TROPICAL GRAVITY-ATMOSPHERIC LONG WAVE AND THE WALKER CIRCULATION

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ABSTRACT

Orders of magnitude of terms related to earth's rotation in linearized vorticity and divergence equations governing tropical large-scale motion are analysed. It is discovered that $\beta y D$ and $\beta y \xi$ are smaller by one order than βv and βu respectively and then may be neglected. On this basis, tropical wave motions are di s-cussed. It is found that there exists a kind of gravity-atmospheric long waves which is non-vorticit atmospheric long wave, whereas the Kelvin wave is essentially the gravity-atmospheric long wave with its velocity being much lower than that of gravity. Computation shows that there also exists a kind of large-scale slow waves whose moving speed is lower by one order of magnitude than that of Kelvin wave. Such slow wave is likely to be the Walker Circulation.

I. INTRODUCTION

For a long time past, the flow pattern structure in equatorial zone has been considered rather simple: in the lower troposphere is the weak eastern flow. Recent observations show, however, that the latitudinal distribution of meteorological element fields, whether wind or temperature, even the weather phenomenon is extremely uneven (Hoskins et al., 1983). Figure 1 shows the east-west circulation along equator presented by Zillman, in which the circulation between Indonesia and eastern Pacific coast is the most well-developed. This is the usually so-called Walker Circulation. Thus it can be known that the equatorial large-scale flow field has a three-dimensional motion pattern. Though its numerical value of velocity convergence and divergence may not be necessarily larger than its corresponding vorticity value, the variation and distribution of convergence and divergence will directly determine the large-scale wea-

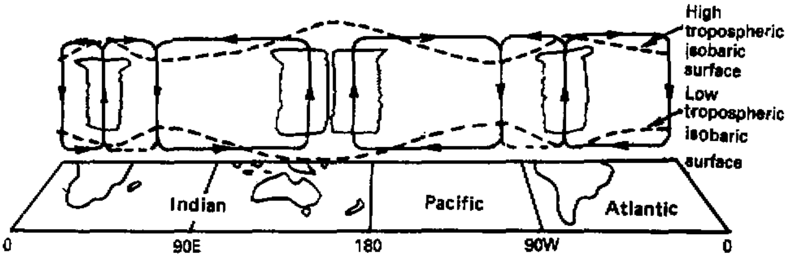

Fig. 1. Schematic view of the equatorial symmetric planetary scale features. Note the dominance of the Pacific Ocean-Indonesian cell which is referred to as the Walker Circulation.

* Gao Hui has a share in part of the work.

ther of the zone. Thus, it may be of certain significance to investigate the large-scale synoptic process in the equatorial zone at an angle of the distribution and variation of velocity convergence and divergence.

II. SCALE ANALYSIS OF TROPICAL VORTICITY AND DIVERGENCE EQUATIONS

The scale analysis of tropical large-scale motion made by Charney does not reveal its essentially distinctive feature from that of mid-latitudes. Recently, Li Maicun (1981) and Chao Jiping (1980) also carried out the scale analysis of the equatorial motion. Chao Jiping et al., who introduced the concept of longitudinal width, performed the scale analysis of the tropical motion without regard to its heating process and defined the motion of *Re* (longitudinal Rossby number) $\geqslant 0.5$ as tropical motion. Given: $x=L\bar{x}$, $y=l\bar{y}$, $u=U\bar{u}$, $v=V\bar{v}$, $\zeta=\xi\bar{\zeta}$, $D=\mathscr{D}\bar{D}$, then the scale analysis indicates

$$\frac{\mathscr{D}}{\xi}\sim\frac{l}{L}Re,$$

where L is the latitudinal scale, and l the longitudinal scale. This formula shows that the ratio between the order of magnitude of divergence and that of vorticity relates to L and l. Based on the work of Chao et al., we now carry out the scale analysis of the linearized equations of vorticity and divergence.

