Blocking Distributions in the Atmosphere

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ABSTRACT

The zonal momentum generation in forced stationary waves may exceed the requirement for momentum balance after long, if the waves do not change their patterns. This suggests that the changes in stationary wave patterns would be required by maintenance of momentum balance over the external forcings. It will be found that the low frequency anomalies like blocking regimes may produce reversed zonal momentum variations, if they happen in the observed centre areas. The zonal momentum balance in the stationary waves may be maintained effectively by alternation between the normal and blocking circulation regimes. Thus, from the point of long–term zonal momentum balance, we may explain the geographical distributions of the blocking centres and the seasonal variations in blocking areas and frequencies.

I. INTRODUCTION

The regional property in distribution of blocking events has been studied for many years since Rex (1950). Also, there is mounting evidence given by numerical experiments that the climatological mean stationary waves are responsible for much of the specific distribution of anomalies. For example, the numerical experiments performed by Frederiksen (1982, 1983, 1984) showed that the observed geographical distributions of low–and band–pass anomalies in both hemispheres may be simulated, successfully to some extent, by a quasi–geostrophic model, when the realistic stationary perturbation fields are adopted. Recently, a number of different theories have been proposed to explain some aspects of these anomalies. No matter what the theory one follows regarding the persistence of the anomalies, the basic problem of these anomalies occurring in specific geographical locations remains.

As the low frequency anomalies like blocking events may exist in a relatively long period, they must have significant influences on the long–term averaged balances of momentum and heat. These, however, were not investigated fully in the theoretical studies before, because the long–term balances depend essentially on nonlinear processes and so they must be studied by the primitive equations. In terms of these balances, we have explained the observed distributions of the planetary stationary waves (McHall, 1991a, b, hereafter referred to as P1 and P2 respectively). These studies showed that stationary waves in the atmosphere may produce asymmetric generations of heat and momentum, in order to balance the asymmetric variations caused by thermal and orographic forcings. These generations increase with amplitude of geopotential perturbation. In general, intensities of the external forcings decrease upward, and the observed stationary waves usually have the maximum amplitudes in the upper troposphere. Thus, the generations of heat and momentum may exceed the amount required by heat and momentum balance at high levels after a sufficiently long time period, if the stationary wave patterns are unchanged.

In P1 and P2, the thermal and orographic responses were discussed separately by means of heat and momentum balances. The feedbacks of heat and momentum from the forced stationary waves was not taken into account. For example, orographically forced stationary waves may produce adiabatic heating, while thermal stationary waves may produce accelerations. As the feedback results from forced waves themselves, it will be referred to as the self–feedback. For distinguishment, the surplus heat produced in thermal stationary waves and the surplus momentum produced in orographic waves will be called as the overgenerations.

We will be concentrated, in this study, only on the overgeneration and self–feedback of zonal momentum in stationary waves. If we assume that occurrence of anomalous circulation regimes is a response to the overgeneration and self–feedback, we may find that zonal momentum balance may be reserved by conversion of normal stationary waves into blocked patterns periodically, and the observed geographic distributions and seasonal variations of blocking events in both hemispheres may be explained. The multiple equilibrium wave regimes forced by the same topography will be discussed also, according to the zonal momentum balance in the different circulation regimes.

II. PHASE OF BLOCKING WAVES

The most prototypical example of the recurrent flow anomalies is the blocking events which typically persist beyond the periods associated with synoptic scale variability. Since the variation cycles of external forcings from oceans and cryosphere are generally much longer than the life of individual blocking episodes, the external forcings are responsible mainly for the climatological frequency of blocking. As revealed by Wallace and Blackmon (1983), the external forcings account for only a small fraction of low frequency variabilities at extratropical latitudes. While, that the low frequency anomalies may be produced in the internal processes is confirmed by various numerical experiments. For example, the 15–year general circulation model experiment performed by Lau (1983) demonstrated that the internal dynamics and physics of the model atmosphere are by themselves able to generate quite realistic blocking events.

We have noted already that momentum generation in the planetary stationary waves may exceed the amount required by momentum balance at high levels. This overgeneration is the possible climatological causes of the low frequency variabilities in the atmosphere. Thus in the present study, we assume that the blocking is an alternative circulation pattern to remove the residual zonal momentum produced by normal stationary waves. Based on this assumption, we may derive the observed phase relations between blocking and normal stationary waves in both hemispheres.

