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On the Development of Blocking Ridge Activity Over the Central North Pacific

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ABSTRACT

Monthly mean atmospheric data taken over the North Pacific during the period 1950-70 are used to investigate blocking ridge activity over the central ocean. The blocking ridge is observed to be a finite-amplitude, quasi-stationary long wave, most often centered over the North Pacific at 170W, superimposed upon the quasi-zonal mid-latitude westerlies. The dominant length scale is 7000 km, the same dimensions as the width of the mid-latitude ocean. The growth time scale is 1-2 weeks, with the duration of blocking activity rarely exceeding 2 months in any given year. The blocking activity is confined almost exclusively to the autumn/winter months, where block development is closely coupled with the sensible heat transfer from the underlying ocean (anomalously small heat transfer under the ridge and anomalously large heat transfer under the associated troughs). Year-to-year variability in blocking ridge activity is found to have a dominant time scale of approximately 5 years from 1950-70 and to be inversely correlated (-0.79) with the strength of the autumn/winter mean mid-latitude westerlies (the mean formed using months not containing blocking activity). Further analysis shows that both blocking ridge activity and the strength of the westerly winds fluctuate together with the Southern Oscillation over this time period.

These space/time scale considerations suggest that this regional blocking activity owes its existence to the marine environment. To test this idea, appeal is made to some theoretical work by Haltiner, where the baroclinic instability process was modified by sensible heat transfer from the ocean to the atmosphere. Haltiner found that for normal winter values of the background flow, the otherwise stable stationary long wave became unstable when sensible heat transfer was allowed. The wavelength for the unstable stationary wave was 7000-8000 km with a growth time scale of approximately 2 weeks. The scales are similar to that of blocking ridge activity over the North Pacific.

In addition to good scale agreement with observations, Haltiner's theory is able to explain both the seasonal and year-to-year variability in blocking activity in terms of corresponding fluctuations in sensible heat transfer and the strength of the mean westerly winds.

1. Introduction

For 25 years a central problem in long-range weather forecasting over North America has been understanding how blocking ridges develop over the central North Pacific Ocean. When blocking occurs, the passage of synoptic storms across the ocean is interrupted, and the storm paths over the North American continent are altered. This, of course, has an important influence upon the weather experienced there.

It has long been recognized (e.g., Rex, 1951) that the mid-latitude westerlies over the North Pacific exist in either one of two quasi-stationary wave states: one associated with primarily zonal motion and the other characterized by meridional motion (i.e., blocking situations). Typical winter monthly mean maps of 700 mb height over the North Pacific are displayed in Fig. 1. The wave state associated with primarily zonal motion is found most frequently and is characterized by that of January 1955 with a trough off the east coast of Asia and a ridge over the west coast of North America. The wave state associated with blocking ridge develop-

ment is found less frequently and is characterized by that of January 1956 with a ridge over the central ocean near 170W and troughs at the ocean's perimeter, resulting in a typical wavelength of ~ 7000 km. Comparing these maps to the long-term mean map of 700 mb height for the month of January (Fig. 2) shows that the blocking ridge is a finite-amplitude wave perturbation to the quasi-zonal mean flow. When blocking activity is absent, the flow configuration is much like the mean state. Therefore, the blocking ridge seems to be a quasi-stationary instability of some kind, whose presence or absence may depend upon characteristics in the annual mean zonal flow over the mid-latitude North Pacific.

Reasons for development of the mean wave state have been known for some time. Smagorinski (1953) has investigated the influence of large-scale heat sources and sinks upon the zonal mid-latitude westerlies utilizing a thermally active, stationary perturbation model of the atmosphere. In his model, heat sources represent the oceans during winter, and heat sinks represent the

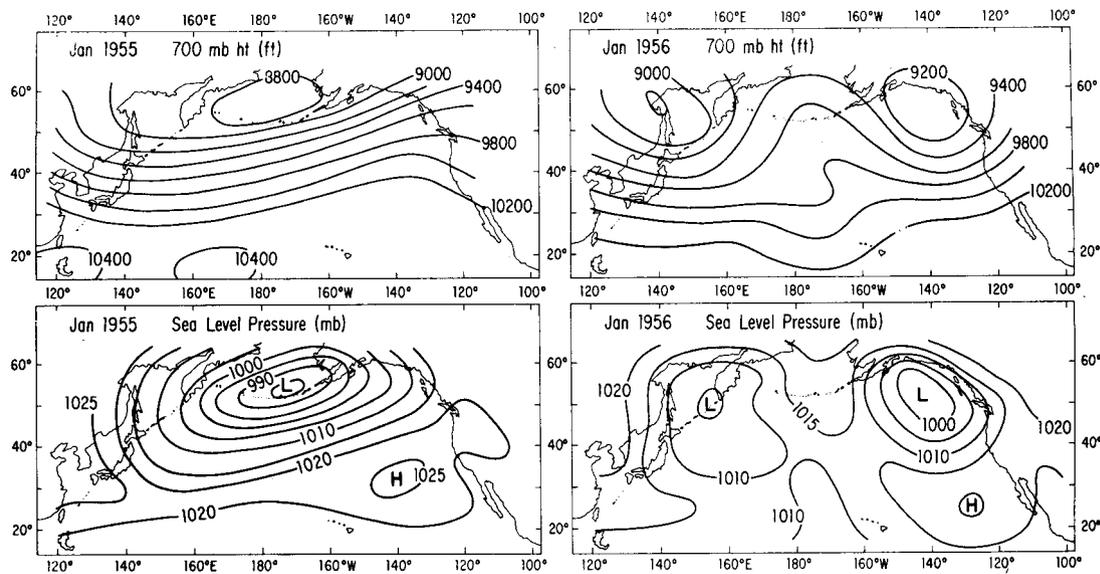


FIG. 1. Monthly mean maps of 700 mb height and sea level pressure over the North Pacific for January 1955 and January 1956.

continents. He was able to show that the present distribution of continental heat sinks and oceanic heat sources in the Northern Hemisphere were responsible (together with continental orographic effects) for the

development of the mean quasi-stationary long waves that are observed (Fig. 2), i.e., ridges over the continents and troughs over the oceans with the latter intensified off the east coast of continents. In addition,

