Blocking Action in the Middle Troposphere and its Effect upon Regional Climate

I. An Aerological Study of Blocking Action

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(Manuscript received 10 August 1950)

Abstract

A comparative study of five cases of blocking action in the upper westerlies is presented with the two-fold objective of obtaining a more complete description of this phenomenon and of attempting an explanation of its initiation, development and dissipation in terms of parameters derived from an hydraulic analogue. The effect of European blocking upon the zonal and meridional circulation indices and the rôle of blocking in the evolution of hemispheric circulation patterns are discussed. In Part II, to be published later, the results of a preliminary semi-statistical analysis of blocking action, together with a description of the regional precipitation and mean surface-temperature anomalies produced by blocking, are presented. The statistical results obtained are discussed in relation to recent climatic fluktuations.

Introduction

Within the sector lying between 120° W and 60° E longitude and at the 500 mb level, the normal circulation pattern may be described as a relatively broad westerly current (jet) circulating around the circumpolar vortex and bounded to the south by the sub-tropical high-pressure belt. Pronounced variations in the width and strength of these westerlies and in the extent and intensity of the circumpolar vortex are observed from day to day and month to month. A particular longitudinal variation in this circulation pattern frequently appears on the synoptic chart irrespective of season. This anomaly expresses itself as follows; the flow over the North American continent and western Atlantic, which is an essentially zonal motion at a relatively high energy level, subsequently "breaks down" over the European continent or eastern Atlantic into a more cellular motion at a lower energy level. A series of wave disturbances are most generally observed superimposed on the zonal motion, whereas the more meridional type is characterized by the appearance of a train of cyclonic and anticyclonic vortices; the energy released along such a flow channel is absorbed in the large-scale horizontal vortices just mentioned. Important characteristics of this pattern are that it is persistent and quasi-stationary and that the change in each case from an essentially zonal to an essentially cellular flow occurs abruptly at a rather well defined longitude, usually between 30°W and 10° E, and not as a progressive change from west to east. The trough-and-ridge diagram given by HOVMÖLLER (1949) for Nov. 1945 (a blocked period) shows these features quite clearly. Figure 1 illustrates a well-developed, although not unusual, example at the 500mb level of the circulation anomaly just described. It is interesting to note the similarity between this pattern

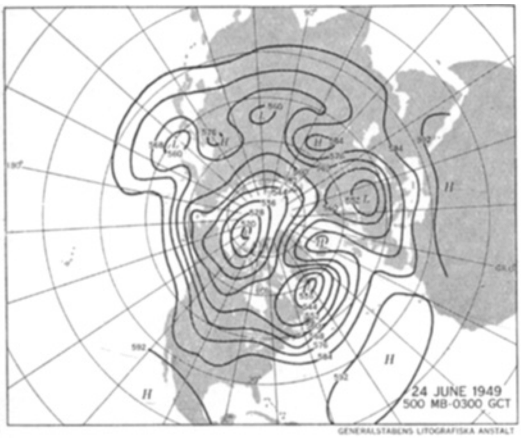

Fig. 1. An example of well developed blocking action over Eurasia. Absolute topography in dynamic decameters.

and the "Viererdruckfeld" described by Raethjen (1949) in connection with his treatment of cyclogenesis; the "Delta" used in his terminology corresponds to the point of jet division shown in Figure 1.

A usual feature of the macro-turbulent region in well-developed cases is the formation of a quasi-stationary warm ridge or anticyclone just downstream from the point of "breakdown". This anticyclone may subsequently progress toward the east or move slowly retrograde, or it may remain essentially stationary in company with its associated high-pressure cell at the surface. Situations, showing the pronounced development of such a quasi-stationary anticyclone were first noted by Garriott (1904), and are now commonly referred to as examples of "blocking action" (the surface anticyclone being called the "blocking high"). Considerable attention has been directed to them because of their pronounced influence upon other weather features even at a considerable distance up- and downstream.

In particular the work of Namias (1947) and Elliott and Smith (1949) should be noted. These writers have presented a comprehensive description of the phenomenon and its development in the lower troposphere and have discussed its effect upon synoptic developments at the surface. Yeh (1949) has presented a theory of blocking which explains the more striking features of the process in terms of the retrograde motion of the longer wave components in a nondivergent baratropic atmosphere. In a more recent paper Berggren, Bolin and Rossby (1949) have described the blocking process at the 500mb level and its association with developments in the lower atmosphere. They point out the difficulty of explaining the blocking development in terms of the growth of wave-like perturbations and suggest that the standing-wave or hydraulic-jump, which may develop in open-channel flow under certain circumstances, resembles at least superficially the blocking phenomenon in the atmosphere. Rossby (1950) has further developed this analogy and, using a simplified model, has been able to derive an analytical expression for one necessary condition for blocking.

The objective of this paper (Part I) is to extend the aerological description of blocking action in the middle troposphere obtained by Berggren, Bolin and Rossby (1949) and to attempt an explanation of its initiation, development and eventual dissipation in terms of parameters derived from the hydraulic-jump analogue. In a second paper (Part II), to be published later, the results of a preliminary semi-statistical analysis of blocking action (1933—1949), together with a description of the regional precipitation and mean surface-temperature anomalies produced by blocking, are presented. These statistical results are discussed in relation to recent climatic fluctuations.

As a result of work to be reported in Part II, a definition of blocking action at the 500mb level has been derived which will be used in the following discussion. A blocking case must exhibit the following characteristics:

a) the basic westerly current must split into two branches,
b) each branch current must transport an appreciable mass,
c) the double-jet system must extend over at least 45° of longitude,
d) a sharp transition from zonal type flow upstream to meridional type downstream must be observed across the current split, and
e) the pattern must persist with recognizable continuity for at least ten days.

In a situation satisfying these requirements blocking is said to be initiated when (a) occurs and is said to have dissipated whenever

