NOTES AND CORRESPONDENCE

The Linear Response of a Slowly-Rotating Atmosphere to Mobile Heating

By Yoshihisa Matsuda

Department of Earth and Planetary Physics, University of Tokyo, Tokyo, 113 Japan

(Manuscript received 14 March 1995, in revised form 25 October 1995)

Abstract

The three-dimensional response of a slowly-rotating atmosphere to mobile heating is investigated by using linearized primitive equations. The primitive equations are separated into the horizontal and vertical structure equations. The Hough functions are used in the numerical treatment of the horizontal equations.

The velocity of planetary rotation and that of solar heating are fixed at the values for Venus. The responses are obtained for various values of the atmospheric stability and damping rate. For the large damping rate, a direct circulation between the day and night sides is obtained, while for small damping rates the zonal winds predominate and the geostrophic relation is established in the extratropics.

1. Introduction

The response of an atmosphere to heating is an important problem in dynamic meteorology. This problem has been studied by many authors, e.g. Hoskins and Karoly (1981), Gill (1980), Kasahara (1984) and Matsuda and Kato (1987). These authors have treated the linear response induced by stationary heating. As an extension of the problem, Kato and Matsuda (1994) (hereafter referred to as KM) examined the response induced by mobile heating; KM investigated the horizontal structure of the circulation induced by mobile heating by using the linearized shallow water equations on the sphere. Their system involves three external parameters, i.e. velocity of planetary rotation, that of the heat source, and the damping rate. Numerical solutions for a wide range of these parameter values are obtained and classified into four types: a direct circulation between the day and night sides, a "Gill pattern"-like circulation, a zonally uniform circulation and a circulation characterized by the resonance of an inertia-gravity wave. They examined the dependency of the type of circulation on the three parameters in detail.

However, KM is restricted to the examination of the horizontal structure of the atmospheric response, since the shallow water equations are used in KM. In the present study we will extend our examination to the three-dimensional structure of the atmospheric response to mobile heating. A theoretical interest in the extension of KM is the first motivation of the present study.

The second motivation of the present study is an application to the study of the circulation in a slowly-rotating atmosphere. In our solar system, Venus is a unique slowly-rotating planet. In contrast to the fast zonal wind observed in the Venusian stratosphere, little is known about the wind distribution near the surface, except that there is a very weak wind (~a few m/s). From the extremely long periods of planetary rotation (243 days) and solar day (117 days) of Venus, one may predict that a quasi-steady direct circulation between the subsolar and antisolar points predominates in all atmospheric layers on Venus. The fast zonal wind contradicts this prediction. However, this fast wind is considered to be an exceptional phenomenon maintained by a special mechanism. The prediction may therefore be applied to the atmosphere near the surface. However, even if a special mechanism does not work in the atmosphere near the surface, this prediction is not necessarily justified for the following reasons. Observed winds are very weak near the surface, so that the Rossby number may be small in spite of the slow planetary rotation; the geostrophic balance may be established. In addition, the thermal re-
response time of the lower dense atmosphere of Venus is very large due to its enormous mass, so that one solar day of Venus (117 days) is small in comparison with this response time. Hence, the prediction of the quasi-steady direct circulation between the subsolar and antisolar points is doubtful. In other words, we cannot predict the type of circulation from speculation only.

Evidently, our linear model which is described in the next section is too simple to be a simulation model of the real Venus atmosphere. In order to simulate the atmospheric circulation, it is necessary to include the non-linearity and various processes neglected in our model. Hence, it is difficult to directly apply the results obtained from our model to the real Venusian atmosphere; our result should be regarded as a prediction as to an imaginary atmosphere on a slowly-rotating planet rather than on Venus, although some parameters in our model are fixed to the values of Venus. However, as the first step toward more realistic models of the circulation of the Venusian lower atmosphere, it is useful to examine the linear response of the three-dimensional atmosphere to mobile heating by our simple model.1

