Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

MIS21-01 Room:301A Time:May 22 16:15-16:30

Regime diagram of thermal convection pattern under horizontal magnetic field in liquid metal

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The study on the nature of thermal convection in liquid metals under a magnetic field is important for the dynamics of planetary metallic cores. Electric current is induced when a flow of liquid metal crosses a magnetic field, and it generates Lorentz force. The Lorentz force changes the force balance, making the flow behavior different from no-magnetic field situations. In general, viscosity of liquid metals is very low and their flow easily becomes turbulent, but when a magnetic field is applied on liquid metals, it makes anisotropic flow structure with suppression of turbulence depending on its direction and intensity. To quantify the effect of magnetic field on flow patterns, we performed laboratory experiments of Rayleigh-Benard convection by using liquid gallium, with various intensities of a uniform horizontal magnetic field B. The vessel we used has a square geometry with aspect ratio five. Flow patterns with their time variation were visualized by ultrasonic velocity profiling method. The range of Rayleigh number (Ra) is from critical value to 100 times above it. The range of Chandrasekhar number (Q), which is proportional to the square of the intensity of B, is from 0 to 1000.

We recognized five flow regimes depending on Ra and Q, that is, (1) isotropic large-scale cell pattern, (2) anisotropic cell with larger flow velocity perpendicular to B, (3) short-period oscillatory behavior of rolls aligned in the direction of B, (4) continuous transitions between roll numbers in the vessel, and (5) steady 2-D rolls. In (4), reversals of the flow direction in rolls were observed several times. These behaviors are summarized as a regime diagram of convection patterns in relation to Ra and Q. The key mechanisms for the variation are the enhancement of two-dimensionality and increase of roll number for larger Q situations. These flow regimes can be classified by Ra/Q, that is the ratio of buoyancy force to the Lorentz force. If buoyancy force is much larger than Lorentz force, the flow is turbulent and isotropic structure is dominant. Short-period of oscillation (3) is observed where the ratio Ra/Q is lower than 100. Continuous transitions of roll numbers (4) are observed at Ra/Q between 10 and 30, and convection pattern keeps steady roll (5) at Ra/Q smaller than 10. We also performed numerical simulations of thermal convection with imposed horizontal magnetic field. Both the Prandlt number and magnetic Prandtl number of the working fluid are set small to simulate liquid metals. Our numerical result successfully reproduced all regimes that observed in the experiments.

Keywords: thermal convection, liquid metal, magnetic field, pattern

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Periodic flow reversals in a MHD Rayleigh-Benard convection

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A spontaneous reversal of flow direction in Rayleigh-Benard convection is an active topic to help our understanding of natural flow motions in the Earth. In a previous study, our group has investigated Rayleigh-Benard convection in a shallow liquid metal layer with relatively large aspect ratio under horizontal magnetic field. The dimension of the fluid layer is 200∗200∗40 mm giving an aspect ratio of 5. Applying the horizontal magnetic field suppresses isotropic turbulent fluctuation of the flow and thus quasi-two dimensional convection rolls appear. These rolls aligned with the direction of applied magnetic field. In the experiments with modifying both Rayleigh number, Ra and Chandrasekhar number, Q, various convection states were observed on the diagram with Ra and Q. Spatio-temporal velocity profile measurements by Ultrasonic Velocity Profiling indicate 3, 4, or 5 steady rolls regimes and also transitional states between each steady state. We reported that flow reversals occur spontaneously in these transitional states and it is a random event regarding time (Yanagisawa, et al., PRE, 2011).

In this paper, we have reported a new regime and also mentioned that a certain inertial factor of the system can regularize the flow reversals into a very periodic event. We have conducted the Rayleigh-Benard experiments in the same vessel as previous one but using other magnetic generator at Helmholtz-Zentrum Dresden-Rossendorf (HZDR). This system can generate much larger magnetic field than the previous employed system. Thus, we could extend a regime diagram (in Ra-Q parameter space) to higher region regarding Chandrasekhar number, Q. In large Q-space, a new flow regime, six rolls, could be observed. The higher magnetic field also strongly suppressed the onset of convection and fluctuation of the convection rolls. These results are well supportable for our previous results and understanding. On the other hand, there is also remarkable difference from our prediction. The flow reversals occurred as very periodic events in this new system. Additionally, we found that the rolls are not always parallel to the magnetic field, but they are with an angle to the magnetic field direction. The most different point between the old and new system is magnitude of non-uniformity of the magnetic field. The new one has a little larger difference of intensity of the magnetic field in the test section. Therefore, one of the possible reasons of the inclination and periodic flow reversals is the non-uniformity of the applied magnetic field. Also, other factors are possible reasons such as small tilting of the fluid vessel to the magnetic field lines and higher values of the Chandrasekhar number Q. From detailed analysis of the velocity information, it will be discussed how the inertial factor of the system like non-uniformity of the magnetic field works on the regularization of the originally random event.

