THE INDEX CYCLE AND ITS ROLE IN THE GENERAL CIRCULATION

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ABSTRACT

On the basis of accumulated aerological data on a hemisphere-wide scale, a reexamination is made of the problem of hemispheric zonal-index variations first raised in the late 1930's. These data lead to a theory explaining the important problem of how and why during each winter the zonal westerlies gradually fall to low strength and subsequently recover—the period of this "index cycle" consuming some four to six weeks. The theory postulates a mechanism for containment of air composing the polar and sub-polar cap by means of strong mid-troposphere westerlies created by large-scale confluence. In this manner cold air is produced and stored in northern latitudes, the atmospheric circulation operating as a vast condenser. The discharge of the condenser in the form of cold air outbreaks, long recognized as necessary for the atmospheric heat balance, is effected by a certain cellular-type blocking, which reaches maximum effectiveness in producing an extended index cycle only when the supply of abnormally cold air is abundant, usually in late February. The principal index cycles of the six years 1944 through 1949 serve as supporting evidence for the theory.

1. Introduction

A little over ten years ago the concept of the zonal index was introduced into meteorology (Rossby, 1939). This quantity, expressing numerically (at sea level or aloft) the strength of the temperate-latitude (35°N to 55°N) westerly winds over a hemisphere, was found to be related to the form of the general circulation, particularly in the longitudinal positions and extent of the great centers of action. The terms "high" and "low" index patterns have emerged to describe the state of the sea-level and mid-troposphere isobaric patterns associated respectively with strong and weak mid-latitude westerlies.

More recently, as emphasized by Willett (1948), variations in the zonal index have been found to be associated with pronounced *latitudinal* as well as longitudinal shifts in the characteristic branches of the general circulation. For example, the low-index pattern referred to above is not only associated with certain longitudinal characteristics of the centers of action but also with a displacement southward of the mid-tropospheric band of maximum westerly winds. Thus, strictly speaking, low index of the temperate latitudes, for the most part, is identified with strong westerly flow in subtropical latitudes. In view of the fact that at least in the middle and high troposphere the zonal westerlies often reach their greatest strength at the time of "low index" as defined above, it would appear that the terms "high" and "low" index are misnomers.

While the index concept has been of considerable help in classifying and studying general circulation patterns, it must be confessed that its usefulness in the practice of extended forecasting has been somewhat disappointing. Inasmuch as general circulation patterns were found to be related to the zonal index, a vast research effort has been directed towards developing statistical methods of predicting this quantity. Aside from a small degree of persistence combined with a tendency to return to a normal seasonal value, attempts to find statistical time-lag relationships have failed (Willett, 1948). In 1947 the writer stated (Namias, 1947a): "In spite of the fact that index forecasts have been made for about seven years, it is noteworthy that up until recently no physical method for forecasting this quantity (the zonal index) has been developed."

In the report in which the above statement was made, some preliminary suggestions were given as to the physical causes of index fluctuations, and this thesis was expanded upon in subsequent papers (Namias, 1947b; Namias and Clapp, 1949). Although not previously stated in such broad terms, in essence this thesis is: *The total hemispherical zonal index is not a primary parameter (independent variable) whose variations can be statistically accounted for on the basis of its own past behavior; rather, it is a derived quantity (dependent variable) which represents the degree of latitudinal organization of certain large-scale energy producing mechanisms in the middle and upper troposphere.*

It is the purpose of this paper to describe and explain this organization in terms of the observed transformations of the component parts of the wintertime general circulation as the zonal index at some period during winter proceeds from high to low values and then recovers.

2. The index cycle

From week to week each winter there are large variations of the zonal index about its seasonal normal.

[1] Paper presented at the 30th Anniversary Meeting of the American Meteorological Society at St. Louis, 4–6 January 1950.

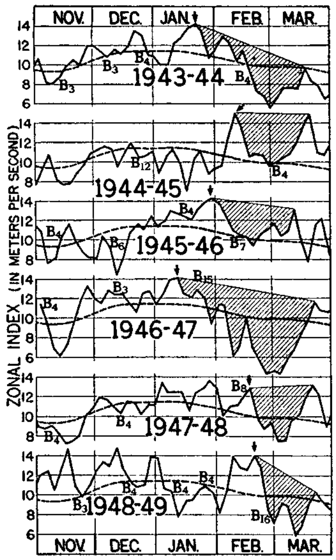

FIG. 1. 5-day mean and monthly normal zonal indices (strength of the zonal westerlies in m sec^{-1} between 35°N and 55°N) at 700 mb over the northern hemisphere from 0° westward to 180° for colder months of the years 1944 through 1949. Values are plotted against the last day of the 5-day period. Heavy arrows point to beginning of primary "index cycles," and the shaded area gives a measure of their duration-intensity. B's refer to periods of blocking as defined in text.

Such variations at the 700-mb level for means of 5 days computed twice weekly are shown for the period November through March of the past 6 years in fig. 1.[2] From these graphs it appears that in each year there is at least one period lasting several weeks in which there takes place a more or less gradual decline of index from high to low values followed by a similar rise. The beginnings of the most pronounced period of this kind are indicated in fig. 1 by arrows, and some measure of their intensity-duration is indicated by the shaded area. Other cycles occurring earlier in the winter would apparently be less pronounced in terms of a similarly constructed shaded area. For want of a better term, such an extended period of falls and rises has been called an "index cycle." Fig. 1 poses a number of problems vital to an understanding of the general circulation:

1. Why during each year is there a tendency for the occurrence of at least one index cycle lasting several weeks?

2. Why do these cycles vary in intensity (*i.e.*, length of duration and departure from normal) from one year to the next?

