On the Vertical Distribution of Wind and Temperature over Indo-Pakistan along the Meridian 76° E in Winter

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Abstract

A mean cross-section over Indo-Pakistan along the meridian 76° E for January and February 1946 has been computed. Three jet stream centers are obtained along this meridian: one in Siberia, one just south of the plateau, and one in the tropics. The effect of the plateau gives rise to Siberian and Himalayan jets. A numerical comparison of the computed mean profile along 76° E with that of HESS (1948) along 80° W over North America is presented.

Computed wind velocity, wind shear and absolute vorticity patterns are discussed, particularly with regard to strong anticyclonic shear and very low absolute vorticity found on the south side of the Himalayan jet. The spatial distributions of the isentropic field, the gravitational stability field, the baroclinity field and the rainfall during the winter months are discussed in regard to the sense of the meridional circulation around the Himalayan and the Equatorial jets.

Introduction

Mean vertical cross sections of the average zonal wind distribution aloft across the northern hemisphere from pole to equator were first prepared by V. BJERKNES and COLLABORATORS (1933). Although at that time the available observations were sparse and not homogeneous in space or time, the authors' sections (fig. 1) nevertheless permit us to deduce that the westerlies even in the mean are not a broad uniform current. Their momentum tends to be concentrated in a narrow meandering river of fast moving air—frequently called »jet stream» (ROSSBY and COLLABORATORS 1947). More recently WILLETT (1944) and HESS (1948) have offered similar profiles for North America. On their sections we find the center of the jet stream near latitude 35° N at a height of about 12 km in winter. We en counter it in summer near latitude 55° N, with diminished intensity.

Cross sections made for individual days by RIEHL (1948), PALMÉN (1948), PALMÉN and NAGLER (1948) and mean cross sections prepared for a certain short period by PALMÉN and NEWTON (1948) have demonstrated the same feature of concentration of the westerlies aloft. As should be expected, the intensity of such instantaneous jets exceeds that of the mean sections. They also show that frequently two maxima are present in the belt of the westerlies, a fact also elaborated on by CRESSMAN (1949). A low latitude west-wind maximum, separated from the main center of the westerlies at higher latitude, is a prominent feature of the tropical circulation over the Atlantic and Pacific oceans (1945).

Until now three different explanations have been offered for the existence of the meandering river of fast moving air. ROSSBY and COLLA-

[1] This research was carried on when the author was studying at the University of Chicago under the sponsorship of the Government of Pakistan.

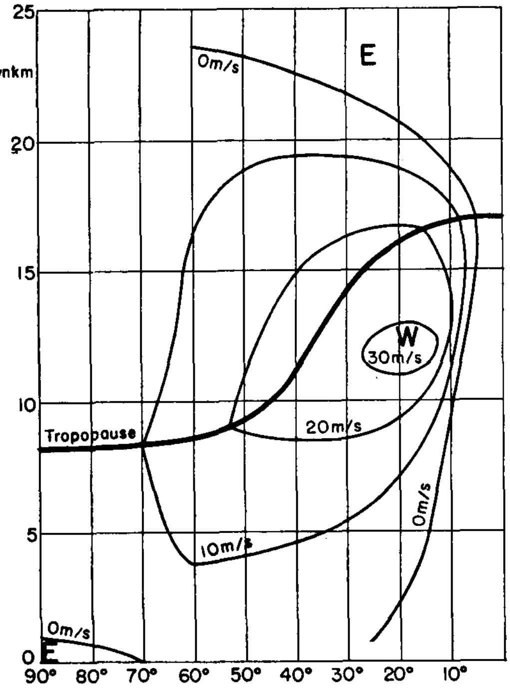

Fig. 1. Mean vertical distribution of zonal component of geostrophic wind in northern hemisphere for February, reproduced from Physikalische Hydrodynamik after BJERKNES and COLLABORATORS (1933).

BORATORS (1947) have advanced a theory based on the principle of conservation of absolute vorticity in connection with large scale horizontal mixing. PALMÉN and NEWTON maintain that the jet stream is associated with the polar front while NAMIAS and CLAPP (1949) have formulated the "Confluence" concept.

It is well known that the principal polar front hardly passes through Indo-Pakistan. There is, of course, evidence that disturbances enter the sub-continent from the west during the winter months. Important low-level concentrations of isotherms, however, are rarely noted in connection with such disturbances. Granted that Bjerknes' cross-section is representative, it is difficult to explain the jet stream as based on association with the polar front. In view of the foregoing discussion it is worthwhile to investigate the mean wind distribution over Indo-Pakistan in winter with recent aerological data, in order to see whether the more numerous observations now available confirm Bjerknes' section.

