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An experimental study on the forcing of large-scale heat sources and topography on baroclinic flow

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RESUMEN

El presente trabajo consiste de dos partes. En la primera se describe un experimento para estudiar el forzamiento topográfico en flujo baroclínico. Comparando experimentos con y sin topografía se discute el papel que juega ésta en la formación de los regímenes de flujo. Los experimentos muestran que las ondas que se propagan vacilan fuertemente con el tiempo debido al forzamiento topográfico. Por otra parte, en los experimentos bajo las mismas condiciones externas pero sin topografía, las ondas baroclínicas se propagan regularmente y casi sin vacilaciones. Se encontró que una característica prominente en el flujo con forzamiento topográfico es la vacilación de gran escala de la onda, con un periodo de 127 rotaciones del anillo, que es equivalente aproximadamente a 26 días en la atmósfera terrestre. Los experimentos muestran que el papel que juega la topografía es el de modular las ondas baroclínicas inestables, tanto en espacio como en tiempo.

En la segunda parte del artículo, se introduce una serie de experimentos comparativos para estudiar la influencia de fuentes de calor y topografía en los flujos baroclínicos básicos de gran escala, definidos como los patrones de flujo determinados por Ω, la velocidad angular de rotación del anillo y ΔT, la diferencia radial de temperaturas entre las paredes interna y externa del anillo. Los patrones de flujo dependen del número y disposición de las fuentes de perturbación. Como resultado del forzamiento no lineal impuesto por las fuentes de calor, el flujo inicial axisimétrico anular cambia a un flujo de onda de orden 4, si el número de fuentes de perturbación es menor o igual que dos no importando el tipo de perturbación, ya sea fuente de calor o topografía. Esto significa que aunque los mecanismos de forzamiento termo-convectivos de la fuente de calor y el forzamiento mecánico de la topografía del fondo son esencialmente diferentes, ambos pueden cambiar la distribución de vorticidad en el flujo y formar nuevos patrones. Cuando el flujo inicial es ondulatorio axialmente simétrico, debido al forzamiento de las fuentes de calor, el flujo se torna inestable, o bien las ondas locales se deforman u ocurre la vacilación.

ABSTRACT

The present work consists of two parts. In the first, an experiment is described to study the topographic forcing on the baroclinic flow. By comparison of the experiments with and without topography, the role of topography in the formation of the flow regimes is discussed. The experiments show that the travelling waves strongly vacillate with time due to the topographic forcing. Otherwise in the experiments with the same imposed external conditions but with no topography, the baroclinic waves would travel regularly with almost no vacillation. It was found that a prominent feature in the flow with topographic forcing is large-scale wave vacillation with a period of 127 annulus rotations, which is equivalent to approximately 26 days in the Earth atmosphere. The experiments show that the role of topography is to modulate the unstable baroclinic waves both in space and time.

In the second part of this paper, a series of comparative experiments is introduced to study the influences of heat sources and topography on the large-scale baroclinic background flows defined as the flow patterns determined by Ω the angular velocity of the annulus rotation and ΔT, the radial temperature difference between the inner and outer walls of the annulus. The flow patterns depend on the number and disposition of the disturbance sources. As the result of nonlinear forcing of imposed heat sources, the initial-axisymmetric-annular flow turns into a 4 wave flow if the number of the disturbance sources is equal to or less than two, no matter which kind of disturbances, the heat source or topography, is. This means that although the mechanisms of thermo-convective forcing of the heat sources and solid-mechanical forcing of bottom topography are essentially different, both of them can change the vorticity distribution in the flow and form new flow patterns. When the initial flow is axisymmetric-wavy, owing to the forcing of heat sources, the flow becomes unstable. Either the local waves deform or vacillation occurs.

I. Introduction

In the last forty years, much work has been done on fluid experiments in rotating annulus. For example, Fultz *et al.* (1959); Hide and Mason (1975); Yeh *et al.* (1974) and Pfeffer *et al.* (1980)

carried out a series of experiments to simulate baroclinic instability and other processes in the general circulation of the atmosphere. A variety of flow regimes will be promoted when an annulus rotates about its vertical axis and the fluid contained in it is subjected to a temperature difference between the annulus walls. The flow is zonally-axisymmetric when the rotation is comparatively slow. A regular-axisymmetric-wave flow appears when the rotation rate is increased and exceeds a certain critical value. The further increase of annulus rotation rate leads to a turbulent flow regime. It was already pointed out by Fultz *et al.* (1959) that, in many aspects, the annulus baroclinic flow resembles the large-scale quasi-geostrophic flow in the Earth's atmosphere and oceans. Therefore, the rotating fluid experiment contributes to a better understanding of the fundamental mechanisms of the general circulation of the atmosphere and the oceans.