3. Why does there appear to be one particular time of year (late February) when the most pronounced index cycle occurs?

Before an attempt can be made to answer any of these questions, it is necessary to look into the flow patterns associated with high and low index. While considerable work of this character was done in the early period of the "index" decade, this work was mostly connected with the characteristic features of sea-level hemispherical maps. In the extended forecasting work at the U. S. Weather Bureau, it has been possible during the past six years to construct, with little extrapolation, hemispheric or nearly hemispheric maps for mid-troposphere levels. Similar maps, obtained in part through use of extrapolation techniques over large areas, have also been prepared by Willett for the colder half of the years from 1932–39 as part of the Weather Bureau-Massachusetts Institute of Technology extended forecasting research project. A study of these latter maps, along with sea-level data, led Rossby and Willett (1948) to the following description of the index cycle:

> . . . four principal stages of the index cycle are recognized, each of which can be briefly characterized essentially as follows:
>
> (1) Initial high index (strong sea-level zonal westerlies), characterized by (*a*) sea-level westerlies strong and north of their normal position, long wavelength pattern aloft; (*b*) pressure systems oriented east–west, with strong cyclonic activity only in high latitudes; (*c*) maximum latitudinal temperature gradient in the higher middle latitudes, little air mass exchange; and (*d*) the circumpolar vortex and jet stream expanding and increasing in strength, but still north of the normal seasonal latitude.
>
> (2) Initial lowering of sea-level high-index pattern, characterized by (*a*) diminishing sea-level westerlies moving to lower latitudes, shortening wavelength pattern aloft; (*b*) appearance of cold continental polar anticyclones in high latitudes, strong and frequent cyclonic activity in middle latitudes; (*c*) maximum latitudinal temperature gradient becoming concentrated in the lower middle latitudes, strong air mass exchange in the lower troposphere in middle latitudes; and (*d*) maximum strength of the circumpolar vortex and jet stream reached near or south of the normal seasonal latitude.
>
> (3) Lowest sea-level index pattern, characterized by (*a*) complete breakup of the sea-level zonal westerlies in the low latitudes into closed cellular centers, with corresponding breakdown of the wave pattern aloft; (*b*) maximum dynamic anticyclogenesis of polar anticyclones and deep occlusion of stationary cyclones in middle latitudes, and north–south orientation of pressure cells and frontal systems; (*c*) maximum east–west rather than north–south air mass and temperature contrasts; and (*d*) development of strong troughs and ridges in the circumpolar vortex and jet stream, with cutting off of warm highs in the higher latitudes and cold cyclones in the lower latitudes.
>
> (4) Initial increase of sea-level index pattern, characterized by (*a*) a gradual increase of the sea-level zonal westerlies with an open wave pattern aloft in the higher latitudes; (*b*) a gradual dissipation of the low-latitude cyclones, and merging of the higher-latitude anticyclones into the subtropical high-pressure belt; (*c*) a gradual cooling in the polar regions and heating of the cold air masses at low latitudes to re-establish a normal poleward temperature gradient in the higher latitudes;

[2] Only half of the hemisphere from 0° westward to 180° had sufficiently adequate upper-air coverage upon which to draw synoptic charts on a current basis over the six-year period 1944–49.