In order to investigate the basic characteristics of the wave motion of tropical large-scale planetary waves in their initial stage linked with precipitation, (Precipitation occurs either within some parts of such large-scale planetary waves or, such waves only provide smaller scale precipitation systems with developing background), we assume that the basic wind field V has little or no variation with y. (i.e., assume V to be constant or the order of $\partial V/\partial y$ to be smaller than that of $\partial V/\partial x$.) Let u', v' denote the disturbance velocity, then the terms related to earth's rotation in vorticity and divergence equations governing such tropical motions can be expressed by the following equations.

$$\frac{\partial}{\partial t}\left(\frac{\partial v'}{\partial x}\right)=\cdots\cdots\cdots -\beta y\frac{\partial u'}{\partial x}-\beta v' \tag{1}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial u'}{\partial x}\right)=\cdots\cdots\cdots -\beta y\frac{\partial v'}{\partial x}-\beta u'. \tag{2}$$

Supposing L, the wave motion's latitudinal scale, is longer by one order than L, the longitudinal scale, it follows that

$$\frac{\beta u'}{\beta y\dfrac{\partial v'}{\partial x}}=\frac{u'}{y\dfrac{\partial v'}{\partial x}}\sim\frac{u'}{y\dfrac{v'}{L}}\sim\frac{L}{y}=\frac{L}{l}>1. \tag{3}$$

Hence, in the divergence equation, the magnitude of term $f\dfrac{\partial v'}{\partial x}$ is smaller by one order than that of $\beta u'$ and can then be neglected.

Similarly, since

$$\frac{\beta v'}{\beta y\dfrac{\partial u'}{\partial x}}\sim\frac{v'}{y\dfrac{u'}{L}}\sim\frac{L}{y}\sim\frac{L}{l}>1, \tag{4}$$

hence, in vorticity equation, when u' and v' are of the same order of magnitude, term $f\partial u'/\partial x$ is smaller than term $\beta V'$ by one order and so can be neglected.

Thus it can be known that for a tropical large-scale synoptic system related to precipitation with L being greater than l by one order, the value of terms containing β is larger by one order than that of terms containing $f=\beta y$ in vorticity, and divergence equations, when the basic wind field shear is small. In other words, as compared with that in mid-latitudes, the value of terms containing f decreases distinctly as approaching the equator and is equal to zero at the equator. Contrarily, the value of terms containing β shows an increase in the equatorial zone. Therefore, in discussing tropical motion, terms containing βy in vorticity and divergence equations can be neglected in given conditions.

III. NON-VORTICIT* ROSSBY ATMOSPHERIC LONG WAVE

Sometimes the order of divergence is not necessarily smaller than that of vorticity when condensation occurs and develops into precipitation. Such atmospheric motion can be expressed by the following divergence equation:

$$\frac{dD}{dt}=-\beta u', \tag{5}$$

where $u'=\partial\varphi/\partial x$, $v'=\partial\varphi/\partial y$, φ is the velocity potential. Its linearized divergence equation is written as:

$$\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)\nabla\varphi+\beta\frac{\partial\varphi}{\partial x}=0. \tag{6}$$

We suppose $u'=0$ when the lateral boundary conditions are $y=\pm D/4$, in which D is the width of disturbance.

Let $\varphi=\tilde{\varphi}e^{ik(x-ct}$,

using lateral conditions we can obtain the wave velocity formula:

$$c=U-\beta/k^2+\left(\frac{2\pi n}{D}\right)^2, \tag{7}$$

where $lD/2=n\pi$, $n=0,1,2,\cdots,l$ is the wave number in y direction. Let $D\to\infty$, then

$$c=U-\beta/k^2. \tag{8}$$

This is completely uniform in form with the formula of Rossby long wave, but here the wave motion is caused by the variations of velocity potential function or divergence field, while the Rossby wave is caused by the variations of stream function or vorticity field. We call the atmospheric long wave caused by the variations of divergence field non-vorticit Rossby atmospheric long wave.

