SEASONAL AND IRREGULAR VARIATIONS OF THE NORTHERN HEMISPHERE SEA-LEVEL PRESSURE PROFILE

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ABSTRACT

The variations of five-day mean sea-level pressure, averaged about selected latitude circles in the northern hemisphere, and the variations of differences between five-day mean pressures at selected pairs of latitudes are examined statistically. The northern hemisphere is found to contain two homogeneous zones, one in the polar regions and one in the subtropics, such that pressures in one zone tend to be correlated positively with other pressures in the same zone and negatively with pressures in the other zone. Considerable difference is found between the seasonal and the irregular pressure-variations which result from mass transport across the equator, but the seasonal and the irregular variations of pressure differences resemble each other closely, as do the seasonal and the irregular pressure-variations which result from rearrangements of mass within the northern hemisphere. The most important rearrangements appear to consist of shifts of mass from one homogeneous zone to the other. These shifts seem to be essentially the same as fluctuations between high-index and low-index patterns. The study thus supports previous conclusions that such fluctuations form the principal variations of the general circulation, and also shows that, except at low latitudes, the seasonal pressure-variations are essentially fluctuations of this sort. The possibility that the seasonal and the irregular variations have similar ultimate or immediate causes is considered.

1. Introduction

The irregular fluctuations of the general circulation of the earth's atmosphere and the accompanying changes in the large-scale weather pattern have been the subject of numerous studies. The state of the general circulation during a given period of several days or longer is frequently represented by a set of maps showing the distribution of the average pressure during this period at various elevations. Fluctuations of the general circulation are then regarded as changes in the pressure patterns of these mean maps.

Changes in these patterns may be resolved into changes in the average pressure at each latitude and changes in the distribution along each latitude circle of the departure of the pressure from the average. The present study deals with the former kind of pressure change. Such changes may be regarded as variations of the north-south profile of average pressure, which will be called simply the pressure profile. In this study only the northern-hemisphere sea-level pressure-profile is investigated.

Many features of the sea-level pressure-profile have been investigated in detail by Willett [5, 7]. These features include pressures at fixed latitudes, differences between pressures at pairs of fixed latitudes (fixed-latitude zonal indices), maximum differences between pressures at pairs of variable latitudes (maximum zonal indices), and pressures averaged over certain areas of the northern hemisphere. They also include changes in these quantities during fixed time intervals. The statistical portion of Willett's investigations includes the determination of linear correlation coefficients, simultaneously and with time lags, between numerous pairs of these quantities. However, most of his correlations involve other important quantities which cannot be obtained explicitly from the sea-level pressure-profile. From these investigations, he concluded that the most important variations of the general circulation consist of fluctuations between high- and low-index patterns, characterized by the presence of strong and weak zonal westerly winds in middle latitudes.

The present study resembles Willett's investigations in its use of linear correlations. It differs in that it is restricted mostly to two kinds of quantities, pressures at fixed latitudes and differences between pressures at pairs of fixed latitudes. It differs also in that these quantities are investigated at latitudes so close together that mean values and standard deviations of the quantities, and correlations between them, can be interpolated for all intervening latitudes without serious errors. In particular, maximum nontrivial correlations between pressures and between pressure differences can be determined. The numerical results lead to several conclusions concerning the fluctuations of the general circulation.

2. Procedure

All the data used in this study were made available through the kindness of the U. S. Weather Bureau—Massachusetts Institute of Technology Extended Forecasting Project. The data consist principally of

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sea-level pressures expressed in tenths of millibars, averaged for selected five-day periods about selected latitude-circles. The five-day periods overlap, so that two periods begin each week. The periods occupy seven "seasons," each extending approximately from 1 October through the following 31 March. The seasons occupy the years 1932–1939 and contain 51, 52, 52, 51, 52, 51, and 52 periods, respectively. The latitudes selected were 75, 65, 55, 45, 35, 25, and 15°N. The pressures at these latitudes for these periods may be regarded as forming a set of 361 pressure profiles. In this study, the symbol P with any subscript always denotes the five-day mean pressure at the latitude specified by the subscript.

The remaining data consist of normal sea-level pressures expressed in tenths of millibars, for each month of the year, at each five degrees of latitude northward from 10°N. These pressures had been compiled from forty years of northern-hemisphere maps [2].

Since the five-day mean and monthly normal pressures were obtained from analyzed maps, they were to some extent determined subjectively. They may be rather accurate at middle latitudes, but they must be regarded as approximations at 75°N and at 15°N, where observations are rather sparse. Moreover, along every latitude-circle under consideration, a portion of the earth's surface lies at a considerable elevation above sea-level. Thus, in the determination of every five-day mean and every monthly normal pressure, pressures observed at sea level were averaged with pressures observed at higher elevations and artificially reduced to sea-level. One result of these unfortunate but unavoidable circumstances is that the variations of any pressure P_x may not always imply similar changes in the mass of atmosphere vertically above latitude x.

On the basis of the monthly normal pressures, a set of 52 "normal" five-day mean pressures was constructed for each of the selected latitudes. The symbol P^0 with any subscript denotes such a five-day normal pressure at the latitude specified by the subscript. The process of determining these normals consists of choosing, at each latitude x, quantities $P^0{}_x$ in such a way that the averages of the first 9, next 8, next 9, next 9, next 8, and final 9 quantities $P^0{}_x$ equal the normal pressures at latitude x for October, November, December, January, February, and March, respectively. At the same time, the curves of $P^0{}_x$ as functions of time, and the profiles for individual periods, are made as smooth as possible. Corresponding to each individual quantity P_x, a quantity $P^0{}_x$ was thus determined. For the seasons with 51 periods, the first 51 values of $P^0{}_x$ were used.