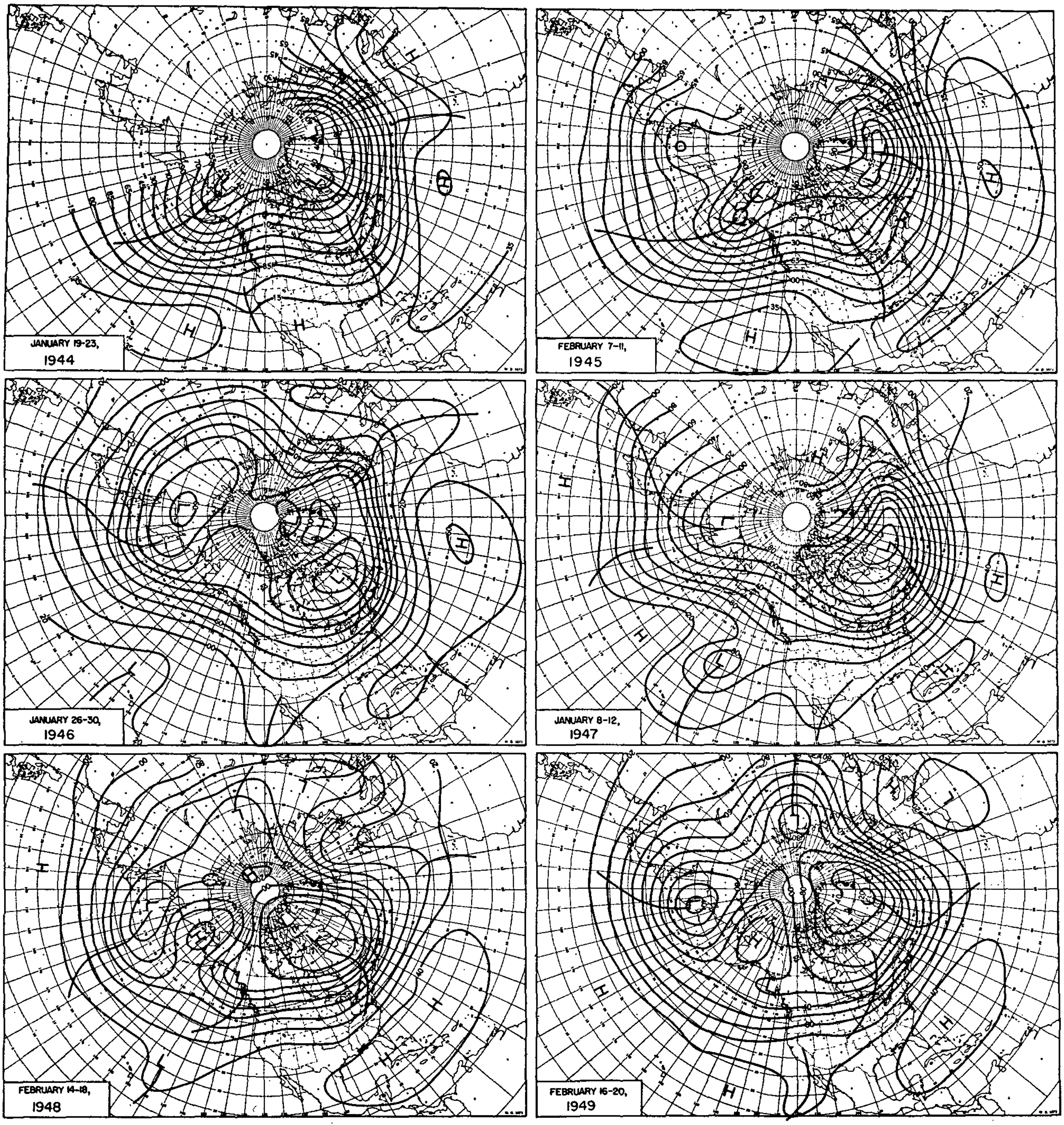

FIG. 2. 700-mb 5-day mean charts at the initial stage (high index) of the index cycle.

and (*d*) dissipation of the high-level cyclonic and anticyclonic cells with a gradual re-establishment of the circumpolar vortex jet stream in the higher latitudes.

In addition to the above description, certain other facts concerning the index cycle seem to be of importance for any treatment of its mechanics. These facts are brought to light in a study of high- and low-index patterns as reflected in 700-mb 5-day mean maps during the last six years (1944–49). Some of these maps, representing the beginning high point of the index cycle (corresponding to the arrows of fig. 1) and the subsequent low point, are shown in figs. 2 and 3.

It appears that high index requires mid-latitude bands of confluence (Namias, 1947) where cold, polar-continental air masses are drawn beside warm, tropical (or polar-maritime) air masses to form high speed "jet streams" which organize into the strong westerlies. From figs. 2 and 3 and other data, there appear to be preferred geographical sites for such confluence—just off the northwest coast of the U. S. (confluence associated with the Gulf of Alaska surface low surmounting the eastern cell of the Pacific High) and in eastern North America (where an Arctic air flow is directed beside polar-Pacific and often tropical-Gulf

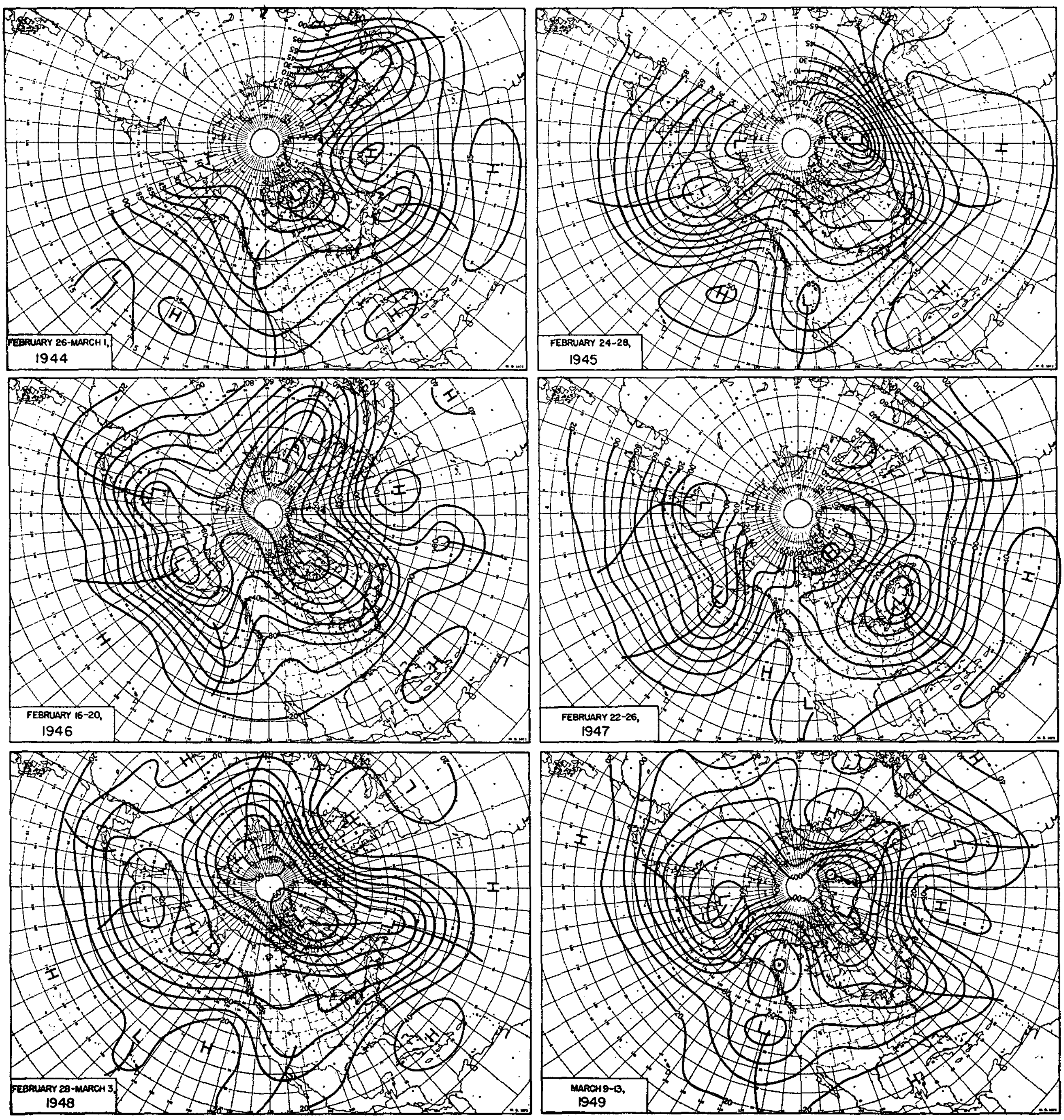

Fig. 3. 700-mb 5-day mean charts at the low index stage of the index cycle.

air to form a strong jet which breaks into the Atlantic).