IV. LOW-LATITUDINAL NON-VORTICIT GRAVITY—ATMOSPHERIC LONG WAVE

Our work starts from the equation set governing low-latitudinal Kelvin wave (Holton, 1979).

$$\begin{cases}\dfrac{\partial u'}{\partial t}=-\dfrac{\partial\varphi'}{\partial x}\\[2mm]\beta yu'=-\dfrac{\partial\varphi'}{\partial y}\end{cases}$$

* Here non-vorticit means that the vertical component of vorticity in the atmosphere is equal to zero t mporally and spatially.

$$\begin{cases} \frac{\partial u'}{\partial x}+\left(\frac{\partial}{\partial z^*}-\frac{1}{H}\right)\omega=0 \\ \frac{\partial}{\partial t}\frac{\partial \varphi}{\partial z^*}+N^2\omega=0, \end{cases} \tag{9}$$

where $H=RT_0/g$, T_0 is the earth's mean temperature and

$$N^2=\frac{R}{H}\left(\frac{\partial T}{\partial z^*}+\frac{\chi T}{H}\right),\quad z^*=-H\ln(p/p_0).$$

By combining the vorticity equation derived from the first two equations with the last two equations in (9), the Kelvin wave can be inferred. Note that the characteristic of Kelvin wave motion is the east-west moving of the zone of convergence and divergence.

We now discuss the feature of such wave motion, starting from the divergence equation derived directly from the first two equations with term $\beta y\xi$ having been neglected, i.e.

$$\frac{\partial}{\partial t}\frac{\partial u'}{\partial x}+\frac{\partial^2\phi'}{\partial x^2}-\beta u'=0. \tag{10}$$

We assume here that $\partial^2\phi'/\partial y^2\equiv 0$, and then by eliminating ϕ', ω', using the last two equations in (9), we obtain

$$\left(\frac{\partial}{\partial z^*}-\frac{1}{H}\right)\frac{\partial}{\partial t^2}\frac{\partial}{\partial z}\frac{\partial u'}{\partial x}+\left(\frac{\partial}{\partial z^*}-\frac{1}{H}\right)\frac{\partial}{\partial t}\frac{\partial}{\partial z}\beta u'+N^2\frac{\partial^2}{\partial x^2}\frac{\partial u'}{\partial x}=0. \tag{11}$$

Let

$$u'=u(z)e^{i(kx-\nu t)}, \tag{12}$$

it follows that

$$\left(\frac{\partial}{\partial z^*}-\frac{1}{H}\right)\frac{\partial}{\partial z^*}u+\frac{N^2k^3}{\nu^2k+\gamma\beta}u=0. \tag{13}$$

Let

$$u(z)=e^{\frac{z^*}{2H}}u^*(z^*), \tag{14}$$

Eq. (13) can then be written as

$$\frac{\partial^2 u^{*2}}{\partial z^{*2}}+\left(\frac{k^3N^2}{\nu^2k+\gamma\beta}-\frac{1}{4H^2}\right)u^*=0. \tag{15}$$

Only when

$$\lambda^*=\frac{k^3N^2}{\nu^2k+\gamma\beta}-\frac{1}{4H^2}>0 \tag{16}$$

can the vertically-propagated wave motion be possible. Since such wave motion is

$$u^*(z^*)=A\sin\sqrt{\lambda^*}z^*+B\cos\sqrt{\lambda^*}z^*, \tag{17}$$

hence

$$u'=(A\sin\sqrt{\lambda^*}z^*+B\cos\sqrt{\lambda^*}z^*)\,e^{\frac{z^*}{2H}}e^{i(kx-\nu t)} \tag{18}$$

and its wave velocity formula can be written as

$$c=\frac{1}{2}\left(\frac{-\beta}{k^2}\pm\sqrt{\left(\frac{\beta}{k^2}\right)^2+4\frac{N^2}{\lambda^*+\frac{1}{4H^2}}}\right). \tag{19}$$

Because the vertical component of the vorticity governing the movement of such wave motion is nought, this wave motion is non-vorticit. Obviously, when $N^2=0$, it becomes Eq. (8), i.e., the non-vorticit Rossby atmospheric long wave.

