The Circulation of the Upper Troposphere and Lower Stratosphere

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THE PRESENT DISCUSSION IS CONCERNED primarily with the circulation of the upper troposphere and lower stratosphere as it is observed to exist on the Northern Hemisphere of the earth. A number of idealized schemes for the general circulation of the earth's atmosphere have been proposed, starting with Hadley's thermal explanation of the trade winds as far back as 1735. None of the models or schemes of the general circulation as proposed up to the present has, however, been adequate to explain the observational facts which are being established by radiometeorograph and radar wind observations from the higher atmosphere. It is beyond the scope of the present paper to discuss at length the inadequacies and difficulties in the circulation models which have been proposed. It is intended, rather, merely to present certain facts of observation concerning the winds aloft which seem to conflict with the classical circulation scheme and to offer some tentative remarks as to the probable operation of the general circulation system.

Unfortunately, it remains true today that observational data from the level of the tropopause in the atmosphere are quite restricted in length of record and in geographical distribution. Even at the 700 mb (3 km) level, Northern Hemisphere weather maps are seriously lacking in completeness. At the higher levels daily charts can be prepared with some degree of dependability, principally over North America and western Europe, whereas only along the 80th meridian west has it been possible to prepare cross sections through the troposphere, extending from above the Arctic Circle to the equator, based on an adequate number of radiometeorograph observations. Consequently, the present discussion is based principally upon observational data from these regions.

It is proposed (1) to note briefly, as the data permit, some features of the seasonal mean or normal state of the general circulation of the Northern Hemisphere, particularly in the vicinity of the tropopause; (2) to observe the character of the principal irregular (nonseasonal) variations of the circulation; and (3) to suggest tentatively some interpretation or explanation of the normal pattern of the general circulation and its large-scale irregular variations.

The Normal State of the General Circulation of the Upper Troposphere and Lower Stratosphere

The outstanding feature of the state of motion of the bulk (lower 9/10 of the total mass) of the atmosphere of the Northern Hemisphere, and undoubtedly also of the Southern Hemisphere, is the existence of an extensive circumpolar cyclonic (west-wind) vortex. This circumpolar vortex has its maximum intensity just beneath the tropopause, near the 12-km level, in middle latitudes, where the relatively narrow band of extreme west-wind velocity, which is bounded especially on the equatorward side by a zone of very sharp decrease of west wind, has been characterized by Rossby as a jet stream. This jet stream varies in intensity and latitude in a normal manner from season to season, irregularly from day to day, and also at the same synoptic time from meridian to meridian, in such a manner as to parallel the major wave pattern of the westerlies at the lower 500- or 700-mb levels.

The mean seasonal characteristics of the jet stream probably are most reliably represented by two vertical cross sections prepared by Seymor L. Hess, of the University of Chicago. Figs. 1 and 3, respectively, represent the mean east-west geostrophic wind velocity, in m/sec, for the winter months January–February and for the summer months July–August, at approximately the 80th meridian west, as given by the radiometeorograph observations from a line of sta-

This paper, which was presented in the Symposium on the Upper Atmosphere, held September 15, during the Centennial Celebration of the AAAS, is based primarily upon the work of Dr. Rossby and material prepared by his colleagues at the University of Chicago and in Stockholm. The general scope of the paper was planned jointly by the authors, but the final preparation of the article was made by Dr. Willett without benefit of discussion with Dr. Rossby, who was in Sweden at that time. Consequently all reference to, and interpretation or critical discussion of, the latter's work is expressed in the third person by Dr. Willett.

tions extending from Arctic Bay at 73° N to Salinas, Ecuador, at 2° S, for the years 1941–45. The winter section is of primary interest, for that is the season of the maximum intensity of the entire circulation, including the jet stream. It must be remembered that the sections in Figs. 1 and 3 represent conditions along one meridian only, and not an average of the hemisphere. It is probable that, owing to the normal presence of a trough of low pressure aloft over eastern North America, the jet stream in this section is moderately stronger and farther south, particularly in winter, than the average of the hemisphere, but the difference is doubtless only one of minor degree.

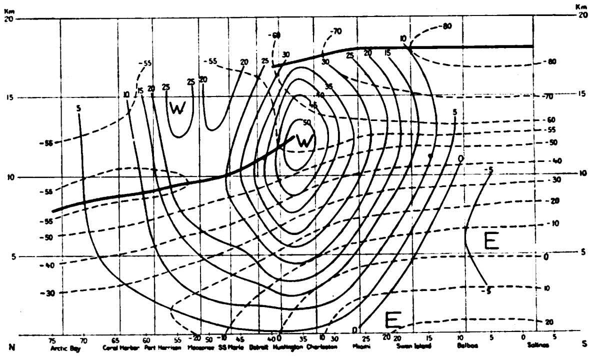


FIG. 1. Mean zonal geostrophic wind velocity and temperature, Arctic Bay to Salinas, for January–February.

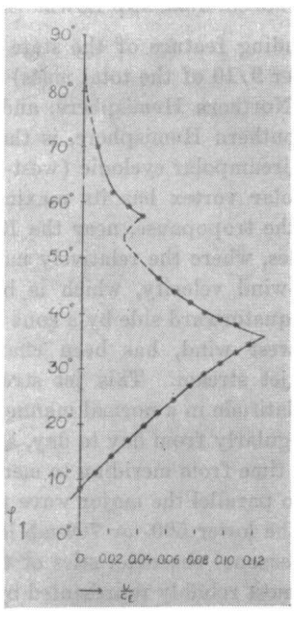


FIG. 2. Profile of the ratio of the mean zonal geostrophic wind at the 12-km level, from Fig. 1, to the rotational speed of the earth's surface at the equator.