On the other hand, low-index patterns (fig. 3) are freer from mid-latitude confluence, and those confluence bands which do exist seem to be developed chiefly at low latitudes. Since confluence requires out-of-phase wave systems in different latitude bands, it appears from geometrical considerations that during high index the amplitude of wave systems increases with distance poleward and equatorward from the jet stream.

Other important facts concerning index variations are brought to light through an analysis of 700-mb zonal-windspeed profiles. In working with these profiles in the 5-day forecast routine, one is impressed by the tendency for the total momentum of the westerlies aloft (neglecting density), as represented by the area under one of these profiles, to remain nearly constant from week to week, or in the case of monthly mean profiles, for the total area to agree with the area under the normal zonal-wind profile for that month. To illustrate this concept quantitatively, computations of the total momentum of the 700-mb flow from $22\frac{1}{2}$°N to $72\frac{1}{2}$°N between 0° and 180°W have

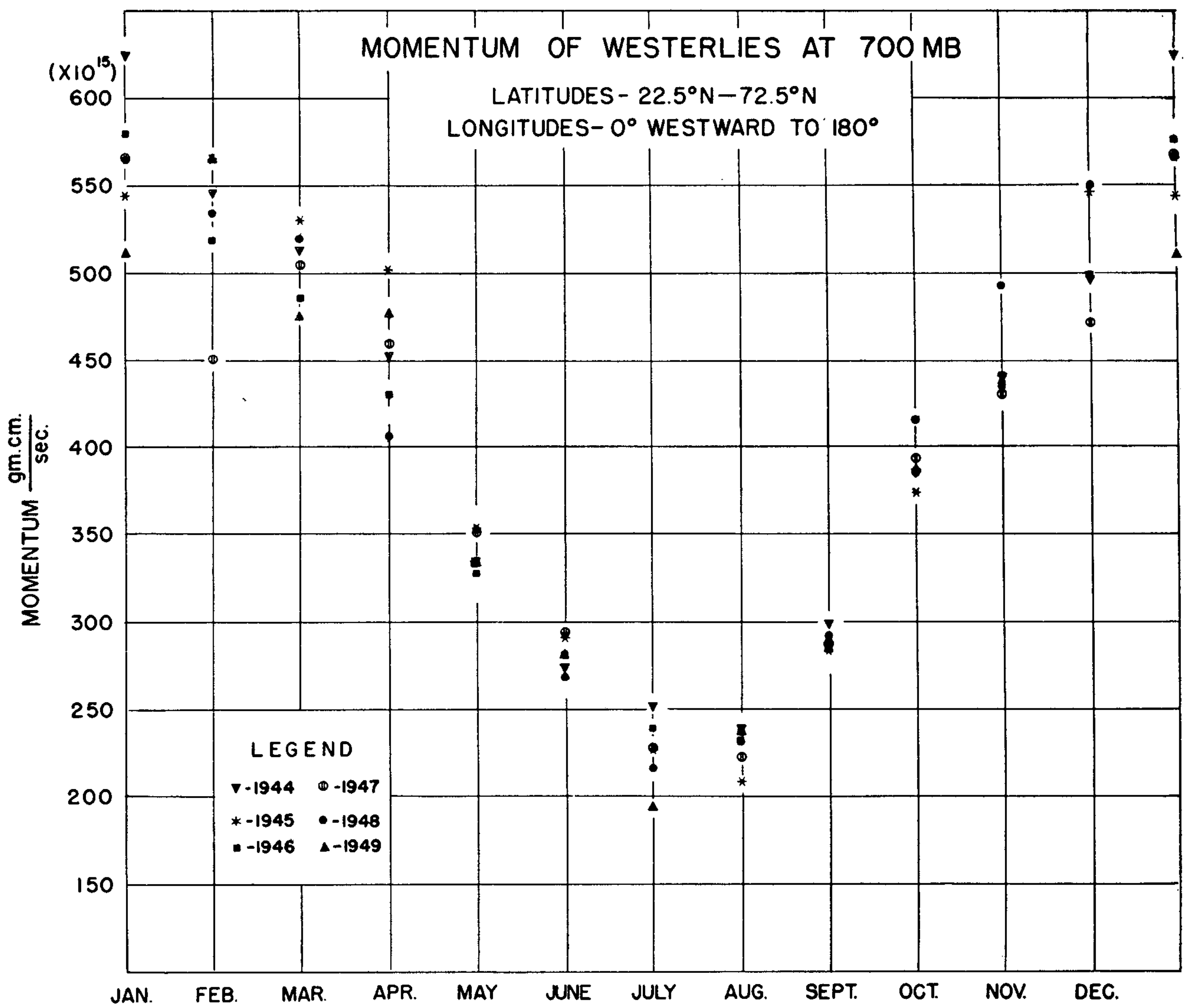

FIG. 4. Monthly mean total momentum of the westerlies at 700 mb as computed from zonal windspeed profiles for the zone from 20°N to 75°N and from 0° to 180°W for the years 1944 through 1949. Momentum is expressed in units of g cm sec^{-1} × 10^{-15}.

been made from monthly mean zonal-wind profiles with the help of a planimeter. The mean density has been computed from corresponding 700-mb temperature profiles. Variations in density due to moisture have been considered negligible. The results of these computations are shown in fig. 4, where the individual monthly mean values for the past six years are indicated. From this figure it appears that, at least for the transition seasons of the year, the total momentum for a given month has a strong tendency to fall into one general range of values peculiar to that month, and these values do not overlap with those of adjacent months. On the other hand, the variations in monthly mean zonal index at 700 mb in the same month of different years (figure not reproduced) are much greater and show no comparable tendency to cluster. Indeed, a statistical analysis indicates a much greater variability of zonal index than of total momentum even when account is taken of the difference in area over which computations are made.