The normal geopotential perturbation described in P1 may be represented generally in the form

$$\varphi' = \Phi_n \sin\Psi_{sn} \ , \tag{1}$$

where, $\Psi_{sn} = my + lp - kx + \gamma$ ($k > 0$, and γ is a constant) indicates the phase planes. The asymmetric momentum generation by the normal waves reads

$$u'_n = A_n \cos(\Psi_{sn} - \gamma_n) \ , \tag{2}$$

in which, γ_n is determined by (24), (25) and (29) in P1. According to the previous assumption, the zonal momentum produced by blocking waves is in the opposite phase, that is,

$$u'_b = A_b \cos(\Psi_{sn} - \gamma_n \pm \pi) \ .$$

Therefore, the blocking geopotential field is written as

$$\varphi'_b = \Phi_b \sin(\Psi_{sn} - \gamma_n + \gamma_b \pm \pi) = \Phi_b \sin\Psi_{sb} \ ,$$

where, γ_b is estimated also by the same relationships in P1. The phases of blocking waves may then be given by

$$\Psi_{sb} = \Psi_{sn} + \gamma_b - \gamma_n \pm \pi \ . \tag{3}$$

If it is confirmed by the observed blocking positions in the atmosphere, we may think that the assumption used for deriving this relationship is proved as well.

III. BLOCKING IN THE NORTHERN HEMISPHERE

It was noted by Rex (1950) that the initiation of blocking systems in the Northern Hemisphere are favoured in the regions lying downstream from cyclone centres. As the major regions of blocking may be identified in low–pass filtered variance fields, the phase relation between block and normal waves may be inspected by comparing the low–pass variance in the geopotential field at 500 hPa shown in Fig.1a with the 500 hPa climatological stationary waves during the same period, displayed in Fig.1b which is similar to Fig.5 in P1.

Fig.1 shows clearly that the three maxima of variance are located slightly to the west of the three major ridges at middle latitudes respectively, and the relative intensity of each maximum is coincident with the intensity of relevant ridge. For the summer srason, the same consequence may be obtained as well by comparing the similar diagrams available from the study of Blackmon (1976). This relation was manifested also in many other studies (e. g., Dole, 1983; Wallace and Blackmon, 1983).

It was revealed in P1 and P2 that the forced planetary stationary waves at high levels are mainly associated with linear orographic response and nonlinear thermal response. Both the orographic and thermal waves may produce zonal momentum. The overgeneration of zonal momentum in the orographic waves is discussed in this section. While the self–feedback in the thermal waves will be investigated later to explain the seasonal changes in blocking events.

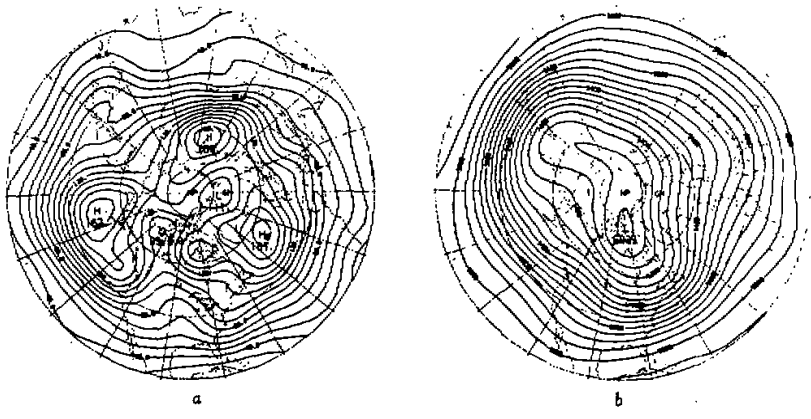

Fig.1. (a) Low–pass filtered variance (Contour interval 5 m) of geopotential height at 500 hPa for 9 winter (1963–1972) in the Northern Hemisphere. (b) mean geopotential height of 500 hPa during the same period (Contour interval 50 m). (After Blackmon, 1976).