Available Observations

During World War II, a large number of radiosonde stations was operated over Indo-Pakistan. This network makes it possible to construct a cross section along the meridian 76° E. If Siberian data are added, the section extends from Bangalore (13° N) to Omsk (55° N).

From the observational viewpoint, January and February 1946 proved to be the most feasible period for computation. Data for India were available from the published meteorological report of the India Meteorological Department. Siberian data (500 and 700 mbs only) were obtained from the Northern Hemisphere Historical Charts of the Air Weather Service. The following stations have been used. India: (1) Bangalore (12°59′ N, 81°51′ E), (2) Poona (18°38′ N, 73°55′ E), (3) Allahabad (25°25′ N, 81°51′ E) and (4) Delhi (28°39′ N, 77°17′ E). Pakistan: (1) Peshawar (34°2′ N, 71°37′ E). U.S.S.R.: (1) Tashkent (41°20′ N, 69°18′ E), (2) Alma Ata (43°15′ N, 76°55′ E), (3) Novosibirsk (54°48′ N, 82°57′ E), (4) Omsk (54°55′ N, 73°24′ E).

Computation of the mean wind distribution was made following the standard method employed by other authors. At first, heights, temperatures, and relative humidities for standard isobaric surfaces from 1,000 mb to 200 mb were tabulated. Only those soundings that reached the 500 mb level were included. Next the arithmetic mean of all these elements was taken. From the averages of temperature and relative humidity, mean virtual temperature was computed. Thus a mean sounding for each station was obtained and heights were recalculated with the help of BJERKNES' tables (1910). These computed heights were found to be more consistent with hydrostatic equilibrium than the mean of the reported heights.

Since the flow is fairly zonal above 900 mbs, all stations were projected on their own latitude to the 76th meridian, and the wind distribution was then calculated from the geostrophic wind formula. For an isobaric surface this formula is $U = -(g/f)\left(\frac{\partial h}{\partial y}\right)_p$ where U is the zonal wind speed taken positive from the west, g the acceleration of gravity, f the Coriolis parameter, h the height of an isobaric surface, p the pressure, and y the north-south coordinate taken positive toward north. As several of the stations are located 1000 to 2000 feet above sea level, some difficulty is encountered in the lowest levels due to extrapolation of temperature below the ground. It turned out to be the best to compute the upper wind field using the 900 mb level as reference surface with zero slope, and later add the zonal component at 1 km as obtained from the mean upper-wind charts published by the India Meteorological Department.

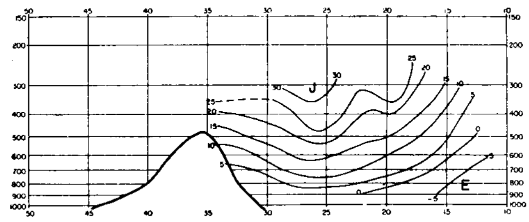

Fig. 3. Mean vertical distribution of *observed* zonal component of west wind (mps) for January along the meridian 76° E.

Field of zonal motion and absolute vorticity

The most interesting feature of the wind field (fig. 2) is the appearance of three separate areas of concentration of west wind. One center lies in Siberia, to the north of the Himalayas and the Tibetan Plateau. Its position and strength cannot be ascertained completely owing to the lack of data above 500 mbs. The second center appears immediately to the south of the plateau at about 31° N while the third lies in the tropics at 15° to 20° N. For the purpose of future reference these jets will be called Siberian, Himalayan, and Equatorial jet respectively.

In order to verify the accuracy of the computed wind profile a cross section based on the upper-wind maps of the India Meteorological Department was also prepared (fig. 3). Comparison between the two sections shows a more or less identical position of wind maxima and minima. However, the wind speeds as given by the India Meteorological Department are lower, in part presumably owing to the short pibal runs on days with strong wind or cloudiness.

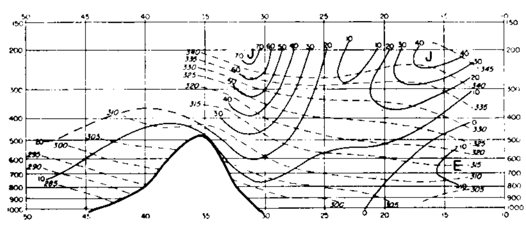

Fig. 2. Mean meridional cross-section for January and February, 1946 from Bangalore in south to Omsk in north along the meridian 76° E. Heavy solid line represents the north-south mountain profile. Thin solid lines represent constant geostrophic wind (west wind component in mps); dashed lines represent isentropes.