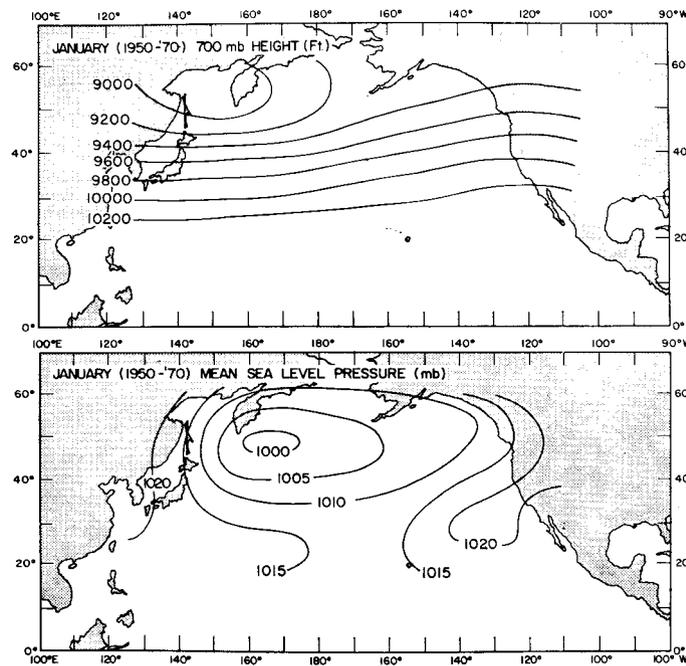


FIG. 2. Long-term (1950-70) monthly mean maps of 700 mb height and sea level pressure for January.

he shows the upper-level troughs and ridges to be in phase with the heat sources and sinks, respectively, whereas the associated low-level pressure systems are displaced one-quarter wavelength downstream (Fig. 2).

The reasons for development of the mid-ocean blocking ridge are not yet known. Various investigators have tried to understand the mechanisms responsible for blocking activity, but with limited success. In an early study, Namias (1950) postulated that the blocking ridge occurred in response to a buildup of cold air over the polar regions that was contained by strong mid-tropospheric westerlies. The formation of the block acted to discharge this cold air into subtropical regions, thereby maintaining a balance between heat gain at the equator and heat loss at the poles. This is equivalent to saying that the blocking ridge is a manifestation of baroclinic instability. At about this same time, Rex (1951) suggested that block development was analogous to a hydraulic jump in open channel flow. More recently, Bjerknes (1969) observed that blocking ridges tended to form when the autumn/winter mid-latitude westerlies were weaker than normal and hypothesized that they were shorter stationary Rossby waves. However, this explanation, like that of Rex, lacks a feasible energy source required to excite this quasi-stationary wave state.

From a different point of view, Namias (1959) hypothesized that the mid-ocean blocking ridge could be a fundamental unstable mode of the coupled ocean/atmosphere interacting system which derives its energy from thermal energy anomalies contained in the upper ocean. However, it seems clear from the work of Clark (1967) and Kraus and Morrison (1966) that the fluctuating ocean temperature does not necessarily play an active role in thermal energy exchange on time scales less than a year. Furthermore, mid-ocean blocking ridge development has been duplicated in numerical simulations of the January climatic state (e.g., Mintz, 1968; Rountree, 1972) by treating the ocean as a passive infinite heat source that gives up thermal energy to the atmosphere on demand.

In the present study, we expand the theoretical idea suggested by Namias (1950) and show that blocking ridges can result through the mechanism of baroclinic instability, but only in the presence of sensible heat transfer from the ocean to the atmosphere. This accounts for the presence of blocking ridge activity over the central North Pacific. In the absence of sensible heat transfer, baroclinically unstable stationary wave growth is not possible, except at unrealistically high values of the thermal wind. However, Haltiner (1967) has shown that with sensible heating from the ocean, which is treated as an infinite heat source, both stationary and retrograde waves can grow in amplitude for normal values of the thermal wind. The time and length scales of these unstable stationary waves are narrowly defined but are the same as those observed in mid-ocean blocking ridge development.

Because mid-ocean blocking ridges can be interpreted as baroclinically unstable waves, seasonal and year-to-year differences in blocking activity may be associated with changes in the characteristics of the annual mean mid-latitude westerlies and the sensible heat exchange over the North Pacific. This is clearly demonstrated in the subsequent development.

2. Blocking ridge defined

Before proceeding further, we need to define what is meant by the term "blocking ridge." In the past, this term has had different interpretations. The best definition seems to have been given by Rex (1951), who cataloged blocking ridge activity over both the North Pacific and North Atlantic from 1933-50. He gave the following definitions (slightly paraphrased):

- 1) A sharp transition in the westerlies from a zonal type upstream to a meridional type downstream must be observed.
- 2) The basic westerly current must split into two branches, each transporting appreciable mass.
- 3) This double jet must extend for more than 45 degrees of longitude and last for greater than 10 days.

Upon inspection of Fig. 1 for January 1956, it is clear that this wave pattern meets all of the criteria listed above. As such, it can be considered an example of a classical blocking situation.

Whereas Rex determined blocking ridge activity from a study of Northern Hemisphere synoptic weather maps, we plan to investigate blocking ridge activity using Northern Hemisphere monthly mean maps (prepared by the Long Range Prediction Group of the National Weather Service). As such, we are not able to determine the growth time of a blocking situation as Rex was able to do; we are able only to determine that it existed for enough time to dominate the monthly mean pressure pattern.

Upon inspection of the monthly mean maps, we found in most cases, when part 1) of Rex's definition was found, that 2) was also satisfied. However, we also discovered many cases where this was not true; a sharp transition in the westerlies from a zonal type upstream to a meridional type downstream was not always associated with a splitting of the westerly current, as for example in Fig. 3. Yet, clearly this wave state represents a block to the eastward passage of storms. Thus, we have altered Rex's definition of a blocking ridge to include waves of the type shown in Fig. 3. In addition we have specified that the amplitude of these waves must exceed 5° of latitude. The definition for our present use reads:

A blocking ridge exists when a sharp transition in the mid-latitude westerlies from a zonal type upstream to a meridional type downstream occurs with an amplitude exceeding 5° of latitude.

We emphasize that we are designating blocking ridge development over the North Pacific and excluding

from data in Table 1. During the period of time from 1950-70, the seasonal maximum occurred in the autumn/winter season (October-March) with an ill-defined minimum in spring/summer. Earlier work by Rex (1951) on the seasonal variability of blocking activity differs somewhat from these results, but this can be traced to his inclusion of mountain blocking activity. We find that blocking activity over the Rocky Mountains is primarily a spring/summer phenomenon and would seriously alter the seasonal variability of North Pacific blocking activity if included.