One of the basic problems of meteorology is to explain the fluid circulation of the atmosphere and its mean flow and time variation characteristics. It is widely recognized that the general circulation of the atmosphere is influenced in a major way by underlying topography as well as by zonally non-axisymmetric heat sources. Such influences are seen in the occurrence of blocking, the position of the standing waves which show up on climatological mean charts, the existence of preferred longitudes for baroclinic instability and the occurrence of index cycle of the atmospheric circulation. Li, Guo-Qing *et al.,* have performed a series of laboratory experiments, using a rotating annulus to study the topographic influence on the baroclinic flow regimes. It is found that the role of topography appears to be to modulate the unstable baroclinic flow regimes both in space and time. The topographic effects depend in a major way on the Rossby number of the flow field. The topographic effects increase with the decrease of the Rossby number. When the Rossby number is low enough (0.06 to 0.2), the baroclinic flow is involved in a strong vacillation due to the topographic forcing and all the characteristics related to the flow field vacillate periodically. In this paper, we continue this investigation, and both influences of large-scale heat sources and topography on the baroclinic flow regimes are considered.

II. A comparative experiment with and without topography

1. Experimental set-up and experimental method

The annulus designed in the experiments was similar to that used by Pfeffer*et al.* (1980) and Li (1986 and 1987). The sketch of the experimental set-up is shown in Fig. 1. The experimental basin B is filled with 5 centistoke silicon oil with a depth of 10 cm. With circulating warm water in bath A and cold water in bath C, a constant temperature difference between the inner and outer walls of the experimental basin B is maintained. The outer radius of the inner brass cylinder of basin B is 7.5 cm, and the inner radius of the outer brass cylinder is 15 cm. The fluid surface is free with a glass cover above the fluid top. In order to visualize the horizontal flow field, we use a kind of streak photography technique. Small white polyethylene particles are used as tracers. From the length of trajectory traversed by the tracers and the exposure time, the fluid velocity may be obtained. A digitizer is used to treat the experimental photopictures. The topography used in the experiments consists of two ridges and two valleys around the annulus and its shape can be described by the formula

$$h_B = H \sin 2\lambda \tag{1}$$

where h_B is the height of the topography at some point, $H = 1.75$ cm is the height of the mountain

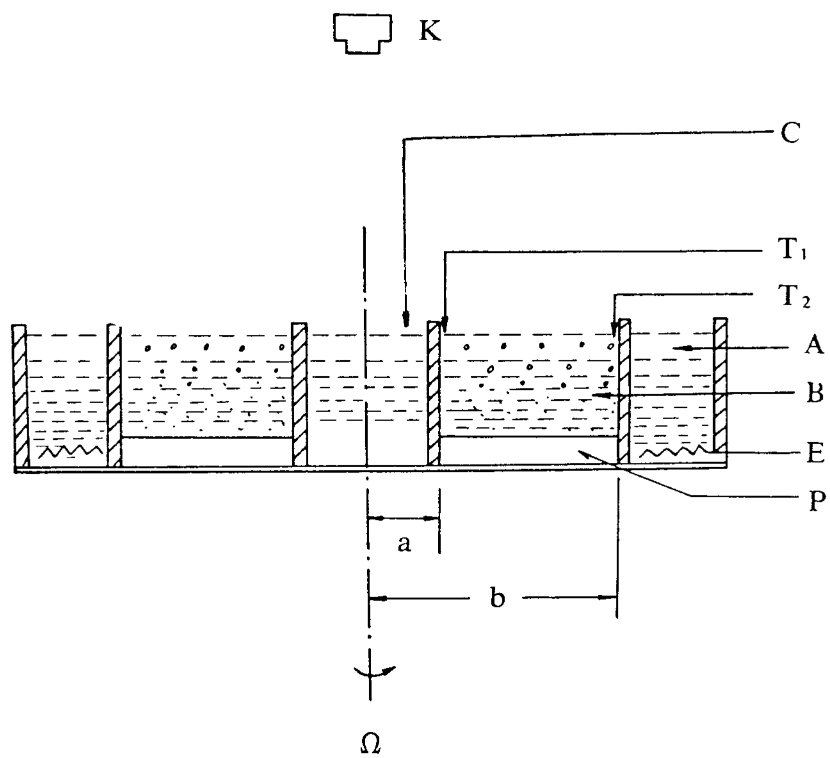

Fig. 1. Sketch of vertical section of experimental set-up. The equipment consists of experimental basin B, warm water bath A, cold water bath C, camera K and topography or heat sources P. "a" is the inner radius of the annulus. "b" is the outer radius of the annulus. T_1 is temperature of the inner wall. T_2 is the temperature of the outer wall of the annulus.

peaks and $\lambda(0 < \lambda < 2\pi)$ is the azimuth angle measured counterclockwise. The height of the topography changes only in zonal direction, while in the meridional direction it is a constant.