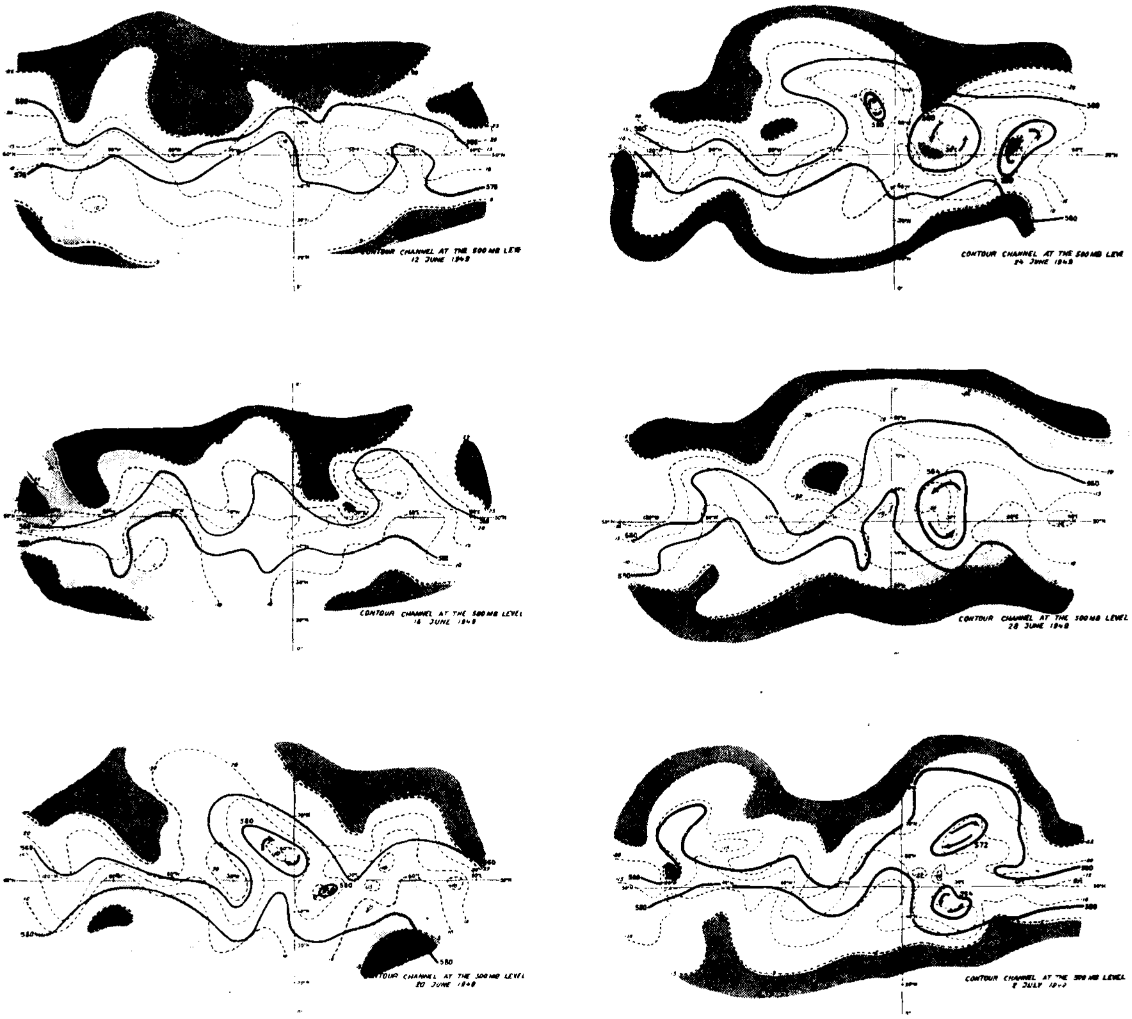

Fig. 2. A series of plates showing the development of a blocking situation at the 500mb level. The flow channel occupied by the hemispheric westerlies at 0300 GCT on 12, 16, 20, 24 and 28 June and on 2 July (1949) is indicated by the heavy black contour lines. The temperature field is shown in colour: dark blue < —25° C < light blue < —20° C < clear < —10° C < light red < —5° C < dark red. Contour heights in dynamic decameters. Temperatures in degrees Centigrade.

(a), (b), (c) or (d) are no longer satisfied. Although such a definition is subjective in character it has proven sufficiently definitive to permit the compilation of a catalog of blocking cases.

Five examples of blocking action, as defined above, have been analyzed in detail; four cases occurred over the eastern Atlantic and Europe (Jan. 1947, Feb. 1948, June—July 1949 and Jan. 1950) and one case occurred over the eastern Pacific and western N. America (Jan. 1949). These examples, both seasonally and geographically scattered, were selected for detailed study from the 113 cases cataloged in Part II and are thought to be representative of typical well-developed blocking situations. In so far as the aerological features of blocking action are concerned, the results of the above mentioned studies are in remarkable agreement. Accordingly the presentation of one case description will suffice.

The basic data used in these studies consists of the daily surface and 500mb hemispheric analyses published in *Daily Series, Synoptic*

Weather Maps (U. S. Weather Bureau) for the January 1949 case and in *Täglicher Wetterbericht* (Zentralamt Bad Kissingen) for the June—July 1949 and the January 1950 cases. Daily 500mb charts prepared by Mr. B. BOLIN, University of Stockholm and surface charts prepared at the Swedish Hydrological and Meteorological Institute were used for the February 1948 case. In order to obtain a continuous daily analysis over a sufficient longitudinal span (150° W—0°—90° E) for the January 1947 case, North American 500mb and surface analyses published in micro-film form by the U. S. Weather Bureau were joined with similar European analyses published in *Täglicher Wetterbericht* (Zentralamt Bad Kissingen). In order to minimize subjective errors no individual analysis has been performed by the writer except that necessary to construct the composite 1947 charts referred to above.

The June—July 1949 Blocking Case

The example selected for detailed description developed over the eastern Atlantic and Europe during June 1949. As defined previously, the period in question began on 16 June with the active development of a high-pressure ridge located approximately at 10°W longitude and ended 22 days later on 7 July with the disappearance of this anticyclone over Scandinavia. The 500mb chart for 24 June, illustrating this blocked case at near maximum development, is shown in figure 1.

The set of colour plates shown in figure 2 was prepared in order to more clearly demonstrate the sequence of events occurring at the 500mb level in connection with the development of a "block". In each instance the two height contours which most nearly bound the circumpolar westerly stream at 500mb were selected and are represented by the heavy solid lines in the figure. These lines approximately delineate the flow channel occupied by the upper westerlies, and are shown superimposed on the observed temperature field at that level. It is clear that the isobaric (contour) pattern can give only an approximate picture of the actual circulation field; in view of the stability of the pattern in blocked cases however, we may expect the approximation to be a rather good one. The projection used in the colour plates is a transformed conic,

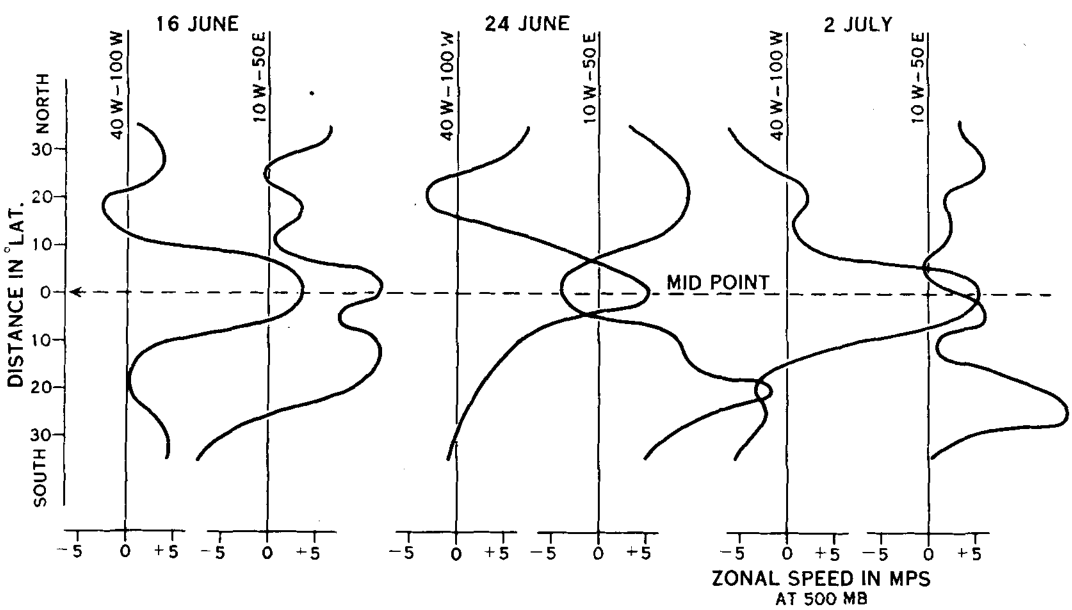

Fig. 3. Space-averaged mean zonal velocity profiles computed over the upstream sector and over the blocked zone for the June—July 1949 case. North—south distances measured in ° latitude from mid-point of the jet. Mid-points in upstream sector: 16 June — 50° N, 24 June — 43° N and 2 July — 52° N; in blocked zone: 16 June — 52° N, 24 June — 57° N and 2 July — 58° N.