There is little that we can add to the description of the growth process of blocking ridges due to the inadequate time resolution involved in working with monthly mean maps. In most instances the presence of blocking activity was not preceded by any suggestion of ridging in the previous month (see Table 1). Yet, in some instances of blocking activity, the block seems to have been preceded by a slight ridging in the previous

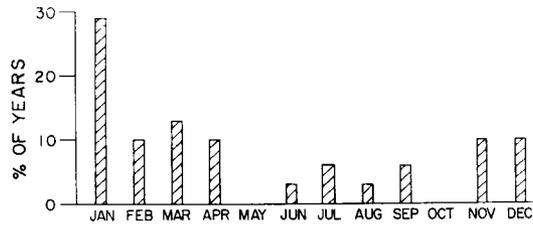


FIG. 4. Histogram based on data in Table 1 displaying the long-term monthly variability of blocking ridge activity from 1950-70 (31 cases).

month. More importantly, in some of these situations, the ridging preceding the block seems to have occurred east of the blocking location, generally just off the west coast of North America. The resulting block development seems to arise from a westward (i.e., retrograde) motion of this initial ridging phenomenon. For an ex-

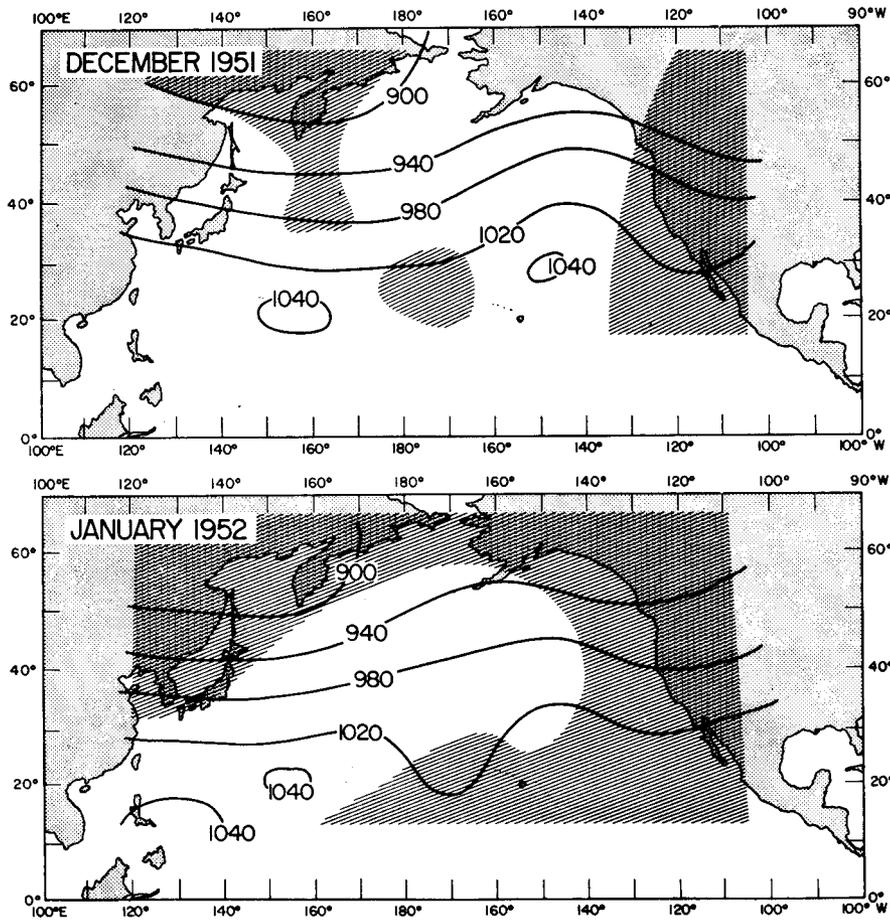


FIG. 5. Monthly mean maps of 700 mb height over the North Pacific for the months of December and January, 1951-52. The background shading indicates regions of negative 700 mb height anomaly.

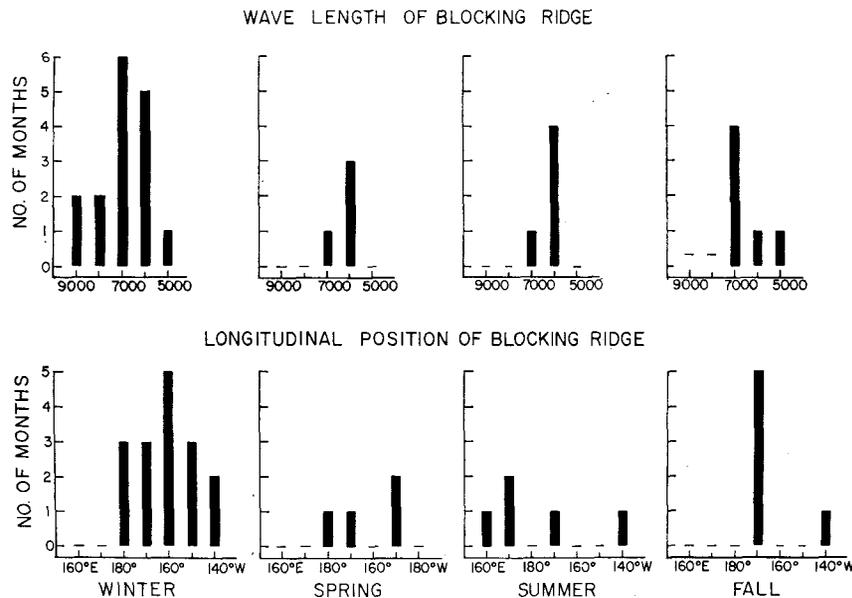


FIG. 6. Histograms based on data in Table 1, displaying the wavelength and longitudinal position of the blocking ridges, with seasonal resolution.

ample of this, consider Fig. 5 which shows the 700 mb height fields for the months of December 1951 and January 1952 when a blocking ridge was fully developed in January. In 1951, the month of November was nearly normal (not shown), but in December a wide ridge began building off the west coast of North America and extended out over the eastern North Pacific. Then in January 1952 the block occurred over the central ocean, apparently developing from a retrograde displacement of the initial ridging off the west coast of North America.

The time scales of year-to-year variability in blocking ridge activity will be discussed in a separate section.

4. Space scales of blocking ridge activity

In most cases of blocking ridge activity noted in Table 1, the center of the ridge was found at 170W which is the center of the North Pacific at mid-latitudes. Associated with this, the modal wavelength of the blocking ridge (i.e., the distance between the troughs off the east coast of Asia and off the west coast of North America) was found to be ~ 7000 km, the same dimensions as the width of the North Pacific at mid-latitude.

Seasonal variability of the blocking ridge wavelength is indicated in Fig. 6. In autumn and winter the modal wavelength is clearly 7000 km, while in spring and summer it is 6000 km. A seasonal breakdown in longitudinal position of blocking activity is also indicated. In autumn and winter the modal position of the blocking activity is between 160 and 170W, but during the

spring and summer it is ill-defined, with individual blocking situations extending from 160E-140W.

In summary, blocking ridge activity is found most often during the autumn/winter months (October-March), is located at 170W near the center of the North Pacific, and has a wavelength (7000 km) that is the same as the zonal dimensions of the mid-latitude ocean. These results provide a basis for the hypothesis that blocking ridge activity owes its existence to the underlying ocean environment. The next section explores this possibility.