2. Vacillation of index cycle in the baroclinic flow

The investigations by Namias (1950) in the early forties indicated that the general circulation of the atmosphere in the middle latitudes of the North Hemisphere, particularly during the winter season, fluctuates between two different regimes. One is characterized by relatively strong circumpolar westerlies and the other a dominant meridional flow pattern with strong developed large-scale troughs and ridges. The transition from a strong zonal circulation regime to a weak one and back again has been referred to as an "index cycle", and each cycle has a period of three to eight weeks. But the reason of the oscillation in the index cycle of the atmosphere, still, is not clearly explained. In meteorology, the strength of the westerlies between 45°N and 65°N is termed the zonal index. Fig. 2 presents variation of the zonal index for the real atmosphere. It shows a roughly cyclic variation in the zonal index, the time scale of which varies from 3 to 8 weeks.

The results of the experiments show that the topographic forcing causes strong vacillation in the baroclinic wave flow. Fig. 3 presents a vacillation of "zonal index" in the experimental baroclinic wave flow with topographic forcing. Here the zonal index for the experimental flow is defined as

$$I = \int_a^b \overline{u} dR$$

and obtained by measuring the area included between the curves of zonally averaged fluid velocity profile and the ordinates for all the sequences of the flow field. Index I represents the total momentum in the flow. The high index is representative of strong zonal flow, and the low index is representative of cellular-meridional flow. Fig. 3 also shows that there is a periodicity of 127 annulus revolutions in the variation of the zonal index of the experimental flow.

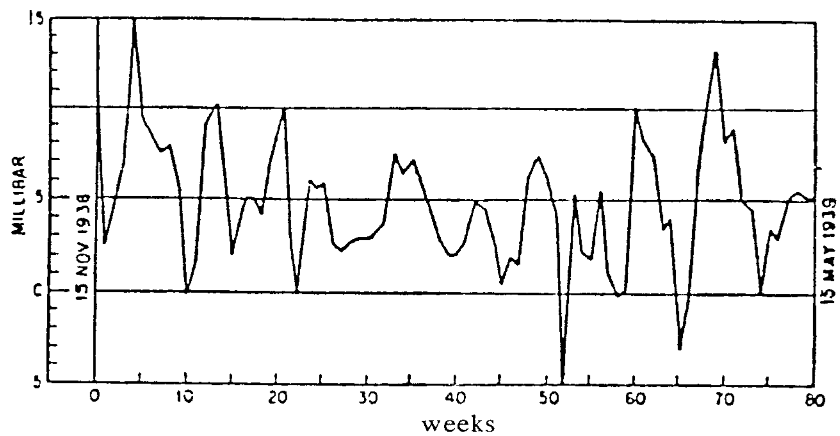

Fig. 2. Variation of the zonal index of the atmosphere (after Namias and Clapp).

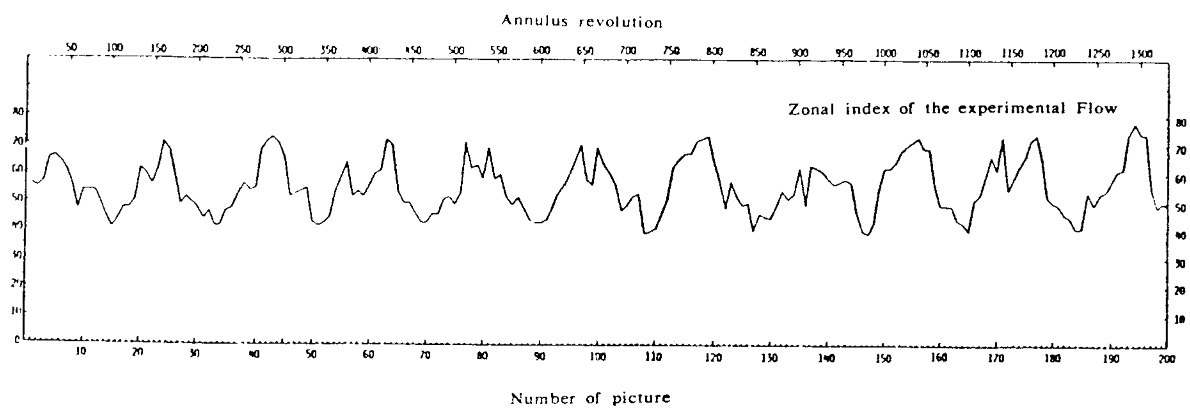

Fig. 3. Vacillation of zonal index in the baroclinic flow with topographic forcing. Numbers along the top line show the time in annulus revolutions. Numbers along the bottom line show sequence of pictures of the flow field taken in the experiment.