In our treatment the three-dimensional structure of the atmospheric response is expressed as a superposition of solutions of the shallow water equations (see below). Since these solutions have been already obtained for various parameter values in KM, we will restrict our calculation to the parameters relevant to the Venusian atmosphere. The period of solar day and that of planetary rotation for Venus are precisely known, though the stability of the lower atmosphere is not exactly known from observations (see below). Further, it is difficult to determine the parameter value representing the damping processes in the Venusian lower atmosphere. Hence, in this study we fix the value of the period of solar day and that of planetary rotation at the values of Venus, while the atmospheric stability and damping rate are treated as variable parameters.

The presentation of this study is organized as follows. Section 2 describes the model used in this study and the procedures for obtaining numerical solutions. In Section 3, the results obtained in our calculations are presented. Concluding remarks are given in the final section.

1 Some numerical experiments have been already conducted (e.g., Safray, 1977; Del Genio et al., 1993). However, the parameter values, such as the atmospheric stability or dynamical and thermal damping rate cannot be exactly known, since the observations so far made on the lower atmosphere of Venus are so limited. Hence, we cannot easily determine the type of the lower circulation from numerical experiments conducted with uniquely determined parameter values.

2. Model

In this study we adopt the frame of reference which moves with a mobile heat source. We will be concerned with solutions which are steady for this frame of reference. Then, the linearized primitive equations on the sphere in log p coordinate are written as follows.

\[
\begin{aligned}
\frac{\partial u}{\partial t} - \omega \frac{\partial u}{\partial \lambda} - 2\Omega \cos \theta v + \frac{1}{a \sin \theta} \frac{\partial \phi}{\partial \lambda} &= -\alpha u \\
\frac{\partial v}{\partial t} - \omega \frac{\partial v}{\partial \lambda} + 2\Omega \cos \theta u - \frac{1}{a} \frac{\partial \phi}{\partial \theta} &= -\alpha v \\
\frac{1}{a \sin \theta} \frac{\partial u}{\partial \lambda} + \frac{1}{a \sin \theta} \frac{\partial (-\sin \theta v)}{\partial \theta} + e^{z/H} \frac{\partial}{\partial z} \left( e^{-z/H} w \right) &= 0 \\
\frac{\partial (\partial \phi/\partial z)}{\partial t} - \omega \frac{\partial \phi/\partial z}{\partial \lambda} + N^2 w &= \frac{R Q}{H c_p} - c \frac{\partial \phi}{\partial z}
\end{aligned}
\]  

(1)

Here, \( \phi \) is the perturbation of geopotential; \( t \) is the time; \( \theta \) is the co-latitude and \( \lambda \) is the longitude; \( a \) is the radius of planet; \( \Omega \) is the angular velocity of planetary rotation; \( \omega \) is that of mobile heat source; \( Q \) is the heating and cooling distribution; \( R \) is the gas constant; \( H \) is the scale height at the surface; \( c_p \) is the specific heat at constant pressure; \( \alpha \) is the Rayleigh friction rate; \( c \) is the Newtonian cooling rate; \( z = -H \ln(p/p_s) \), where \( p/p_s \) is the pressure (at the surface); \( u \) and \( v \) are the eastward and northward component of horizontal velocity, respectively; \( w = dz/dt \); \( N^2 = (T/T_0)^2 N_0^2 \), where \( T(T_0) \) is the temperature (at the surface), and \( N_0 \) is the Brunt-Väisälä frequency.