Although the process of determining five-day normals is admittedly subjective, it does reveal some details which might not be noticed during a casual inspection of the monthly normals. For example, at 35°N the monthly normals for October, November, December, and January are given as 1018.4, 1019.8, 1019.8, and 1020.2 mb, respectively. Aside from the maximum in January, the five-day normals must almost certainly possess a secondary maximum in November and a minimum in December. On the other hand, short-period fluctuations having maxima and minima at the end of a month need not always be revealed. A minimum of this sort has recently been investigated by Namias [3].

It is hardly to be expected that 40 years of data are sufficient for determining monthly normal pressures precisely; but yet, from one point of view, any situation which can persist for 40 years is a perfectly normal one, even though it may differ from the situations during other 40-year periods. Very likely the definition of a monthly normal pressure cannot be precise, in which case the subjectivity involved in determining five-day normals from monthly normals may be of little consequence.

For each of the seven seasons individually, the sum ΣP_x was obtained for each of the seven selected latitudes x, and the quantity $n\Sigma P_x P_y - \Sigma P_x \Sigma P_y$ was obtained for each of the 28 pairs of latitudes (x,y), n being the number of periods during the season. The same quantities were also obtained for the seven seasons combined into one long season of 361 periods. From these quantities, the mean value $\bar{P}_x$ of P_x, the standard deviation $\sigma(P_x)$ of P_x, and the linear correlation coefficient $r(P_x,\ P_y)$ between P_x and P_y were determined.

If L and L' are any linear combinations of five-day mean pressures, the quantities ΣL and $n\Sigma LL' - \Sigma L\,\Sigma L'$ are readily obtained as linear combinations of quantities ΣP_x and $n\Sigma P_x P_y - \Sigma P_x \Sigma P_y$. The quantities $\bar{L}$, $\sigma(L)$, and $r(L,L')$ are then easily determined.

The linear combinations studied include pressure differences U_x, for each five degrees of latitude from $x = 70$ through $x = 20$, defined by the relations.

$$U_x = P_{x-5} - P_{x+5} \quad \text{when } x \text{ is divisible by 10,}$$
$$U_x = P_{x-10} - P_{x+10} \quad \text{when } x + 5 \text{ is divisible by 10.} \quad (1)$$

Evidently U_x affords a fair approximation to the average low-level westerly wind within a zone centered at latitude x. The use of alternate ten-degree and twenty-degree zones permits the study of eleven differences U_x as linear combinations of seven pressures P_x. For the seven seasons combined, the 55 correlations $r(U_x, U_y)$ were obtained.

At each latitude x, the variations of P_x include normal seasonal variations, represented by the variations of $P^0{}_x$, as well as irregular variations, represented by the variations of $P^1{}_x$. Here $P^1{}_x = P_x - P^0{}_x$ is the departure of P_x from normal. Likewise, the variations of U_x include seasonal and irregular variations, represented by the variations of U^0_x and U^1_x, which are defined in terms of pressures by relations analogous to (1). To determine the contribution of each kind of variation to the standard deviations and correlations previously mentioned, the quantities $\sigma(P^0_x)$, $\sigma(P^1_x)$, $r(P^0_x,P^0_y)$, $r(P^1_x,P^1_y)$, $r(U^0_x,U^0_y)$ and $r(U^1_x,U^1_y)$ were determined for 1932–1939 combined.

Both the seasonal and the irregular variations of sea-level pressure in the northern hemisphere result partly from a transport of mass across the equator and partly from a rearrangement of mass within the northern hemisphere. The mass transport across the equator may be measured by the variations of the average pressure over the entire northern hemisphere, which may be approximated by the linear combination

$$M = \sum_{i=0}^{8} [\sin(10i + 10) - \sin(10i)] P_{10i+5}. \quad (2)$$

In computations involving M, P_{85} and P_5 were replaced by P_{75} and P_{15}, values of the former pressures being unavailable. Similarly, the normal seasonal and the irregular mass-transport across the equator may be measured by variations of the normal average pressure over the northern hemisphere and of the departure of the average pressure from normal, which may be approximated by M^0 and M^1, defined in terms of pressures by relations analogous to (2). To study the mass transport across the equator, the standard deviations $\sigma(M)$, $\sigma(M^0)$ and $\sigma(M^1)$, and the correlations $r(M,P_x)$, $r(M^0,P^0_x)$ and $r(M^1,P^1_x)$, were obtained for 1932–1939 combined.

The rearrangements of mass within the northern hemisphere were studied by means of the quantity

$$Q_x = P_x - \bar{P}_x - \sigma^{-1}(M)\, \sigma(P_x)\, r(M,P_x)\, [M - \bar{M}], \quad (3)$$

which is the remainder left after subtracting from P_x the value which is given for P_x by a regression equation based on M. It is evident that $r(M, Q_x) = 0$, so that the variations of Q_x are unrelated to the variations of M and result only from rearrangements of mass within the northern hemisphere. The effects of variations of M^0 and M^1 were similarly removed from P^0_x and P^1_x by formulae analogous to (3), defining Q^0_x and Q^1_x. The standard deviations $\sigma(Q_x)$, $\sigma(Q^0_x)$ and $\sigma(Q^1_x)$, and the correlations $r(Q_x, Q_y)$, $r(Q^0_x, Q^0_y)$ and $r(Q^1_x, Q^1_y)$, were then obtained for 1932–1939 combined.