Keywords: liquid metal, flow reversal, horizontal magnetic field, regularization

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Influence of rotating field on the cell pattern formation of internal heating convection

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Influence of a background rotation on the transition of flows is one of the interesting topics in fluid mechanics. The influence in thermal convections also has great importance not only for fluid mechanics but also for geophysics to understand large scale phenomena in the planets. Many studies about influence of rotation on Rayleigh-Benard convection have been carried out. For example, formation of the spiral flow in convection cells is theoretically predicted by Chandrasekhar(1961). On the other hand, only a few research of the effect of rotation on the internally heating convection has investigated. In generally, convection cells occurring in the internally heating convection expand as increasing Rayleigh number. Conversely, convection cells shrunk as the effect of background rotation. As described above, the increasing rotation speed and increasing Rayleigh number provide the opposite effect on the size of convection cells. The aim of this study is to clarify how the convection pattern changes with changing balance of these opposite effect.

This experimental study deals in the response of thin horizontal fluid layer with background rotation. The bottom boundary of the layer is composed by an insulating glass plate. And the top boundary is contact with copper plate where the temperature is kept constant by circulating water from a thermo-static bath. Internally heat generation is induced by Joule heating due to passing electric current in the ionic fluid. After electrifying to fluid layer, rotation immediately is begun.

Four characteristic flow patterns were observed with modifying the rotation speed and power of the heat generation. First one is that there are stable, polygonal convection cells. Second, flow pattern is irregular without forming any cell structure. Third is the unsteady cell pattern formation: roll or polygonal cells form but immediately change into different form with combining and dividing. The fourth one is conduction state without convection.

We have organized the results by Rossby number showing the relationship between the Rayleigh number and Taylor number. The convection cell is stable when Rossby number is greater than 3 or less than 0.7. But the cell pattern formation becomes unstable and repeats split and join when the Rossby number is around zero. In addition, when Taylor number is greater than 1000, convection does not form cell structure even if Rossby number is greater than 3.

When we focus on the parameter region of stable convectional cell, flow structure and cell size differ between Rossby number is less than 0.7 and greater than 3. The shape of convectional cell is regular hexagon and the flow inside the cell takes large distortion due to Coriolis force when Rossby number is less than 0.7, in other word the effect of rotation is relatively stronger than the effect of convection. On the other hand, when Rossby number is greater than 3, the shape of cell is irregular polygon and the flow inside the cell has little distortion as the effect of rotation.

Keywords: natural convection, internally heating, rotating field, flow pattern

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The effect of wind waves on the upper ocean circulation

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There is an ongoing discussion in the community concerning the wave-averaged momentum equations in the hybrid vertically Lagrangian and horizontally Eulerian (VL) framework and, in particular, the form stress term (representing the residual effect of pressure perturbations) which is thought to restrict the handling of higher order waves in terms of a perturbation expansion. The present study shows that the traditional pressure-based form stress term can be transformed into a set of terms that do not contain any pressure quantities but do contain the time derivative of a wave-induced velocity. This wave-induced velocity is referred to as the pseudomomentum in the VL framework, as it is analogous to the generalized pseudomomentum in Andrews and McIntyre. This enables the second expression for the wave-averaged momentum equations in the VL framework (this time for the development of the total transport velocity minus the VL pseudomomentum) to be derived together with the vortex force. The velocity-based expression of the form stress term also contains the residual effect of the turbulent viscosity, which is useful for understanding the dissipation of wave energy leading to transfer of momentum from waves to circulation. It is found that the concept of the virtual wave stress of Longuet-Higgins is applicable to quite general situations: it does not matter whether there is wind forcing or not, the waves can have slow variations, and the viscosity coefficient can vary in the vertical. These results provide a basis for revisiting the surface boundary condition used in numerical circulation models.