Particularly striking in Fig. 1 is the extreme sharpness of the jet stream in winter. This fact is observed most clearly in Fig. 2, which represents the meridional velocity profile at the 12-km level of the mean geostrophic zonal wind from Fig. 1. The zonal wind speed in Fig. 2 is plotted in the form of the ratio to the rotational speed of the earth's surface at the equator, U/C_E. The sharpness of the jet stream in the mean seasonal cross sections is particularly striking in view of the fact that considerable irregular fluctuation of both the latitude and the intensity of the jet stream is observed from day to day. In its daily synoptic occurrence the jet character of this current is much more pronounced, particularly along its lower latitude boundary, where the latitudinal wind shear becomes very great. An illustration of a typical zonal wind profile at time of strong development of the jet is illustrated by Fig. 11, prepared by E. Palmén (*1*).

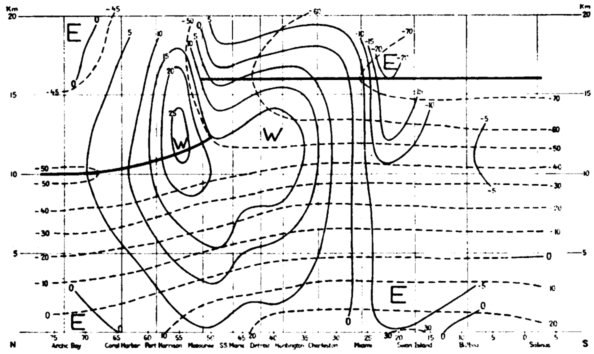
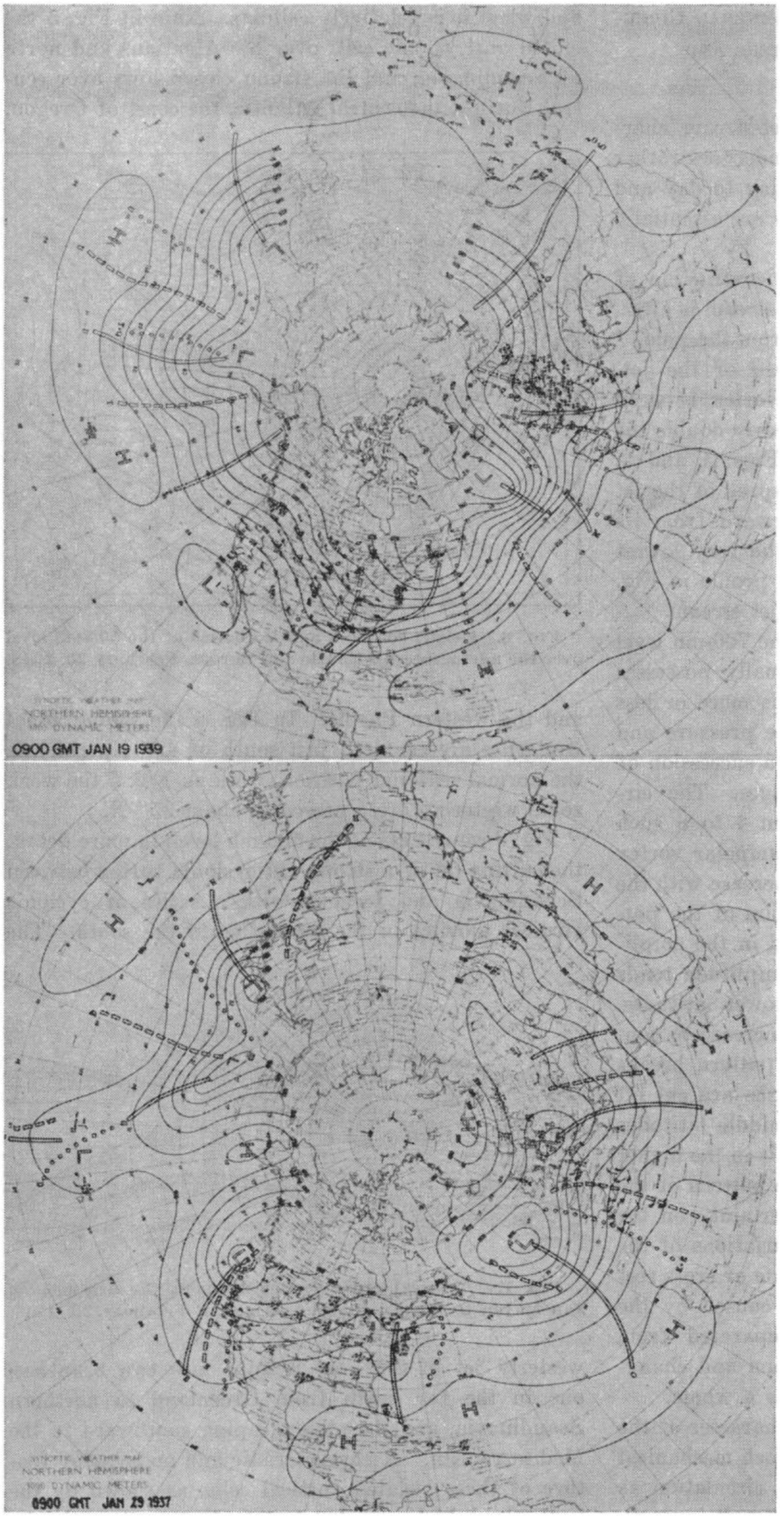


FIG. 3. Mean zonal geostrophic wind velocity and temperature, Arctic Bay to Salinas, for July–August.