tangent at 50°N — this projection is orthogonal but expands areas lying north of 50°N latitude and shrinks those lying to the south.

Prior to the development of the block (12 June) we observe a regular pattern of shallow waves around the entire half-hemisphere, though they are somewhat confused over Europe due to the presence of a stagnant cold cut-off cyclone. On 16 June the first sign of a developing block appears in the form of a split in the westerly jet at about 20°W longitude. Meanwhile the wave pattern persists with somewhat increased amplitude. By 20 June a well developed block is apparent which may be seen in each of the succeeding plates (24 June, 28 June and 2 July). In these last three illustrations the essentially zonal character of the westerlies over North America as contrasted with the markedly cellular (macro-turbulent) character of the flow over Europe, as well as the almost stationary position of the blocking ridge, may easily be seen. The characteristic sharpness of the "flow discontinuity" across the block is also clearly shown. Active large-scale horizontal mixing is evident from an inspection of the temperature field in the blocked zone, and a consequent relaxation of the mean meridional temperature gradient results.

In order to show changes occurring during the development of the block in the temperature and velocity fields at the 500mb level, figures 3 and 4 have been prepared. The longitudinal sector between 100°W and 40°W is taken as representative of upstream conditions, and the sector between 10°W and 50°E is taken as representative of the blocked zone. Figure 3 shows a series of mean zonal (space-averaged) geostrophic velocity profiles computed over the sectors just defined on 16 and 24 June and on 2 July; figure 4 shows the corresponding temperature profile series. The following significant changes are observed within the *upstream zone* at the 500mb level during the blocked period:

1. The velocity profile sharpens and the velocity maximum increases slightly during the first half of the period; later the jet broadens again.
2. The latitude of the mean jet in this zone shifts slowly southward during the developing stages (from 50° N to 43° N). As the block deteriorates the mean jet moves rather rapidly northward again (to 52° N).
3. A small but relatively uniform warming-up of the air in this zone is observed over a wide latitudinal span (from 20° N to 85° N). This observation suggests a general subsidence effective over the whole upstream region and associated with the southward displacement of the jet during the developing stages of the block. Later the temperature falls again in conjunction with the final northward movement of the jet.

The following significant changes are observed within the *blocked zone:*

1. The original single westerly jet, which was located at about 52° N latitude, is replaced during the development of the block by two westerly jet-branches, which are located approximately at 78° N and 36° N latitude with a zone of easterly mean flow between (at about 58° N). During the final stages of blocking the jet branches weaken and move further apart. It is perhaps significant to point out that these two jet branches are of approximately equal intensity throughout the active stages of the development — the velocity profile observed is suggestive of the action of a momentum jump such as that described by Rossby (1950).
2. The mean latitude of the blocked zone moves slowly northward throughout the period (from 52°N to 58°N).

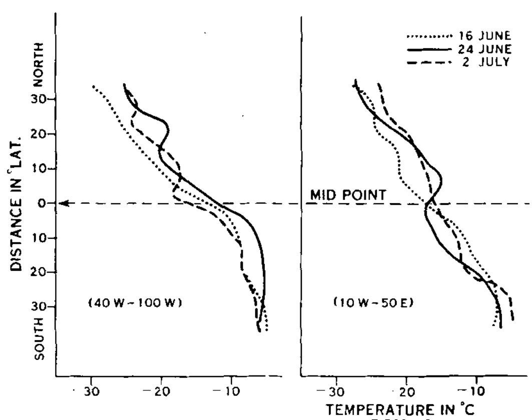

Fig. 4. Space-averaged temperature profiles computed over the upstream sector and over the blocked zone for the June—July 1949 case. Distances measured as in fig. 3.

3. A pronounced warming (6° C at 64° N) in that part of the blocked zone lying to the north of 52° N latitude and a cooling (4° C at 45° N) in that part of the zone lying to the south of 52° N latitude is observed. The mean meridional temperature gradient across the zone has therefore been greatly weakened, or even reversed, as a result of the large-scale horizontal mixing processes operating.

In concluding this description of the development of a typical block the changes produced in the velocity field will be discussed. In figures 5 and 6 the development of zonal velocity as a function of time is depicted graphically. Values of the geostrophic zonal speed were computed for successive latitudinal bands, five degrees in width and extending from 30° N to 80° N latitude, at each tenth meridian. Mean values of these speeds, taken over the upstream zone (120° W—30°W) and averaged over overlapping five day periods, are shown as time functions at various latitudes in figure 5. A similar presentation computed over the blocked zone (30°W—30° E) is shown in figure 6. In both figures isolines of geostrophic zonal speed have been drawn for each 2 mps. The development of the double jet system and its eventual dissipation are clearly shown in figure 6. The changes in mean jet width, strength and location which were discussed in connection with the velocity profiles may again be seen in these figures.

At this point it may be of some interest to discuss the effect of blocking action upon the zonal and meridional circulation indices. This is particularly true in view of the numerous conflicting statements which may be seen in current literature relative to index behavior during a blocking development. Both the zonal and the meridional geostrophic velocity components at the 500mb level have been computed on a 10° grid for each day during the period 16 June—7 July. In table I are given the mean geostrophic zonal index values obtained, in each ten-degree band of latitude from 30° N to 80° N, for the entire half-hemisphere (120° W—60° E), for the upstream zone (120°W—60° W) and for the blocked zone (30° W—30° E). Also given are normal index values averaged over the same zones and the departures of the observed indices from normal. For a discussion of the method of computing circulation indices, and their interpretation, the reader is referred to Stone and Willet (1943).