3. Numerical results

Table 1 presents mean values and standard deviations of P_x, P^0_x, and P^1_x for the seven seasons 1932–1939 combined. The outstanding features of the average pressure-profile for fall and winter are the pressure minimum near 65°N and the pressure maximum near 35°N. The differences between $\bar{P}_x$ and $\bar{P}^0_x$ show that seven years of data are far from enough to determine normal pressures and suggest that even forty years are insufficient. The standard deviations $\sigma(P_x)$ show that the five-day mean pressure is much more variable at high latitudes than at low latitudes. The irregular variations account for most of the variability at high latitudes, while at low latitudes the variability depends almost equally upon the seasonal and the irregular variations.

TABLE 1. Mean values and standard deviations, at latitudes x, of P_x, $P_x{}^0$, and $P_x{}^1$ for the fall and winter seasons (October–March) of 1932–1939. Values are in millibars.

x	75	65	55	45	35	25	15
$\bar{P}_x$—1000 mb	14.03	12.77	14.17	17.06	18.60	17.01	13.33
$\bar{P}_x{}^0$—1000 mb	15.54	13.01	13.94	17.43	19.12	17.81	13.66
$\bar{P}_x{}^1$	−1.51	−0.24	0.23	−0.37	−0.52	−0.80	−0.33
$\sigma(P_x)$	6.86	5.02	3.20	2.66	2.17	1.56	1.10
$\sigma(P_x{}^0)$	1.67	1.37	0.76	0.61	0.93	1.34	0.90
$\sigma(P_x{}^1)$	6.48	4.77	3.17	2.53	1.88	1.07	0.87

At this point it should be mentioned that if the data covered the entire year rather than half the year, the standard deviation of P^0_x would persumably be increased at most latitudes, since the seasonal pressure changes from winter to summer are in general greater than those within the colder half of the year. On the other hand, the standard deviation of P^1_x would probably be decreased at most latitudes, since the irregular pressure variations are probably smaller in summer than in winter. The standard deviations of P_x and P^1_x could also be increased or decreased by the use of periods shorter or longer than five days.

Fig. 1 shows the correlations $r(P_x, P_y)$ for each of the seven seasons 1932–1939 individually and also for the seven seasons combined. Each correlation diagram is accompanied by a curve of $\sigma(P_x \cos x)$, which is proportional to the standard deviation of the mass of atmosphere per unit latitude vertically above latitude x, to the extent that sea-level pressure represents atmospheric mass. It is worth noting that the correlations for 1932–1939 combined closely approximate the arithmetic averages of the corresponding correlations for the individual seasons.

Certain features of these correlation diagrams might have been anticipated. Positive correlations between pressures at latitudes only ten degrees apart might be expected, simply because of continuity of pressure. Negative correlations between pressures at more widely separated latitudes might be expected, because air leaving one latitude must accumulate at other latitudes. Thus, one might have anticipated correlation diagrams like the one for 1937–1938 in fig. 1, in which the isopleths closely resemble straight lines, parallel to the diagonal.

It is apparent, however, that most of the isopleths are far from straight. Instead, for 1932–1939 combined, the value of $r(P_{45}, P_{55})$ constitutes a definite minimum among the computed correlations between pressures at latitudes separated by ten degrees, while minimum