5. Sensible heating and blocking ridge activity

Mid-ocean blocking ridge activity occurs during the autumn and winter months (Fig. 4) when the maximum heat transfer from the ocean to the atmosphere takes place (Clark, 1967). Therefore, because the blocking ridge also develops near the center of the North Pacific, it is reasonable to suggest that the local sensible heat transfer from the sea surface, Q_s , may be important in its development.

First, consider some individual months where the anomalous sensible heat flux field (taken from Clark, 1967) is compared with the anomaly of 700 mb height associated with mid-ocean blocking ridge activity. Fig. 7 shows these anomalous fields from November 1956 to January 1957. Note that the anomalous ridging associated with the growth of the blocking ridge is associated with anomalously low sensible heat transfer at the surface. Alternately, anomalous troughing is

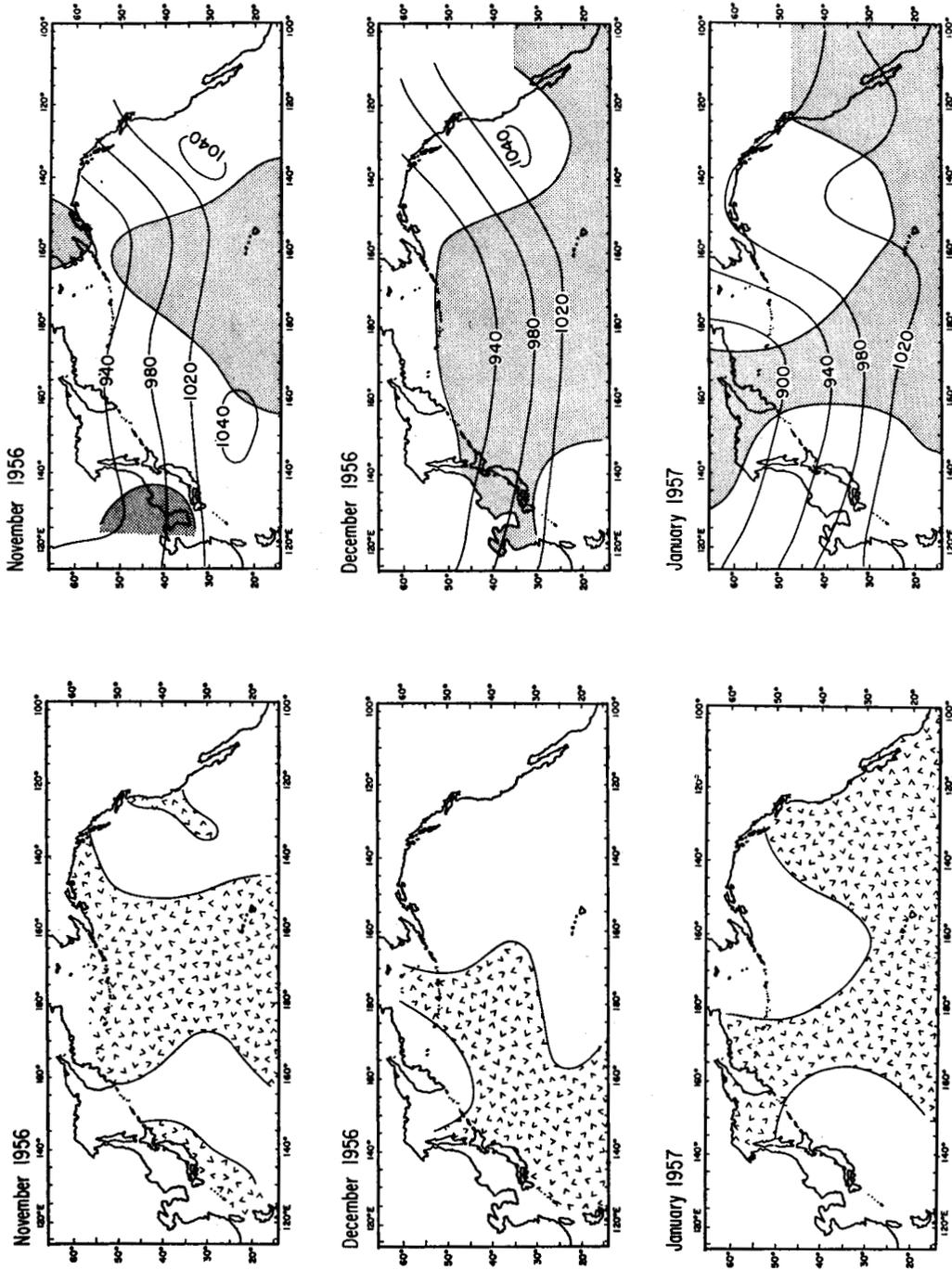


FIG. 7. The sensible heat flux anomaly Q_s (left) and 700 mb height anomaly (right) for the months of November, December and January of 1956-57. The mean in this case was taken over the period 1951-57, the time period over which heat flux information was available (Clark, 1967). In the left-hand panels, patterned areas designate anomalously high sensible heat flux; in the right-hand panels, shading designates anomalously low 700 mb height.

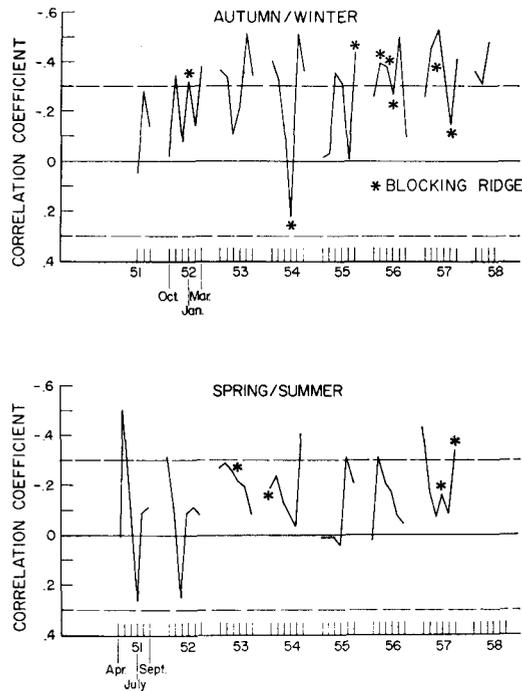


FIG. 8. The time sequence of pattern correlation between anomalous sensible heat exchange (taken from Clark, 1967) and 700 mb height anomaly over the North Pacific from 20–55N: upper panel, autumn/winter months (October–March); lower panel, spring/summer months (April–September).

associated with anomalously high sensible heat transfer at the surface. Pattern correlations between anomalies of Q_s and 700 mb height fields for these three months are -0.46 , -0.52 and -0.36 , respectively.