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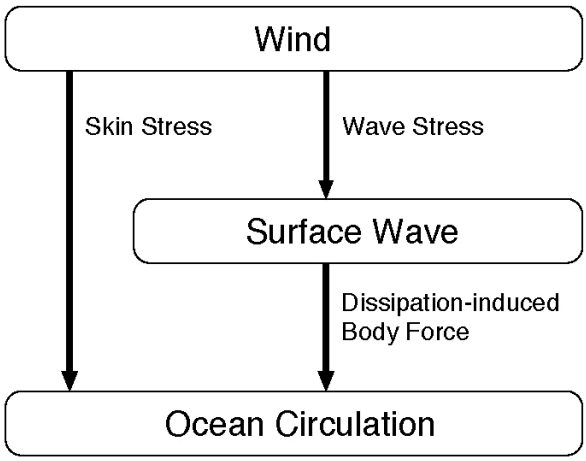
Keywords: Wind waves, Wind stress, Wave dissipation, Momentum transfer, Lagrangian coordinates



Japan Geoscience Union Meeting 2013
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MIS21-05 Room:301A Time:May 22 17:15-17:30

A theoretical study on the mechanism for spontaneous gravity wave generation using the renormalized perturbation method

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Gravity waves (GW) are categorized into orographic ones and non-orographic ones. The mechanisms for non-orographic GW generation are not clear, because the dynamics is quite nonlinear and complicated unlike orographic GW. Recently, it has been revealed that GW are spontaneously radiated from an approximately-balanced flow, especially in the jet/front systems (e.g. O'Sullivan & Dunkerton 1995). The balanced adjustment theory proposed by Plougonven & Zhang (2007) is considered to be the most likely to describe the spontaneous radiation. However, their theory has the following three flaws. [1] The physical interpretation for GW sources is not given. [2] The (singular) perturbation method is not used. [3] The reaction by GW radiation to the vortical flow is not considered. In this study, we propose a new theory, which is free from all these flaws. Validity of this new theory is carefully examined by using the result of numerical model simulation.

The essence of this new theory is that GW are radiated from the slaved components of the vortical flow through a quasi-resonance, when the ground-based frequencies of GW are significantly Doppler-shifted by the vortical flow and have timescales comparable to that of the slaved components.

So as to make the physics clear, linear potential vorticity (q), horizontal divergence (d), and ageostrophic vorticity (g) are used as dependent variables. The vortical flow is defined as the flow associated with q, and the slaved components are defined as d and g that are diagnostically determined from the distribution of q. In the linear theory, d and g contain high ground-based frequency components. As the nonlinear terms in these high frequency components contain slowly varying components with timescales comparable to that of q, it is necessary to include them in the theory. Thus, in order to consider both GW and these slowly varying components, five variables are used to construct the theory which describes the spontaneous radiation through the quasi-resonance (problem [1] is solved): q, two variables (d^{GW}, g^{GW}) for GW, and two variables (d^{diag}, g^{diag}) for slowly varying components.

For theoretical formulation, we use the renormalized perturbation method which is one of singular perturbation methods (problem [2] is solved). In addition, in order to take account of the Doppler shift, the eigenmode expansion in a given arbitrary vortical flow field is made for d^{GW} and g^{GW}. On the other hand, the ordinary renormalized perturbation method is applied to d^{diag} and g^{diag}. Diagnostic components, d^{diag} and g^{diag}, are separated into two parts: the GW radiation reaction and slaved component. The derived theoretical equations also contain the variation of q by the GW radiation reaction. This means that the problem [3] is solved.

In order to examine validity of the theory, the quasi-steady spontaneous radiation of GW in a vortex dipole is simulated using the Japan Meteorological Agency nonhydrostatic mesoscale model (NHM). The modon solution, that is an exact solution for three dimensional QG equations on the beta plane, is given as initial values to perform numerical integrations of the compressible nonhydrostatic equations. Similar to the previous studies, GW are radiated upward and downward from the jet exit region. GW phase structure is almost symmetric around the jet axis in the vertical cross section. The nearer to the dipole edge, the shorter the GW wavelength becomes. The GW are wrapped into the dipole vortices at its edge. Next, the renormalized group equations are integrated with GW sources obtained from the initial modon field that does not include GW. As a result, it turns out that these equations successfully reproduce spontaneously radiated GW in the jet exit region as is consistent with the result of NHM.

Keywords: spontaneous radiation, gravity wave, renormalized perturbation method

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Consideration of latent heat transport processes in the Penman-Monteith equation

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It is considered that there are two processes in the latent heat transport, which are turbulent diffusion and molecular diffusion, but when we estimate the latent heat flux from the place whose spatial scale is as large as the plant community (tens to thousands meters), the expression is often used taking into account only the turbulent diffusion process and the molecular diffusion process is rarely considered.