A comparison of Fig. 1 with Fig. 3 indicates that in the seasonal mean the jet stream, which is less clearly defined in summer than in winter, shifts its position poleward from 35° to 55° and decreases its speed by half from winter to summer. This change is doubtless fairly typical of the entire Northern Hemisphere conditions. It might be noted that this seasonal shift of the jet stream may also be characterized as the deterioration of the principal low-latitude winter season jet and the emergence to relatively primary importance of a weak secondary jet which is present in the mean in winter also at 55° N. Another well-known feature of the seasonal variation of the zonal wind circulation, which is evident in these two sections, is the appearance of the deep subtropical easterlies in summer with a vertical boundary between them and the westerlies at about 28° N, while in winter the easterlies are greatly weakened and are displaced by westerlies in the upper troposphere to quite low latitudes.



FIGS. 4 and 5. (4, top) Northern Hemisphere flow pattern of relatively zonal character at the 700-mb level, January 19, 1939. (5, bottom) Northern Hemisphere flow pattern of relatively cellular character at the 700-mb level, January 29, 1937.

A very significant feature of the cross sections in Figs. 1 and 3, a feature which is most striking in the stronger winter circulation pattern, is the concentration of the principal latitudinal temperature contrast, or poleward temperature gradient in the troposphere, directly beneath the principal jet stream of the circumpolar vortex. The concentration of solenoids beneath the jet stream is indicated by the maximum poleward slope of the isotherms between latitudes 25° and 45° in Fig. 1. It is obvious, since the jet stream determines the latitudinal zone in which the west wind increases most rapidly with height in the troposphere, that the thermal wind relationship requires that this also be the zone of maximum poleward temperature gradient in the troposphere. However, it will be seen later that the maintenance of the jet stream, *i.e.* the question of the extent to which the corresponding solenoid field is to be considered a thermodynamic cause or a dynamic consequence of the jet, constitutes a primary problem in the interpretation of the mechanics of the general circulation.

Another obvious fact which is evident in Figs. 1 and 3 is that above the maximum jet level, at about 12 km, the poleward temperature gradient is reversed. The mean tropopause level, which is marked in Figs. 1 and 3 by a heavy black line, is quite clearly defined by the temperature field in the higher latitudes and in the lower latitudes, but there is a narrow zone in middle latitudes above the jet stream where it is rather indeterminate. This is the zone in which the tropopause level fluctuates greatly from day to day between the low polar tropopause and the high subtropical tropopause. It seldom extends in one continuous inversion layer through this latitude zone.

The Irregular Variations of the General Circulation of the Upper Troposphere and Lower Stratosphere

The circumpolar vortex with its jet-stream characteristics in the upper troposphere undergoes rather extensive irregular fluctuations from day to day and from week to week. These fluctuations are essentially threefold in character, namely:

(1) There is a simple expansion or contraction of the circumpolar vortex, so that the jet stream is alternately closer to and farther removed from the pole.

(2) A variation occurs in the speed of the jet-stream maximum of the circumpolar vortex between values of approximately one-half to nearly double the seasonal normal values indicated in Figs. 1 and 3. There is a tendency for the maximum speed of the jet stream to be reached near or equatorward from its normal seasonal latitude, but not in the very lowest latitudes at which it is observed. The profile in Fig. 11 is typical of a strongly developed jet stream.

(3) The circumpolar vortex, from the 700-mb level upward through the tropopause, normally possesses an undulatory wave character, which is more or less symmetrical about the pole, so that the pressure and wind patern at any level is marked by a succession of cyclonic troughs and anticyclonic ridges. The circumpolar vortex usually contains from 4 to 8 such waves. This wave pattern in the circumpolar vortex varies in wave length, which tends to increase with the speed of the westerlies, in the orientation of the pattern with respect to the meridians, and in the amplitude of the individual waves. This amplitude tends to increase as the vortex expands to lower latitudes. There is a tendency at times for this increase to continue until the wave character of the pattern breaks down in such a manner that the troughs are cut off as stationary closed cyclonic cells in middle latitudes and the ridges as closed anticyclonic cells in the higher latitudes. This variability of the wave pattern of the circumpolar vortex imposes much uncertainty on the interpretation of observed irregular variations of the jet stream in a restricted meridional zone or cross section, because the irregular variations caused by the changing wave pattern cannot be separated from those caused by expansion or contraction and changing speed of the circumpolar vortex as a whole.