The normal values were computed from a new summer mean 500mb chart (June, July and August) by Flohn (1949). With regard to the half-hemisphere values it is significant to note from table I that only in the region from

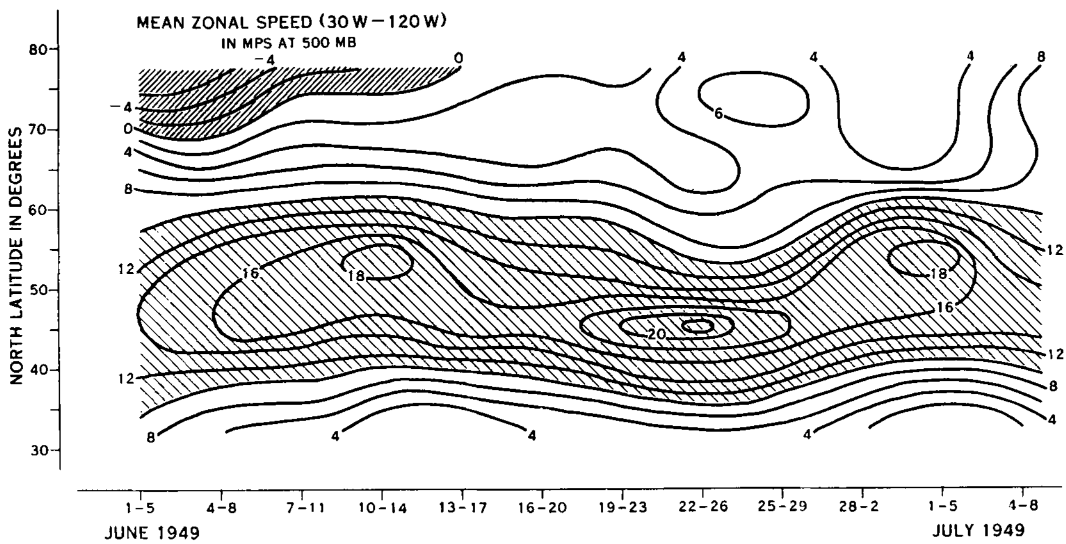

Fig. 5. Time trend of mean zonal speed computed over the upstream sector for the June—July 1949 case. Westerly flow stronger than 10 mps indicated by coarse hatching. Easterly flow indicated by fine hatching.

Table I. Zonal Index — Mean Zonal Component at 500mb Level — 16 June—7 July 1949

Latitude zone	120° W—60° E			120° W—60° W			30° W—30° E		
	Index	Normal	Departure from Normal	Index	Normal	Departure from Normal	Index	Normal	Departure from Normal
70—80° N	4.8	1.5	3.3	3.0	0.3	2.7	6.0	2.0	4.0
60—70° N	2.5	4.2	— 1.7	4.4	4.4	0	2.9	3.9	— 1.0
50—60° N	6.3	8.2	— 1.9	10.6	10.0	0.6	3.9	7.0	— 3.1
40—50° N	11.7	11.2	0.5	14.2	13.2	1.0	7.9	10.3	— 2.4
30—40° N	8.0	7.6	0.4	4.0	7.3	— 3.3	9.0	7.3	1.7
30—80° N	6.7	6.5	0.2	7.2	7.0	0.2	5.9	6.1	— 0.2

(All values in meters per second — west wind positive.)

50° N to 70° N latitude is the blocked period characterized by negative departures from the normal index values. Particularly at higher and to a lesser extent at lower latitudes, zonal velocities have greater than normal values. Thus, the zonal westerly index as usually defined (35° N to 55° N), although it includes the westerly maximum, maintains an essentially normal value during the blocking development. We may explain the index anomalies obtained in the upstream zone in terms of a contracted and somewhat intensified jet during this period. The above-normal index obtained at high latitudes (70° N—80° N) in this zone no doubt results from the marked northward displacement of the jet stream over western N. America during the developing stages of the block. In the blocked zone we obtain a remarkably symmetrical anomaly profile with the maximum reduction in zonal flow occurring at about 50° N latitude. The net changes in index produced in each zone over the entire latitudinal belt (30° N—80° N) are insignificant (± 0.2 mps). We conclude therefore that mean zonal index anomalies, computed for blocked periods, are not only dependent upon the latitudinal boundaries chosen but also depend directly upon the longitudinal sector

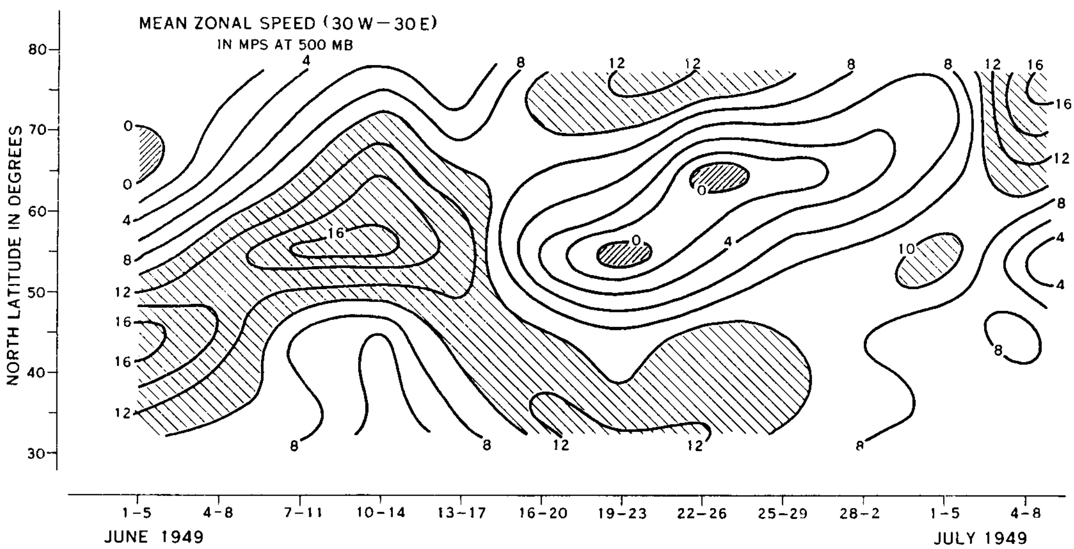

Fig. 6. Time trend of mean zonal speed computed over the blocked zone for the June—July 1949 case. See figure 5 for further explanation.

over which the computations are extended. This result is to be expected in view of the sharp quasi-stationary flow discontinuity shown in figure 2 at about 20° W longitude.

In table II below are given the mean meridional index values obtained at every tenth parallel of latitude from 30° N to 70° N in the three sectors, 60° W—30° W, 30° W—0° and 0°—30° E. Also given are the normal meridional index values and the departures of the observed indices from normal.

Normal values were again computed from Flohn's summer mean 500mb chart. In the zone from 60° W—30° W longitude we obtain small departures from normal except at 70° N latitude. The strong positive anomaly observed at this latitude results from the strong southerly flow around the deep cyclonic vortex which stagnated over southern Greenland during the first part of the blocked period. In the zone from 30°W—0° longitude the jet split is clearly located between 40° N and 50° N latitude with northward moving flow over higher latitudes and southward moving flow over lower latitudes. If we compute the mean magnitude of the meridional index anomalies over the entire latitudinal band we obtain a quantity ($\overline{|A|}$) which may be used as a measure of "cellular growth" in the circulation pattern. These values, given in table II, show a marked increase in cellular growth in the two zones lying downstream from the block (30°W—0° and 0°—30° E).