In this study, we obtain the three-dimensional atmospheric response to thermal forcing by the same procedure as Kasahara (1984). First, we expand \( u \), \( v \) and \( \phi \) as follows.

\[
\begin{aligned}
u &= \sum_n U_n(\lambda, \theta, t)G_n(z) \exp(z/2H) \\
v &= \sum_n V_n(\lambda, \theta, t)G_n(z) \exp(z/2H) \\
\phi &= \sum_n \Phi_n(\lambda, \theta, t)G_n(z) \exp(z/2H)
\end{aligned}
\]  

(2)

where \( G_n(z) \) is the eigenfunction of the vertical structure equation:

\[
\frac{d^2 G_n}{dz^2} - \frac{1}{4H^2} G_n + N^2 \frac{d}{dz} \left( \frac{1}{N^2} \right) \left( \frac{dG_n}{dz} + \frac{1}{2H} G_n \right) = -N^2 G_n. 
\]  

(3)

Here \( h_n \) is the equivalent depth, which is the eigenvalue of this equation. Then, \( U_n, V_n \) and \( \Phi_n \) satisfy the shallow water equations:
\[
\frac{\partial U_n}{\partial t} - \omega \frac{\partial U_n}{\partial \lambda} + 2\Omega \cos \theta V_n + \frac{1}{a \sin \theta} \frac{\partial P_n}{\partial \theta} - \alpha U_n \\
\frac{\partial V_n}{\partial t} - \omega \frac{\partial V_n}{\partial \lambda} + 2\Omega \cos \theta U_n + \frac{1}{a \sin \theta} \frac{\partial P_n}{\partial \theta} = -\alpha V_n \\
\frac{\partial \Phi_n(g_n)}{\partial t} - \omega \frac{\partial \Phi_n(g_n)}{\partial \lambda} + \left\{ \frac{1}{a \sin \theta} \frac{\partial U_n}{\partial \lambda} + \frac{1}{a \sin \theta} \frac{\partial (\sin \theta V_n)}{\partial \theta} \right\} = -c(\Phi_n/g_n) + q_n 
\]

(4)

Here

\[
q_n(\lambda, \theta) = \frac{R}{H} \int_0^D e^{z/2H} \frac{\partial}{\partial z} \left( \frac{e^{-z/2H} Q(\lambda, \theta, z)}{N^2c_p} \right) G_n(z) dz \\
\int_0^D (G_n(z))^2 dz, 
\]

(5)

where \(D\) is a depth of the atmospheric layer under consideration. For simplicity, we assume that \(N\) is constant. We adopt the boundary condition that \(w\) vanishes at the upper and lower boundary; this condition is written as

\[
\frac{dG_n}{dz} + \frac{1}{2H} G_n = 0 \quad \text{at } z = 0 \text{ and } D. 
\]

(6)

For constant \(N\), the eigensolutions and eigenvalues of Equation (3) with the boundary condition (6) are readily obtained as

\[
G_n(z) = \sin(n\pi z/D - \theta_n), \\
h_n = \frac{N^2H^2/g}{(n\pi)^2(H/D)^2 + 1/4},
\]

(7)

where

\[
\theta_n = \tan^{-1}(2n\pi H/D).
\]

In this study, we assume

\[
Q(\lambda, \theta, z) = Q_0(z)Q_1(\lambda, \theta).
\]

(8)

For \(Q_1(\lambda, \theta)\), we adopt the same distribution as in KM:

\[
Q_1(\lambda, \theta) = \left\{ \begin{array}{ll}
Q_{in} \sin \theta \cos \lambda - Q_{out} & \text{for } |\lambda| \leq \pi/2, \\
-Q_{out} & \text{for } |\lambda| > \pi/2,
\end{array} \right.
\]

(9)

where \(Q_{out} = Q_{in}/4\) from the condition that net heating and cooling vanish. Note that \(\int_{-\pi}^{\pi} Q_1(\lambda, \theta) d\lambda\) is positive (negative) for the equatorial (polar) region. The vertical distribution of heating function we adopt is \(Q_0(z) = \sin(z/D)\), which attains its maximum value at the mid-level.