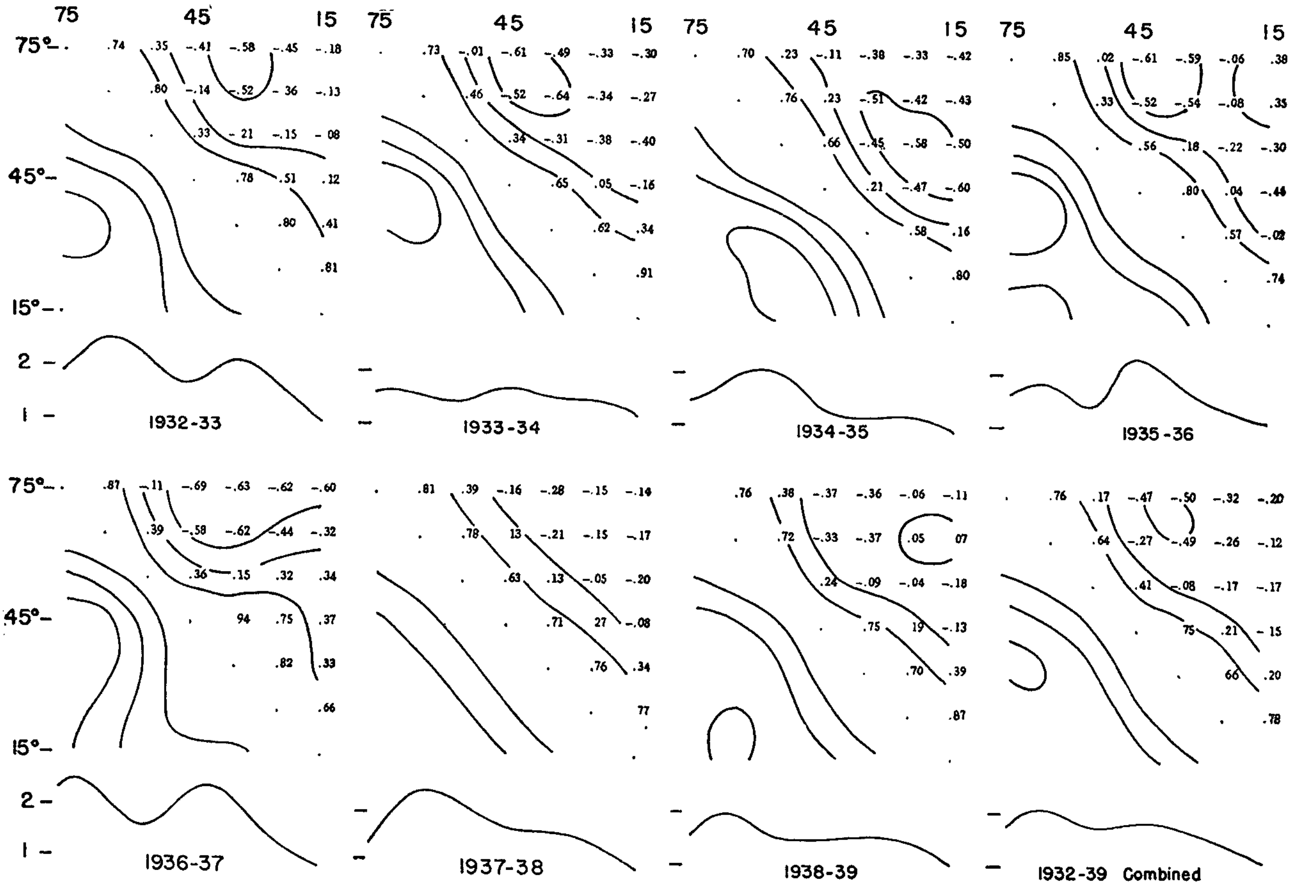

FIG. 1. Correlations $r(P_x, P_y)$ between northern-hemisphere sea-level five-day mean pressures P_x and P_y, at latitudes x (horizontal scale) and y (vertical scale), for the seven seasons (October–March) 1932–1939 individually and for 1932–1939 combined. Isopleths are drawn for the values +0.5, 0, and −0.5. Correlation diagrams are accompanied by curves showing values in millibars (vertical scale) of $\sigma(P_x \cos x)$ at latitudes x.

correlations between pressures twenty degrees and thirty degrees apart appear nearby on the diagram. These minima are so located that the northern hemisphere tends to contain two homogeneous zones, centered near 70°N and 35°N, separated by a transition zone near 50°N. Pressures within either homogeneous zone tend to be correlated positively with other pressures in the same zone and negatively with pressures in the other zone, while pressures within the transition zone tend to be uncorrelated with other pressures. Thus, the correlations $r(P_{35}, P_x)$ and $r(P_{70}, P_x)$, as interpolated and extrapolated from the computed correlations, each appear to exceed +0.5 for a range of about 30 deg of x and to be less than −0.5 for about 10 deg of x, while the correlations $r(P_{60}, P_x)$ exceed +0.5 for only 20 deg of x and never reach −0.5.

The homogeneous zones and the transition zone are present to some extent in each individual season, although they are displaced about 10 deg southward in 1934–1935, somewhat northward in 1935–1936 and 1936–1937, and are almost absent in 1937–1938. It might be argued that, since in general in any given season one correlation $r(P_{x+5}, P_{x-5})$ is smaller than any of the remaining ones, the statement that homogeneous zones are present in each season is trivial. However, application of Student's "t" test shows that the difference between the means for the seven seasons of $r(P_{55}, P_{45})$, and $r(P_{75}, P_{65})$, and the difference between the means of $r(P_{55}, P_{45})$ and $r(P_{35}, P_{25})$, are significant beyond the levels of 0.001 and 0.005, respectively, while the difference between the means of $r(P_{65}, P_{35})$ and $r(P_{45}, P_{15})$ is significant beyond the level of 0.05. The presence of homogeneous zones in the northern hemisphere therefore appear to be a real feature of the general circulation, at least for the fall and winter seasons studied.

The curve of $\sigma(P_x \cos x)$ for 1932–1939 combined possess two maxima. These maxima lie near the centers of the homogeneous zones, while the minimum between them lies within the transition zone. Two maxima also appear in each individual season except 1937–1938, when the homogeneous zones are almost absent. In each year the maxima occur near the centers of the homogeneous zones. A pronounced southward shift of the minimum in 1934–1935, and northward shifts in 1935–1936 and 1936–1937, accompany similar shifts in the transition zone.

Fig. 2 shows the correlations $r(P_x, P_y)$, $r(P^0_x, P^0_y)$ and $r(P^1_x, P^1_y)$ for 1932–1939 combined. The diagrams are accompanied by standard-deviation curves. It