An Hydraulic Analogue

Before proceeding with a discussion of the initiation, development and dissipation of blocking, it may be desirable to review Rossby's reasoning (ROSSBY 1950) in a summary way and to state here again the particular quantitative results which will be used in this paper. Let us suppose that we have a simple 2-dimensional steady current of width $2a$ and speed u in the positive x-direction, which is independent of y and vanishes in the surrounding environment, as depicted in figure 7A. Further, if we take the x-direction as easterly and assume a constant Coriolis parameter, f, which is independent of latitude we note that the pressure field necessary to balance the motion will have a linear cross-current profile. In figure 7B this pressure profile is shown at the two normal cross-sections 0 and 1 as the solid lines MAN and LAO respectively. In this case it becomes immediately evident that no pressure gradient exists in the direction of flow. If however we introduce a variable Coriolis parameter, $f = f_0 + \beta y$, we note that the balancing cross-current pressure profile is no longer linear but rather is of the form MBN and LCO as shown by the dashed lines in figure 7 B. Thus we see that this second pressure field exceeds the first in magnitude at every point and further that this pressure excess, p', reaches its maximum value at the center of the current. Rossby gives an expression for the value of p' max. as follows:

$$p'_{\text{max.}} = \varrho \beta V \frac{a}{4} \tag{1}$$

where ϱ is the density and V the volume transport, which can be expressed as follows:

$$V = 2\,a\,u \tag{2}$$

Table II. Meridional Index — Mean Meridional Component at 500mb Level — 16 June—7 July 1949

Latitude	60° W—30° W			30° W—0°			0°—30° E		
	Index	Normal	Departure from Normal	Index	Normal	Departure from Normal	Index	Normal	Departure from Normal
70° N	9.0	1.8	7.2	7.2	4.1	3.1	— 1.8	2.3	— 4.1
60° N	2.7	2.7	0	13.4	3.6	9.8	— 10.7	1.7	— 12.4
50° N	1.2	1.2	0	5.9	1.5	4.4	— 9.4	0.8	— 10.2
40° N	0	0.8	— 0.8	— 2.4	— 0.4	— 2.0	— 3.5	— 1.2	— 2.3
30° N	— 1.3	— 0.4	— 0.9	0	0.4	— 0.4	0	— 2.7	2.7
$\overline{\|A\|}$			1.8			3.9			6.3

(All values in meters per second — south wind positive.)

The magnitude of the pressure-excess maximum, p' max., increases with increasing volume transport or current width. Returning then to the simple case of figures 7 A and 7 B we see that a particle travelling along the streamline located at the center of the current will be acted upon by a negative pressure gradient and will thereby be decelerated in moving from cross-section 0 to 1. This follows from equation (1) and the fact that the volume transport must remain constant from cross-section to cross-section along the current. It may be shown in this case that all particles moving in the current, except at the boundaries, will be decelerated by an amount diminishing toward zero as their distance from the current's center approaches $|a|$. Rossby has shown further that the effect described above will exist in general, i.e. irrespective of the form of the current's boundary or of its velocity profile, as long as symmetry about the center latitude prevails. He has therefore described an internal physical mechanism which is capable of reducing the speed of westerly current systems in the atmosphere and which suggests that under certain conditions a single current may tend to split into two branches.

Returning again to figure 7 A it may be shown that the expression for the momentum transfer, M.O.T., across a plane perpendicular to the current is given as follows:

$$\text{M.O.T.} = \varrho \int_{-a}^{+a} u \left(u + \frac{\beta y^2}{2}\right) dy \qquad (3)$$

which in this case may be easily integrated and with the aid of equation (2) expressed in the following form:

$$\text{M.O.T.} = \varrho V \left(u + \frac{\beta V^2}{24\, u^2}\right) \qquad (4)$$

It is evident therefore that for a given volume transport the momentum transfer will have a minimum value when the current speed is equal to:

$$u = \sqrt[3]{\frac{\beta V^2}{12}} = \frac{\beta a^2}{3} \equiv u_{00} \qquad (5)$$

where this critical speed is denoted as u_{00}. Whenever the current speed exceeds the

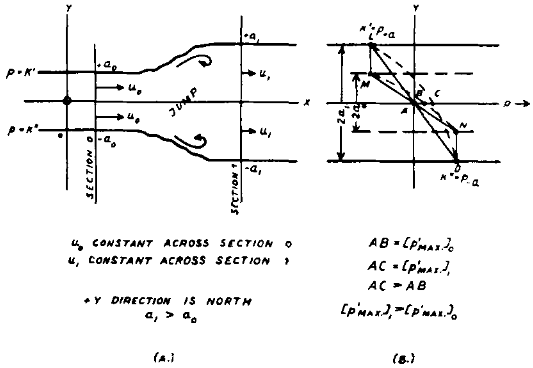

Fig. 7. Atmospheric block model.

critical speed, u_{00}, there are two permissible modes of flow, one at a higher energy level (speed) than the other. This may be compared with conditions existing up- and downstream from an hydraulic jump as described by STOKER (1948). A *necessary condition* for the development of a jump in the atmosphere analogous in character with that observed in hydraulic flow in open channels has thus been derived, and a plausible *internal mechanism* for producing the required reduction in speed across the jump has been described. It must be emphasized however that the velocity profile assumed in the integration of equation (3) is unrealistic, and therefore that the expression obtained for the critical speed (equation 5) can not be expected to accurately describe actual conditions in the atmosphere. ROSSBY (1950) has also given an expression for the rate of propagation of such an atmospheric jump which moves without change of shape as follows:

$$c = u_{00} \left[N - \frac{n\,(n+1)}{2} \right] \qquad (6)$$

where the critical ratio, N, and the expansion ratio, n, are defined as follows:

$$N \equiv \frac{u_0}{u_{00}} \text{ and } n \equiv \frac{a_1}{a_0} \qquad (7)$$

The subscripts used in equations (7) above have the significance indicated in figure 7.

In order to obtain a partial test of the theory just summarized daily (0300 GCT) values of N and n (equations 7) at the 500mb level have been computed for the five blocking cases before mentioned. In such an actual computation some assumption as to the boundaries of the westerly flow must be made; in view of the unfortunate sensitivity of the calculations to stream width this selection of boundaries assumes a critical importance. In this case the contour lines lying furthest north and furthest south, yet still traversing the entire hemisphere, were defined as the flow boundaries. One must nevertheless exercise a certain amount of subjective judgement in placing these boundaries and as a result the values obtained are only crudely approximate. In view of the fact that the same technique has been used throughout it may be assumed that the trends obtained, if not the numerical values, reflect actual conditions.

The values obtained for the expansion ratio, n, (ratio of down- to upstream widths) in three of the five cases analyzed are shown graphically as time functions in figure 8. The three cases given illustrate the extremes obtained. In order to permit a better comparison, a uniform time scale is used in this figure. Each case is "zeroed" on "B-day", the day on which blocking was initiated as defined previously. The time trends for the 1949 and 1950 cases show a slow rise until B-day; afterwards growth continues at a somewhat accelerated rate until blocking is fully developed. The January 1947 case is in reality a rejuvenated cycle of a blocking situation which began in December 1946, as is shown in Part II. The time trend of n in such a case would be expected to have the form shown. After maximum development, except for the 1950 case which extends into February and is not shown, the values of n fall rapidly as the block deteriorates. Also shown, for comparison, in figure 8 is the time trend of n computed for the month of January 1949, an excellent example of a persistent zonal-type flow pattern in the Atlantic-European area. We conclude from these results that an average value for the ratio of down- to upstream widths during blocking is about 2.5 whereas at other times it falls to about 1.5. A fixed definition of up- and downstream sector limits is permissible for all cases of Atlantic-European blocking since in all such cases the jet split remains within a relatively narrow longitudinal span centered about 10° W longitude (Part II).