The practical procedure for the numerical calculations is as follows. Substituting (7) and (8) into (5), we obtain \(q_n\). The Equations (4) (with this \(q_n\)) are the shallow water equations describing the horizontal flow induced by mobile heating. We can obtain the numerical steady solutions in much the same way as KM, where the Hough functions are used. (See KM or Matsuda and Kato (1987) for the procedure for obtaining the numerical solutions.) Substituting \(U_n, V_n\) and \(\Phi_n\) obtained for each value of \(n\) into (2), finally we obtain the three-dimensional distribution of \(u, v\) and \(\phi\).

It should be noted that for constant \(N\), \(G_0 = \exp[-z/2H]\) and \(h_0 = \infty\) are an eigensolution and an eigenvalue of (3) with the boundary condition (6), respectively; these are an external mode and its equivalent depth. Since we adopt \(Q_0(z) = \sin(z/D)\), \(Q(\lambda, \theta, z) = 0\) is obtained at \(z = 0\) and \(D\). From this condition at the boundaries, (5) gives \(q_0(\lambda, \theta) = 0\) for this external mode for constant \(N\). Hence, the external mode cannot be induced directly by thermal forcing in our calculations with constant \(N\). However, in more realistic cases \(N\) is not constant. Then, the external mode can be induced by thermal forcing. Even in this case, since \(\exp[z/2H/G_0(z)]\) is weakly dependent on \(z\) for the external mode, it is difficult that \(q_0\) has a large value. In fact, Kasahara and Silva Dias (1986) have shown that the response of the external mode to thermal forcing is small without the vertical shear of the basic zonal flow. For the excitation of the external mode, it is more important to consider effects which are not involved in this study (such as the effect of vertical shear of the basic flow). In a word, the exclusion of the external mode in this study is not so misleading, as long as, as in this study, we are concerned with the circulation directly induced by heating.

3. Results

As described in the introduction, the present model is not a simulation model of the Venusian atmosphere. However, for definiteness, some parameter values are fixed to those of Venus. The angular frequency of planetary rotation (\(Q\)) and that of mobile heating (\(\omega\)) are fixed at the values of Venus: \(2\pi/\Omega = 243\) days and \(2\pi/\omega = 117\) days. Since the temperature lapse rate of the Venusian atmosphere below 13 km has not been observed by Pioneer Venus probes, we adopt the stability data derived from Veneras 10, 11 and 12 (Seiff, 1983): \(dT/dz = 0.3\) K/km i.e. \(N^2 = 3.8 \times 10^{-6}/s^2\) is assumed as the standard value. It does not appear that this value of \(N^2\) is firmly established, so that we have obtained the numerical solutions for \(N^2 = 3.8 \times 10^{-7}/s^2\) and \(N^2 = 3.8 \times 10^{-5}/s^2\) also. In our study, the Rayleigh friction (\(\alpha\)) and Newtonian cooling (\(c\)) are involved in order to represent the dynamical and thermal damping effects in the atmosphere. It is very difficult to determine uniquely the values which represent appropriately these effects in the Venusian lower atmosphere. In this study, \(\alpha = c\) is assumed for simplicity; and tentatively we have adopted the values \(\alpha = 1/2500\)
In Fig. 1 we present the results for the case $N^2 = 3.8 \times 10^{-6}/s^2$ (standard value) and $D = 15$ km. For $\alpha = 1/(25$ days), together with the horizontal velocity field, the height and divergence fields at the upper level ($z = 3/4D$) are shown in Fig. 1a and 1b, respectively. The horizontal velocity, height and divergence fields at the lower level ($z = 1/4D$) (not shown) are almost the same as those at the upper level but of opposite sign. Together with flow patterns in the vertical section (not shown), these results indicate that in this case a direct circulation between the day and night sides is induced by mobile heating. In KM the direct circulation between the day and night sides is obtained as a solution when the motion of heat source is slow and the damping rate is large. This condition is satisfied for the case depicted in Fig. 1.

In Fig. 2 the results for $\alpha = 1/(250$ days) are presented. The flow pattern is modified from the direct circulation between the day and night sides and 1b, respectively.