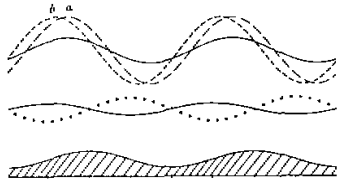

Fig.2. Blocking in the Northern Hemisphere. The normal stationary geopotential perturbation for the linear orographic response is represented by the upper solid line with $\gamma_n = 1.75\pi$. The dashed lines are blocking geopotential waves with $\gamma_b = 0.75,\ 0.6\pi$ for lines a and b, respectively. The zonal momentum generation in normal waves is expressed by the lower solid line, while in blocking waves is by the dotted line. The idealized topography is shown on the bottom.

From P1, when mean zonal flow is strong in the usual time, the normal geopotential perturbation forced linearly by orographic forcing at middle latitudes may be displayed by the upper solid line in Fig.2, of which $\gamma_n = 1.75\pi$. The asymmetric zonal momentum generation is then expressed by the lower solid line. As baroclinity enhances and mean zonal flow decreases in a blocking layer, (24), (25) and (29) in P1 show $A_1 < 0$, $A_2 > 0$ and so $\pi / 2 < \gamma_b < \pi$. Consequently, the blocking geopotential perturbations will be represented by the dashed lines a or b in Fig.2. Thus, the asymmetric generation of zonal momentum in the blocking waves, shown by the dotted line, is opposite in phase to that of normal waves.

It is obvious in Fig.2 that the position of blocking highs in the Northern Hemisphere is located near the ridges of normal stationary waves with a slightly westward displacement. When ageostrophic motions increase in the blocking events occurring on the polar side of a westerly jet as they usually do, magnitude of A_1 decreases so that the blocking highs may shift further to the west as shown by the dashed line b, for which generation of zonal momentum may be indicated identically by the dotted line.

The phase displacement of blocking waves depends also on some other factors. For example, as the sign of A_1 is dominated by the term of baroclinity, blocking ridges may exhibit a more plausible westward shift at higher latitudes. This result is consistent with the statistics repoted by Treidl et al. (1981). They concluded, after analysis of more than 30 years observations, that the blocks at high latitudes tend to retrogress more than the blocks initiated south of 55°N.

For the phases of orographic stationary waves have a specific relationship with asymmetric topography, the most favourable geographic regions for blocking events may be predicted by Fig.2 as well. In the Northern Hemisphere, they are located over windward sides of continents. Moreover, since the climatological stationary waves have the maximum amplitudes around 55°N in the upper troposphere (Wallace, 1983), which is on the north side of main topography, it is principally understandable that the most frequent latitude for occurrence of blocking events is about 56°N (Treidl et al., 1981; Coughlan, 1983) where the orographic forcing is relatively weaker compared with lower latitudes.

IV. BLOCKING IN THE SOUTHERN HEMISPHERE

Generally speaking, the maximum geopotential amplitudes in the Southern Hemisphere are about half of those in the Northern Hemisphere, because the orographic forcing there is

weak. Since the linear orographic response is proportional to the amplitude of geopotential wave, overgeneration of zonal momentum in stationary waves is smaller in the Southern Hemisphere, unless the mean zonal velocity is about twice as large as that in the Northern Hemisphere (P1). Therefore, the blocking events required to balance the overgeneration may be less intense and last for a shorter period in comparison with those in the Northern Hemisphere.

The geographic distribution of blocking events in the Southern Hemisphere was studied firstly by van Loon (1956). He pointed out that the positions of blocking relative to the phases of large scale waves were not similar in two hemispheres. From the studies of, for example, Lamb (1959), Coughlan (1983) and Kidson (1986), we may find that the favourable positions of blocking highs in the Southern Hemisphere are near or in the downstream of ridges. To give an evidence here, we compare Fig.3 with Fig.4. Fig.3 shows the climatological mean zonal asymmetries of 500 hPa geopotential height for the period of 1972–1978, produced by Trenberth (1980). While the longitudinal variation in frequency of blocked 500 hPa flow during the similar years (1972–1980) is displayed in Fig.4. It is shown that blocked flows are most preferred in the Australian region. Besides, they occur, in much less frequency, over the Atlantic and the Indian Oceans to the east of South America and South Africa respectively, especially during the winter season.