Pattern correlations between anomalous sensible heat exchange and anomalous 700 mb heights for other years are plotted in Fig. 8. The upper panel of Fig. 8 displays the correlation coefficients for the autumn/winter months while the lower panel shows those for the spring and summer months. Because Clark's sensible heat flux data only extend over the period 1951–57, and because no other heat flux data exist over the North Pacific, the statistical analysis was restricted to that time period.

The correlations between anomalous sensible heat flux and 700 mb height fields during the autumn and winter seasons in the upper panel of Fig. 8 are nearly always negative, with a distribution skewed toward values ranging from -0.3 to -0.5 . These values represent significant pattern correlations as can be seen with Fig. 7. The months containing blocking ridge activity were designated by asterisks; in most cases (6 out of 8) the pattern correlations exceed -0.3 .

The correlations between anomalous sensible heat flux and 700 mb height fields in the lower panel of

Fig. 8 remain primarily negative, but with values that are mostly less than -0.3 . Because it is difficult to assign degrees of freedom to this statistic, the determination of the significance of these correlation values is uncertain. Certainly, the degree of correlation is much less during the spring and summer months than it is during the autumn and winter months. Moreover, those months that had blocking ridge activity (denoted by asterisks) all had larger negative correlation coefficients.

An explanation of the persistent inverse relationships between anomalies of Q_s and 700 mb height can be found by examining the bulk formula for the calculation of sensible heat transfer:

$$Q_s = \rho C_p C_D W (T_s - T_a), \quad (1)$$

where ρ is the air density, C_p the specific heat of air, C_D the drag coefficient, W the wind speed, T_s the sea surface temperature, and T_a the air temperature near 1000 mb. From Clark (1967) and Kraus and Morrison (1966), fluctuations in anomalous sensible heat transfer on a time scale of months to a year is dominated by the fluctuating (i.e., anomalous) atmospheric parameters, W' and T_a' . If individual parameters in (1) are written in terms of mean and anomaly quantities, and we only consider the effect of fluctuations in T_a , then the anomalous sensible heat formula can be written

$$Q_s' = -\rho C_p C_D \bar{W} T_a'. \quad (2)$$

From the hydrostatic relation, the thickness between 1000 and 700 mb is a function of the mean virtual temperature (T_v) of the layer. In anomaly terms, the hydrostatic relation is written

$$(\Delta Z)' = -\frac{R}{g} \ln \left(\frac{P_1}{P_2} \right) T_v', \quad (3)$$

where R is the gas constant, g the acceleration due to gravity, P_1 the pressure of the lower surface, and P_2 the pressure of the upper surface. Therefore, if we consider the surface air temperature to be proportional to the mean virtual temperature in the lower troposphere, then (2) and (3) can be combined, in which case

$$Q_s' = -a(\Delta Z)' = -a(H_{700}' - H_{1000}'), \quad (4)$$

where a is a constant of proportionality and H_p the height of the pressure surface p . Therefore, Q_s' is inversely proportional to the anomalous height of the 700 mb pressure (H_{700}').

These results indicate that during the autumn and winter seasons anomalous sensible heating is associated with anomalous heights of the 700 mb pressure surface and is induced by the anomalous virtual temperature associated with the latter. During the spring and summer months, this relationship breaks down somewhat although certain months display high correlations. These results suggest further that any mechanism that is offered to explain the formation of the blocking ridge

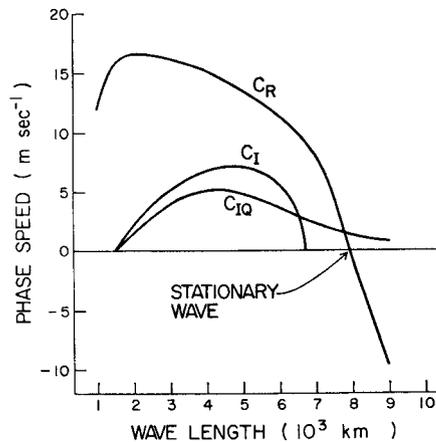


FIG. 9. The real (C_R) and complex (C_I) phase speeds of the baroclinically unstable waves, both with sensible heat transfer and without [taken from Haltiner (1965) for a mean wind of 30 m s^{-1} and a thermal wind of 10 m s^{-1}].

must take into consideration the flux of sensible heat between ocean and atmosphere.

6. The baroclinically unstable blocking ridge

The simplest hypothesis that can fit these descriptive results is that the mid-ocean blocking ridge is a baroclinically unstable long wave which derives its energy from the mean available potential energy in the atmosphere and is modified by sensible heat transfer from the ocean.

Normal baroclinically unstable waves have maximum growth rates on the order of a few days and propagate in the direction of the mean wind with a speed that is on the same order as that of the vertically averaged wind. Haltiner (1967) has investigated this instability mechanism in the presence of sensible heat exchange utilizing a two-layer, quasi-linear model of the atmosphere and treating the ocean as an infinite heat source. In his model, the perturbations in sensible heat flux are induced by air temperature fluctuations in a formulation similar to that found in the observed data discussed in the previous section. Furthermore, the magnitude of sensible heat transfer was set at a value ($Q = 63 \text{ cal cm}^{-2} \text{ day}^{-1}$) that is about two-thirds of the average across the North Pacific during January (Clark, 1967).

Haltiner finds that the presence of sensible heat flux has an effect upon the dispersion relationship of unstable waves, shifting the maximum growth rate to shorter wavelengths, yet also allowing longer waves to become baroclinically unstable (Fig. 9). Furthermore, with sensible heat exchange, it becomes possible for baroclinically unstable long waves ($\sim 7000\text{--}8000 \text{ km}$) to become stationary and for slightly longer waves to be retrogressive. These results begin to describe some of the time and length scales of blocking ridge activity.

To be more quantitative (yet still realizing the limitations of this model), Haltiner also made a parametric study of the dispersion relations for different values of the mean thermal wind. The growth rate for stationary long waves between 7000 and 8000 km is plotted versus the strength of the thermal wind in Fig. 10. The latter is defined as the difference in the wind between 400 and 800 mb . Although we have no data at upper levels to determine the thermal wind between 400 and 800 mb over the North Pacific, the long-term zonally averaged shear at 45N over the globe is about 12 m s^{-1} (Mintz, 1968). If we assume this to be true also for the North Pacific, then the time scale of growth is about one month, slightly larger than those observed during the development of mid-ocean blocking ridges (Section 3). Furthermore, the length scale of these stationary waves is $\sim 8000 \text{ km}$, again slightly larger than that of the blocking ridge (Section 4).