From the computed meridional distribution of the zonal wind the field of absolute vorticity (fig. 5) has been computed. For currents moving approximately along a latitude circle, the absolute vorticity (ζ_a) is obtained with little approximation from the relation $\zeta_a = +f - \frac{\partial U}{\partial y}$

The most interesting feature of this section is the appearance of zero values of absolute vorticity in a narrow belt 4 degrees latitude wide at the southern rim of the Himalayan jet. According to the criterion of instability for north-south acceleration of air particles moving under conservation of absolute angular momentum (Solberg 1936), little resistance can be offered by the stabilizing effect of the Coriolis force against southward acceleration in this region. Although the validity of this criterion for atmospheric motion has not yet been demonstrated generally, it will be of interest to look for evidence of descending motion near latitude 25° N, in accordance with the suggestions of Rossby and Collaborators (1947). No explanation for the region of zero absolute vorticity, however, is implied since, as also pointed out by Palmén and Newton (1948), it is not possible to obtain zero absolute vorticity in finite air columns from the operation of divergence alone.

Temperature and potential temperature

In accordance with the computed wind field, a pronounced concentration of the meridional temperature gradient (fig. 4) just south of the Himalayas is evident. Compared to other regions of the world, temperatures encountered here in the upper troposphere are remarkably low. South of the jet stream region there is an actual reversal of the meridional temperature gradient above 400 mbs between latitudes 25° and 18° which, in a mean picture, cannot be explained easily on the basis of advective processes.

The configuration of the isentropes (fig. 2) conforms closely to the patterns emphasized by ROSSBY and COLLABORATORS (1947). North of the jet center we observe a pronounced upward bulge of the isentropes and vertical crowding in the upper troposphere. On the south side, the vertical gradient is small through a deep layer of the middle troposphere. This stability distribution can be established in a more detailed way (fig. 6) by the computation of stability (S) from the relation $S = \Theta^{-1}\dfrac{\partial \Theta}{\partial z}$ where Θ is the potential temperature and z is the vertical coordinate taken positive upward.

Baroclinity field

In order to study the distribution of solenoids in the mean cross section the average baroclinity (fig. 7) has been computed. Baroclinity

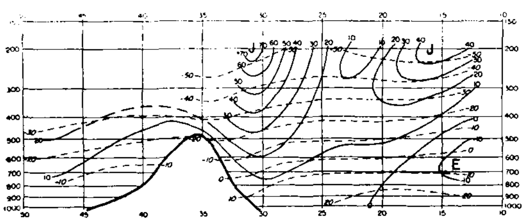

Fig. 4. Mean temperature and zonal component of geostropic wind for January and February, 1946. Thin solid lines are isolines of westerly component of wind (mps); dashed lines represent isotherms in 0°.

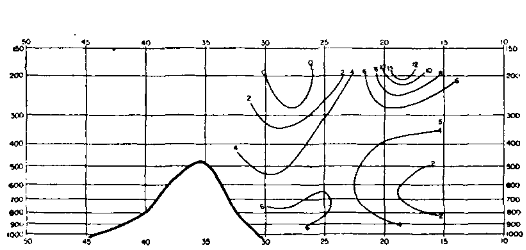

Fig. 5. Mean distribution of absolute vorticity (units $10^{-5}\,sec^{-1}$). Note very low absolute vorticity in a latitudinal belt of 4 degrees in the high troposphere on the southside of the Himalayan jet.

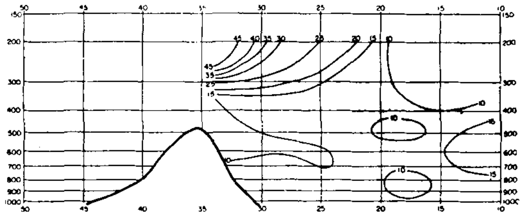

Fig. 6. Mean distribution of vertical stability (units $10^{-8}\,cm^{-1}$). Note the general decrease of stability downward on the southside of the Himalayan jet.

is defined as the number of solenoids per unit area (N) and is given by $-\dfrac{g}{T}\left(\dfrac{\partial T}{\partial y}\right)_p$. Maximum baroclinity appears between 400 and 300 mbs below and somewhat north of the Himalayan jet, but below and somewhat south of the Equatorial jet. Two barotropic lines are observed. One separates Himalayan and Equatorial jets with negative baroclinity above 300 mbs in correspondence with the decrease of the west wind with height between latitudes 20° and 25°. The other barotropic line lies mostly in the transition zone between easterlies and westerlies.