Another illustration of the conservative nature of the total momentum of the mid-troposphere westerlies is furnished by a comparison of individual windspeed profiles for the high– and low–index cases of the index cycle. Two such cases, for 1944 and 1947, are reproduced in fig. 5. They suggest that there is a net loss of momentum at intermediate latitudes which is made up by an increase in low latitudes. In fact, these and other comparisons of monthly windspeed profiles indicate that the compensation to some extent occurs at latitudes even farther south than our data permit computations (20°N). In this connection, it is to be noted that the area represented in the computations constitutes less than one-third of the entire hemisphere. In all probability, the compensation would be more exact if one considered the entire hemisphere.

The conclusion suggested by the above data is that, in spite of large departures from normal of the zonal index between fixed latitudes in the same month of different years, the total momentum of mid-tropos-

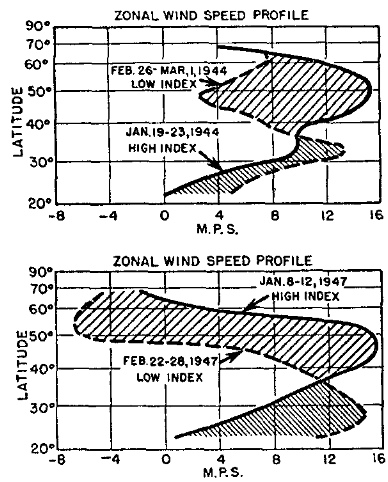

FIG. 5. 5-day mean windspeed profiles for high- and low-index stages of the index cycles of 1944 (upper) and 1947 (lower).

phere westerlies over the hemisphere in any month does not vary much from year to year; or, from another point of view, it appears probable that the *total momentum of the mid-troposphere westerlies around the hemisphere reaches a certain value at any given period each year, and it is only the distribution of this momentum with latitude that varies.*

In this concept we find evidence for the feature of low index stressed by Willett—namely, that low, temperate-latitude westerlies are generally associated with an expanded circumpolar vortex (*i.e.*, westerlies which are displaced southward). It is noteworthy that of the index cycles shown in fig. 1, only one (1944–45) showed a contraction of the circumpolar vortex (*i.e.*, the polar westerlies aloft, rather than those of the subtropics, increased).

If it is only the form of the westerly circulation which varies appreciably and not its absolute, overall, integrated strength (considering the entire hemisphere), it would appear that variations in the zonal index (or for that matter any zonal wind flow between fixed latitudes) are due to the degree of organization (or lack of organization) of the large-scale mid-tropospheric wave systems into confluence or difluence patterns, for it is the confluence patterns which usually concentrate the energy of the westerlies in narrow zones (jet streams) where peak speeds are reached and the difluence patterns which represent areas of strong "blocking."

Granting the above line of argument, the problem of index variations is reduced one step further to the fundamental problem of what factors lead to the peculiar long-wave structures favorable to sustained confluence, preferably in more than one area (for high index) and what factors are associated with the breakdown of these wave structures into difluence (blocking) patterns with their resulting low index.

3. Initial stage of the index decline

By examining the 700-mb 5-day mean maps subsequent to the periods of high index at the start of the index cycle (arrows of fig. 1), it became clear that each case of index decline was attended by a wave of "blocking" in the Atlantic, *i.e.*, by a strong localized diminution in zonal index over the Atlantic. Since the Atlantic constitutes a portion of the index band (0° to 180°W) with which we are concerned, this conclusion may at first glance appear to be a statistical necessity. The question may be raised as to what extent the initial index decline begins in the Atlantic rather than in North America or the eastern Pacific—areas which also compose the total index used. In tables 1 and 2 are given the local changes in index for the three equal areas, the Atlantic (5°W to 55°W), North America (65°W to 125°W), and the eastern Pacific (135°W to 175°E) during the first week of the index cycle (one-week change following the week indicated by the arrows in fig. 1). Both at sea level and aloft, the bulk

TABLE 1. Changes in regional sea-level zonal indices in m sec^{-1} during the first week of the index cycle.

Period	Atlantic	North American	Eastern Pacific
19–23 January to 26–30 January 1944	−2.0	−2.7	−4.6
7–11 February to 14–18 February 1945	−4.4	−3.0	−4.6
26–30 January to 2–6 February 1946	−1.2	−1.3	+0.1
8–12 January to 15–19 January 1947	−8.3	+0.6	−0.6
14–18 February to 21–25 February 1948	−8.8	−5.1	+4.1
16–20 February to 23–27 February 1949	−10.0	−4.4	+2.4
Mean	−5.8	−2.6	−0.5

TABLE 2. Changes in regional 700-mb zonal indices in m sec^{-1} during the first week of the index cycle.

Period	Atlantic	North American	Eastern Pacific
19–23 January to 26–30 January 1944	−4.5	−2.9	−2.9
7–11 February to 14–18 February 1945	−5.9	−2.4	+3.6
26–30 January to 2–6 February 1946	−1.9	−5.3	+0.4
8–12 January to 15–19 January 1947	−8.3	+1.8	+2.4
14–18 February to 21–25 February 1948	−9.3	−8.2	+4.1
16–20 February to 23–27 February 1949	−8.8	−7.0	−1.3
Mean	−6.4	−4.0	+0.2

of evidence suggests that the Atlantic usually contributes most heavily to the initial index decline. Notable exceptions occur in 1944 at sea level and 1946 at 700 mb. But we are expecting too much if we ask the atmosphere to release its secrets completely to a "straight-jacketing method" such as this, in which we have set up restricted zones and time intervals. Indeed, it is surprising that the results are as uniform as they are in tables 1 and 2.