The most frequent latitudes of blocking events in the Southern Hemisphere are also different from those in the Northern Hemisphere. Among many others (e. g., Langford, 1960; Taljaard, 1972 and Wright, 1974), Coughlan (1983) concluded, by reviewing and comparing the statistics of blocking action in both hemispheres, that the mean latitude of Australasian / West Pacific blocking high is in the vicinity of 45°S, being slightly north of this latitude in the eastern Indian Ocean sector and slightly south in the western Pacific Ocean sector. This is in marked contrast to the most typical latitude of about 56°N for blocking highs in the Northern Hemisphere. This difference can be explained partly when we think that almost whole the earth's surface is covered by water at the middle latitudes of the Southern Hemisphere.

In the Southern Hemisphere, the observed stationary waves have maximum amplitudes on the equator side of the Antarctic Continent. The meridional flux of zonal momentum in the troposphere produced by stationary waves is generally equatorward at middle latitudes. This equatorward stationary eddy flux may be found in the statistic study of Newell et al. (1972), and shows a sharp contrast with the Northern Hemisphere's. Thus, in these waves $km > 0$. From (24), (25) and (29) in P1 then, the stationary geopotential perturbation may be represented by the upper solid line in Fig.5, of which $\gamma_n = 0.25\pi$. This is confirmed by the figures of climatological mean distributions of stationary geopotential perturbation at 200 hPa level produced by Wallace (1983). Generally during both winter and summer, two major ridges at middle latitudes appear in the downstream around 175°W and 65°W. The upstream troughs are centred at 30°E and 105°E.

In the blocking period when mean zonal flow is reduced and baroclinity is enhanced, there is $\pi < \gamma_b < 3\pi / 2$. If the blocking geopotential waves are in the phases shown by the dashed lines in Fig.5, they may produce the zonal acceleration opposite in phase to that generated by normal waves. Thus, the blocking highs appear near the ridges on the side of downstream. When affected by meridional shear of mean zonal flow, they may shift further down the wind on the polar side of westerly jet as represented by the dashed line b in Fig. 5.

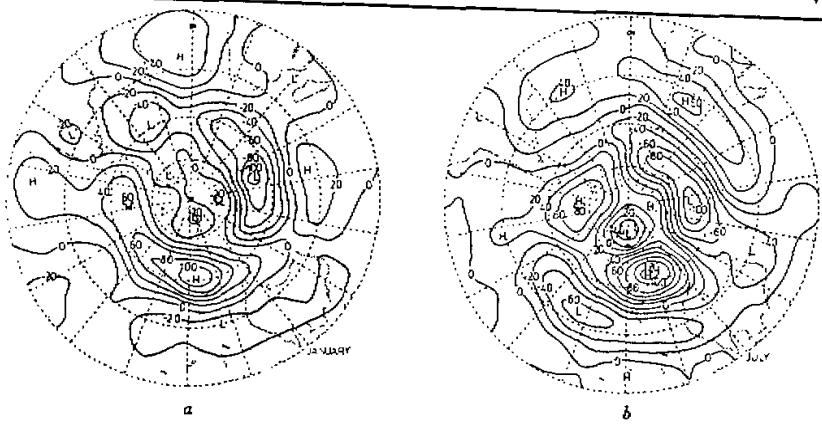

Fig.3. The 6–year (1972–1978) mean zonally asymmetric component of 500 hPa geopotential height in the Southern Hemisphere. Latitude cycles are every 20° beginning at 10°S. (After Trenberth, 1980).

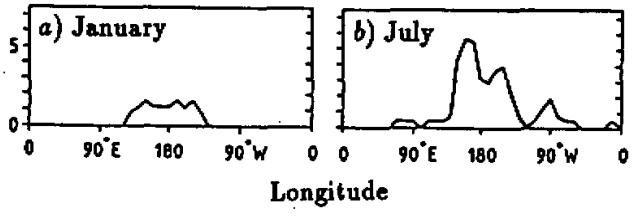

Fig.4. Longitudinal variation in frequency of blocked 500 hPa flow for 8–year (1972–1980) mean in the Southern Hemisphere, January (a) and July (b). (after Lejenas, 1984).

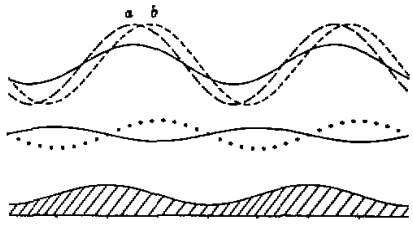

Fig.5. Blocking in the Southern Hemisphere. As in Fig.2 except $\gamma_b = 1.25$, 1.4π for the dashed lines a and b respectively. The normal geopotential perturbation is displayed by the upper solid line with $\gamma_n = 0.25$.