Discussion of the Himalayan jet

The new computations bear out the zonal wind profile given by Bjerknes in its most important aspect—the existence of a jet stream center in the high troposphere south of the Himalayas. Beyond this point, however, there are marked differences, presumably resulting from the wide variations in longitude of the

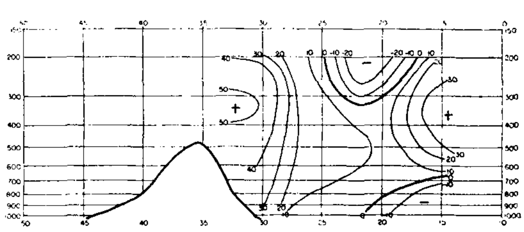

Fig. 7. Mean distribution of baroclinity (units $10^{-8}\,sec^{-2}$). Note that the maximum baroclinity is below and somewhat north of the Himalayan jet while it is below and south of the Equatorial jet. Heavy solid lines represent zero baroclinity or barotropic lines.

stations used by Bjerknes. This observation suggests at once that there is no latitudinal symmetry around the northern hemisphere. A glance at the North American winter section of HESS (1948) confirms that this is so, provided that the unequal periods used for the computation of both cross sections are comparable. In order to bring out this asymmetry more clearly, the Hess section for 80° W was subtracted from that for 76° E (fig. 8).

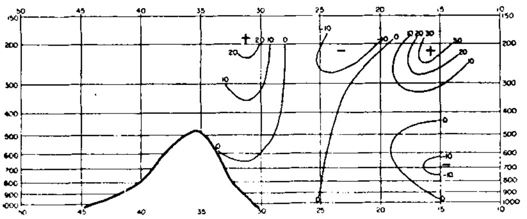

Fig. 8. Numerical comparison of zonal component of the geostropic wind along 76° E with that along 80° W after HESS (1948), the HESS section being subtracted from that along 76° E. The anomaly has been expressed in mps.

In the upper troposphere, the flow is markedly faster near latitude 30° at 76° E compared to 80° W. Because of more southerly position and greater intensity, it is easy to explain the difference in the maximum speed of the jet stream center. If the southward displacement of this center at 76° can be ascribed to the effect of the Himalayas, its position changes little from year to year, and from day to day in comparison with regions where a permanent obstacle of large size is absent. In consequence, higher wind speeds should be expected in a mean section at 76° E than at 80° W where the position of the jet is subject to much larger aperiodic variations.

It is of interest also to compute the mass transport in both sections. Total flow of mass across 80° W from 1000 to 200 mbs between latitude 10 and 65° N is $570 \cdot 10^6$ tons sec^{-1}. The latitude belt 15°—35° contributes $210 \cdot 10^6$ tons sec^{-1} (37 %) to this total. At longitude 76° E the mass transport is about the same. Although it would be necessary to study the conditions at many meridians to obtain a conclusive picture, this fact nevertheless suggests that mass transport through the troposphere is constant within latitudinal belts of limited width. At first glance fig. 8 indicates that because of the higher speeds aloft the transport should be greater; it turns out, however, that there is a compensating effect in the layer 1000—500 mbs. *Over India this compensation takes the form of the winter monsoonal current.*

It is not possible at this time to pursue this reasoning further, although it points to some interesting speculative hypotheses concerning the dynamical hypothesis of the winter monsoon. It appears permissible merely to state that the basic zonal current upon striking the plateau splits into two parts that circle the mountain ranges. It is suggested that the appearance of two west wind maxima is due to the effect of the mountain barriers. Some qualification, however, is necessary. It is well known that on many occasions a marked split of the westerly current takes place already in Europe, one branch moving along the northern rim of the continent and the other travelling across the Mediterranean Sea. Although it would be difficult to explain the observed *mean* conditions over Central Asia from this *intermittent* feature, it should certainly not be denied that on many days there is a jet stream center near latitude 30° N extending across the entire width of Eurasia.