Note that the relaxation time of the radiative process of the lower atmosphere of Venus, i.e. ratio of heat capacity of the Venus atmosphere to the solar energy absorbed by (the surface of) Venus, is $1000-10000$ days.

With these values of $N^2$ and $D$, eq. (7) gives $h_1 = 9.5$ m, $h_2 = 2.4$ m, $h_3 = 1.1$ m, and so on.
in Fig. 1. The flow pattern in the vertical section on the equator (not shown) indicates that a direct circulation between the day and night sides is predominant in the equatorial region for this case also, while in the extratropics westerly (easterly) winds are predominant at the upper (lower) level. Figure 2a shows not only a gradient of the pressure perturbation between the day and night sides in the equatorial region, but also a gradient between the polar and equatorial regions. The distribution of the perturbed pressure field at the lower level is similar to, but of opposite sign to, that at the upper level. It should be noted that there is a tendency toward the geostrophic relation between the almost zonally uniform height field and zonal winds in high latitudes.

Figure 2b shows that the pattern of the divergence field for $\alpha = 1/(250 \text{ days})$ is the same as that for $\alpha = 1/(25 \text{ days})$.

In Figs. 3 and 4 the results for $\alpha = 1/(2500 \text{ days})$ are shown. It is found that the westerly winds predominate except for the region near the equator, and the geostrophic relation between these westerly winds and the height field is established. On the other hand, Fig. 4a shows that the direct circulation between the day and night sides holds on the equator; this direct circulation cell has approximately an east-west symmetry. The flow field in the vertical section at the latitude 45° is presented in Fig. 4b. This figure indicates the relation between the predominant zonal winds and the direct circulation cell in the extratropics. The flow pattern in the middle layers is reminiscent of the eastern branch of the direct circulation cell. The upper part of this branch continues to the westerly winds in the upper layer and its lower part continues to the easterly winds in the lower layer. The western branch of the direct cell disappears. In contrast to the velocity and height field, the divergence field for $\alpha = 1/(2500 \text{ days})$ remains the same as that for $\alpha = 1/(25 \text{ days})$ or $\alpha = 1/(250 \text{ days})$. This fact suggests that the
thermal balance, \( N^2w \sim (R/H)Q/c_p \), holds in the last equation in (1) for all values of \( \alpha \) adopted in this study (see below).

As described above, we have obtained the result that winds in the extratropics are zonally uniform and geostrophic for \( \alpha = 1/(2500 \text{ days}) \). This result can be explained as follows. In our linear theory the velocity field is expressed as a superposition of the waves (Hough functions) excited by heating. The amplitude of the excited wave is proportional to \( 1/((\omega_k - \omega_q) + i\alpha) \), where \( \omega_k \) and \( \omega_q \) are the eigenfrequency of the wave and that of the heat source, respectively. If \( \alpha \) is small, this amplitude strongly depends on \( \omega_k - \omega_q \). For \( s = 0 \), the eigenfrequency of the wave corresponding to the geostrophic mode (Rossby wave) is zero, while that of inertio-gravity wave is not zero (Longuet-Higgins, 1968). Since \( \omega_q = 0 \) for \( s = 0 \), the wave corresponding to the geostrophic mode of \( s = 0 \) predominates over the wave of \( s \neq 0 \) and the inertio-gravity wave of \( s = 0 \), if the resonance \( (\omega_k = \omega_q \neq 0) \) does not occur. Hence, for small \( \alpha \) the velocity field has a tendency to be zonally uniform and geostrophic.\(^4\)

We have obtained numerical solutions for \( N^2 = 10 \times \text{(standard value)} \) and \( N^2 = 1/10 \times \text{(standard value)} \), also. The circulation patterns obtained are almost independent of the value of \( N^2 \), although the magnitude of the circulation strongly depends on \( N^2 \). The dependency of the maximum velocity on the value of \( \alpha \) and \( N^2 \) is shown in Table 1. Since we treat only a linear theory in this study,