3. The periodicity of the flow vacillation

Using dimensional analysis and the principle of similarity of fluid dynamical systems, we have compared the periodicity of the experimental flow and that of the Earth's atmosphere. In the experiments, a characteristic length scale is $R = 11.0$ cm, and the maximum value of u observed at middle elevation of the fluid is of the order 0.10 cm sec^{-1}. So a characteristic time scale for the experimental flow is

$$t^* = R/\overline{u} = 110\text{s}$$

It was pointed out that the baroclinic flow vacillates with a period of 127 annulus rotations due to the topographic forcing, and since the time for one revolution of the rotating table is 3 seconds, then the period of vacillation is

$$t = 127 \times 3 = 381\text{s}$$

The dimensionless magnitude of the period of vacillation is

$$\hat{t} = t/t^* = 3.5$$

For the real Earth's atmosphere, supposing that the characteristic scale of length $R' = 6300$ km, and the characteristic velocity $\overline{u}' = 10\ \text{ms}^{-1}$, the characteristic time-scale would be

$$t^{*\prime} = R'/\overline{u}' = 6.3 \times 10^5\text{s}$$

As it was pointed out that the experimental fluid system and the Earth's atmosphere are alike, so the period of vacillation of the experimental flow corresponds to a value of t' in the Earth's atmosphere,

$$t' = t^{*\prime} \times \hat{t} = 2.2 \times 10^6\text{s} = 26\ \text{days}$$

It seems, therefore, the vacillation in the experimental flow corresponds to the low frequency oscillation in the Earth's atmosphere. This renders us an idea that the cause of the low frequency oscillation that occurs in the index cycle of atmospheric circulation lies in the forcing of large-scale topography such as Asian and American mountains.

III. A comparative experiment on forcing of large-scale heat sources and topography on baroclinic flows

1. Experimental set-up and method

Another series of laboratory experiments was performed to study the influences of heat sources and topography on the large-scale baroclinic background flow defined as the flow patterns determined by Ω, the angular velocity of the annulus rotation, and ΔT, the radial temperature difference between the inner and the outer walls of the annulus. In this experiment, we use a larger annulus designed similarly to that used by Yeh *et al.* (1974). The experimental basin B is filled with a liquid mixture of water and glycerine as the working substance of density = 1.043 gr. cm^{-3} at a depth of 8 cm (Fig. 1). The cylindrical walls of the annulus basin are of transparent plexiglass. A constant temperature difference between the walls of basin B is maintained by circulating water baths, with the inner wall (radius a = 18.25 cm) always maintained colder than the outer wall (radius b = 40.00 cm). The baths' temperatures are kept constant during the experiments. The adjustment of the annulus rotation rate Ω, the measurement of the fluid temperature and the visualization of the flow field are similar to those employed by Yeh *et al.* (1974).

Fig. 4 shows the regime diagram of distribution of the large-scale background flow patterns in space of thermal Rossby number R_{OT} and Taylor number T_α,

$$R_{OT} = \frac{gD_o a \Delta T}{\Omega^2 (b-a)^2}$$

$$T_a = \frac{4\Omega^2 (b-a)^4}{\nu^2}$$

Here $D_o = 8$ cm is the depth of the fluid, g is the acceleration of gravity, $a = 3 \times 10^{-4}\ {}^{o}C^{-1}$ is the coefficient of volume expansion of the fluid, ΔT is the imposed temperature difference between the inner and outer cylindrical walls of the annulus, and $\nu = 2 \times 10^{-2}$ cm^2 s^{-1} is kinematic viscosity of the fluid. The flow patterns are distributed as follows: the most stable-axisymmetric flow patterns are located in the area with large R_{OT} and small T_α. The most unstable-turbulent flows appear in the area with small R_{OT} and large T_α. The stable-wave flows are located in the area between them.