Since this open wave *vs.* closed cell character of the circumpolar vortex is probably of as much mechanical or dynamic significance to the general circulation as it is of synoptic or prognostic significance, it is worth noting some details of the pattern change. Figs. 4 and 5 represent the Northern Hemisphere flow pattern at the 700-mb level at times, respectively, when the circumpolar vortex is relatively zonal in character and when it is relatively cellular. Note in Fig. 5 the closed anticyclonic cells over the Aleutians and north of Scandinavia, and the strong closed lows over central Europe, the central Atlantic, the coast of Oregon,

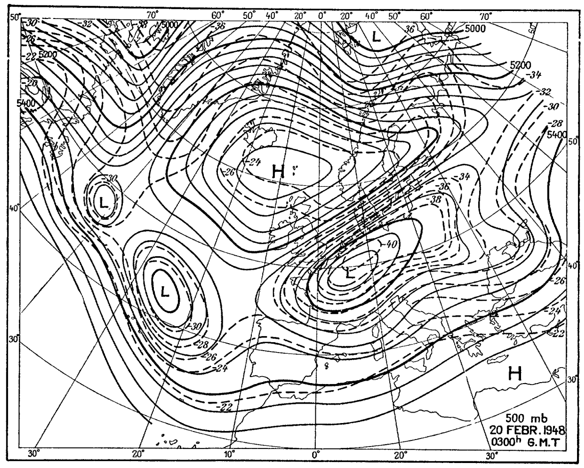


FIG. 6. Height contours and isotherms at the 500-mb level over the northeastern Atlantic and Europe, February 20, 1948.

and the western Pacific. In Fig. 4 the strong zonal westerlies are centered just south of 45° N, which is the normal seasonal position, while in Fig. 5 the weak zonal westerlies are centered at about 35° N.

Fig. 6 represents at the 500-mb level, in more detail, the cutting off of a strong anticyclonic vortex between Scandinavia and Iceland, with a series of cyclonic vortices moving in the westerlies to the south. The

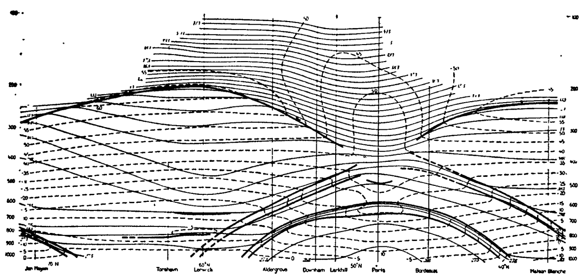


FIG. 7. Vertical cross section through the atmosphere, Jan Mayen to Maison Blanche (Algiers), February 20, 1948.

westerly jet in this case is split into two branches, one in the far north from Greenland to northern Scandinavia, and the other dipping southward to the Mediterranean. A characteristic and noteworthy feature of these isolated vortical cells, as shown by the isotherms which are sketched in broken lines, is the marked warmth of the anticyclonic cells, which are cut off from lower latitudes, and the marked coldness of the cyclonic cells, which are cut off from the higher latitudes. This temperature distribution is indicated even more clearly in Fig. 7, which represents the corresponding vertical cross section from Jan Mayen in the far north to Algiers in the south. The cold troposphere and the low warm tropopause and stratosphere

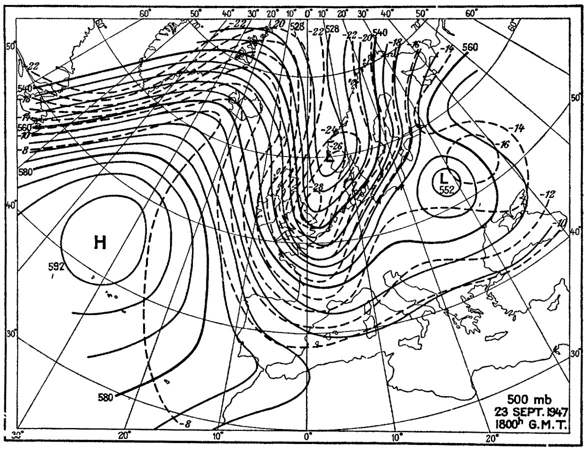


Fig. 8. Height contours and isotherms at the 500-mb level over the northeastern Atlantic and Europe, September 23, 1947.

in the cyclonic cell and the warm troposphere and the high cold tropopause and stratosphere in the anticyclonic cell are unfailing characteristics of these deep vortical circulations. The question of the extent to which these thermal characteristics of the vortices are advected with the circulating air mass or are created dynamically on the spot is a moot one.

Figs. 8, 9, and 10 represent on three successive days, at the 500-mb level over western Europe and the north Atlantic, the successive steps in the cutting off of an isolated cyclonic vortex from a deep trough in a large-amplitude wave in the westerlies. Once again it will be noted how the isobaric contours and the isotherms tend to parallel each other so that low temperature coincides with low pressure, and vice versa.

The synoptic and statistical analysis of Northern Hemisphere weather data from different levels in the atmosphere has led to the concept of an over-all basic but rather irregular cycle of change of the general circulation pattern. This cycle, which is usually best defined in winter, varies in period from 3 to 8 weeks and also in amplitude and regularity. Fundamentally, it consists of a fluctuation of the circulation pattern from a state which is essentially zonal in character, with a minimum of storminess and meridional, or air mass, exchange in middle latitudes—a pattern referred to as high index in character—to a state which is much less zonal and more cellular in character, with a maximum of storminess and meridional, or air mass, exchange in middle and lower latitudes—a pattern referred to as low index in character. The high and low index designation refers essentially to the strength of the zonal westerlies.