In deriving the Kelvin wave (Wu, et al., 1983), the λ^* which corresponds to the λ in equation (16) is

$$\lambda=\frac{k^2N^2}{\nu^2}-\frac{1}{4H^2} \tag{20}$$

whereas

$$u'=(A\sin\sqrt{\lambda}\,z^*+B\cos\sqrt{\lambda}\,z^*)e^{\frac{z^*}{2H}}e^{-\frac{\beta y^2}{2\nu}}e^{i(kx-\nu t)}, \tag{21}$$

moreover,

$$c=\pm N\left(\lambda+\frac{1}{4H^2}\right)^{-\frac{1}{2}} \tag{22}$$

Notice that λ^* differs from λ in that there is an additional term $\beta(\nu/k)$ in the denominator of term of k^2N^2 value. In form, Eq. (19) is mixed waves of the gravity-atmospheric long wave type. (Notice that the relative vorticity is assumed to be zero in such wave motion.) When

$$4\frac{N^2}{\lambda^*+\frac{1}{4H^2}}\gg\left(\frac{\beta}{k^2}\right)^2$$

it exuviates into gravity inner wave essentially similar to Kelvin wave. They are both wave motions caused by the variation of distribution of convergence and diver gence in zonal current on the rotating earth with its Coriolis parameter f changing with latitudes. The main difference in the structure of the two waves is in their amplitudes. The amplitude of Kelvin wave shows a Gaussian distribution in y direction, so the wave motion is limited within the equatorial zone. The non-vorticit gravity-atmospheric long wave, however, has no such property. Besides, the Kelvin wave is strictly not non-vorticit wave. They are also different in the physical process of their forming. The process of $\beta u'$ and $\partial^2\phi'/\partial x^2$ brings divergence into local change, causing the gravity inner wave, as we called above, while the propagation of Kelvin wave is caused by the variation of divergence field which is brought about by the advection and local change of $\partial^2\phi/\partial z^2$ (in essence, the change of temperature field). The mutual adjustment between vorticity field and divergence field only makes the amplitude of Kelvin wave change in y direction, hence confining it within the equatorial zone.

V. TROPICAL ATMOSPHERIC WAVE MOTION WITH WEAKLY SHEARED ZONAL CURRENT

Tropical troposphere is principally dominated by easterly current, and the general horizontal shear $\partial\bar{U}/\partial y\neq 0$. When the order of magnitude of the shear $\bar{U}$ of basic flow $\partial\bar{U}/\partial y$ is smaller than that of $\partial v'/\partial x$, i.e., when $L\gg l$, as stated above, we can obtain the following linearized vorticity, divergence, as well as thermodynamical equation set in (x,y,p,t) coordinate system:

$$\begin{cases} \lambda_2\left(\frac{\partial}{\partial t}+\bar{u}(y)\frac{\partial}{\partial x}\right)\frac{\partial v'}{\partial x}+\frac{\partial \bar{U}}{\partial y}\frac{\partial u'}{\partial x}+\beta v'=0 \\ \lambda_1\left(\frac{\partial}{\partial t}+\bar{u}(y)\frac{\partial}{\partial x}\right)\frac{\partial u'}{\partial x}-\frac{\partial \bar{U}}{\partial y}\frac{\partial v'}{\partial x}+\frac{\partial^2\phi'}{\partial x^2}+\beta u'=0 \\ \frac{\partial u'}{\partial x}+\lambda_3\frac{\partial \omega'}{\partial p}=0 \\ \left(\frac{\partial}{\partial t}+\bar{u}(y)\frac{\partial}{\partial x}\right)\frac{\partial \phi'}{\partial p}+\frac{c_a^2}{p^2}\omega'=0. \end{cases} \tag{23}$$