Thus there is a suggestion that blocking is a necessary condition for the inception of an index cycle. But the long-range weather forecaster is well aware of the fact that blocking is not a *sufficient* condition. There arise during winter many more blocking waves in the Atlantic than there are hemisphere index cycles. For example, indicated by a "B" in fig. 1 are the beginnings of those cases of blocking taken from an independent study.[3] Here a period of Atlantic blocking was defined as one in which the 5-day mean sea-level pressure anomaly in the area 50°N to 70°N and 20°E to 50°W has a positive value of 15 mb or greater and persists for at least one and one-half weeks. The "B" is placed at the beginning of such a blocking wave (*i.e.*, the first period which meets the criterion stated). It is noteworthy that one of these so-defined blocking periods occurs during each one of the index cycles of fig. 1, but there are other such blocking waves that do not materialize into an extended index cycle. An inspection of the maps (not reproduced) associated with all the blocking cases indicated by the letter B fails to disclose a fundamental difference in the nature of initial Atlantic blocking waves which are part of index cycles and those which are not. It thus appears that some external factors (external in the sense of being outside the Atlantic area) must be of importance. These external factors may be expressed in the more complete state of the general circulation, involving areas far distant from the blocking, and/or possibly the effect of differing quality and quantity of radiation from the sun. Notwithstanding the growing popularity of solar hypotheses, it appears to the author that there is sufficient cause for variations in the earth-atmosphere system to explain the effectiveness of Atlantic blocking in producing an index cycle. Such a theory follows.

The strength of the mid- and upper-troposphere westerlies is to a considerable extent a measure of the degree of imprisonment or containment of cold air masses composing the polar cap. A special case of such containment (during the winter 1946–47) was discussed in some detail in an earlier report (Namias, 1947). During these periods, strong westerlies forbid any extensive meridional transport, and the radiational cooling permits the air overlying northern land areas to grow into a vast cold-air reservoir. To some extent we may draw an analogy to a condenser where the containment mechanism of the strong westerlies is the most efficient method of operation to store cold air. Since an exchange of air between pole and equator is an obvious necessity for the atmospheric heat balance, it would appear that those *blocking waves which occur simultaneously with a great reservoir of cold polar air are the ones which materialize into an index cycle.*

Some substantiation of this idea may be found in the fact that the year's primary index cycle usually occurs considerably later than the December solstice, *i.e.*, after the polar atmosphere has had time to develop into an extensive cold pool. Not only during this six-year period from 1944 through 1949 does the index cycle prefer February, but it shows up even in the period 1932–39 (see fig. 6). Here are plotted means of the index curves of fig. 1 for successive 10-day intervals for the entire six years 1944–49. It might be argued that such a phenomenon might be peculiar to this 6-year period. While no strictly comparable upper-air data for other years are available, an attempt to obtain upper-air maps for the period 1932–39 was made during the war by the U. S. Weather Bureau in collaboration with the University of California at Los Angeles and the Massachusetts Institute of Technology. Willett (1947) has made considerable use of this material in his exhaustive statistical studies of this period and lists 7-year average 3-km zonal index values for successive twice-weekly 5-day periods for the years 1932–39. Values taken directly from his data (with some small interpolation when necessary) are given in fig. 6. While it is apparent that the same major index cycle is present in the 1932–39 data as in the 1944–49 data, the amplitude of variation in earlier years is considerably less. The principal explanation of this suppression is to be found in the fundamental assumption under which the maps comprising Willett's data were prepared—namely, that the lapse rate in data-sparse areas (Atlantic and Pacific) was the moist adiabatic. Hence, under low-index conditions of winter, when warm highs appear in northern latitudes, these assumptions are erroneous in the direction of giving fictitiously high zonal indices. Similarly, with high index, subtropical anticyclones are well developed and have lapse rates more stable than the moist adiabatic, and computed indices are

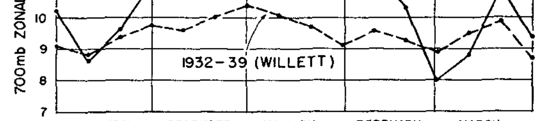

FIG. 6. Average zonal indices taken at 10-day intervals from the graphs of fig. 1 (solid curve) and from similar data for 1932–39 given by Willett (dashed curve).

[3] Aubert, E. J., *Solar-weather relationships.* Unpublished manuscript in the Extended Forecast Section, U. S. Weather Bureau, Washington, D. C., November 1949.

thus too low. Operating in the same direction (*i.e.*, to reduce the variability) is the fact that Willett's data embrace about one-third again more data in longitudinal expanse than do ours. Both factors minimize index variations. It appears that the scale of the curve for Willett's data should be multiplied by some factor and this would bring it into a better agreement with the 1944–49 curve. Thus, there is a distinct suggestion of a global "singularity" in the general circulation.

As further evidence for support of the condenser theory, one might examine the observed temperatures of air comprising the polar cap preceding or at the onset of the index cycles. Precisely what thermal indices should be used for this test is difficult to decide, for certainly large areas and long periods of time must be considered. The extent of available data during this period makes it impossible to obtain reliable upper-air temperatures from the polar cap north of 70°N and also for a large portion of the northern hemisphere between 0° eastward to 180°. Thus our data are restricted to the polar cap south of 70°N and lying between 0° and 180°W. This area considers one important large source of manufacture of cold air, northern North America, but neglects the perhaps more important cold air factory of Siberia. Considering, therefore, the restricted area between 55°N and 70°N and between 0° and 180°W as representative of the entire polar cap, the average thicknesses and corresponding mean virtual temperatures of the air between 1,000 and 700 mb over this area for the six Januarys from 1944 through 1949 are given in table 3. (January is the month which immediately precedes most of the cycles, and such data were readily available.)