The blocking positions demonstrated in Fig.5 may be applied to explain the blocking at higher latitudes in the Australian and the Atlantic regions. As the ridge to the northeast of Australia is stronger, the frequency of blocking is higher there. Moreover, the ridges over the Pacific and the Atlantic Oceans are both intensified during the winter season, so the frequencies of blocking in these regions are increased (Referring to Fig.4) correspondingly.

In contrast, the blocking in the Indian Ocean during the winter season looks to be more

closely connected with the circulation pattern at lower latitudes. The mean latitude of blocking there is the lowest compared with other two blocking regions.

At lower middle latitudes of the Southern Hemisphere where angular momentum flux is poleward, we have $m < 0$ as $k > 0$. When mean zonal flow is strong, there is $3\pi / 2 < \gamma_n < 2\pi$ for normal waves. But if baroclinity is increased and mean zonal flow is decreased, there will be $\pi / 2 < \gamma_b < \pi$ in blocking waves. So the blocking highs at middle latitudes of the Southern Hemisphere take place, on average, around ridges of stationary waves. They will displace to downstream in strong baroclinic areas, especially on the equator side of maximum westerly flow.

V. MULTIPLE EQUILIBRIUM STATES

Charney and DeVore (1979) proposed firstly that there may be more than one stable solutions in a highly truncated two–layer barotropic model forced by the same orographic forcing. The similar discovery was made in baroclinic models (Charney and Straus, 1980; Roads, 1980a, b) also. At the beginning, the multiple equilibrium states were identified with the multiple mathematical solutions of simplified or truncated steady models, and dependent equally on the incorporated mean fields and physical processes. For these simultaneous multiple equilibrium states, a difficult question is to know how to select, from among the myriad of possibilities, the most revealing representations of general circulation state in a multi–dimensional phase space. Recently, the multiple states are investigated by time–dependent models (e. g., Legras and Ghil, 1985; Mukougawa, 1988) with special attention on the transitions between different regimes.

Since an equilibrium state may exist stably for a significant time period, the momentum and heat balances in the state must be considered in full scales, and cannot be dealt with, in principle, by means of the highly simplified or truncated models as in many other studies. However it is learned in P1, that linear orographic response is related, to a great extent, to mean zonal flow, but thermal response is not, so the momentum balance in the geostrophic stationary waves depends more crucially on the wave regimes compared with heat balance. Thus, we may consider that the weather regimes are associated mainly with zonal momentum balance. Here, we discuss some possible weather regimes, which meet only with momentum balances.

In the atmosphere with asymmetric thermal and orographic forcings, the various stationary wave patterns discussed in P1 and P2 may be regarded as the examples of equilibrium states in normal cases. The effects of external forcings may be balanced in rough by the adiabatic heating and zonal acceleration produced in the normal stationary waves. While, as the blocking waves described previously are a necessary complementary circulation regime, for the stationary waves to maintain zonal momentum balance, they may be regarded as another wave regime. As these two regimes complement each other to remain the zonal momentum balance in the atmosphere, and do not exist at the same time in a specified region, they are the non–simultaneous equilibrium states. In addition to these, we discuss below the possibility for the existence of simultaneous equilibrium states corresponding to the same orographic forcing.

As emphasized earlier, the amplitudes and phases of orographically forced stationary waves depend not only on topography, but also on the structure of mean circulation, such as the intensities of baroclinity and mean zonal flow. When the typical scales of the observed mean structure are applied, the stationary waves required by zonal momentum balance are those as illustrated in P1 and P2. However, in some particular cases, different stationary wave

Fig.6. Multiple equilibrium regimes of stationary waves corresponding to the same linear orographic response. Dotted line: $\gamma_1 = 1.75\pi$; dashed line: $\gamma_1 = 0.75\pi$. The generation of zonal momentum by either the two wave regimes is sketched by solid line.

patterns may satisfy the local balance as well, so that they may exist stably in a significant duration. Therefore, if considered locally, different mean fields may possess different wave patterns which produce the equivalent heating and acceleration to balance the variations caused by the same external forcings.