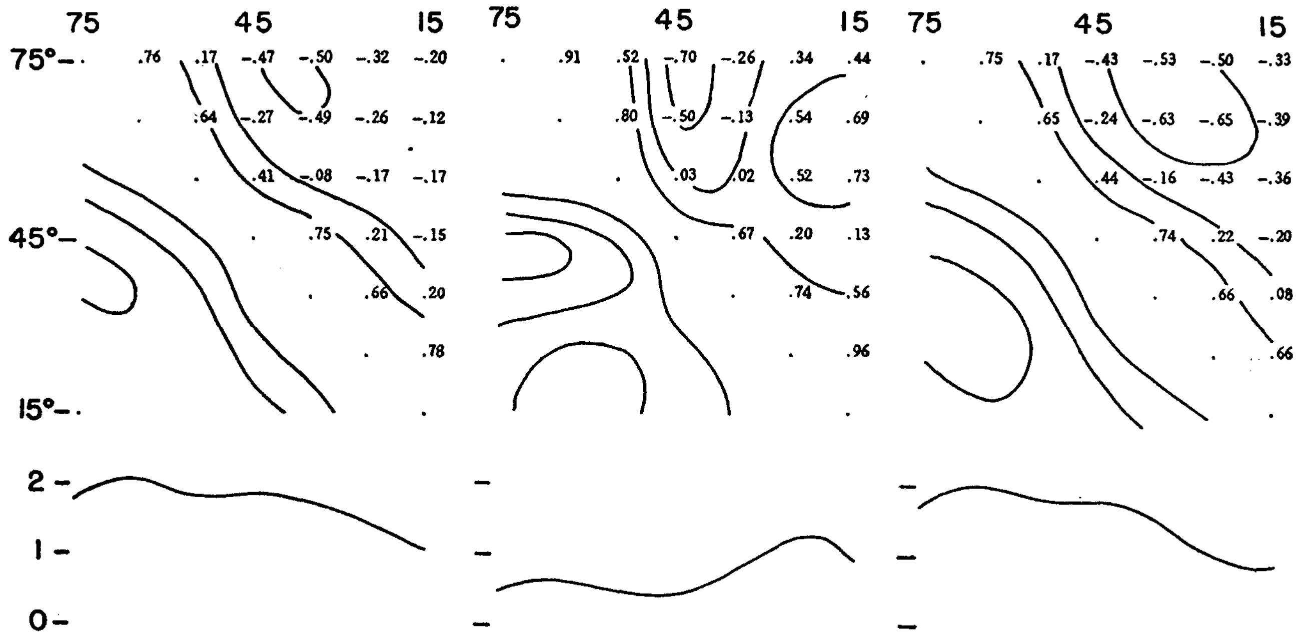

FIG. 2. Correlations $r(P_x, P_y)$ (left), $r(P_x^0, P_y^0)$ (center) and $r(P_x^1, P_y^1)$ (right) for 1932–1939 combined. Correlation diagrams are accompanied by curves for $\sigma(P_x \cos x)$, $\sigma(P_x^0 \cos x)$ and $\sigma(P_x^1 \cos x)$.

should be noted that if a scatter diagram of P^0_y against P^0_x were constructed, it would actually be a curve rather than a cluster of points. A low correlation may therefore indicate not that P^0_x and P^0_y are unrelated, but that the relation is nonlinear.

Evidently there is considerable difference between the seasonal and the irregular variations of pressures. To a certain extent, the correlations $r(P_x, P_y)$ should resemble weighted averages of $r(P^0_x, P^0_y)$ and $r(P^1_x, P^1_y)$, since variations of P^0_x and P^1_x both contribute to variations of P_x. Apparently the largest negative values of $r(P^1_x, P^1_y)$ are accompanied by positive or only small negative values of $r(P^0_x, P^0_y)$. As a result, the largest negative values of $r(P_x, P_y)$ fail to equal those of $r(P^1_x, P^1_y)$. Further evidence that the variations of P^0_x and P^1_x are dissimilar is provided by the standard-deviation curves. There are no large irregular variations of mass over the tropics accompanying the large seasonal variations of mass there.

Fig. 3 shows the correlations $r(U_x, U_y)$, $r(U^0_x, U^0_y)$ and $r(U^1_x, U^1_y)$ for 1932–1939 combined. In contrast to fig. 2, the seasonal and the irregular variations of pressure differences resemble each other closely, except at 20°N, at least as far as correlations are concerned. As a result, the values of $r(U_x, U_y)$ differ only slightly from those of $r(U^1_x, U^1_y)$.

Evidently the northern hemisphere contains homogeneous zones for variations of pressure differences, centered somewhat south of the homogeneous zones for variations of pressures. To some extent, these two kinds of homogeneous zones may be manifestations of the same phenomenon, since the pressure difference across a twenty-degree zone frequently varies in much the same way as the pressure at the northern edge of this zone. Specifically, the correlations $r(U^1_x, P^1_{x+10})$ were found to be -0.88, -0.91, -0.88, -0.91 and -0.90 for $x = 65$, 55, 45, 35 and 25, respectively. These large correlations occur because when two quan-