The values obtained for the critical ratio, N, in the three cases just discussed are plotted as functions of time in figure 9. The critical ratio at any particular time is defined as the ratio of the observed stream velocity to the critical velocity, u_{oo}, at that time; it may be taken as a measure of the stream's susceptibility to blocking development. In each of the three cases we observe at least a secondary maximum in N on B-day. It is significant to note that large values of N are observed also prior to the initiation of blocking although there is some suggestion of an increasing trend (except for the 1947 case as before) up to B-day. The large values of N (> 15) were computed for very narrow stream widths, under conditions apt to render calculations of u_{oo} inaccurate. They may therefore be largely discounted. The time trend of N during January 1949 is again shown in figure 9 for comparison.

Computations of the movement of the block using equation (6) were made in each of the five cases analyzed. General agreement between the computed and observed direction of movement was obtained, but the computed speeds in almost every instance exceed the actual by a factor of two or three. In view of the assumption of constant shape, which was made in the derivation of equation (6) and since only approximate values for N and n were available, it is not surprising that the computed motion should be in error.

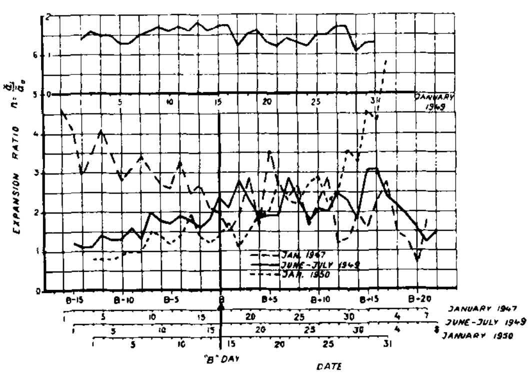

Fig. 8. Daily values (0300 GCT) of the expansion ratio computed for the 1947, 1949 and 1950 blocking cases. Expansion ratios for January 1949 (zonal flow) are shown above for comparison. Upstream sector taken as 120°W — 30° W. Downstream sector taken as 30°W—30° E. Blocking development initiated on B-day.

The Initiation, Development and Dissipation of Blocking

It is clear that, because of the normally low value of the critical velocity, u_{00}, values of the critical ratio, N, normally exceed unity. The existence of supercritical velocities in the upper westerlies cannot therefore be used as a sufficient criterion for the initiation of blocking. It has been shown for the case of hydraulic jumps that such developments must be initiated through the action of finite external impulses on the system. Further, it has been experimentally demonstrated by RUSSEL (1936) that the minimum energy required in any such impulse to precipitate a complete breakdown of the flow in an open channel decreases rapidly as the ratio, N, increases. Accordingly, only extremely deep, slow-moving stream systems are stable to impulses of *any* intensity; whereas decreasing depth and increasing speed lower the system's "threshold of sensitivity". That is, successively less intense impulses are sufficient to initiate a breakdown of the simple flow pattern (an hydraulic jump results).

In the atmosphere the westerly jet is subjected to an almost continuous barrage of external impulses of varying intensity. If one accepts the concept of lateral friction as a driving mechanism of importance in producing and maintaining the westerly jet, (ROSSBY 1947), it must be assumed that accelerations thereby produced in the jet stream

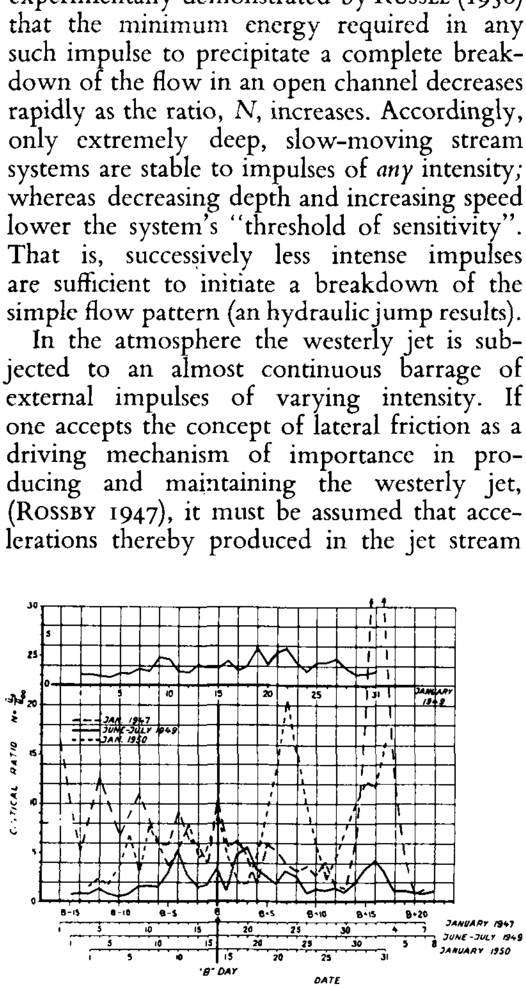

Fig. 9. Daily values (0300 GCT) of the critical ratio computed for the 1947, 1949 and 1950 blocking cases. Critical ratios for January 1949 (zonal flow) are shown above for comparison. Upstream sector taken as 120° W —30° W. Downstream sector taken as 30° W—30° E. Blocking development initiated on B-day.

are neither constant in direction nor in magnitude, but rather vary markedly as mid-tropospheric cyclonic vortices move in space and vary in intensity. Regions of forced local acceleration are thus produced in the westerly stream which will in turn tend to produce difluent flow in adjacent areas immediately downstream. In such difluent zones one would expect the initiation of a momentum jump to be favored through the action of the pressure excess, p', defined before (equation 1). In the colour plates of the June 1949 development (figure 2) we note that the initial appearance and subsequent rapid development of the blocking ridge took place just downstream from an area exposed to the effects of an intense cyclonic vortex lying just to the north of the jet stream itself. Such a relationship has been observed in each case of blocking action inspected. We therefore postulate that the initiation of a block is *impossible* downstream from any region in which the critical ratio, N, is less than unity and further, that such developments will be initiated whenever (and wherever) a *sufficiently intense* "cyclonic" impulse, for the then existing critical ratio, is imparted to the stream. The appearance of blocking is therefore more probable when a strong and relatively narrow westerly current system aloft prevails over the upstream area; such a flow pattern is often associated with confluence as described by NAMIAS and CLAPP (1949).

If the above-described theory is substantially correct we should expect to observe, at the "instant" of initiation in past cases of blocking, an inverse relationship between the magnitude of impulse intensity, I, and the critical ratio, N. In table III below, the values of I and N, observed in the 1947, 1949 and 1950 cases of blocking, are given.