Since this fluctuation of the general circulation between high and low index patterns seems to be in-

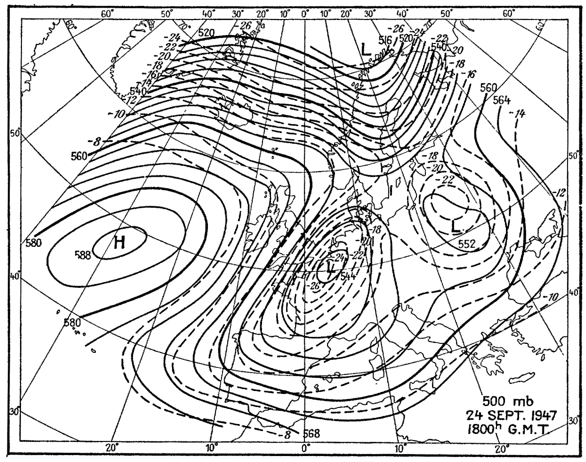


Fig. 9. Height contours and isotherms at the 500-mb level over the northeastern Atlantic and Europe, September 24, 1947.

herent in the mechanics of the operation of the general circulation, it is of interest to note briefly, as definitely as the observational data permit, how the zonal index cycle is related to the fluctuations of the

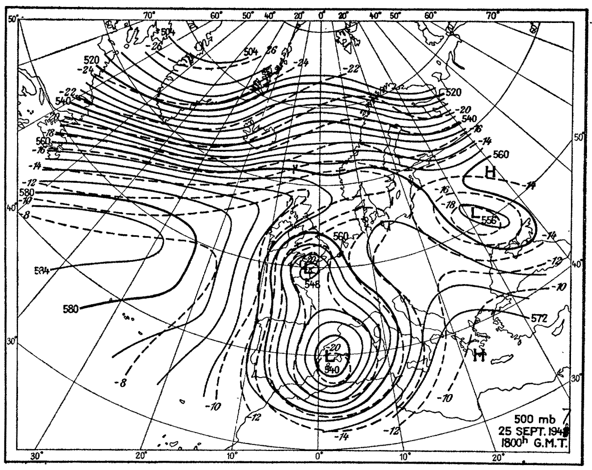


Fig. 10. Height contours and isotherms at the 500-mb level over the northeastern Atlantic and Europe, September 25, 1947.

circumpolar vortex and jet stream at the top of the troposphere.

For the correlation of the jet-stream cycle with the zonal 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 wave-length pattern aloft; (b) pressure systems oriented east-west, with strong cyclonic activity only in higher 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 wave-length 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 a 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; 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.

A Possible Mechanism of the Circulation of the Upper Troposphere

It is evident that the large-scale fluctuations of the general circulation of the Northern Hemisphere throughout the troposphere and probably well into the stratosphere must be closely tied together in some coordinated dynamic or thermodynamic system. It is necessary in the light of the recently acquired observational information on the circulation of the upper troposphere to look critically at the classically accepted notion as to how this circulation works.

In their essential features, the classical explanations of the general circulation depend on two principles: (1) the circulation principle, which expresses the tendency of the atmosphere in the presence of a horizontal temperature gradient to develop a thermally direct circulation from the warm to the cold region aloft and from the cold to the warm region at the ground; and (2) the principle of the conservation of angular momentum, which requires poleward-moving air masses on the rotating earth to acquire relative eastward velocity and equatorward-moving air masses to acquire relative westward motion.

According to these principles, thermally direct cells with northerly to easterly winds at the surface and southerly to westerly winds aloft are maintained between the pole and approximately 60° N latitude, and between the thermal equator and approximately 30° latitude, at which the equatorial outflow aloft has become deflected to a westerly current. In each of these thermally direct cells, rising motion must occur on the equatorward side and sinking motion on the poleward side, while the easterly wind component at the surface must decrease and become a westerly component aloft. These circulations require, at sea level, belts of minimum pressure at the equator and at 60° and subtropical high pressure belts at 30°. This pressure distribution must be reversed in the upper troposphere.

Between these two thermally direct cells there must exist in middle latitudes a third cell with west winds at sea level. Since surface friction insures some poleward movement of air in this cell at lower levels, it must be a thermally indirect circulation which is forced by the two direct cells flanking it. This circulation requires that the equatorward return of air must take place in this cell in the upper troposphere, either as an easterly current (by conservation of angular momentum) or as a forced (supergradient) westerly current.

It follows from this concept of the general circulation that there is a tendency to produce west winds in the higher latitudes wherever air motion is poleward as a result of the transport of angular momentum from the lower latitudes, and, conversely, to produce east winds at lower lattitudes wherever the air motion is equatorward. In general, in so far as the angular momentum principle holds in meridional air mass exchange by means of large quasi-horizontal cells, it matters little whether the meridional circulation within a zonal cell is uniformly zonal in character or whether, corresponding to the observed facts, it tends to be more cellular in character. In either case the net effect of the exchange must be to produce a relatively westerly flow in the northern portion of the zone and an easterly flow in the southern portion.

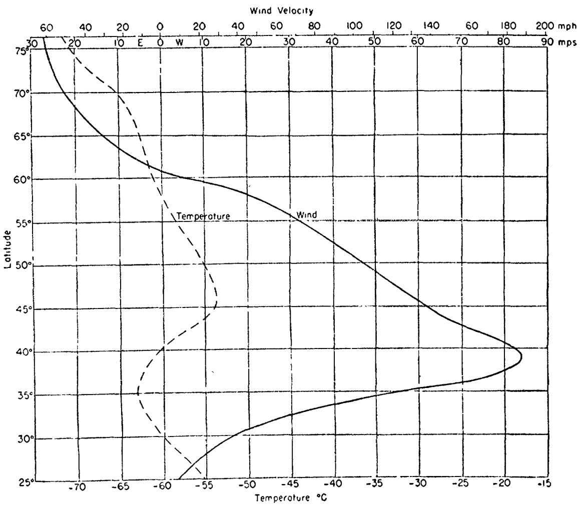


Fig. 11. Distribution of temperature (dashed curve) and geostrophic zonal wind (solid curve) at the 200-mb level along the meridian 80° W for January 17, 1947.