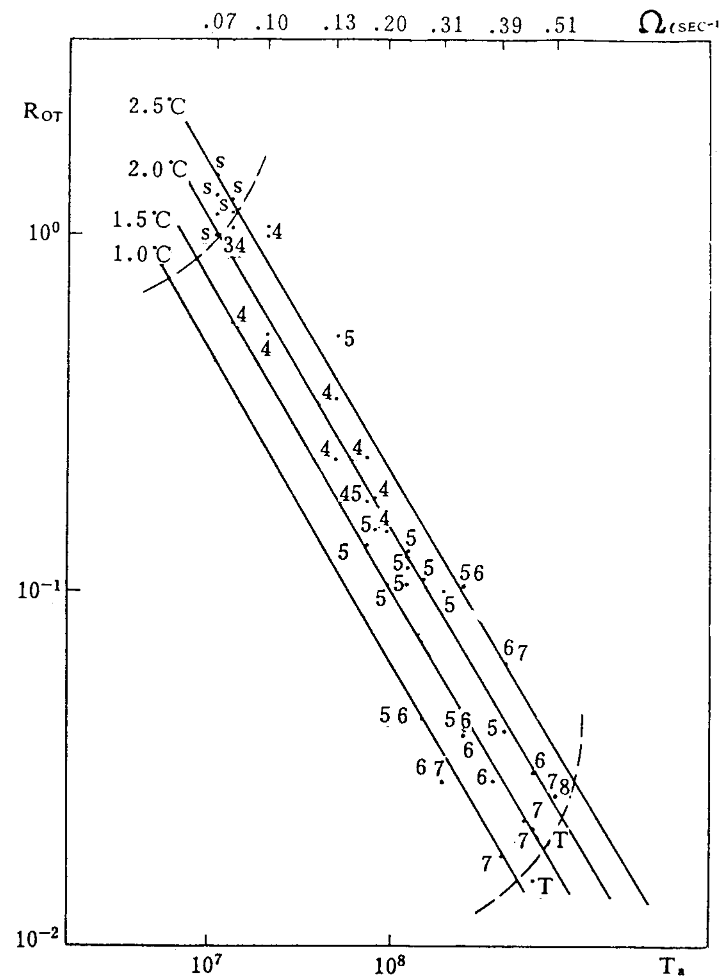

Fig. 4. Regime diagram showing the dominant wavenumber of the background flows. The abscissa shows the Taylor number and the ordinate shows the thermal Rossby number. The diagonals are lines with constant temperature differences. The numbers indicate the dominant wavenumbers in the flows. *S* denotes zonally-axisymmetric flow, and T denotes turbulent flow.

We have tested two kinds of external forcing, the pure thermal forcing and the pure bottom topographic forcing. The heat sources are made of thin ladder-shaped plexiglass pieces with spread angle of $\pi/10$, and with thermal resistence wires well paved on it. Fig 5 shows the geometric dimension and the distribution of heat sources. The heat sources, with a power of 22 watts for each, can be switched on separately or jointly to imitate the influences of heat sources of different disposition. We denote the heat sources in action by Q'_{ijk}. For example, Q'_{12} means only heat sources No. 1 and 2 are in use, but the heat sources No. 3 and 4 are not. As the topography we use the ladder-shaped platforms of 2.5 cm high and with the same horizontal dimensions of the heat sources. The experimental procedures are as follows. At first, we adjust the annulus rotation rate Ω to the

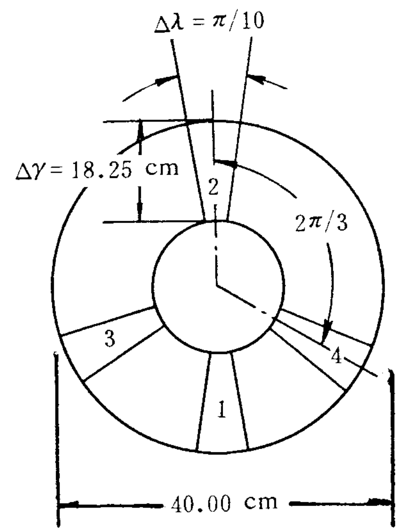

Fig. 5. Disposition of the heat sources on the annulus bottom. The ladder-shaped sections 1, 2, 3 and 4 are thin pieces of plexiglass with well paved thermal resistance wires.

appointed value, then, impose the assigned temperature difference to the bath's walls and keep the temperature difference constant. After a long term rotation of the annulus (usually it lasts more than one hour), a certain stationary flow pattern appears in the fluid. Then, switching on the heat sources, we impose the thermal forcing on the already existed initial background flow, and observe the transition of the flow patterns. For simplicity, we discuss the more representative experiments with Δ T = 2.0° C and Ω ranging from 0.065 s^{-1} to 0.40 s^{-1}, and with heat sources ranging from No. 1 to No. 3. The disposition of the heat sources is either axisymmetric or non-axisymmetric.

2. Influence of heat sources on large-scale background flow

Fig. 6 shows the flow pattern change in the experiments with initial-axisymmetric background flow and with different disposition of heat sources. When the number of the heat sources is equal to or less than two, the initial-axisymmetric flow turns into a 4 wave flow. When the number of the heat sources is equal to three, and especially when the imposed heat sources are disposed uniformly (the distance between heat sources is equal to 2 $\pi/3$), the initial- axisymmetric flow turns into a stable 5 wave flow (series 6.1-6.2 in Fig. 6). It seems that the heat source number is an important parameter for the flow pattern transition. Obviously, the reason the initial-axisymmetric flow turns into wave flow is due to the thermal forcing of the imposed heat sources.