Eliminating u', v', ϕ', from (23) leads to

$$\lambda_3\left(\frac{\partial}{\partial t}+\bar{u}\frac{\partial}{\partial x}\right)\frac{\partial^2}{\partial p^2}\left\{\left(\frac{\partial \bar{u}}{\partial y}\right)^2\frac{\partial^2}{\partial x^2}+\left[\lambda_1\left(\frac{\partial}{\partial t}+\bar{u}\frac{\partial}{\partial x}\right)\frac{\partial}{\partial x}+\beta\right]\right.$$
$$\left.\left[\lambda_2\left(\frac{\partial}{\partial t}+\bar{u}\frac{\partial}{\partial x}\right)\frac{\partial}{\partial x}-\beta\right]\right\}\omega'+c_a^2p^2\frac{\partial^3}{\partial x^3}\left[\lambda_2\left(\frac{\partial}{\partial t}+\bar{u}\frac{\partial}{\partial x}+\beta\right)\right]^{\omega'=0}, \tag{24}$$

where $c_a^2=\alpha R\bar{T}$, $\quad \alpha=\frac{R}{g}(\gamma_d-\gamma)$

Suppose the wave solution is

$$\omega'=\Omega(p)e^{ik(x-ct)} \tag{25}$$

and it is known from the boundary condition that

$$A=0, \tag{26}$$

thus

$$\Omega^*=B\sin m\xi, \tag{27}$$

where m is the wave number in vertical direction, showing that wave motion also occurs vertically. Thus we obtain

$$\lambda_1\lambda_2\lambda_3\left(m^2+\frac{1}{4}\right)k^4(c-\bar{u})^3+\lambda_3\beta k^2(\lambda_1-\lambda_2)\left(m^2+\frac{1}{4}\right)$$
$$(c-\bar{u})^2-\left[-\lambda_3\left(m^2+\frac{1}{4}\right)\beta^2+\left(m^2+\frac{1}{4}\right)\lambda_3\left(\frac{\partial \bar{U}}{\partial y}\right)^2k^2\right.$$
$$\left.+\lambda_2c_a^2k^4\right)\Big](c-\bar{u})-k^2\beta c_a^2=0. \tag{28}$$

Our approach to the problem here agrees with that of Yang Dasheng et al. (1980).

1. *Tropical Atmospheric Gravity Inner Wave*

When $c-\bar{U}\gg\beta/k^2$ and β/k^2 is smaller than $c_a^2/\left(m^2+\frac{1}{4}\right)$ from Eq. (28) we know that

$$c=\bar{U}\pm\sqrt{\left(\frac{1}{k}\frac{\partial \bar{U}}{\partial y}\right)^2+c_a^2/\left(m^2+\frac{1}{4}\right)}. \tag{29}$$

This is the atmospheric gravity inner wave having both basic flow and horizontal shear. The wave velocity formula of such gravity inner wave will become the same as that of Kelvin wave in essence if it has no basic flow. This is the atmospheric gravity wave with variations of both vorticity and divergence. It can exist only when its wave-length is relatively short. Such west-moving atmospheric gravity wave with its basic flow having shear and with its wave-length being short is likely to be the easterly wave.

It should be noted that when $\lambda_2=0$, Eq. (29) can also be obtained by supposing $c_a^2/(m^2+\frac{1}{4})\gg\beta/k^2$, which indicates that it is the divergence field, rather than the vorticity field, that determines the developing property of the atmospheric gravity wave—easterly wave motion in tropical easterlies. It is for this reason that the easterly wave is often followed by relatively strong precipitation weather.