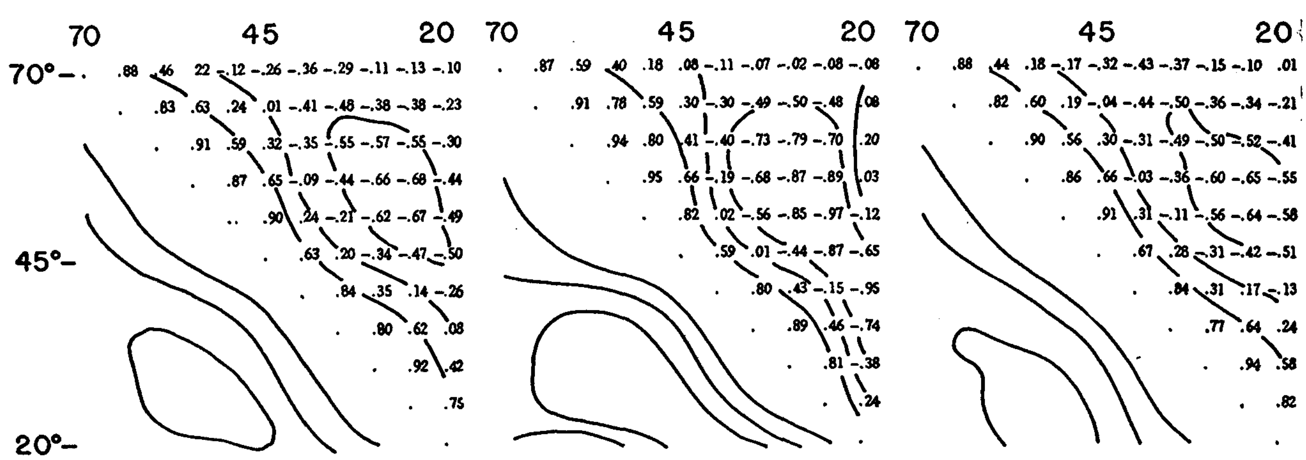

FIG. 3. Correlations $r(U_x, U_y)$ (left), $r(U_x^0, U_y^0)$ (center) and $r(U_x^1, U_y^1)$ (right) for 1932–1939 combined.

TABLE 2. Standard deviations of M, M^0 and M^1, expressed in millibars, and correlations, expressed in hundredths, of M, M^0, and M^1 with P_x, P_x^0, and P_x^1, respectively, at latitudes x, for the fall and winter seasons of 1932–1939.

	x	75	65	55	45	35	25	15
$\sigma(M)=1.02$	$r(M, P_x)$	28	53	62	38	37	52	40
$\sigma(M^0)=0.77$	$r(M^0, P_x^0)$	46	68	71	16	61	97	99
$\sigma(M^1)=0.76$	$r(M^1, P_x^1)$	33	52	70	50	22	07	−02

tities (here P^1_{x+10} and P^1_{x-10}) are not highly correlated, their difference (here U^1_x) is highly correlated with the quantity having the larger variance (here P^1_{x+10}). Thus it is not surprising that the third diagram in fig. 3 resembles the third diagram in fig. 2, displaced southward.

Similar reasoning does not apply to the second diagrams of figs. 2 and 3, since the correlations $r(P^0_{x+10}, P^0_{x-10})$ are not all insignificant, and, according to table 1, $\sigma(P^0_x)$ has no systematic southward decrease. Thus there is no *a priori* reason why these diagrams should be similar.

The resemblance between the first diagrams of figs. 2 and 3 may therefore be attributed to the irregular variations. The failure of the largest negative values of $r(P_x, P_y)$ to equal those of $r(U_x, U_y)$ may be attributed to the seasonal variations.

The seasonal and the irregular variations of sea-level pressure in the northern hemisphere both result partly from a transport of mass across the equator and partly from a rearrangement of mass within the northern hemisphere. Variations due to mass transport across the equator may be studied with the aid of table 2. Evidently, seasonal and irregular variations are about equally responsible for the variance of M. The values of $r(M^0, P^0_x)$ reveal that the rise and fall of M^0 to and from its midwinter maximum consist of an increase and decrease of mass primarily over the subtropics and to some extent over the polar regions, with only minor variations in middle latitudes. The values of $r(M^1, P^1_x)$ tell an entirely different story, indicating that the increases and decreases of M^1 during the northern-hemisphere fall and winter consist primarily of increases and decreases of mass over the polar regions, with only minor variations in the subtropics. There is thus not much resemblance between the seasonal and the irregular variations of M.

Fig. 4 shows the correlations $r(Q_x, Q_y)$, $r(Q^0_x, Q^0_y)$ and $r(Q^1_x, Q^1_y)$ for 1932–1939 combined. The diagrams are accompanied by standard-deviation curves. The homogeneous zones, now centered near 65°N and 35°N, are pronounced, and the negative correlations are large. In contrast to fig. 2, the second and third diagrams of fig. 4 show that, except at 15° N, the seasonal and the irregular variations of pressure resemble each other closely after variations of M^0 and M^1 are removed. As a result, the values of $r(Q_x, Q_y)$ differ only slightly from those of $r(Q^1_x, Q^1_y)$.

The lack of resemblance between the variations of Q^1_{15} and Q^0_{15} may result partly from the approximations used in defining M^0. The high correlation +0.99 between M^0 and P^0_{15} shows that about 98 per cent of the variation of P^0_{15} is associated with variations of M^0 rather than Q^0_{15}. Minor changes in the definition of M^0 may therefore cause important changes in Q^0_{15}.

A further resemblance between the variations of Q^0_x and Q^1_x appears in the standard-deviation curves in fig. 4. Each curve possesses two maxima of comparable intensity, located near the centers of the homogeneous zones. However, $\sigma(Q^1_x)$ is about three or four