\(^4\) One of reviewers kindly suggests a different explanation of the predominance of the zonal wind in the extratropics as follows. When \( \alpha \) is small, for \( s = 0 \) we obtain \( w \approx (R/N^2H)Q/c_p \). From the equation of continuity, this vertical motion means the meridional circulation. Then, in the equation of motion in the zonal direction, the Coriolis force acting on this meridional circulation can be balanced only by the Rayleigh friction: \( u \approx 2\Omega \cos \theta v/\alpha \). Since \( w \) and \( v \) do not depend on \( \alpha \), \( u \) becomes large for small \( \alpha \).
the magnitude of the circulation is simply proportional to that of the forcing (heating) term. The values shown in Table 1 are results for \( Q_{\text{in}}/c_p = 1.6 \times 10^{-3} \) K/day.\(^5\) Table 1 shows that the maximum vertical velocity is almost independent of \( \alpha \) when \( N^2 = \text{(standard value)} \) or \( N^2 = \text{(standard value)} \times 10 \). For \( N^2 = \text{(standard value)} \times 1/10 \) also, the dependency of the maximum vertical velocity on \( \alpha \) is not strong. In fact, a simple estimation shows that \( N^2 w = (R/H)Q/c_p \) holds almost always in the equation of thermodynamics; hence in the thermal balance the effects of the motion of heat source and Newtonian cooling are almost negligible for the parameter range examined in this study.

Further, Table 1 shows that, unlike the vertical velocity, the maximum horizontal velocity is sensitive to \( \alpha \). Hence, the type of dynamic balance in the equations of motion also depends on \( \alpha \). For large \( \alpha \), Rayleigh friction terms are important and the magnitude of the horizontal velocity is reduced. For small \( \alpha \), the geostrophic balance is established (in the extratropics) in the equations of motion and the horizontal velocity is large.\(^6\)

In the rest of this section we re-examine the results obtained above in connection with KM. When \( \alpha \) (damping rate) is large, the direct circulation is

---

Table 1. Maximum horizontal velocities (m/s) for \( Q/c_p = 1.6 \times 10^{-3} \) K/day. Numerical values in parentheses are maximum vertical velocities (m/s).

<table>
<thead>
<tr>
<th>( N^2 ) ( \alpha )</th>
<th>standard value × 10</th>
<th>standard value</th>
<th>standard value × 1/10</th>
</tr>
</thead>
<tbody>
<tr>
<td>large</td>
<td>( 0.0027 (4.7 \times 10^{-6}) )</td>
<td>( 0.027 (4.7 \times 10^{-8}) )</td>
<td>( 0.20 (3.87 \times 10^{-4}) )</td>
</tr>
<tr>
<td>medium</td>
<td>( 0.0056 (4.7 \times 10^{-6}) )</td>
<td>( 0.057 (5.0 \times 10^{-8}) )</td>
<td>( 0.84 (1.7 \times 10^{-3}) )</td>
</tr>
<tr>
<td>small</td>
<td>( 0.032 (4.7 \times 10^{-6}) )</td>
<td>( 0.33 (5.0 \times 10^{-8}) )</td>
<td>( 3.3 (2.3 \times 10^{-3}) )</td>
</tr>
</tbody>
</table>

---

\(5\) This value of \( Q_{\text{in}} \) is derived from the fact that 2.5% of the total solar energy incident on Venus is absorbed at the surface (Tomasko et al., 1980). We can consider that this amount of solar energy forms an energy source of the general circulation in the lower atmosphere.