TABLE 3. Monthly mean thickness and corresponding mean virtual temperature between 1,000 and 700 mb for the Polar reservoir between 0° and 180°W and between 55°N and 70°N.

Period	Thickness (ft)	Mean virtual temperature (°C)
January		
1944	8,920	−12.8
1945	8,940	−12.1
1946	8,870	−14.2
1947	8,820	−15.7
1948	8,890	−13.7
1949	8,870	−14.2

From these data it is apparent that 1947, the year of the largest and most intense cycle which led to world-wide record-breaking weather in many areas (Namias, 1947), was characterized by the coldest January[4] while 1945, the year of a very weak cycle (particularly in departure from normal of the low point of the index) was preceded by one of the warmest Januarys in the sub-polar region. However, the year 1944, with its fairly intense and long-lasting cycle but warm January polar reservoir, and also 1946, with a weak cycle preceded by a moderately cold reservoir, appear out of line.

A better and more quantitative measure of the intensity of an index cycle can be determined from the wind profiles during the period encompassing a good part of the low index portion of the cycle. Data of this sort have already been presented in fig. 4 for monthly mean wind profiles during the 6-year period. Returning to fig. 4, it is apparent that the month of February has the greatest year-to-year variability in momentum between latitudes 22½° to 72½°N and between 0° and 180°W—apparently a reflection of the marked year-to-year differences in the intensity of the cycle. From the wind profiles (not reproduced) upon which fig. 4 was based, it is clear that, particularly at times of low index, when the jet stream is displaced far to the south, westerly momentum is apparently lost by the atmosphere north of 20°N and is gained (reappears) south of here. Examples appear in fig. 5. The momentum computed and indicated in fig. 4 may therefore in a rough sense be a measure of the intensity of the index cycle—low values representing an intense cycle in which the upper-level westerlies of the tropics are strengthened, and high values a weak cycle. Now, the index minima during these six years (1944–49) were generally reached around the end of February or the first part of March. Interpolating in fig. 4 between February and March, we obtain the following values:

	Momentum from mid-February to mid-March (gram cm/sec)
1944	530×10^{16}
1945	548
1946	502
1947	478
1948	528
1949	520

These values are plotted against the original January mean temperatures of the sub-polar cap (from table

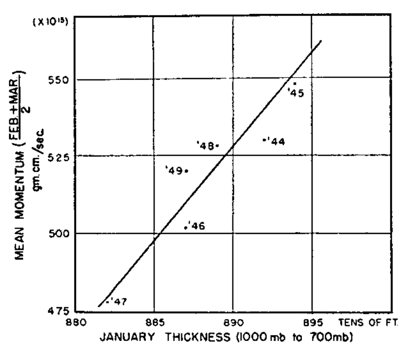

FIG. 7. Mean monthly momentum of the flow at 700 mb from mid-February to mid-March (ordinate) as a function of mean thickness of the layer 1,000–700 mb over sub-polar regions (55°N to 70°N and 0° to 180°W) during the preceding January.

[4] Temperatures in the latter half of January and early February 1947 in the Canadian Yukon reached an unofficial minimum of −84F at Snag Airport and during the period 29 January–5 February a mean of −62F was recorded. The manner of production of this cold air was described by H. Wexler (1948), who traced originally very cold air from Siberia into the Canadian Yukon via the polar cap and computed from aerological soundings minimum surface temperatures in fair agreement with those observed.

3) in fig. 7. Thus it appears that *the intensity of long index cycles is largely determined by the reservoir of cold air preceding their onset.*

Since the reservoir of cold air is assumed to be largely a function of the period of high-index imprisonment, here is a clue to the possible effectiveness of a blocking wave in producing an extended index cycle. Thus, in the blocking waves marked B in fig. 1, it is evident that many of those which failed to produce a major cycle were too close to a recent period in which the atmospheric condenser had discharged in the form of an index minimum well below normal. It would thus appear that a certain recovery time is needed before the condenser can restore its reservoir of cold air and produce another discharge in the form of a great index cycle. This conclusion, arrived at independently, is reminiscent of the one by Rossby and Willett (1948):

> Rossby visualizes this cycle of index change as having a natural period which depends upon the relative effectiveness of the radiational cooling processes in the higher latitudes. This period appears to be shorter at the beginning of the winter and because the rate of cooling is most rapid at that time. Each index cycle tends somewhat to expand the effective polar cap and to diffuse the thermal contrasts equatorward.

The flow patterns in the Atlantic during the initial decline of the index tend to favor cellular structures with warm pools (highs) at high latitudes and cold pools (lows) at low latitudes. The well-known stability of such great vorticities is especially favored during late winter when the surface stability, because of increased Arctic ice and cold surface water, can reach a maximum in northern latitudes under the warm highs and thus, as Wexler (1943) points out, permit little air to escape from the friction layer of the anticyclones. At the same time, the cold lows at low latitudes (which are prevailingly found over the ocean between the Azores and Spain), because of strong vertical temperature gradients, can probably be maintained against the filling inflow in the friction layer by vigorous convective showers with their vast supplies of latent heat. As pointed out in an earlier work (Namias, 1944), the decline of circulation first appearing in the Atlantic progresses slowly westward at about 60 deg per week. But it is important to note that this westward local diminution in index during an index cycle proceeds without disrupting the initial cellular blocking pattern set up in the Atlantic. This contention is strengthened by the large number of half-week periods the Atlantic blocking persisted within index cycles as compared with the smaller number elsewhere. These numbers are indicated by subscripts attached to the B in fig. 1. Here again only 1945, the unique cycle year, is out of line. Thus we may consider the initial Atlantic wave of blocking of the index cycle as an infection of the westerlies which spreads upstream as a malignant growth, progressively decaying the zonal circulation.