We did other series of experiments to test the influence of heat sources on the initial-wave flow. Fig. 7 shows the flow pattern change in the experiments with initial wave flow and with different disposition of the heat sources. In the case of stable-initial 4 or 5 wave flow, the flow turns into

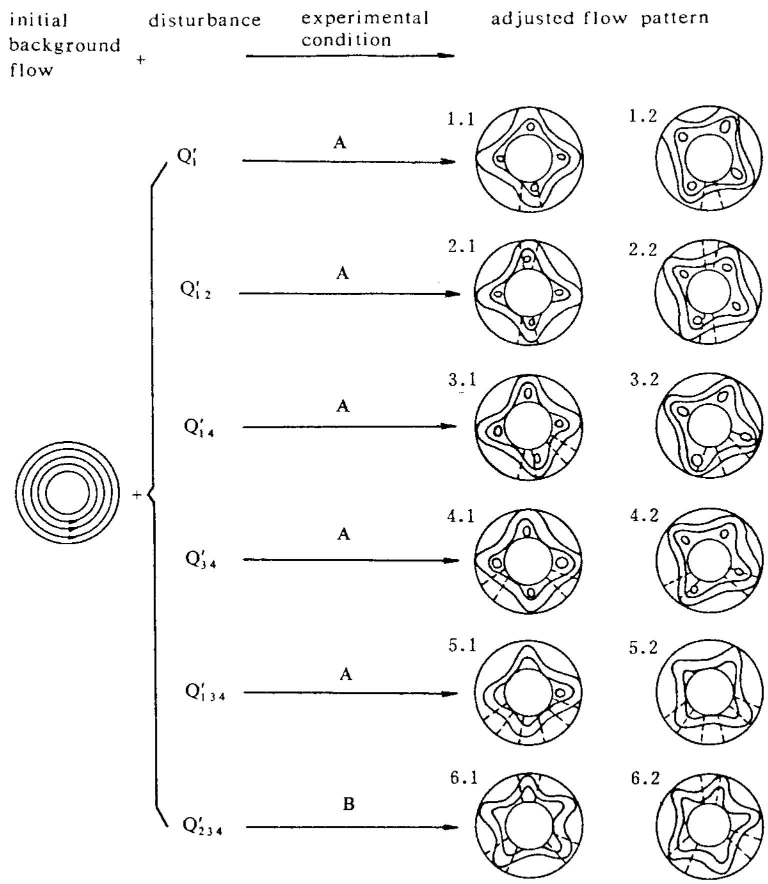

Fig. 6. Flow pattern change in the experiments with initial-axisymmetric background flow and with different disposition of heat sources. The dotted lines denote the heat sources. The experimental conditions are (A) – R_{OT} = 2.0, $T_a = 2.5 \times 10^7$; (B) – R_{OT} = 1.6, $T_a = 3.2 \times 10^7$.

unstable, in spite of the number and disposition of heat sources. Either the flow patterns change locally, or the whole flow patterns change with wave dispersion and wavenumber vacillation. In case of a single heat source, a periodical vacillation occurs in the initial 4 wave flow (series 1.1-1.4 in Fig. 7). In an experiment without radial temperature difference between the inner and outer walls of the annulus, we have observed divergent anticyclone flow in the middle and upper layers over the heat source. A very weak convergent cyclone flow is observed in a very thin low layer, large in area around the heat source. So when a wave trough with positive vorticity approaches the heat source Q'_1 from the upstream (the trough travels counterclockwise), the trough slows down, because the negative vorticity at middle and upper levers generated by Q'_1 is poured on the trough. When the trough moves over heat source, the meridional motion of the flow over the heat source turns into zonal one (see 1.2 in Fig. 7). After the trough has gone over the heat source, the flow pattern returns and accelerates downstream. When the number of heat sources is more than 1, the forcing of heat sources leads to an unstable wavenumber vacillation. For example, due to the influences of heat sources Q'_{12} the initial 4 wave flow turns into a unstable flow with vacillation between wave 4 and wave 5 (see series 2.1-2.4 in Fig. 7) . The forcing of heat sources Q'_{234} leads the initial 4 wave flow to a state of wave 6 and wave 7 vacillation (see series 3.1-3.4 in Fig. 7) . The forcing of heat source Q'_1 leads the initial 5 wave flow to a state of wave 5 and wave 6 vacillation. However, the forcing of heat sources Q'_{234} leads the initial 5 wave flow to a state of a deformed 5 wave flow (see 5.1-5.3 in

Fig.7). The observation shows that it seems there is a relation between characteristic wavelength and the horizontal scale of thermal disturbances. When the characteristic wavelength of the background flow is large enough comparatively to the heat disturbances, the influence of the disturbances on the background flow would be local. When the characteristic wavelength of the background flow is not large enough comparatively to the heat disturbances, the influence of the heat sources leads the whole flow field to a wavenumber vacillation. A more accurate experiment is recommended to study this relationship.