For example, we consider the two extreme cases of the orographic waves discussed in P1. In regime 1 with amplitude Φ_1, the mean zonal flow is very strong so that we may write

$$A_1 \approx \left(\frac{\bar{u}}{a^2\beta} + \delta - \frac{1}{f}\frac{\partial \bar{u}}{\partial y}\right) k\Phi_1 \ , \quad A_2 \approx -\frac{\bar{u}}{f} km\Phi_1 \ ,$$

and the geopotential perturbation at middle latitudes of the Northern Hemisphere may be expressed by the dotted line in Fig.6. The asymmetric zonal acceleration produced by this regime is represented by the solid line below. While for regime 2 with feeble mean zonal flow and strong baroclinity,

$$A_1 \approx -\frac{\sigma_y^2}{f^2\sigma_z}\Phi_2 \ , \quad A_2 \approx \frac{\delta km\Phi_2}{f(k^2+k_T^2)}\left(\beta + \frac{a^2}{a^2\beta}\right) ,$$

where, Φ_2 measures the amplitude. The corresponding geopotential perturbation is displayed by the dashed line in Fig.6. This different regime produces the same zonal acceleration as regime 1. It is found that these two wave regimes are opposite in phase, which is similar to that obtained by Charney and DeVore in a low–order barotropic model with orographic forcing underlying.

For the same orographic forcing with amplitude F, the amplitudes of regimes 1 and 2 are given by

$$\Phi_1 = \frac{F}{k\sqrt{\left(\frac{\bar{u}}{a^2\beta} + \delta - \frac{1}{f}\frac{\partial \bar{u}}{\partial y}\right)^2 + \frac{\bar{u}^2}{f^2}m^2}}$$

and

$$\Phi_2 = \frac{fF}{k\sqrt{\frac{\sigma_y^4}{f^2\sigma_z^2} + \delta^2\frac{\left(\beta + \frac{f^2}{a^2\beta}\right)^2}{(k^2+k_T^2)^2}m^2}}$$

respectively. As the magnitudes of A_1 and A_2 in regime 1 are greater than those in regime 2, the amplitude of regime 1 is smaller than that of regime 2.

Therefore, the selection of a presentation from multiple states depends on mean circulation structure. As this structure makes effect on the transport of heat and momentum, the

corresponding sources and sinks of heat and momentum must be taken into account as well. For example, as shown in P2, the zonal mean wave flux of heat is proportional to the square of geopotential perturbation, and we may prove that it is also true for the zonal mean wave flux of angular momentum. So, the heat and momentum transport by a low–index regime may be greater than that by a high–index regime. For provided mean circulation structure and boundary conditions, only the regime with heat and zonal momentum flux coincident to the real sources and sinks may actually take place in the atmosphere.

For the reasons discussed above, the choice of representative regime in the atmosphere of provided mean structure will be made uniquely if the nonlinear processes and boundary conditions have been considered fully, since the zonal mean momentum and heat fluxes or long–term averaged momentum and heat balances depend essentially on the nonlinearity. This conclusion may be verified by the studies of Tung and Rosenthal (1985) and Cehelsky and Tung (1987). When the effect of full nonlinearity was included in the two–layer model which was used previously by various authors to produce multiple equilibrium states after severe truncation, they found that the converged solution exhibited only one weather regime.

VI. SELF–FEEDBACK OF ZONAL MOMENTUM

In P1 and P2, balances of heat and zonal momentum in stationary geostrophic waves were considered separately, but the self–feedback of heat and momentum was not accounted. In this study, we are interested merely in self–feedback of zonal momentum in the stationary waves induced nonlinearly by thermal forcing. As linear orographic response is generally greater than nonlinear response at high levels, only the linear self–feedback of zonal momentum is accounted, which may be calculated also by (2). For the self–feedback affects zonal momentum balance, it may have influences on the alternation of circulation regimes. These influences may change with season as the thermal stationary waves do. In terms of the seasonal changes, we may explain the geographic asymmetry of annual variations in blocking frequency in the Northern Hemisphere. Comparing this explanation with observations will give another critical test of the theory.

In general, amplitudes of perturbations and mean westerly flows in the atmosphere are stronger in winter than in summer. As there is the positive correlation between zonal momentum generation and geopotential perturbation or mean zonal flow, blocking events may be more frequent in winter hemisphere. However, this seasonal variation is not symmetric along latitude. Some examples of the annual variations near 60°E and 160°W of the Northern Hemisphere are shown in Fig.7, which are selected from the diagrams produced by Lejenas and Økland (1983) with 30 years datasets from 1950 to 1979.