This theory not only accounts for the similar time and length scales of mid-ocean blocking ridge development, but also for the observed retrogressive development of quasi-stationary waves with slightly longer wavelengths (see Section 3). On the other hand, it does not explain why blocking ridges exist for only one or two months. The inability to predict what happens to the blocking ridge after it is fully developed is due to the quasi-linearity of the model; it can only indicate what happens in the initial growth stages. For a better understanding of what happens after the mid-ocean blocking ridge has formed, a simple global general circulation model could be useful.

7. Discussion of seasonal variability

Based upon the interpretation of the mid-ocean blocking ridge as a manifestation of baroclinic instability, we should be able to explain the seasonal character of blocking ridge development: Why does the

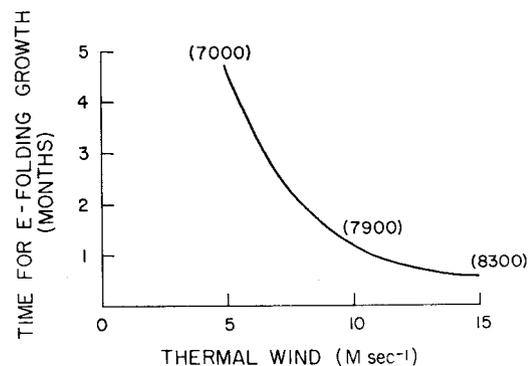


FIG. 10. A plot of the e -folding growth time of stationary, baroclinically unstable waves for different values of thermal wind (taken from Haltiner, 1967). The mean wind and sensible heat flux are held constant at 30 m s^{-1} and $63 \text{ cal cm}^{-2} \text{ day}^{-1}$, respectively. Wavelengths are contained in parentheses.

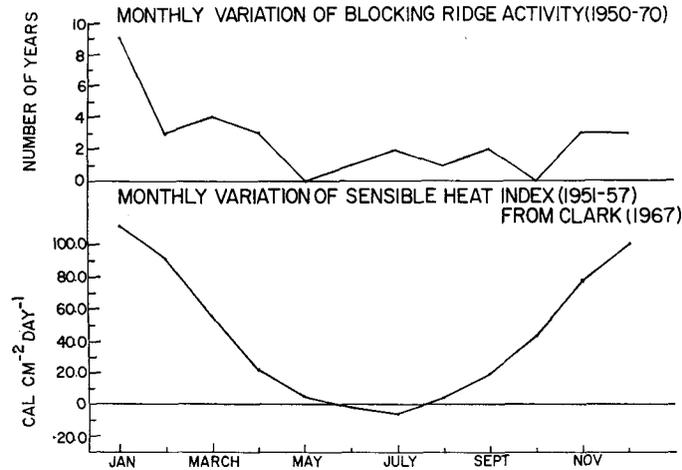


Fig. 11. Monthly variability of blocking ridge activity, equivalent to upper panel of Fig. 4, together with monthly variability of sensible heat flux index (defined in the text).

blocking activity form more often in the autumn and winter seasons and less often in spring and summer? From Fig. 7, the development of the stationary unstable wave owes its existence foremost to the presence of sensible heating from the ocean to the atmosphere. If this heating is reduced from Haltiner's values during the summer, then we might expect that blocking ridges would be absent during this time.

To see if this is true, consider the seasonal variability of blocking ridge activity from 1950–70, repeated from Fig. 4, displayed together with the seasonal variability of a sensible heat index (Fig. 11). This sensible heat index represents averages computed over the area from 135E to 135W at latitudes from 32.5 to 47.5N. The sensible heat data is taken from Clark (1967), extending from 1951–57. Note that the sensible heat index has a seasonal variability which resembles that of blocking ridge activity. More important, however, is the fact that on the average, sensible heating over the North Pacific is effectively zero from May through August during most of the spring and summer months. On the basis of Haltiner's theory, this would preclude the existence of blocking activity during this period of time, and, indeed, blocking activity is much suppressed during these months. On the other hand, during the autumn and winter months, the sensible heat index is between 50 and 100 cal cm⁻² day⁻¹, values that are comparable to that (63 cal cm⁻² day⁻¹) used by Haltiner. Therefore, it appears that Haltiner's theory can adequately explain the seasonal variability of blocking ridge activity.

These results also explain why pattern correlations between the anomalous sensible heat and 700 mb height fields in Fig. 8 are lower during the spring and summer months than they are in the autumn and winter.

During spring and summer, very little sensible heat signal exists, and the noise contained in these computations becomes large enough to reduce the correlation much below what it is in the autumn and winter seasons when the signal is relatively large.

8. Year-to-year variability in blocking ridge activity and in the mean mid-latitude westerlies

Table 1 shows that mid-ocean blocking ridge activity varies from year to year. The number of months in autumn and winter seasons when blocking ridges occurred is plotted in the upper panel of Fig. 12. Autocorrelating this time sequence yields a 5–6 year dominant time scale during 1950–70. This is the same dominant time scale found when autocorrelating the autumn/winter mean surface and thermal wind indices over the same time period. This suggests that the year-to-year variability of blocking ridge activity may be related to the strength of the mid-latitude westerlies.

To determine what the relationship is between blocking ridge activity and the strength of the mid-latitude westerlies, consider the time sequences of the autumn/winter mean indices of the surface and thermal winds in the lower troposphere (two lower panels of Fig. 12), which represent averages computed over the area 32.5–47.5N and 135E–135W. The surface wind was computed from monthly mean pressure data (published by the Long Range Prediction Group of the National Weather Service) using the geostrophic assumption. The thermal wind for the lower troposphere between 1000 and 700 mb was computed from monthly mean thickness charts (prepared by Jerome Namias at Scripps Institution of Oceanography) using the thermal wind relation.

Correlating surface wind and thermal wind indices with the frequency of blocking ridge activity yields in each case a negative correlation of -0.78 that is significant at the 95% confidence level. Therefore, blocking ridge activity was higher than normal when both the surface wind and the thermal wind in the lower troposphere were weaker than normal. To make sure that the autumn/winter mean surface wind and thermal wind indices were not weak because of blocking ridge development, the autumn/winter means were recomputed using only those months of each year that were free of any ridging activity (Table 1). Comparing these time sequences (not shown) with those in the lower two panels of Fig. 9 shows little difference in the year-to-year variability, although the long-term mean in each case is about 5% higher.