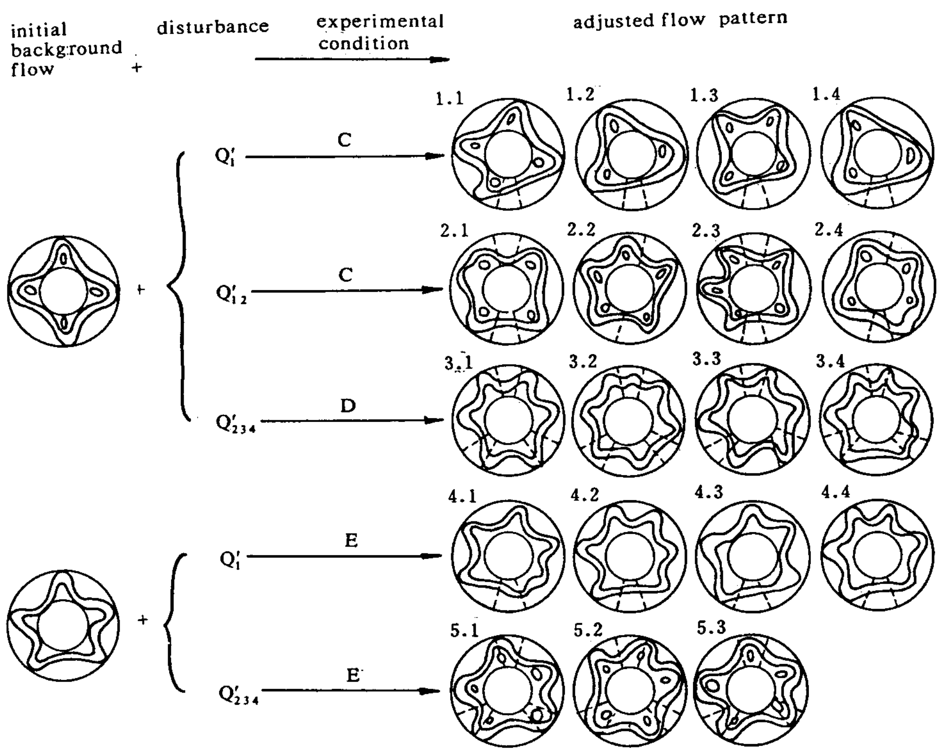

Fig. 7. Flow pattern change in the experiments with different disposition of the heat sources. The dotted lines denote the heat sources. The experimental conditions are: (C) – $R_{OT} = 4.4 \times 10^{-1}$, $T_a = 1.1 \times 10^8$, (D) – $R_{OT} = 3.4 \times 10^{-1}$, $T_a = 1.4 \times 10^8$, (E) – $R_{OT} = 1.6 \times 10^{-1}$, $T_a = 3.1 \times 10^8$.

3. A comparative experiment on topographic forcing

In order to make a comparison between the influences of the heat sources and topography, we have performed another series of experiments with topography. The topography used in the experiments consists of ladder-shaped platforms of 2.5 cm high with the same horizontal dimension and the same disposition of the heat sources in the above stated experiments. We use a symbol h'_{ijk} to represent the topography. Fig. 8 shows the flow pattern change in the initial zonal-axisymmetric and initial-wave flows due to the topographic forcing. The experiments show that if the initial background flow is zonal-axisymmetric (M=0) and the number of the disturbances is equal to or less than two, a 4 wave flow pattern appears (see series 1.1-1.2 and 2.1-2.2 in Fig. 8). In the case of the initial wave flow, the topographic forcing leads to a state of wave vacillation (see series 3.1-3.4 and 4.1-4.4 in Fig. 8). Returning to Fig. 6 and Fig. 7 and by comparison with Fig. 8, we can conclude that the responses of background flows to the forcing of Q'_{ijk} and h'_{ijk} are similar. Although the mechanisms of the thermal-convective forcing of the heat sources and the solid-boundary forcing of