As discussed earlier, blocking action in the Northern Hemisphere is preferred in the upstream of ridges. Referring to Fig.1 in P2, we find that the region over the Pacific Ocean is behind the ridge of thermal stationary wave in winter, but behind the trough in summer. When affected by the thermal stationary waves, the contrast of b locking frequencies between winter and summer in this region will be most plausible, and the wintertime blocking frequency wherein may be much higher than in any other places. Whereas, the region over North Africa has the reversed relations to the thermal stationary wave phase during winter or summer. Thus, seasonal contrast of blocking frequency is minimum there, and the summertime blocking frequency reaches the highest compared with that in other places. This similar consequence was reported also in the statistic study of Treidl et al. (1981). Additionally, it was

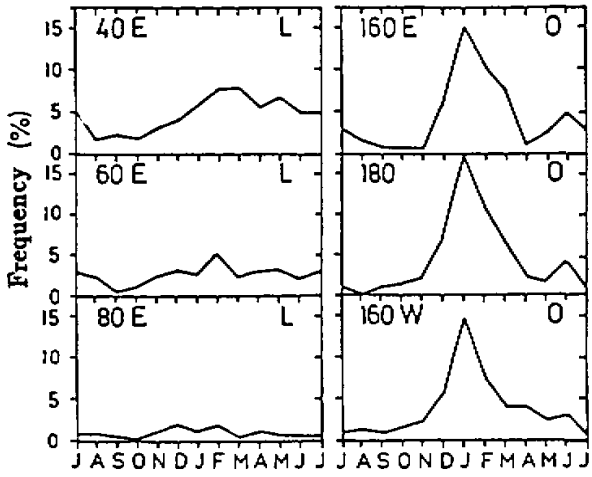

Fig.7. Annual variations in frequency of blocked 500 hPa flow for every 20° longitude, produced by 30–year datasets (1950–1979). L = land; O = ocean. (After Lejenas and Qkland, 1983).

predicted in P2 that thermal stationary waves at high levels displace eastward from winter to summer. Therefore, as manifested by Treidl et al. (1981), seasonal variations in the principal regions of blocking in the Northern Hemisphere reveal a systematic shift eastward from winter through summer, then towards reversely the winter distribution in autumn.

VII. SUMMARIES

It has been supposed that the zonal momentum generation in forced stationary waves may destroy the momentum balance especially at high levels, if the stationary wave pattern is unchanged over a sufficiently long period. The alternation between normal and block regimes is hence necessary for maintenance of zonal momentum balance in the atmosphere. From this point of view, we have explained the distributions of the most preferential regions of blocking highs, which usually occur around ridges or in many cases slightly to the upstream in the Northern Hemisphere, but to the downstream in the Southern Hemisphere. Thus, blocking events in the Northern Hemisphere are characterized by discontinuous retrogression of ridges, especially at high latitudes. In contrast, the blocking events in the Southern Hemisphere exhibit frequently the downward progression of highs, as noted early by van Loon (1956), Lamb (1959), Wright (1974) and recently by Trenberth and Mo (1985).

Since the intensities of zonal momentum feedback and orographic overresponse are correlated to the amplitude of geopotential perturbation and mean zonal flow, blocking events in both hemispheres are more frequent during the winter season. It is found also that in the Northern Hemisphere, the self–feedback of zonal momentum from thermal stationary waves at high levels is much responsible for the seasonal swing of the most frequent blocking longitudes, and has great contribution to the zonal asymmetry of annual variation in blocking frequency. For the orographic response in stationary waves is nearly independent of baroclinity, the blocking waves present an almost barotropic structure.

Obviously, the normal and blocking waves are the alternative regimes of planetary wave

circulations required by zonal momentum balance. These two regimes correspond to different mean circulation fields respectively, such as the mean zonal flow and its horizontal and vertical shears. Thus, if they are regarded as the example of multiple equilibrium states, they will be different from the multiple solutions with respect to the same mean fields. In terms of the long–term zonal momentum balance, the weather regimes corresponding to the provided mean fields together with the sources of heat and momentum will be determined uniquely in physics and should be studied in the whole atmosphere involving full nonlinear processes and realistic boundary conditions.

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