4. Initial increase of zonal index following the minimum

TABLE 4. Changes in regional zonal index at 700 mb in m sec^{-1} during the week immediately following the minimum of the index cycle.

Period	Atlantic	North American	Eastern Pacific
26 February–4 March to 4–8 March 1944	8.4	3.4	−3.4
24–28 February to 3–7 March 1945	−6.5	4.5	5.2
16–20 February to 23–27 February 1946	6.0	0.6	−2.1
1–5 March to 8–12 March 1947	5.0	1.0	1.2
28 February–3 March to 6–10 March 1948	4.0	2.0	0.0
9–13 March to 16–20 March 1949	0.9	6.0	3.9
Mean	3.0	2.9	0.8

The recovery of zonal index from its minimum of the cycle appears to take place in late February or early March. Some light is shed on the manner in which this increase is effected by regional changes in index for the week subsequent to the minimum. The changes are shown in table 4 in a similar fashion to those for the initial decline shown in tables 1 and 2. Apparently the initial increase is favored in the Atlantic (4 out of 6 cases and the highest mean change), to a lesser degree in North America, and seldom (only 1945) in the eastern Pacific. Remembering that 1945 was a contracted circumpolar-vortex

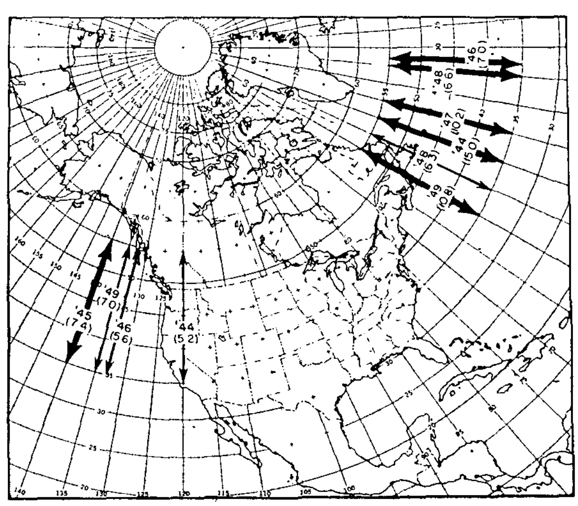

FIG. 8. Longitudes of primary and secondary increase of zonal index at sea level for the week following the index minimum (upper figure gives year, lower figure the rise in m sec^{-1}).

cycle, it appears that the Atlantic is normally favored for the initial index increase, just as it was for the initial decrease. A further study of sea-level pressure-change maps suggests that an even more localized area of major increase can be found in the western Atlantic. The longitudes of greatest increase and secondary increase in local index are shown in fig. 8. It appears that the greatest initial increases in index occur in the western Atlantic with a secondary area of increase just off the Pacific coast. These two areas are precisely those in and to the east of common confluence zones—in the western Atlantic between cold, Labrador and tropical-Gulf (and Atlantic) air and off the Pacific coast between cold, Arctic air from Alaska and warmer, sub-tropical air from the eastern cell of the Pacific High.

The above paragraph is merely a *description* of how the index begins its upward climb from the minimum of the cycle. It does not explain *why* the flow patterns evolve in a manner favorable to the initiation of these zones of confluence. Indeed, this problem is a most difficult one to solve, and at present we can only bring up for consideration some apparently relevant points. One of these is that around the time of the index minima (late February and early March), total incoming solar radiation begins to increase rapidly and thereby tends to destroy the very elements responsible for low index—the cold pools of low latitudes and the warm pools of high latitudes. Perhaps this factor becomes dominant at this time of year. It is quite probable that the increasing insolation may produce different effects in different areas of the upper-level flow patterns and that these effects favor the initiation of the flow patterns favorable to the confluence cited above.

5. Summary

To sum up, we may now return to the three questions posed earlier in this study.

1. Why during each year is there a tendency for the occurrence of at least one index cycle lasting several weeks?

Because the heat balance of the atmosphere demands an exchange of air between polar and equatorial latitudes. This exchange could operate in short week-to-week oscillations of the index, were it not for slow-moving blocking waves with their strong, deep, meridional components of flow gradually operating to deplete vast reservoirs of cold air which are imprisoned at high latitudes during extended periods by strong mid-latitude westerlies.

2. Why do these cycles vary in intensity from one year to the next?

Because, for reasons unknown, the quasi-permanent anchor troughs and ridges of the mid-troposphere are fixed in different regions in different years and thus in some years the flow patterns become more highly organized into confluence (high index) bands than others. In this manner, the cold reservoir becomes stored or depleted at different times of the year. Since the intensity of the cycle appears to be dependent upon the amount of stored cold air, which in turn depends both on the net outgoing radiation and upon the storage time, it is clear that there must be considerable variation in the character of index cycles through the years. What we do not yet know is why the quasi-permanent anchor troughs and ridges of mid-troposphere are fixed in different regions in different years; it is quite possible that lag effects of ocean currents, snow cover, *etc.*, are dominant factors.

3. Why does there appear to be one particular period (late February) when the most pronounced cycle occurs?

Because the two primary factors responsible for the cycle, an extensive cold air reservoir and the initial, stable, cellular-type, Atlantic blocking-mechanism are both favored at this time of year. The cold reservoir is favored by the long polar night over a pre-established, extensive, snow cover. The Atlantic warm anticyclone to the north and the cold low to its south, concomitant features of blocking, are both favored by considerations of vertical stability in the friction layer as deep pools of polar air move into southerly latitudes and deep pools of tropical air move into high latitudes. The stability under the warm highs results in less "leakage" from below, while the instability at low latitudes, extending through a deep layer of air over water surfaces, more than compensates the frictional filling by producing copious showers releasing much latent heat.

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