Table III

Case	Critical Ratio — N	Impulse Intensity — I	Date of Initiation
1949	3.6	+ 0.39 K	16 June
1950	9.0	+ 0.17 K	14 January
1947	10.3	+ 0.11 K	17 January

$I \cong \bar{S}K$ where S is defined by equation (8) and K is a constant of proportionality.)

The date of initiation was determined in accordance with the definition of blocking given before. The impulse intensity, for want of a better definition, has been assumed to be proportional to the average of the mean horizontal geostrophic wind shears, computed normal to the jet's northern boundary on the 500mb surface at three separate points around the cyclonic vortex lying nearest upstream from the developing blocking ridge. If the contour height in dynamic meters at a point, B, on the northern boundary of the jet is denoted as B, then the mean horizontal geostrophic wind shear, S, between the points, A and C, is given as follows:

$$S = \frac{505.3}{f \times 10^4} \left[\frac{2\,B - (A + C)}{L^2} \right] \qquad (8)$$

where A and C denote the contour heights in dynamic meters at the points, A and C, situated along the normal line at a distance, L, (in nautical miles) respectively north and south of point B. In the computation of table III the distance, L, has been taken as 300 nautical miles. Shear values computed from equation (8) are given in meters / second / 10 nautical miles; positive values indicating anticyclonic shear across the northern jet boundary at point B. We observe that the three values of N and I shown in table III are inversely related as we should expect.

It may be of some interest to speculate upon the seasonal and geographic variations which block development should be expected to exhibit in accordance with this theory. With regard to seasonal influences we may state from observational evidence that during the summer the intensity of mid-tropospheric cyclonic systems, the average jet speed and the average width of westerly currents will be relatively diminished. We cannot therefore state directly any conclusion as to the seasonal frequency of block occurrence, since decreased impulse intensity is associated with an indeterminate change in N. Evidence presented in Part II shows that the maximum frequency of occurrence is actually observed during the late winter or early spring.

With regard to geographical influences we recall the observed fact that the strongest cyclonic vortices found aloft over the northern hemisphere (and within the sector 120° W—60° E) are most frequently situated over the eastern seaboard of North America and western Atlantic in association with strong polar outbreaks down the Mississippi Valley and across the eastern United States. The collapse of such cold anticyclones in the lower troposphere and their rôle in the initiation of mid-tropospheric cyclonic systems has been discussed by ROSSBY (1949). As a result we should expect to find a "preferred region", of most frequent block initiation, over the eastern Atlantic. A similar preferred region, associated with the eastern Asiatic continent, should be expected to appear over the east-central Pacific and would produce blocking situations which would at times affect western North America. In Part II observational evidence substantiating the existence of these preferred regions is presented in agreement with the prior findings of ELLIOTT and SMITH (1949).

The development of blocking situations, both in meridional and longitudinal extent, can not be described in detail until the dynamics of the macro-turbulent zone itself are better understood. Meridional growth is most commonly accomplished through the intensification and northward extension of the blocking anticyclone aloft and is accompanied by a general increase in the amplitude of meridional flow components down stream. Meridional growth is typically followed by an extension of the blocked area downstream (longitudinally) through the addition to the train of more cut-off vortices. This train of cyclonic and anti-cyclonic cells may often extend more than halfway around the hemisphere and in extreme cases may transform the entire hemispheric circulation pattern into a purely cellular type. Figure 10, showing the transformations produced in the hemispheric westerly pattern during the 1949 case previously described, illustrates such an example of extended growth. It should also be mentioned that the growth rate of blocks is often not uniform, but rather the development may pass through several cycles. The 1947 case, previously mentioned, illustrates the rejuvenation of a blocking situation which was initiated many weeks earlier. From observational evidence we may state that large values of the critical ratio, N, are associated with (favor) accelerated growth. The motion of blocks is, in general, irregular although a trend toward retrograde motion during the developing stages and toward progressive motion during dissipation may be detected. In general retrograde motion is associated with large values of N and vice versa.

The eventual dissipation of blocking action has been preceded in each case analyzed by a decrease in the critical ratio to a very low value, less than or near to unity. We note in figure 9 that in the dissipating stages of both the 1947 and 1949 cases, values of N less than unity were observed. The critical ratio may be lowered by increasing the mean stream width and/or by decreasing the mean stream velocity in the upstream sector. Either or both effects are commonly produced by changes occurring in the lower troposphere over the upstream zone, i.e. a relaxed temperature gradient, decreased vertical stability, decreased confluence, etc. Occasionally the blocked region may extend so far downstream as to affect its own upstream area and, in so doing, may destroy itself. An example of such a self-destructive block is shown in figure 10 already referred to.

In concluding this section, it may be desirable to discuss briefly two variations of the typical single warm-anticyclone blocking situation. Blocking has previously been described and illustrated as originating with a warm anticyclone situated immediately downstream from the jet split. Instead in many cases the first vortical element in the developing block is a cold cut-off cyclone. Such a case in its more mature stages is illustrated in figure 11. In other cases, which were initiated with a typical warm anticyclone, cold vortices are, during the life of the block, cut-off in advance of the blocking anticyclone and included in the macro-turbulent zone — see BERGGREN, BOLIN and ROSSBY (1949), figure 26. In all cases however, an anticyclone tends, in the mean, to dominate the area lying just downstream from the jet split due to the more stable character of a warm vortex. The anticyclone shown in figure 11 has partially replaced the already dissipating cyclone.

Although it is more usual to find only one block in the hemispheric flow pattern, at times two blocking situations may exist simultaneously. Such a situation is illustrated in figure 12. Perhaps due to the type of self-interference already referred to such double blocks are normally short-lived. One or the other dissipates, leaving a single block which may persist for several weeks.

Fig. 10. An example of extended blocking development. Absolute topography of the hemispheric westerlies is shown at 10-day intervals. Contour heights in dynamic decameters.

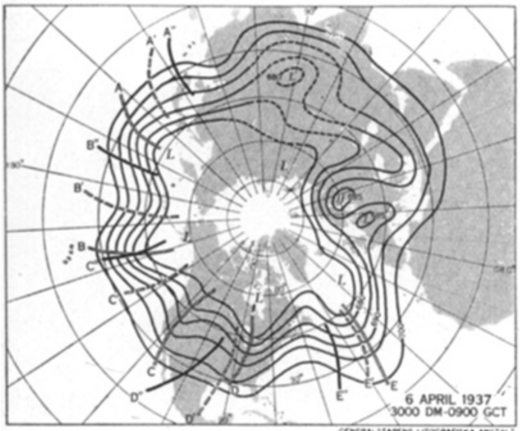

Fig. 11. An example of a cold cyclone blocking case. Movement of troughs retarded as they approach the block; present position — double, preceding 24hrs. — dashed and preceding 48hrs. — solid. Pressure field over the hemispheric westerlies in millibars.