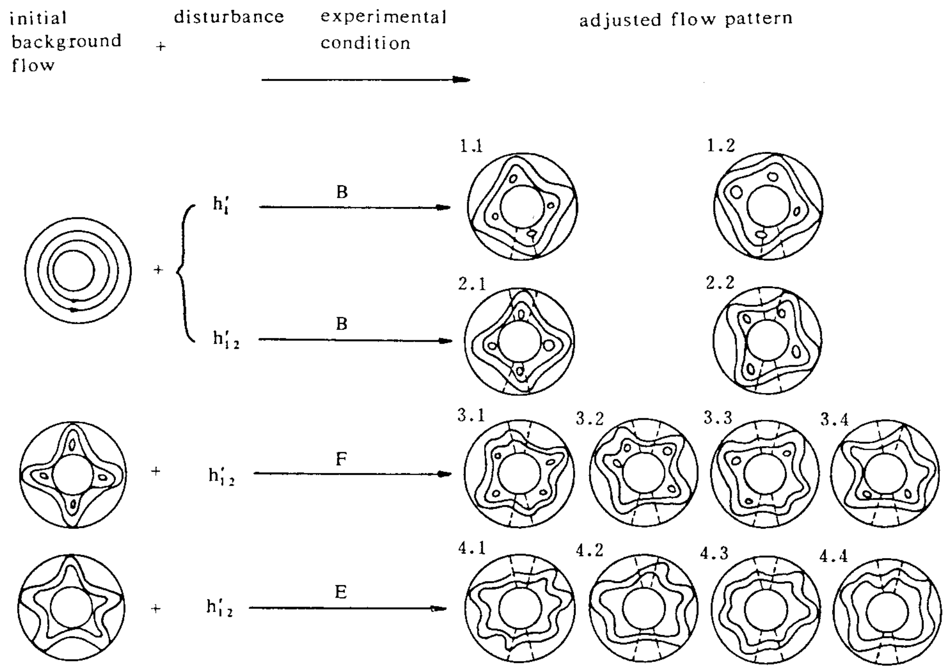

Fig. 8. Flow pattern change due to topographic forcing. The dotted lines denote the position of the topography. The experimental conditions are: (B) – R_{OT} = 1.6, $T_a = 3.2 \times 10^7$; (F) – $R_{OT} = 5.9 \times 10^{-1}$, $T_a = 8.5 \times 10^7$, (E) – $R_{OT} = 1.6 \times 10^{-1}$, $T_a = 3.1 \times 10^8$.

topography are essentialy different, both can change the vorticity distribution in the flow and lead to a new distribution of the vorticity in the flow field. Usually, there is a negative vorticity source at middle and upper levels over the heat source, and so a standing ridge exists over the heat sources. In the meantime a trough is generated on the downstream side of the heat sources. All the ridges and the troughs move downstream together with the background flow and are affected by both the background flow and the heat sources. Only when a dynamical balance of energy and vorticity is established between the background flow and the disturbances, a new equilibrium of the flow field appears. However, in the case of topographic forcing, the mechanism is essentially different. The topographic impact lies in the mechanical forcing on the background flow. It does not add any energy and vorticity to the flow. There is only the change of potential vorticity which causes the flow pattern to change. This change acts according to the principle of conservation of potential vorticity. In other words, the topography leads just to the redistribution of the vorticity already existing in the flow, but it does not generate new vorticity. Therefore, although the flow patterns formed due to forcing of heat sources and topography are alike, the total energy and vorticity in the flow for these two cases are different.

IV. Conclusion

1. The fundamental effect the large-scale topography exerts on the baroclinic flow is to modulate the flow and to make the flow uneven in space and in time. All the characteristics related to the flow field would vacillate periodically. Under the fixed experimental conditions, at least two kinds of flow regimes, the zonal and the meridional, exist. The period of the flow vacillation is equal to 127 annulus rotations which corresponds to 26 days in the Earth's atmosphere. This result renders us an

idea that the cause of the low frequency oscillation in the index cycle of the atmospheric circulation lies in the forcing of large-scale topography of the Earth.

2. Due to the forcing of large-scale heat sources the initial-zonal-axisymemtric background flow turns into wave flow. If the number of heat sources is less than two, a 4 wave flow is produced. That the number of heat sources is less or equal to two is a sufficient condition for a 4 wave flow formation. When the number of heat sources are more than two, the initial-stable-axisymmetric wave flow would turn into an unstable flow with wave vacillation. The newly formed flow patterns are dependent on the number of heat sources and their geographic distribution.

3. So long as the number of disturbance sources is less than or equal to two, no matter which kind of disturbances is, heat source or topography, the initial-zonal-axisymmetric flow turns into a 4 wave flow. In the case of an initial-wave background flow, the consequences due to the topographic forcing or to the heat source forcing are similar. This means that although the mechanisms of thermal-convective forcing due to the heat sources and the mechanical forcing due to the bottom topography are completely different, both can cause the fluid to ascend over the disturbance sources, and change the vorticity distribution in the flow and lead to the formation of new flow patterns.

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