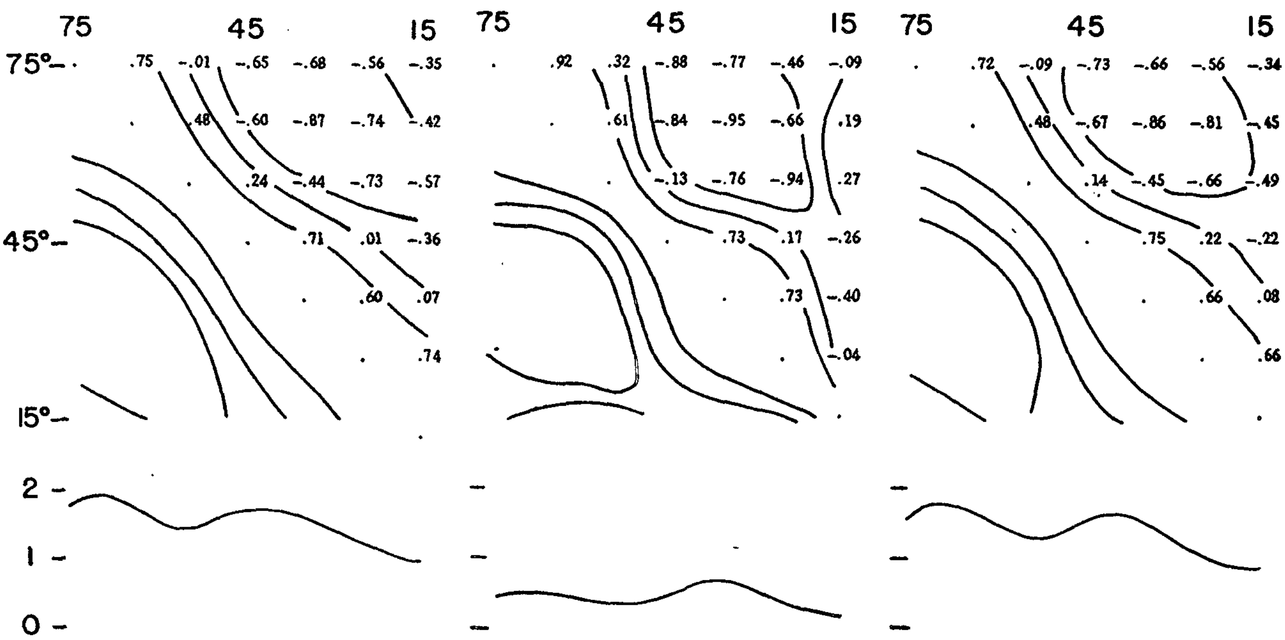

FIG. 4. Correlations $r(Q_x, Q_y)$ (left), $r(Q_x^0, Q_y^0)$ (center) and $r(Q_x^1, Q_y^1)$ (right) for 1932–1939 combined. Correlation diagrams are accompanied by curves for $\sigma(Q_x \cos x)$, $\sigma(Q_x^0 \cos x)$ and $\sigma(Q_x^1 \cos x)$.

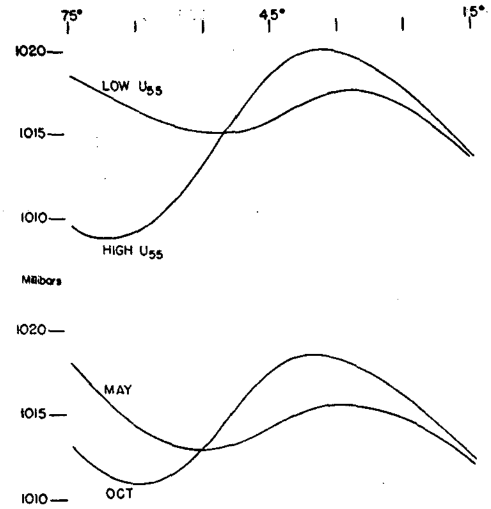

FIG. 5. Typical northern-hemisphere sea-level pressure-profiles (upper curves) accompanying high and low values of U_{55}, compared with normal sea-level pressure-profiles (lower curves) for October and May. Upper curves were computed from the formula $P_x = \bar{P}_x \pm (2/\pi)^{\frac{1}{2}} \sigma(P_x)\, r(U_{55}, P_x)$, and closely approximate the average curves for the higher half and the lower half of the values of U_{55}. Values of $\bar{P}_x$, $\sigma(P_x)$ and $r(U_{55}, P_x)$ for 1932–1939 combined were used in the computations.

times as large as $\sigma(Q^0_x)$ at most latitudes. Thus the variations of Q^0_x and Q^1_x differ in magnitude but are otherwise much alike.

The correlations in fig. 4 suggest that the most important rearrangements of mass within the northern hemisphere are transfers of mass from one homogeneous zone to the other. The standard deviations support this idea, since the standard deviation of mass per unit latitude is greater in the homogeneous zones than elsewhere. A good index of these transfers of mass should be Q_{65} or Q_{35}. A more easily computed quantity, U_{55}, is nearly equivalent, since $r(Q_{65}, U_{55}) = -0.91$ and $r(Q_{35}, U_{55}) = 0.87$, for 1932–1939 combined. The index U_{55} has the further advantage that its definition does not depend upon correlations which involve M, and which may therefore vary from season to season. Since $r(M, U_{55}) = 0.26$, mass transport across the equator has only a minor effect upon U_{55}. Fig. 3 indicates that U_{55} is also a good index of the principal variations of pressure differences.

Fig. 5 compares typical pressure-profiles for high and low values of U_{55} with the normal profiles for October and May, the months of extreme normal values of U_{55}. Associated with high values of U_{55} are a strong polar pressure-minimum and a strong subtropical pressure-maximum, both displaced northward from their mean positions, and a belt of strong zonal westerlies. These features are prominent in the normal profile for October. Quite the opposite conditions accompany low values of U_{55}, and appear in the normal profile for May.