Conclusion

Certain apparent differences between the development of wave-like perturbations in the zonal current and the development of atmospheric blocks may be pointed out. Both processes produce strengthened north-south flow components and increased meridional exchange in the area affected. Either, under favorable conditions, may produce a complete breakdown of the hemispheric zonal westerlies. Wave development is typically associated with changes in the stream channel which are continuous both in space and time. The process, if continued, may lead to the formation of one or more cut-off cyclonic and/or anticyclonic vortices as has been described by PALMÉN (1949). The appearance of such vortices does not in general produce a flow pattern which satisfies the definition of blocking action as given herein; they commonly appear quite independently of blocking phenomena. An example of the transformation of the hemispheric circulation pattern into a distinctly cellular type, through the action of developing waves, is shown in figure 13.

The development of a block in the upper westerlies is typically associated with the appearance of a persistent quasi-stationary discontinuity in the flow characteristics along the stream channel. Upstream from this discontinuity, or "shock", an essentially zonal flow at a high energy level (speed) is observed; downstream the flow becomes markedly meridional at a lower energy level. A comparison of figure 10 with figure 13 will illustrate these apparent differences. Actually no sharp distinction may exist between these two types of development since in a 2-dimensional treatment both may be solutions, although of quite different appearance, to $\frac{dZ_a}{dt} = 0$ where the vertical component of absolute vorticity is represented as Z_a. It is hoped that such a solution for a representative blocking development may be undertaken with the electronic computer; the results of such a computation would permit a more rigorous comparison of wave and block development.

In a recent paper RIEHL, YEH and LA SEUR (1949) have computed time sections of the change in angular momentum at various levels in the upper air. They have shown that the transfer of angular momentum across the middle latitudes usually takes place from south (tropics) to north (arctic) but that during certain periods the direction of this transfer may be reversed. It is interesting to note that periods of blocking, as taken from the blocking-case catalog, Part II, correlate well in time with periods during which a north to south transfer of angular momentum is observed. For example note the Δu-momentum trends

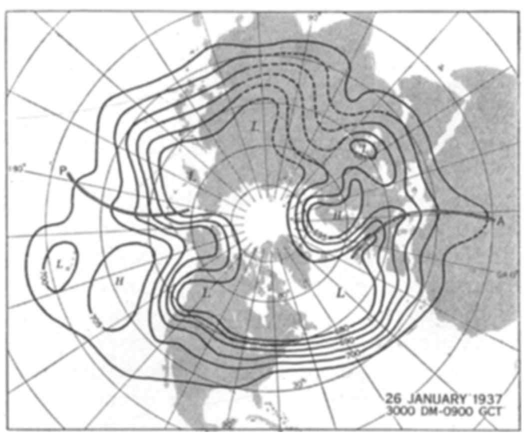

Fig. 12. An example of a double block with the Atlantic "shock front" shown at "A" and the Pacific "shock front" shown at "P". Pressure field over the hemispheric westerlies in millibars.

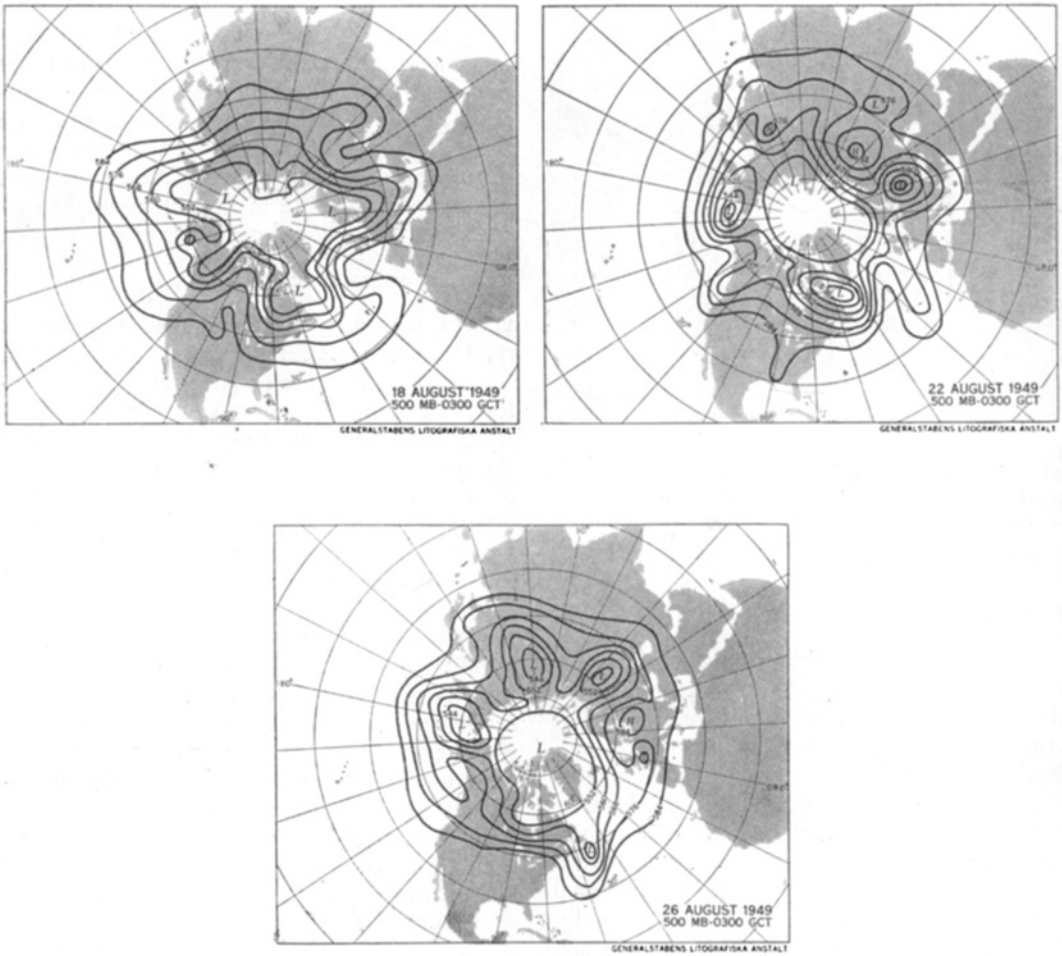

Fig. 13. An example of the transformation of the hemispheric circulation pattern into a cellular type through the action of wave development. Absolute topography of the hemispheric westerlies is shown at 4-day intervals. Contour heights in dynamic decameters.

shown by RIEHL, YEH and LA SEUR (1949, figs. 6 and 7) during February—March 1948 and January—February 1949 (blocking cases discussed previously). The destruction of angular momentum in the mid-troposphere is no doubt accomplished more effectively through the action of an atmospheric block than by any other available means. The development of such blocks acts as a kind of "safety-valve" on the atmospheric motion in that it limits the maximum value of angular momentum permissible in the upper westerlies. Blocking action therefore plays a fundamental rôle in atmospheric dynamics in that it limits the accumulation of angular momentum in the upper westerlies and provides a mechanism for the southward transport of angular momentum across mid-latitudes.

Various facts of observation relating to the blocking process have been presented in this paper. Although no adequate theory of blocking is at present available an attempt has been made herein to fit these observations into a tentative theory and to discuss the blocking process as an element of the general circulation of the atmosphere.

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