Although both the surface wind and the thermal wind in the lower troposphere are weaker in those years when mid-ocean blocking activity is higher, it is still possible that the thermal wind is stronger in the upper troposphere. At present, no monthly mean data are at hand to test this possibility. However, the strength of the thermal wind at upper levels can be inferred from the strength of convective activity in the central equatorial North Pacific, which is directly related to the local Hadley circulation. Bjerknes (1969) explains this in the following way: warmer equatorial surface water increases convective activity along the ITCZ that leads to the release of latent heat at upper levels and causes the local Hadley circulation to in-

tensify. This, in turn, results in an increase in the mean poleward transport of heat. The thermal wind in the subtropical jet stream (at approximately 30N) increases at upper levels, which results in intensified baroclinic instability (i.e., synoptic storms) that transfers excess equatorial heat poleward across the mid-latitude zone. This enhanced baroclinic instability also leads to Reynolds stresses that intensify the mean zonal westerlies. On the other hand, when equatorial waters are colder than normal, baroclinic instability at mid-latitudes is reduced in intensity since there is less mean available potential energy to draw upon. Furthermore, the Reynolds stresses are weak, and the mean zonal westerlies are reduced.

This explanation for the teleconnection between convective activity at the equator and the intensity of zonal westerlies has been supported by Rowntree (1972) using a hemispheric general circulation model constructed at the NOAA Geophysical Fluid Dynamics Laboratory at Princeton. Rowntree finds that when the central and eastern equatorial Pacific have higher than normal temperatures, the convective activity is greater, the local Hadley circulation is intensified, and the mid-latitude westerlies over the central and eastern latitude Pacific are intensified and displaced southward. Any sign of blocking ridge activity is absent. On the other hand, when the equatorial ocean has lower than normal temperatures, the Hadley Cell is weakened, with both blocking and non-blocking situations found in the mid-latitude westerlies.

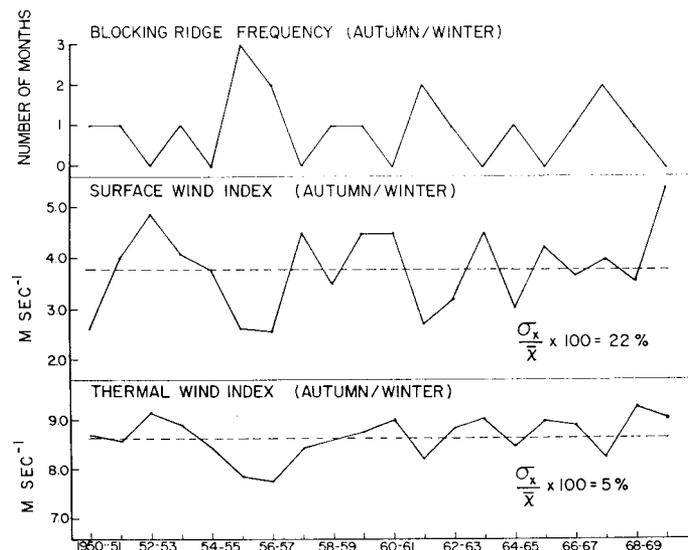


FIG. 12. In the upper panel is the number of months of the autumn/winter season in each year when the blocking ridge activity was detected. In the lower panels are the time sequences of the autumn/winter mean surface wind and thermal wind indices. Both indices are taken from 32.5 and 47.5N and from 135E to 135W. The thermal wind is the difference in geostrophic wind between 1000 and 700 mb.

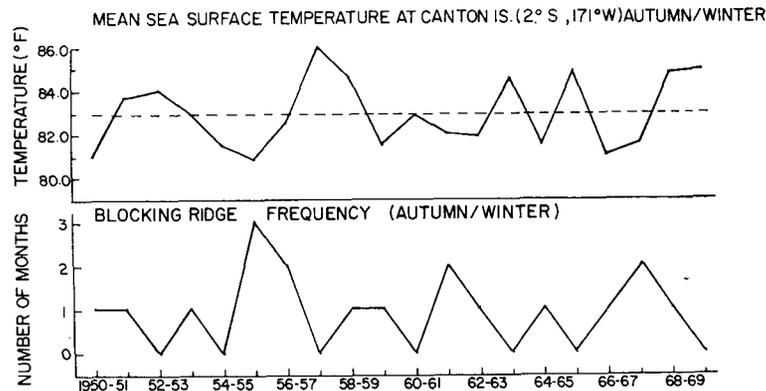


FIG. 13. Time sequence of the autumn/winter mean sea surface temperature at Canton Island (2S, 171W) and the time sequence of blocking ridge activity, repeated from Fig. 12.

These numerical results concerning blocking ridge development can be supported by considering in Fig. 13 the time sequence of autumn/winter mean sea surface temperatures near Canton Island (2S, 171W), and the autumn/winter frequency of blocking ridge activity. The sea surface temperature at Canton Island has been shown by T. Barnett (personal communication) to be representative of sea surface temperature over the entire central and eastern equatorial Pacific. Moreover, Bjerknes (1969) has shown that from 1955–67, the sea surface temperature at Canton Island (and indeed over the entire central and eastern equatorial Pacific) fluctuates in concert with the Southern Oscillation, as represented by sea level pressure anomaly at Djarkarta, Indonesia.

Autocorrelating the time sequence in the upper panel of Fig. 13 yields the same 5–6 year dominant time scale as found in the time sequence in the lower panel. Cross correlating these two time sequences yields a negative correlation (-0.69) that is significant at the 95% confidence level. The sign of this correlation is the same as that of the correlation between blocking activity and the thermal wind in the lower troposphere.

Therefore, it appears from both observation and numerical experiment, that a necessary, yet not sufficient, condition for blocking ridge activity to develop at mid-latitudes is that convective activity in the local Hadley cell over the central and eastern equatorial Pacific Ocean be lower than normal, which is associated with a reduction of the mean zonal westerlies in both the upper and lower troposphere of the mid-latitude westerlies. Moreover, it is clear that both the blocking ridge activity and the strength of the zonal westerlies at mid-latitude fluctuates from year to year in concert with the Southern Oscillation.

9. Discussion of year-to-year variability

If we consider year-to-year changes in the autumn/winter sensible heating, little change is found in the

way sensible heating is correlated with 700 mb height (Fig. 8) and in its overall magnitude (i.e., the year-to-year variability is less than $\pm 5\%$ of the long-term mean). A similar statement can be made about year-to-year changes in the autumn/winter thermal wind index (Fig. 12). On the other hand, the year-to-year variability in the mean wind (assumed proportional to the surface wind) is about $\pm 25\%$ of the long-term mean. This gives us a clue for understanding the year-to-year variability in blocking ridge activity.

In Haltiner's theory, unstable wave growth depends upon the magnitude of the thermal wind and of the sensible heating from the ocean to the atmosphere. On the other hand, the wavelength of the stationary wave depends upon the magnitude of the mean zonal wind. In fact, the stationary wave has a wavelength L , determined by the Rossby wave dispersion relation:

$$L = 2\pi(U_0/\beta), \quad (5)$$

where U_0 is the mean wind (vertically averaged) and β the meridional derivative of the Coriolis parameter.