\(6\) We have obtained the solutions for \( D = 30 \) km, also. The results are similar to those for \( D = 15 \) km, so that we will omit its presentation.
tained as an atmospheric response for slowly mobile heating in this study. This result agrees with KM, since the direct circulation appears in KM when $\alpha$ is large and the motion of mobile heating is slow. However, according to KM, "Gill pattern"-like circulation appears when $\alpha$ becomes small, while the circulation of this type is not found in the present study. The reason is as follows. Figure 9 of KM shows that the extent of "Gill pattern"-like circulation in the régime diagram is diminished with a decrease of Lamb parameter $\varepsilon = 4a^2\Omega^2/gh$, where $h$ is an equivalent depth); "Gill pattern"-like circulation is peculiar to large $\varepsilon$. If $h$ of the first baroclinic mode is determined from (7) with $n = 1$, the corresponding value of $\varepsilon$ is 0.16; this value is less than $\varepsilon = 1$ in Fig. 9a of KM. Then it is probable that "Gill-pattern"-like circulation is not found in this study.

Dimensionless $\dot{\alpha} = \alpha(a/\sqrt{gh})$ is 0.03 and 0.003, for $\alpha = 1/(250 \text{ days})$ and $1/(2500 \text{ days})$, respectively. As seen in Fig. 9 of KM, calculations have not been conducted for such small values of $\dot{\alpha}$ in KM. The results in the present study show that the zonally-uniform circulation appears for $\alpha = 1/(2500 \text{ days})$, even if both the planetary rotation and motion of heat source are slow. The reason for this is described above. It should be emphasized that the zonally-uniform circulations obtained in KM result from the fast motion of the heat source.

4. Concluding remarks

In this study we examine the circulation induced by mobile heating for the slowly rotating atmosphere in the framework of linear theory. For all cases examined in this study, the vertical heat transport by vertical motion ($N^2w$) is almost balanced with heating in the thermodynamic equation; the zonal advection term due to the motion of the heat source (i.e., $\frac{\partial w}{\partial x}$ in the thermodynamic equation of (1)) is negligible. For large damping rates, we have obtained the direct circulation between the day and night sides. For small damping rates, zonally uniform winds predominate and the geostrophic balance is established in the extratropics; in this case the dynamic effect of the planetary rotation is important.

In this study, our examination is restricted to the case that the dynamical damping rate ($\alpha$) is equal to the thermal damping rate ($c$). This restriction ($\alpha = c$) is one of important limitations of our simple model for the application to the real Venusian atmosphere. The thermal damping rate is considered to be small because the relaxation time in the Venusian lower atmosphere is so large. On the other hand, the dynamical damping rate may be large by the effect of the boundary layer. Hence, it is required to investigate the atmospheric circulation for the case that the two damping rates are different. This investigation is a matter for future work.

The treatment in this study is restricted to a linear theory. In addition to the neglect of non-linear terms, the atmospheric stability i.e. $N^2$ is given as an external parameter in our treatment. However, the stability is determined as a result of dynamic processes in a real atmosphere, so that stability should be obtained in the model. We will study the circulation induced by mobile heating by using non-linear model including the process of the determination of atmospheric stability.

As described at the end of Section 2, we exclude the external mode in this study. The excitation and the effect of the external mode will be investigated in future work.

Acknowledgments

I wish to thank anonymous reviewers for their valuable comments from various viewpoints. I am grateful to Mr. Kato (MRI) for the discussions.

References


移動する熱源に対するゆっくり回転する大気の応答

松田佳久
（東京大学理学部）

線型化されたプリミティヴ方程式を使って、ゆっくり回転する大気の、移動する熱源に対する三次元的応答を研究した。まず、プリミティヴ方程式を水平構造方程式と鉛直構造方程式に変数分離した。水平構造方程式の数値的解法においては、Hough関数を利用した。

この研究においては、惑星の自転速度と太陽加熱の移動速度を恒星の値に固定されている。大気の線型応答が大気の安定度とダンピングレートの値を求めて求められている。ダンピングレートが大きな値時には、夜昼間の直接循環が得られた。一方、ダンピングレートが小さな値時には、東西風が卓越し、地衡風の関係が中高緯度において成立した状態が観われた。