2. *Tropical Atmospheric-Gravity Long Wave*

There is another type of fast wave with $\beta/k^2\gg c_a^2/(m^2+1/4)$ in the tropical area. Neglecting the term containing c_a^2 from Eq. (28), it follows that

$$k^4(c-\bar{U})^2+2\beta k^2(c-\bar{U})-\left(-\beta^2+\left(\frac{\partial\bar{U}}{\partial y}\right)^2k^2\right)=0$$

i.e.,

$$(c-\bar{U})^2+2\beta/k^2(c-\bar{U})+\left[(\beta/k^2)^2-\left(\frac{\partial\bar{U}}{\partial y}\right)^2\Big/k^2\right]=0$$

$$\left(c-\bar{U}+\frac{\beta}{k^2}\right)=\pm\frac{\partial\bar{U}/\partial y}{k} \tag{30}$$

$$\therefore \qquad c-\bar{U}=-\frac{\beta}{k^2}\pm\frac{\partial\bar{U}}{\partial y}\Big/k.$$

Assuming that the basic flow has no shear, we obtain the atmospheric long wave formula

$$c=\bar{U}-\beta/k^2, \tag{31}$$

which can also be obtained by neglecting the third and fourth terms from Eq. (28). This shows that in tropics, atmospheric long wave is in the category of fast wave, too, though its moving speed is actually equal to the wave velocity of mid-latitude atmospheric long wave. Of course, such atmospheric long wave is basically west-moving, the larger the shear of basic flow (when $\partial\bar{U}/\partial y>0$), the higher the west-moving speed of the easterly wave.

VI. TROPICAL ULTRALONG WAVE

Neglecting the first two terms from Eq. (28), we obtain the wave velocity equation of the slow wave governing tropical atmospheric wave motion:

$$\left[(\beta/k^2)^2-\left(\frac{1}{k}\frac{\partial\bar{U}}{\partial y}\right)^2-\frac{c_a^2}{\left(m^2+\frac{1}{4}\right)}\right](c-\bar{U})-\frac{\beta}{k^2}\frac{c_a^2}{\left(m^2+\frac{1}{4}\right)}=0, \tag{32}$$

i.e.,

$$c=\bar{U}+\frac{c_a^2/\left(m^2+\frac{1}{4}\right)}{(\beta/k^2)^2-\left(\frac{1}{k}\frac{\partial\bar{U}}{\partial y}\right)^2-\frac{c_a^2}{m^2+\frac{1}{4}}}\beta/k^2. \tag{33}$$

This is the wave motion caused by the common action of terms $\beta u'$ and $\beta v'$ containing in the vorticity and divergence equations and other dynamic factors. It is also the wave motion whose velocity changes only when the large-scale temperature field changes while $\partial\bar{U}/\partial y$ keeps constant. It is gravity-atmospheric long wave, too. During the wave motion course the atmospheric movement basically keeps its balance, while the action of $\beta u'$ makes the divergence change.

Within the low-latitudinal large-scale domain, the velocity of Kelvin wave c_a is about 25 m/s. As for the wave motion shown in Eq. (33), we suppose that its velocity is smaller than that of Kelvin wave by one order, i.e., about 3 m/s. because it is slow wave. In other words, the gravity-atmospheric long wave moves only about 100 km a day. To draw a distinction, we call the wave motion shown in Eq. (33) gravity-atmospheric long wave (slow wave).

Though large-scale stationary waves are generally thought impossible in low-latitudinal easterlies, they can emerge when the wave number of atmospheric long wave is small enough, as far as ultralong wave system and gravity-atmospheric long wave (slow wave) are concerned. e.g., supposing that the wave number $k=4$, β/k^2 is 57 m/s at 5°N, and assuming $\partial\bar{U}/\partial y=0$, $c_a^2/(m^2+1/4)$ is about 25 m/s, it follows that:

$$|v_{crI}|=\frac{c_a^2\Big/\left(m^2+\frac{1}{4}\right)}{\left(\frac{\beta}{k^2}\right)^2-\frac{c_a^2}{\left(m^2+\frac{1}{4}\right)}}\beta/k^2=\frac{(25)^2}{(57)^2-(25)^2}\times 57=13(m/s), \tag{34}$$

i.e., stationary wave can appear when the easterly wind velocity is 13 m/s. The existing of stationary wave relates to the fact that the denominator in Eq. (33) contains term $(\beta/k^2)^2$, in other words, to the fact that the vorticity and divergence equations contain terms βu and βv which are related to the rotation of the earth.