However, Furuya et al. (2011, JpGU meeting) suggested that molecular diffusion process, compared to turbulent diffusion process, contributes to the sensible heat transport near land surface, and if we estimate the sensible heat flux, we should use the estimation formula considering molecular diffusion process because the formula expresses the real physical mechanism. This can be said about the latent heat transport.

Therefore, we calculated Penman ? Monteith equation (Monteith, 1968) which is often used to estimate the latent heat flux assuming turbulent diffusion or molecular diffusion and compared the estimations with the observed interception loss which is reported by Furuya et al.(2012, JpGU meeting).

In result, whether the estimated values fit the observed value depended on the day, but the estimations with two different theories were similar.

We used values by Rutter et al. (1971) to calculate the estimation assuming turbulent diffusion but the values are not in accordance with the physical law and they are decided in order to fit with observations, while the calculation with molecular diffusion has no arbitrary constant. Considering this point, this result showed that the method assuming molecular diffusion to estimate latent heat flux can explain the real mechanism.

Keywords: latent heat, heat transport, land surface process, atmospheric boundary layer, vegetation

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Movie Moire Method, applied to Internal Gravity Wave.

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In laboratory experiment, an internal gravity wave is propagating in stratified transparent fluid. When the wave id visualized, using a large-scale optical system , such as shuri-ren . But it can easily apply to rectangular tank, but it is need to rearrange the optical system to suit to certain shape of tank.

There is an other method , called moire method. It has not such issue, but it require strict setting of two stripes, combination of wave length of two stripes , and position of a camera .

Years before, we carried out visualization of internal gravity wave of QBO experiment, double exposure of distortion of one stripe, and digital processing makes moire pattern.A short of picture resolution and processing throughput does not make possible to real time visualization.

This time, We use digital Video camera and PC,and real time visualization is carried out.

Keywords: Moire, Experiment

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Experimental study of liquefaction and fluid transport

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Liquefaction is a phenomenon in which the inter-particle contact of a liquid-saturated granular matter is loosened by vibration and as a result, the bulk behaves like a fluid. It is widely known that earthquakes can cause soil liquefaction which can manifest in the form of sand boils and mud volcanoes. Liquefaction can also occur in a more viscous fluid (e.g, Sumita and Manga, 2008, EPSL), one example of which is a magma chamber. Magmatic liquefaction may also be caused by earthquakes, and may even trigger a volcanic eruption. Moreover, on Mars, there are topographic features which seem to have formed from the eruption of fluid. There have been a number of experimental studies using water saturated soil and sand in the field of soil mechanics or civil engineering. However the details of the critical condition to cause the liquefaction, and how the consequences of the liquefaction differ with the changeable parameters, are still insufficiently known. Here we conduct an experimental study of liquefaction under a vertical vibration to understand the elementary process of liquefaction and fluid transport. We aim to explore the variety of phenomena which may occur, and to better constrain the conditions which cause these results.

An experimental cell (cross section 22.0mm x 99.4mm, height 107.6mm) is filled with a granular matter and liquid (water or glycerin solution). The lower 33.7mm is a two-layered granular medium; the upper layer and lower layer consist of packed glass beads with a size of 0.05 and 0.2 mm, respectively, such that the upper layer becomes a low-permeability layer. The cell is placed on a vertical shaker which vibrates sinusoidally with an acceleration of 2.0-41.1m/s^2 and a frequency of 10-40 Hz.

Here we describe the results for a water-saturated case. From a series of experiments, we find that as we increase the acceleration there are 4 styles of pore water discharge; No-change, Percolation, Transitional, and Flame (i.e., Rayleigh-Taylor type instability). Under a small acceleration, there is no apparent change in the thickness of the granular medium and the two-layer boundary (No-change). As we increase the acceleration, the two-layered granular medium compacts by expelling the pore-water. First there is no apparent change in the form of the two-layer boundary (Percolation), but as the acceleration increases, an instability appears (Transition) whose amplitude grows and a flame structure forms (Flame).

In a two-layered water-saturated granular medium, we find that the pore water which originated from the bottom layer temporary accumulates at the interface of the two layers, and then ascend through the upper layer in the form of vertical channels. We find that the critical acceleration for the formation of the flame structure is of the order of ((the particle-water density difference)/(the particle density))g, where g is the gravitational acceleration.