It has long been realized with the increasing amount of observational data on the general circulation that in many ways this circulation fails to meet the requirements of the classical theory as indicated above. Rossby (*4*) has recently discussed a number of points at which the disagreement is notably evident, particularly the following:

(1) In the tropics there exists no horizontal latitudinal temperatures gradient such as is required by a thermally direct cell of the Hadley type. Consequently, the east winds do not decrease with height, but extend to the top of the troposphere, even with some increase near the tropopause.

(2) Furthermore, the wind structure in the tropics is much too complex, indicating, instead of a single thermally direct cell, probably two or more cells which are partly forced in character.

(3) In middle latitudes, far from decreasing with height, the west winds increase to the jet characteristics of the circumpolar vortex at the top of the troposphere.

It is this increase of west wind with height in middle latitudes which has been the greatest obstacle to the concept of a middle indirect cell in the zonal wind system. Rossby (*2*) made the first real attempt to obviate this difficulty by assuming that the upper westerlies in middle latitudes are frictionally driven at supergradient velocity so that air is thrown southward against the pressure gradient and piled up in the subtropical high-pressure belt, whence it sinks and is removed to lower latitudes in the surface trade winds and to higher latitudes in the surface westerlies. This frictional drive is effected supposedly by the upper-level westerlies in the two flanking thermally direct cells by means of large-scale horizontal (cellular) turbulent exchange.

This explanation has been rendered untenable by more recent aerological observations. If the momentum principle is retained, it is apparently impossible to account for any such phenomenon as the circumpolar jet stream by lateral frictional drive from the adjacent cells. Furthermore, it is not reasonable to expect to find in the mean a forced circulation cell filling the entire middle-latitude zone, where the principal concentration of circumpolar solenoids (poleward temperature gradient) occurs throughout the troposphere.

Recognizing these difficulties, Rossby (*3*) initiated a new attack on the problem. He points out that

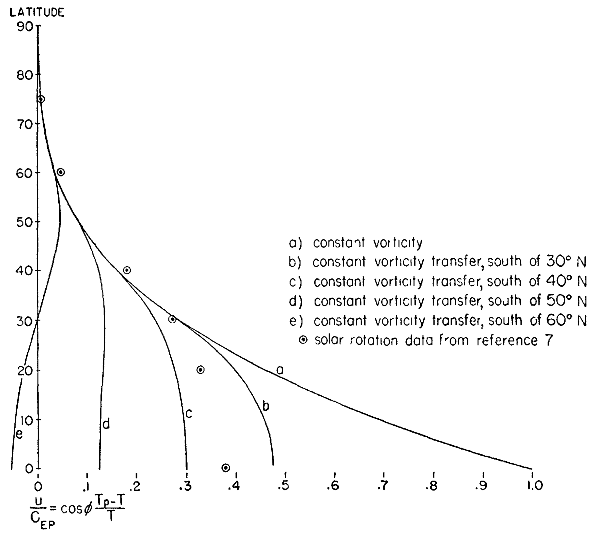


Fig. 12. Distribution of zonal motion in a thin atmospheric shell, measured relative to the underlying planetary surface, and expressed in fractions of the equatorial linear velocity of the planet. All profiles computed on the assumption that the polar angular velocity of the shell is equal to the angular velocity of the planet itself.

there is good reason to expect that lateral mixing in a thin hemispherical shell on a rotating globe, corresponding to any planetary atmosphere, should effect an equalization of absolute vorticity rather than one of angular momentum. He computes the zonal velocity profile in such an envelope on the assumption that the vertical component of the vorticity of the absolute motion should be independent of latitude and equal to that of the planetary rotation at the pole (Fig. 12). He points out the similarity of this profile to that of the observed velocity of the solar atmosphere from the poles to about 30° heliographic latitude. Equatorward from this latitude the solar velocity profile approximates that required by constant latitudinal transport rather than by constancy of the absolute vorticity (Fig. 12). He refers further to the established existence in some of the major planets (Jupiter, Saturn) of equatorial "accelerations," which might best be explained as a consequence of vorticity transfer.

Rossby assumes that it is only in the upper troposphere, beyond the influence of surface friction, that the full effect of the vorticity transport should be reflected in the zonal wind distribution. He has observed in numerous cases of strong jet-stream development in the upper troposphere the essential similarity of the zonal velocity profile to that of constant vorticity (not necessarily the vorticity of the pole, but frequently that at some lower latitude, as in Fig. 11) southward to the jet-stream maximum, at which point the profile changes discontinuously to one suggesting constant vorticity transport equatorward.

