (strong), the energy propagates and disperses westward (eastward). Compared with the zonal propagation of typical CISK-Rossby waves[9], the above wavenumber 1 presented above embraces main characteristics of the former and can acquire, within consecutive thermodynamic domain (η = 1.5～4.5)[9], eastward velocity of about 10 m/s, which is similar to actual tropical 30-50 oscillation.

For the multiple modes of zonal propagation shown to exist in the 30-50 day oscillation, interpretations can be made as follows. Under general circumstances, thermodynamic differences, being smaller outside the equator than around it, cause the west-traveling 30-50 day oscillation to appear in the region near the equator where the thermodynamic effect is relatively small and the east-traveling oscillation to appear in areas where the effect is relatively large. If there is, however, strong convective heating in tropical areas outside the equator, the 30-50 day oscillation it produces may take on the form of propagating to the east. Likewise, if the thermodynamic action weakens near the equator, then the 30-50 day oscillation it corresponds to may propagate westward.

In other words, whether the oscillation is propagating west or east is very much dependent on the thermodynamic conditions of the region in which it is located.

In addition, the CISK-Rossby wavenumber 1 are computed in terms of the 2-dimensional propagation and dispersion. The result shows that the westward propagation of the oscillation is usually accompanied by southward movement and northwest dispersion of wave energy; the eastward propagation of the oscillation is usually accompanied by northward movement and southeast dispersion of wave energy. With observed data, Murakami[10] points out that the tropical cyclone (usually with strong latent heat from condensation) inside the 30-50 day oscillatory systems of the summer monsoon in South Asia disperses the energy to the southeast. Blackman[11] also finds, in his study with Northern Hemisphere data, that wave-lead exists in low-frequency tropical disturbances that can lead to southeastward dispersion of energy. These properties of CISK-Rossby wave dispersion are compatible with the analyses based on observations. It may then be inferred that the 30-50 day oscillation of troughs and ridges in South Asia Monsoon may have additional movement towards east in the slow, northward propagation; for the 30-50 day oscillation of the East Asian summer monsoon, the low-level northward and upper-level southward propagation may be associated with low-level eastward and upper-level westward propagation, to adjust to the "boraclinic" structure in the vertical direction. The meridional propagation velocity, computed to be C_y = ±1.05 ~ ± 1.61 m/s, which is equivalent to 0.825 ~ 1.265 latitude / day, generally agrees with observational facts.

Differences of meridional propagation displayed in the 30-50 day oscillation can also be interpreted from the point of regional thermodynamic difference. In South Asia (south of the point 80°E, 30°N), the 30-50 day oscillation is of Type Ⅳ, a strong thermodynamic effect in our discussion, which is propagating northward. The classification of the type is not hard to explain due to the fact that the thermodynamic effect is large in west Pacific (south of the point 130° E, 15 °N) in the summertime, matching Type Ⅳ with northward propagation, while it is small in areas north of 15°N , matching Type Ⅲ with southward propagation.

For wavenumber 3 ~ 4 in the tropical area near the equator (taking $L_x = 1.0 \times 10^7$ m, $L_y = 3.5 \times 10^6$ m and vertical wavenumber 1), computations are also conducted. In comparison with the case of wavenumber 1, the thermodynamic domain in which the 30-50 day oscillation is generated is generally the same as the one computed in terms of propagation and dispersion, and they, too, perform both eastward and westward propagation as they occur in real tropical 30-50 day oscillation in the atmosphere and interpret multiple propagating modes present in it. The difference is that the 30-50 day oscillation is usually of zonal wavenumber 1 near the equator but of zonal wavenumber 3 ~ 4 outside the equator. It is therefore believed that the 30-50 day oscillation with small zonal scales out of the equator will move along east-west route much more slowly than the one with large zonal scales. The oscillation with zonal wavenumber 3 ~ 4 is also slower than wavenumber 1 with respect to the meridional velocity of propagation, being about C_y = 0.72 ~ 1.31 m/s and equivalent to 0.566 ~ 1.029 latitude / day. It is close to the meridional movement observed.

In his study of the variation of C_{gy} (in which $C_{gx} = C_x$) of typical CISK-Rossby waves with thermodynamic intensity[9], Li suggests that disturbances with large meridional scales generally disperse the energy southward if there is strong heating but those with all meridional scales disperse the energy northward if there is weak heating; C_y and C_{gy} usually propagate in opposite directions with comparable intensity corresponding to weak heating but they propagate either in the same or opposite direction with the magnitude varying substantially between them. The meridional dispersion of energy drawn up here for the 30-50 day oscillation agrees well the result above, though the former indicates that dispersion also exists in the zonal direction, making it 2-dimensional. The route and direction (northwest-southeast by an angle about 25° ~ 39°) are corresponding to one of the two basic patterns of low-frequency teleconnection[12], the Eurasian-Pacific Pattern, in the 30-50 day oscillation in the boreal atmosphere.

6 CONCLUDING REMARKS

The mechanisms by which the tropical 30-50 day oscillation generates and propagates has been studied dynamically, with detailed derivation and discussions of meridional and vertical propagation which are less addressed previously. Some of the major features of the oscillation are described and explained in depth. Taking into account the vertical propagation of the wave, the "baroclinic" structure found in the troposphere can be interpreted by assuming proper vertical modes. Besides, the work shows that the CISK-Rossby propagates in different ways responding to the meridional and zonal wave structures that produce it. The 30-50 day oscillation being consistent with the waves also have different modes of propagation accordingly. They are the factors for facilitating the diversity and complexity of the propagation modes. In addition to explaining all the characteristics and mechanisms that have been identified so far, the work also presents some viewpoints on the propagation and dispersion of energy in the 30-50 day oscillation of the tropical atmosphere on the basis of dynamic derivation and computations. The result remains to be verified against observations and more theoretic study.

Owing to relatively simple structure of the model, the work does not include basic air currents and their distribution. It is quite reasonable to take the finding here as a result obtained from adequate structure of base currents or identical circulation background. It is just because of this limitation, issues like varying modes of propagation of tropical low-frequency oscillations, which may arise from differences in circulation structure in the regions of the Pacific trade winds and South Asia monsoon, cannot be well addressed. Neither can the geographic features present in low-frequency oscillations be satisfactorily reflected.

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