It is of interest to compare these results with the results of previous studies. Walker [4] investigated the variations of quarter-year average values of pressure, temperature and precipitation at selected locations. His correlations between these quantities led him to the discovery of three oscillations. His North Atlantic oscillation, consisting of an oscillation of pressure between the subpolar and subtropical regions in the vicinity of the North Atlantic, was revealed by the presence of high negative correlations between subpolar and subtropical pressures. His North Pacific oscillation is a similar phenomenon, while his Southern osciallation involves an oscillation of pressure between the South Pacific and the Indian Ocean.

It seems altogether likely that the presence of the North Atlantic and North Pacific oscillations is an important contributing factor to the high negative correlation between pressures in the two homogeneous zones. Indeed, a recent study by Gates [1] implies that much of the variability of U_{55} may be due to the North Atlantic oscillation.

Willett [5] investigated three fixed-latitude zonal indices, which he called the indices of the polar easterlies, zonal westerlies, and subtropical easterlies. They are proportional to $P_{70} - P_{55}$, $P_{35} - P_{55}$, and $P_{35} - P_{20}$, respectively, and in this study may be denoted by $-U_{62.5}$, U_{45}, and $-U_{27.5}$. The average correlations between these indices for 1932–1939, obtained by Willett after he removed the seasonal trend, necessarily agree closely with the final diagram in fig. 3. Willett[7] also investigated the weekly changes ΔP_x of five-day mean pressures P_x at latitudes 70, 55, 35, and 20°N. The average correlations which he obtained between these quantities are nearly equal to the corresponding correlations in the final diagram of fig. 2.

One might, therefore, regard these diagrams as mere enlargements of the diagrams which could be constructed from Willett's correlations. However, such enlargements seem necessary for determination of the location and magnitude of the maximum negative correlations, and for establishing the existence of the homogeneous zones.

4. Conclusions

The variations of the northern-hemisphere sea-level pressure-profile consist of normal seasonal variations and irregular variations. Both the seasonal and the irregular variations may be resolved into variations associated with mass transport across the equator and variations due to rearrangement of mass within the northern hemisphere.

During the northern-hemisphere fall and winter, the seasonal mass transport across the equator has the effect of large shifts of mass between the northern-hemisphere tropical regions and the southern hemisphere, and somewhat smaller shifts between the northern-hemisphere polar regions and the southern hemisphere. In contrast, the irregular mass transport across the equator has the effect of large shifts of mass between the southern hemisphere and the polar regions of the northern hemisphere. In each case, the apparent shifts of mass between the southern hemisphere and the polar regions of the northern hemisphere are probably accomplished by shifts between the southern hemisphere and the tropical regions of the northern hemisphere and compensating shifts between the tropical and polar regions of the northern hemisphere, rather than by shifts of individual air masses between the northern-hemisphere polar regions and the southern hemisphere.

During the same period, the seasonal and the irregular pressure variations due to rearrangement of mass within the northern hemisphere resemble each other closely. The most important variations of this sort result from shifts of mass between two homogeneous zones, one centered near 65°N and one near 35°N.

The shifts of mass between the homogeneous zones appear to be essentially the same as the fluctuations between high- and low-index patterns. This study therefore supports Willett's conclusions that these fluctuations constitute the principal variations of the general circulation. It also indicates that, except at low latitudes, where the effect of mass transport across the equator is strong, the seasonal variations of the general circulation are essentially fluctuations between high-index and low-index patterns.

Willett [6] has described long-period changes of the general circulation as secular, climatic, and geological changes, according to the length of the period involved. His results indicate that these changes are similar to the week-to-week fluctuations between high- and low-index patterns. The present study adds another kind of variation to the list of similar variations, namely the normal seasonal variations. One distinction must be made. The seasonal variations in the northern and the southern hemisphere presumably differ in phase, while the long-period variations in the two hemispheres appear to be alike in phase, and the existence of a phase relation between the week to week fluctuations in the two hemispheres has not been established.

It is difficult to observe the similarity between the seasonal and the irregular variations without wondering whether they have similar causes. The ultimate cause of the seasonal variations must be variations of insolation due to changes in the sun's declination, but it is not obvious why the pressure variations take exactly the form which is observed. For example, it is not obvious why, according to the monthly normal pressures used in this study, the zonal index U_{45} has its normal maximum in December and its minimum in June and July, while U_{55} has its maximum in October and its minimum in May, with its July value equal to its December value.

On the other hand, the ultimate cause of the irregular variations has not been definitely established. Willett [6] has stressed the advantages of the theory that the long-period fluctuations are due to variations of insolation, resulting in this case not from changes in the sun's declination but from variable solar activity. One of the obstacles to proving such a theory has been the difficulty of demonstrating a mechanism through which variations of insolation can lead to the observed fluctuations. The present study does not attempt to describe such a mechanism, but it does imply that such a mechanism can exist, since it shows that variations of insolation do lead to certain fluctuations between high- and low-index patterns, namely the seasonal fluctuations.

If the immediate causes of the seasonal and the irregular variations are similar, an investigation of the features of the general circulation typical of each individual month should be an important contribution to the study of the irregular variations. It may then be discovered, for example, that high and low values of U_{55} are generally accompanied by some features which resemble normal features for fall and spring, respectively, or perhaps rising and falling values of U_{55} are accompanied by features typical of summer and winter, respectively. If, in addition, the mechanism of the seasonal pressure-variations can be explained, the way may be clear to an explanation of the mechanism of the short-period and long-period irregular fluctuations of the general circulation.

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