In Haltiner's model, U_0 is set equal to 30 m s^{-1} , which from Mintz' global climatic data is only slightly higher than the mean westerly wind for winter. This value of mean wind yields through (5) a 7600 km wavelength, as can be seen in Fig. 9. Consider what would happen to this dispersion relation if the growth characteristics were to remain the same (i.e., Cr_Q in Fig. 9 remains unchanged), but the mean winds were reduced by 25% (i.e., from 30 to 22.5 m s^{-1}) in agreement with observed year-to-year changes in the autumn/winter mean surface wind. The stationary wave would then be found at 6800 km, and, more important, the e -folding growth rate would be increased by a factor of 2 (see Fig. 14).

In this case, we would expect to see stationary blocking ridge development of length 6500–7000 km, with an e -folding growth time of about two weeks. These growth time scales are what has been observed by Rex (1951)

in his study of blocking ridge development with synoptic data. The length scales are what we observe in the North Pacific in those years when the winds are weaker than normal.

In those years when the mean wind is stronger than normal by 25% (i.e., from 30 to 37.5 m s⁻¹), the stationary wavelength would be 8700 km, with an *e*-folding growth rate nearly half the normal rate. Therefore, not only would the allowable unstable stationary waves be longer than the zonal dimensions of the North Pacific basin, but the *e*-folding growth times would be about two months. Therefore, it seems that blocking ridge development is precluded in those years of intense westerly winds, which agrees with observation.

10. Conclusions

From this description of mid-ocean blocking ridge activity, a number of results can be summarized:

1) The blocking ridge over the central North Pacific is a finite-amplitude, quasi-stationary perturbation that is superimposed upon the otherwise quasi-zonal mid-latitude westerlies. It is usually centered near 170W, in the center of the North Pacific basin, and has a typical wavelength of 7000 km which also happens to be the width of the North Pacific at 40N. This suggests that mid-ocean blocking ridge activity owes its existence to the marine environment.

2) The time development of the mid-ocean blocking ridge has been previously determined by Rex (1951) to be from 1–2 weeks. From the monthly mean data presented here, the duration of the blocking activity is found to extend not more than 2–3 months in any one year.

3) A study of the seasonal variability of mid-ocean blocking ridge activity shows that blocking is more intense in the autumn and winter months (defined as October–March) and less intense in the spring and summer months (April–September).

4) Because blocking ridge activity is confined to the marine environment during autumn and winter seasons, the sensible heat transfer from the ocean to the atmosphere was thought to be important in its development. This is indeed the case; the anomalous distribution of sensible heat transfer during the autumn and winter seasons was strongly correlated (inversely) with the anomalous 700 mb height associated with blocking ridge development. Above-normal sensible heat exchange was found under the associated troughs and below-normal heat exchange under the ridge itself. This anomalous heat flux distribution arises in response to anomalous air temperature fluctuations associated with the blocking ridge development.

5) A study of year-to-year variability in autumn/winter blocking ridge activity shows that it is intense in those years when the surface wind and the thermal wind in the lower troposphere are both weaker than normal (correlated at -0.78).

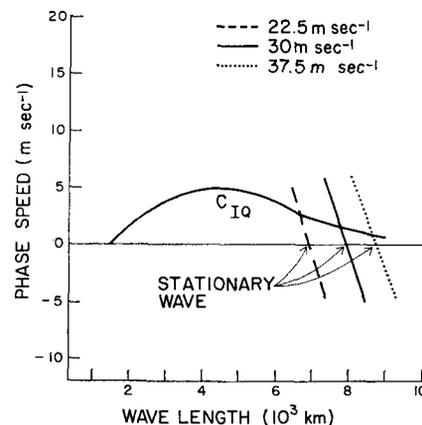


FIG. 14. Figure 9 repeated where C_R is plotted for three different values of mean wind (22.5, 30.0, 37.5 m s⁻¹) representing low, normal and high values, respectively.

6) The autumn/winter blocking ridge activity and the strength of the mean zonal westerlies fluctuate from year to year in concert with the Southern Oscillation.

Because the formation of mid-ocean blocking ridges occurs most often in autumn and winter months when the mid-latitude westerlies and sensible heat exchange are at their maximum values, the hypothesis is formed that blocking activity is due to baroclinic instability processes which are modified by sensible heat transfer between ocean and atmosphere. To support this hypothesis, appeal is made to the theoretical results of Haltiner (1967) who has established that for normal winter values of mean wind, thermal wind and sensible heat exchange, a stationary wave of 8000 km length scale has an *e*-folding growth time of about one month. These scales are somewhat larger, but similar to those observed for blocking ridge development over the North Pacific.

The seasonal variability of blocking ridge activity emphasizes the importance of sensible heat exchange between ocean and atmosphere to the baroclinic instability of stationary waves. In the absence of sensible heat exchange, stationary waves cannot be made unstable since their wavelengths are too long. However, with sensible heat exchange the long waves are made unstable, and stationary waves can grow. We observe them as mid-ocean blocking ridges. The reason blocking ridge activity is much reduced in spring and summer over that in autumn and winter is because from May to September the net sensible heat exchange over the mid-latitude North Pacific (Fig. 6) is almost negligible.

The year-to-year variability of blocking ridge activity emphasizes how well Haltiner's model agrees with observations. Earlier in this section, we stated that for normal winter values of mean wind, thermal wind, and sensible heat exchange, the resulting length and time scales derived from Haltiner's model were

slightly too large compared with observations. Yet, observation also shows that autumn/winter blocking ridge activity is most intense in those years when the mid-latitude westerlies are weaker than normal and that it is often precluded in those years when the mid-latitude westerlies are stronger than normal. It is established that the year-to-year variability in the thermal wind and sensible heat exchange is small (i.e., $\pm 5\%$ of the long-term mean) but that the surface wind experienced a $\pm 25\%$ range of variability. Therefore, in Haltiner's model, keeping the thermal wind and sensible heat exchange the same, but decreasing the winter mean wind by 25%, reduces the wavelengths of the stationary unstable wave to 6800 km and decreases the time for e -folding wave growth to about two weeks. These time and length scales are in excellent agreement with observations.

Moreover, for mean winds 25% greater than the winter normal, the stationary wavelength is 8700 km, much larger than the North Pacific basin (7000 km wide), and has an e -folding growth time of from about two months. These time and length scales seem to be too large for stationary waves to realistically develop.

Although this application of baroclinic instability theory seems reasonable, it requires additional confirmation before it can be accepted as the dominant mechanism responsible for the formation of blocking ridges over the central North Pacific. Additional theoretical approaches to the problem are needed—for example, to determine what influence continental constraints and latent heat release have upon instability mechanisms over the ocean.

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