Keywords: low-permeability layer, Rayleigh-Taylor type instability, Flame structure

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Grain shape dependence of the convective structure in a vertically vibrate granular bed

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Miyamoto et al. reported that the migrations and sorting of regolith could result from gravel fluidization induced by vibration caused by an impact on surface of asteroid Itokawa [1]. In order to understand the detailed mechanism of such phenomena, fundamental physics of vibrated granular matter must be revealed. When granular materials such as regolith are shaken, we can see various phenomena, e.g. convection, segregation, and so on. In this study, we study the granular convection by the experiment. Although many literatures have reported on both experimental and numerical studies of granular convection [2-5], most of them have used spherical grains as constituents. In general, geophysically relevant sand grains are not spherical. Thus, we use rough shaped sand (JIS standard sand) as well as spherical glass beads, to examine the influence of grains shape to the granular convection. In the experiment, we investigate the global structure of granular convection and measure the convective velocity.

The experimental setup consists of a cylinder made by plexiglass of 75 mm inner diameter and 150 mm height, which is mounted on an electromechanical vibration exciter (EMIC 513-B/A). The vibrator frequency f is varied from 10 to 300 Hz and the dimensionless accelerations from 2 to 6. The grains used are glass beads (0.8 mm in diameter) and JIS (Japan Industry Standard) standard sand (from 0.71 mm and 1.4 mm in diameter). The granular layer height is fixed to 50 mm. We use a high-speed camera (Photoron SA-5) with a macro lens to record the motion of grains at 1000 fps. PIV (Particle image velocimetry) method is used to obtain the convective velocities on the side wall of the container.

We find that global structure of convection shows a transition from single cycle roll state to doughnut like roll state when f increases. In the former, grains rise up on the one side wall and fall down on the other side wall. In the latter, grains rise up at the center of container and fall down on all over the wall. We also find that the measured convective velocity decreases rapidly in deep region of the bed. While this tendency is more or less similar to previous studies [2,3], the form of decreasing function is clearly different between glass beads and rough shaped sand. Moreover, the convective velocity field seems to have spatial and temporal inhomogeneities.

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Keywords: Grain shape dependence, Convection, Vertical vibration, Itokawa

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Numerical Experiments for Concentric Eyewalls of Typhoon Bolaven (2012)

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Eyewall is a ring of convective clouds that encircles the eye of a tropical cyclone (TC) such as typhoon and hurricane. TC occasionally has some eyewalls which are called as concentric eyewalls. Striking concentric eyewalls of some hurricanes are studied by airborne radar observations and numerical simulations. These previous studies indicate that eyewall replacement often occurs once concentric eyewalls are formed. The eyewall replacement is a process that the inner eyewall gradually decays and the outer eyewall moves into the position of the inner (old) eyewall. In addition, the wind speed of TC rapidly varies during the replacement. It is important for prediction of TC's intensity to understand the process of the eyewall replacement. However, typhoon Bolaven, which passed in main Okinawa island in 2012, had stationary concentric eyewalls for very long time. And the replacement of Bolaven's concentric eyewalls did not occur. It is clear from observation by Doppler radars of Japan Meteorological Agency (JMA). It shows that the eyewall replacement does not always occur even if concentric eyewalls are formed. As seen above, the process of the eyewall replacement are not fully known.

In this study, we investigate that Bolaven's concentric eyewalls structure and their maintaining reason, using the Cloud Resolving Storm Simulator (CReSS) which is a three-dimensional, nonhydrostatic model. According to some previous studies for concentric eyewalls of hurricanes, concentric eyewalls has horizontal scale of about 10 km. In order to simulate the concentric eyewalls of Bolaven, it suggests that we conduct numerical experiment with horizontal resolution of about 1 km. First, we perform the experiment with 5 km horizontal resolution whose initial and boundary conditions are given by the initial data of the Global Spectral Model (GSM; 0.5 degree horizontal resolution) provided by JMA. Second, we perform the experiment with 2.5 km horizontal resolution based on the output data of 5 km horizontal resolution. Finally, we perform the experiment with 1 km horizontal resolution based on the output data of 2.5 km horizontal resolution.

We could simulate the striking concentric eyewalls which were located within about 100 km radius from Bolaven's center with 1 km horizontal resolution. Simulated concentric eyewalls are stationary for over one day. It substantially exceeds the time required for the eyewall replacement And, the simulated concentric eyewalls have the moat regions, which is very dry and weakly descending. These results almost agree with some observations.