Next we discuss the structure of stationary wave in the non-vorticit gravity-atmospheric long wave (slow wave) in easterlies.

Given: $u'=u(p)e^{ik(x-ct)}$

it follows that

$$\frac{\partial u'}{\partial x}=iku(p)e^{ik(x-ct)}$$

$$\frac{\partial \omega'}{\partial p}\cong\frac{\partial w}{\partial z}=-\frac{\partial u'}{\partial x}=-iku(p)e^{ik(x-ct)}$$

$$v'=\frac{-\frac{\partial\bar{U}}{\partial y}ik}{\beta+k^2|\bar{U}|}u(p)e^{ik(x-ct)}$$

$$\frac{\partial v'}{\partial x}=\frac{k^2\frac{\partial\bar{U}}{\partial y}}{\beta+k^2|\bar{U}|}u(p)e^{ik(x-ct)}$$

$$\phi'=\frac{1}{k^2}\left[\frac{(k^2|\bar{U}|+\beta)^2-k^2\frac{\partial\bar{U}}{\partial y}}{k^2|\bar{U}|+\beta}\right]u(p)e^{ik(x-ct)}$$

$$\theta' = -\frac{1}{F}\frac{\partial \phi'}{\partial p} = -\frac{1}{F}\frac{1}{k^2}\left[\frac{(k^2|U|+\beta)^2 - k^2\dfrac{\partial \bar{U}}{\partial y}}{k^2|\bar{U}|+\beta}\right] \times \frac{\partial U(p)}{\partial p} e^{ik(x-ct)}, \tag{35}$$

where $F = R/p \times (p/p_0)^{R/c_p} > 0$. Assuming $\partial\bar{U}/\partial y < 0$, $-\partial\bar{U}(p)/\partial p > 0$, then we can obtain the schematic view of wave motion shown in Fig. 2.

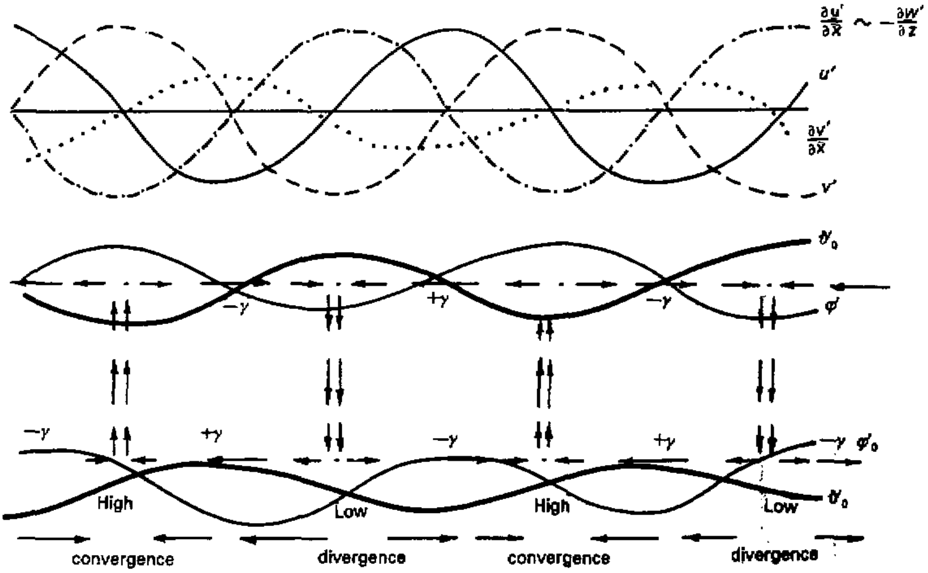

Fig. 2. Schematic view of the stationary structure of gravity-atmospheric long wave acting as slow wave.

The following characteristics of the wave motion are shown in Fig. 2:

(1) Such wave motion has a three-dimensional structure and its most evident feature is the wave-shaped distribution of its velocity convergence and divergence.