Rossby conceives of the general circulation as fluctuating through cycles of activation and relaxation of the circumpolar vortex and jet stream. He indicates the zonal cellular pattern at time of maximum development of the jet in Fig. 13. This figure represents a period of strong lateral mixing by means of quasi-horizontal cyclonic and anticyclonic cells in the higher and middle latitudes or, in other words, a period of breakdown of a sea-level high index into a low index pattern. The intense lateral mixing produces uniformity of the absolute vorticity, of a value probably somewhat less than that of the rotation at the pole, in a broad circumpolar zone of the upper troposphere, a zone which includes in its outer portion all of the principal areas of frontal and cyclonic activity and which is sharply bounded on the equatorial side by the strong jet stream. Equatorward from the jet-stream maximum the zonal westerlies decrease very sharply in a narrow zone in which the vorticity decreases rapidly as the regime of constant vorticity transport takes over. This sharp shear zone constitutes a horizontal negative vorticity inversion in the same sense that a vertical positive potential temperature inversion marks the top of a layer of turbulent mixing and constant potential temperature. During the preceding period of intensification of the jet it is displaced southward by the strong lateral mixing in the same sense that the turbulence inversion level is raised by continued strong vertical mixing, *i.e.* a broader zone of atmosphere is incorporated into the constant vorticity regime.

It is probable that a limit is placed on the development of the jet by the inertial stability of the atmosphere. When the zonal wind shear at the outer edge of the jet stream exceeds that which corresponds to constancy of angular momentum, a narrow, indirect, forced meridional circulation develops, as indicated in Fig. 13. This feature should be normal with strong

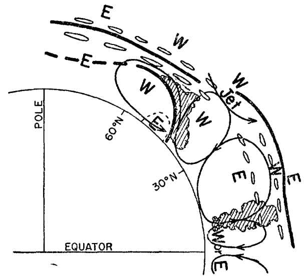


Fig. 13. The zonal cells of the general circulation (after Rossby, 1948).

jet development and tends to produce dynamically the vertical separation of the isentropic surfaces at the southern edge of the jet stream, which lifts the tropopause aloft and concentrates the principal circumpolar solenoid field beneath the jet. In other words, the strong concentration of solenoids which must accompany strong jet-stream development is essentially dynamically produced by the kinetic energy of the jet stream. The energy of the jet stream, then, is to be considered a cause rather than an effect of the local solenoid field. The energy of the forced jet stream has its origin in the widely distributed quasi-horizontal cellular circulations which force the lateral transport and equalization of vorticity. Both synoptic observation and theoretical reasoning (*4*) indicate that the kinetic energy which is released in any quasi-horizontal circulation is rapidly dispersed downstream in the westerlies around the globe and that kinetic energy obtained from many such sources would, by such dispersal, ultimately accumulate in one or more jet streams. Hence, according to Rossby, there is no longer any compelling reason to build the theory of the maintenance of the general circulation exclusively on direct meridional-solenoidal circulations, *i.e.* it is permissible to accept the dynamic maintenance by forced circulation of a meridional solenoid field that is stronger than those which exist in the driving branches of the general circulation.

Equatorward from the indirect meridional circulation cell Rossby assumes a continuation of the same constant transport of vorticity. The inertial stability of the zonal wind profile in the large, thermally direct, zonal cell of the subtropics requires that the transport shall take place in the quasi-horizontal cellular circulations as in the higher latitudes. This transport is assumed to continue through the equatorial zone, where the relative constancy of angular momentum may permit two or more direct meridional cells of the Hadley type, as Rossby has indicated in his sketch (Fig. 13). Two or more such cells combined with the effects of constant transport of positive vorticity from the Northern Hemisphere, or of negative vorticity from the Southern, probably lead to the very complicated wind systems which are observed near the equator and about which too little is known to justify further speculation at this point. It is to be emphasized, however, that Rossby assumes that the constant vorticity transfer extends through the equatorial zone, which effects a certain cancellation by lateral mixing of the opposite vorticity of the two hemispheres.

The deterioration of the jet stream, when it has reached its strongest development, apparently takes place during the period of lowest sea-level index. This is the period during which the wave pattern in the circumpolar vortex aloft becomes unstable, with increasing amplitude and shortening wave length, terminating with the movement into higher latitudes and seclusion of warm anticyclonic vortices and the movement into lower latitudes and seclusion of cold cyclonic vortices. In other words, the interaction of cold and warm air masses (occlusion process) reaches its ultimate development by extending to the top of the troposphere and diminishing latitudinal temperature contrasts at all levels. The deterioration of the jet stream in the lower latitudes follows rapidly and, with that, a period of relaxation of the circumpolar vortex. Apparently the westerlies aloft are gradually reactivated in the higher latitudes by the slow radiational cooling of the polar troposphere and consequent sharpening of the poleward temperature gradient, preparatory to another cycle of index change. 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 cold season than it is later, perhaps because the zone of effective polar coldness is more restricted to the immediate vicinity of the pole 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 thermal contrasts equatorward.