The inner eyewall of a TC gradually decays when supply of vapor into the inner eyewall due to low level inflow from outside of TC is constrained by existence of moat region. This structure is characteristic when replacement of eyewall occurs in TC. Despite of these features, the inner eyewall of Bolaven is stationary. Thus, it suggests that vapor supplied from the periphery of the inner eyewall region is enough to maintain the inner eyewall, even if the moat regions suppress supply of vapor by inflow from outside of Bolaven.

Keywords: tropical cyclone, concentric eyewall, vortex dynamics, numerical modeling, nonhydrostatic cloud resolving model

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Dynamic and thermal processes of a surface low developed by a vortex aloft

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Over high-latitude oceans in winter, polar lows sometimes develop, whose typical size is a few hundred kilometers. Upper level trough is considered to be one of the important factors for development of polar lows. In this study, this type of process of development is focused: dynamical and thermal processes by which a vortical disturbance aloft excites a surface low are investigated through numerical simulations in an idealized atmosphere.

Some numerical studies in an idealized atmosphere for polar lows caused by upper level vortical disturbances have been conducted. In many studies, not only a vortex aloft but also a disturbance on the surface are located in the initial state, but it is reported recently that surface disturbances could be excited only by vortical disturbances aloft and some sensitivity experiments for such situations are carried out. However, the height of tropopause and upper level vortices are often set at 5000m to 6500m which is lower than real cases. Moreover, excitement of surface disturbances by upper vorticies are mainly investigated through dynamical processes and effects of thermal processes such as convections raised by weak stratification beneath the cold air aloft are not considered enough in idealized simulations.

Therefore, simulations in a zonally uniform baroclinic channel with a higher tropopause level are carried out. As a result, a comma-shaped polar low was simulated even when the upper level vorticies and tropopause is located at 8000m height level. However, it is revealed that in an early stage, the low was developed due to convective processes which are caused by destabilization of stratification rather than dynamical processes which are frequently mentioned in early studies. In order to understand the mechanism of the early stage of the development, simulations with various combinations of tropopause height and the stratification of the background atmosphere. As a result, the mechanism of the disturbance excitement could be classified into some patterns. Dynamical processes tend to occur when the height of a vortex and tropopause is low, and the stratification of the background is weak. In other cases, the low was excited by convective processes and in some cases with high tropopause height and strong stratification, the low was not developed. The condition of dynamical excitement of disturbances resembles that of Eady instability. A low will be emerged by interaction between vorticies when it is under the condition of instability of Eady model, but otherwise surface disturbances are developed convectively. The height which convective vertical flows can reach was calculated by using emagram and compared with the results of numerical simulation. When stratification is weak, the height of convection explains the result of the simulations well. There is, however, discrepancy when stratification is strong; it may be because potential temperature anomalies associated with vorticies and heat fluxes from sea surface are not taken into account.

Keywords: polar low, vortex aloft, stratification, convection

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Boundary layers of an axisymmetric flow in a cylindrical tank with a rotating bottom

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In an image from the spacecraft Cassini, hexagonal flow pattern around Saturn's pole is observed. In typhoon images in meteorological sattetiles, we often find typhoon eyes with polygonal shapes. In the terrestrial and planetary atmospheres, non-axisymmetric flows are often formed in axisymmetric environments

Such a breaking of axisymmetry is realized in a simple laboratory experiment: water in a cylindrical tank is driven by a rapidly-rotating disk at the bottom. In this experiment, not only flows with polygonal patterns are observed but also hysteresis between axisymmetric circular flow and eliptical non-axisymmetric flow, and excitation of a large amplitude wave propagating along the side wall, on which we have been reported.

When we understand the mechanism of these phenomena, however, we must know the axisymmetric flow realized under this condition in spite that the phenomena themselves are not axisymmetric, since we should consider the mechanism based on the basic axisymmetric flows. Therefore, we tried to obtain analytically the axisymmetric flow in a cylindrical container with a bottom rotating in a constant angular velocity.

It is impossible to solve the exact solution of the flow, but we successfully obtained the approximate solution under the condition that the Ekman number is small with help of boundary layer theory. The flow is solved by dividing the flow in the cylindrical container into six regions with different balances: (i) inner region with rigid rotating flow, (ii) inner region with constant angular momentum, (iii) Stewrtson's 1/4-layer between two inner regions, (iv) Ekman layer near the rotationg bottom, (v) boundary layer near the side wall, and (vi) corner region where the side wall and the bottom disc meets.

In particular, we estimated the flow flux of the meridional circulation by integrating the flows obtained in each region, described the whole features of the axisymmetric flow.

Keywords: axisymmetric flow, rotating flow, boundary layer