(2) The center of convergence and divergence does not coincide with that of vorticity and they are out of phase by $\pi/2$.

(3) The structure of temperature-pressure field in lower troposphere is basically of the warm-low and cold-high type. (Assuming $-\partial\bar{U}(p)/\partial p < 0$, then the amplitude of u' wave decreases as the height increases.)

(4) The velocity convergence and divergence zones do not coincide with high and low pressure zones, with their difference being $\pi/2$. too. In high pressure area it is the velocity divergence and descending movement.

In terms of the characteristics of the wave motion structure stated above, we can consider that such large-scale wave motion of gravity-atmospheric long wave (slow wave) is nothing but Walker Circulation. When stratification changes evidently, distinct east-west moving of the gravity-atmospheric long wave (slow wave) occurs. This agrees with the observational fact that Walker Circulation changes when El Nino occurs.

VII. SUMMARY AND CONCLUSIONS

In summary, we have the following conclusions:

(1) In tropical area, the action of earth's rotation on vorticity (divergence) variation is shown in the two terms of βyD and βv ($\beta y\xi$ and $\beta u'$). In the linearized vorticity (divergence) equation, βyD ($\beta y\xi$) is smaller than βv (βu) by one order and can then be neglected. In fact, the nearer it gets to the equator, the smaller the terms of βyD and $\beta y\xi$ become, and they equal zero at the equator. On the contrary, terms βu and βv show an increase there. So terms βyD and $\beta y\xi$ can be neglected when approaching the equator. Our discussion of the wave motion in tropical atmosphere is based on the equations of divergence and vorticity which only contains terms βu and βv, combined with equations of thermodynamics etc.

(2) In the atmosphere there exists the non-vorticit planetary wave (The vertical component of relative vorticity constant is nought during the process of such wave motion.) whose wave velocity formula is the same as that of Rossby wave (The divergence constant is nought during the process of such wave motion.). Just as Rossby wave, non-vorticit planetary wave is also purely idealized wave motion. For in the atmosphere actually existing on the earth, divergence will certainly occur once vorticity occurs and vice versa. But the study of purely theoretical wave motion will help us understand the complex atmospheric movement. In fact, it can be inferred theoretically that there exists non-vorticit gravity-atmospheric long wave at the equator. The Kelvin wave is essentially non-vorticit gravity-atmospheric long wave with its β/k^2 value being relatively small.

(3) In tropical area, there are three large-scale wave motions: Kelvin wave, tropical atmospheric long wave and tropical ultralong wave.

Tropical fast waves, their wave length being relatively short and their moving speed comparatively fast, are wave motions which occur when both local and advective changes of divergence and vorticity occur. It is a kind of gravity-atmospheric long wave. When term β/k^2 is relatively small, the non-vorticit gravity-atmospheric long wave is approximate to Kelvin wave. They are both relevant wave motions caused by the east-west moving of the zone of velocity convergence and divergence. The Kelvin waves are large-scale fast waves which appear in the tropics.

The tropical atmospheric long wave is also a kind of fast wave, though its speed and that of the mid-latitudinal atmospheric long wave are in the same order of magnitude. At least one branch of such waves propagates westward.

Tropical ultralong waves are extremely slow-moving gravity-atmospheric long waves. This is the large-scale wave motion, acted upon by β effect, determined by such special properties as atmospheric stratification. Stationary waves do not appear easily in easterlies, but such ultralong wave may show stationary wave in easterlies. Its east-west moving is very slow, only 100 km per day. According to the computation in terms of the fact that its period is greater by one order than Kelvin, its period is 60 days. Judging by its structure and property, such wave motion is probably the Walker Circulation. When the distribution of tropical sea surface thermodynamical property changes, e.g., when El Nino phenomenon occurs, the change of atmospheric stratification will occur, thus bringing new change to the structure of such ultralong wave. Moreover, relatively evident east-west moving of such wave motion occurs.

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