Rossby's application of the vorticity theorem to the atmosphere accounts very handily for the jet-stream characteristics of the circumpolar vortex and offers a very plausible explanation of the general sequence of events which typifies a major cycle of variation of the general circulation pattern. In contrast to the angular momentum theorem, the vorticity theorem requires that the strong zonal westerlies be driven from the higher latitudes rather than from the lower. In fact, Rossby's insistence on the continuous equatorward transport of vorticity in the higher atmosphere as an essential feature of the basic mechanism of the general circulation requires that, likewise, a continuous net transport of angular momentum equatorward must characterize the normal state of the general circulation. If this condition is fulfilled, it necessitates that the troughs and ridges of the circumpolar vortex in the upper troposphere must, on the average, have a certain northwest-southeast orientation of their axes, so that in the mean the gradient wind crossing any latitude circle from north to south shall have more eastward motion than the gradient wind crossing from south to north. Furthermore, as Victor Starr (*5*) has pointed out, since angular momentum can be effectively supplied to, or removed from, the atmosphere only through surface friction at the ground, a net equatorward transport of angular momentum by the atmosphere requires either a relatively strong zone of polar easterlies compared to subtropical easterlies or a one-way transport of angular momentum from the subtropical easterlies of either hemisphere across the equator, *i.e.* a mutual cancellation of vorticity (and momentum) between the two subtropical easterly belts. There is no observational evidence that either of these conditions is fulfilled. In the mean the subtropical easterlies at the ground are much stronger and cover a much greater area than the polar easterlies. Hence, there must be more angular momentum supplied to the atmosphere in the lower latitudes. Starr (*5*) has made an effort to evaluate the latitudinal transport of angular momentum from the sea-level, 700-mb, and 500-mb Northern Hemisphere isobars. He finds almost without exception a substantial poleward transport of angular momentum at these levels in middle and lower latitudes on the Northern Hemisphere. Consequently, it remains to be proved just to what extent the westerlies of middle latitudes are driven from the polar or from the equatorial side and how much of a role the local solenoid field may play directly in their acceleration.

From a consideration of the long-period changes of the general circulation pattern, the changes that are reflected in the secular, climatic, and geological variations of world weather, one point should be noted. Willett (*6*) has suggested that there is a striking basic similarity between these long-period variations of the world weather patterns and the week-to-week cycle of high- and low-index patterns. Particularly in connection with the double sunspot cycle, there is considerable statistical and synoptic evidence of a definite influence of irregular solar variability on the index characteristics of the general circulation pattern. The inference is made that irregular solar activity may be a controlling factor in all of the extensive long-period fluctuations of the general circulation.

No real attempt has been made as yet to explain how this solar variability directly affects the circulation patterns. However, if the effect is there in the long-period variations, and since the shorter-period variations are similar in character and the sun is known to undergo quite violent short-period variable activity, the possibility is by no means excluded that the irregular short-period variations of solar activity also affect the changing index patterns of the general circulation. If this is the case, it might help to explain the fact that the ordinary cycles of index change of the general circulation are so variable and erratic from cycle to cycle, and between different years, that statistical analysis fails to yield significant indications either of regular periodicity or of regular lag effects in the change of the general circulation pattern.

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TECHNICAL PAPERS

Some Experiments in the Freezing of Water

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Although the supercooling of water is recognized as a very common occurrence, numerous reports have recently been published about it.

In our research we have found that the freezing of water without supercooling would be much more surprising, since we have so far been unable to find anything which will cause freezing at 0° C, except in contact with ice. Normally, water will not freeze until it is cooled to about – 20° C.

Lately, Rau (*8*) claimed to have cooled water to – 72° C before it froze. He accomplished this by means of a "system of successive sterilization of the nuclei of solidification." After the publication of this work, Bangham (*1*), Frank (*4*), and Ubbelohde (*10*) attempted to explain this phenomenon and also to predict certain properties of water in the low-temperature range. Since then, Cwilong (*2*) has tried to repeat Rau's experiment and has proven Rau's measurements to be invalid.

Another reported case of the low-temperature freezing of water is stated by Oltramare (*7*). He reported that R. Pictet and L. Dufour had cooled water to – 40° C, but no paper by either Pictet or Dufour gives this value.

Martin (*6*) cooled water to – 26° C by repeated distillation *in vacuo* without ebullition.

The above experiments were carried out on water in bulk. On the other hand, Vincent J. Schaefer (*9*) found that a supercooled water-droplet cloud dispersed in air, in the absence of sublimation nuclei, spontaneously changes to an ice-crystal cloud when any portion of the cloud is cooled to – 38.9° C or lower. A few ice crystals can be observed at a slightly higher temperature, but the above temperature may be regarded as critical.

Bernard Vonnegut (*11*) found a number of foreign particles, most notably silver iodide, which cause the transformation from a water-droplet cloud to an ice-crystal cloud at considerably higher temperatures. He obtained varying results, depending not only on the material of which the particles were composed but on their crystalline structure, size, etc.

Cwilong (*3*) has also made measurements of the sublimation temperature in the atmosphere and claims a value of – 41.2° C for spontaneous ice-crystal formation in pure air and about 9° warmer for impure air.

In Cwilong's experiment in a Wilson Cloud Chamber, the minimum temperatures reached were calculated and not measured. Furthermore, the presence of ice crystals was shown by their seeding action on a sample of supercooled water. In Schaefer's experiment, the temperature was measured directly and held constant, and the ice crystals observed visually and samples obtained. The validity of his results seems beyond criticism, and his temperature of – 38.9° C should, therefore, be accepted as more exact.

Cwilong's assumption that ions act as sublimation nuclei has not received support from our experiments. In a forthcoming paper, Schaefer will describe a number of foreign-particle sublimation nuclei and their relative effectiveness at various temperatures.

I. Langmuir, in a paper not yet published, reports that he has conceived of a mechanism for the spontaneous nucleation of a supercooled cloud. His explanation is based on the existence of an air-water interface. According to the Langmuir hypothesis, it should be possible,