Schematically the effect of the Himalayan plateau is represented in fig. 9. Here the solid line stands for an isobaric surface associated with a fast moving current in the initial stage before striking the plateau. The dashed

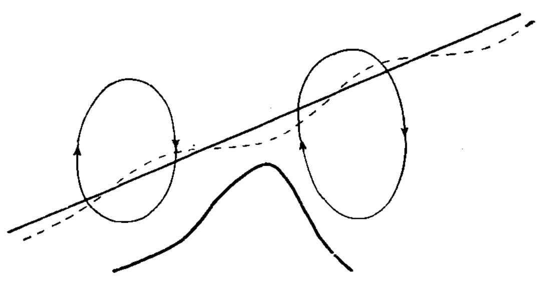

Fig. 9. Schematic representation of vertical circulation patterns around the plateau. Solid line represents an undisturbed isobaric surface associated with a mean jet stream center at about latitude 35° N; dashed line represents the deformed isobaric surface upon striking the plateau. Vertical circulation patterns are indicated by the arrows.

line represents the deformation of this isobaric surface after the current has passed through a portion of the area subject to the mountain influence. As demonstrated in the theoretical study, by the author (1949), the velocity distribution in the currents circling the mountain ranges will be such as to produce maxima in the immediate vicinity of the plateau, gradually diminishing on both sides. While this arrangement of current speed can be obtained in two-dimensional flow up to the mountain crest, this approach does not tell us why the jet along the southern border continues to intensify and sharpen well above the mountains. It is necessary to assume that a system of vertical circulations exists in the upper troposphere. Since hydrostatic equilibrium is always maintained to a high degree of approximation, this vertical circulation[1] must be in the sense indicated in fig. 9.

All supplementary cross sections support this contention. The isotherm pattern has shown us the concentration of the meridional temperature gradient just south of the mountains and an existence of an area of actual reversal of this gradient south of the jet. It is especially this latter fact that points to pronounced subsidence between latitudes 20° and 25°, since an advective hypothesis is not maintained by the mean section.

The sections of potential temperature and vertical stability bring out the effect that the field of horizontal convergence and divergence necessary to maintain the vertical circulation cell must have on the stability of air column under its influence. It is here assumed that this field of divergence has been operative for some time before the air reaches the meridian 76° E, a reasonable contention since the plateau of Pamir—»the roof of the world»—lies to the east of this meridian. North of the jet center ascent of air can account for the very low potential temperature of the high troposphere. As the ascent decreases with approach to the level of highest wind speed and the tropopause, divergence and vertical shrinking must occur from continuity requirements. Such shrinking is indicated by high values of stability in the high troposphere. After the air is displaced southward across the jet stream center, descent and stability decreasing downward should be encountered. As noted before, this stability gradient is clearly observed. This description accords with that given by ROSSBY and COLLABORATORS (1947).

The observed gradient of absolute vorticity shows that the vertical motion pattern as outlined is at least dynamically possible, even though not proved, in view of the assumptions on which the Solberg instability criterion is based. However the baroclinity section offers strong support in favor of indirect circulation. If the jet stream were maintained through direct circulation, we should encounter maximum baroclinity south rather than north of the jet stream.

As final evidence we may turn to rainfall conditions during winter. If the Himalayan jet is orographically produced, its position should suffer little change from year to year as stated before. In consequence a zone of minimum rainfall should occupy central India during winter. This is born out by actual conditions (fig. 10). Noteworthy also is the narrow rainy zone extending along the northern edge of the sub-continent where "winter" depressions move eastward underneath the jet stream.

It is not possible at this time to propose a concrete explanation of the vertical circulation system. It may, however, be suggested that the surface frictional stresses of the enormous plateau area can be an important factor. This suggestion is backed by the fact that the mountains are extremely rough, and that they rise steeply along their western border from low elevations to the vicinity of the 500 mb surface or higher, so that the upper-air current must strike them at a high speed.

Discussion of the Equatorial jet

The structure of atmosphere over southern India is very different from that over the northern part of the country. Here we find a region of west wind concentration over a lower layer of easterlies. Inspection of temperature, potential temperature and baroclinity fields (figs. 2, 6 and 7) indicates that there are enough solenoids to maintain both lower easterlies and upper westerlies, provided that there is a vertical circulation system in the

[1] Such a vertical circulation may be partly due to the radiative cooling over the top of the plateau.

work-producing sense. Although the existence of such a circulation has been assumed by writers on the general circulation for many years, it was not until quite recently that the actual strength of inflow into the equatorial zone and the distribution of convergence in that region has been computed (1949). It follows from these computations, together with the continuity principle, that the previously assumed direct solenoidal circulation in low latitudes should be a reality.

This argument also finds support in the baroclinity field. In pronounced contrast to conditions over northern India maximum solenoidal concentration in the equatorial zone appears below and south of the equatorial jet. Direct vertical circulation should build up a region of west wind concentration north of the maximum as is observed.

In consequence, ascending motion should occur south of the jet stream center and descent to its north. Winter rains should be confined largely to the region south of the jet, as is indeed the case (fig. 10). It therefore appears permissible to conclude that the equatorial jet over Indo-Pakistan can be considered as an example of the "HADLEY" type (1735) of circulation.

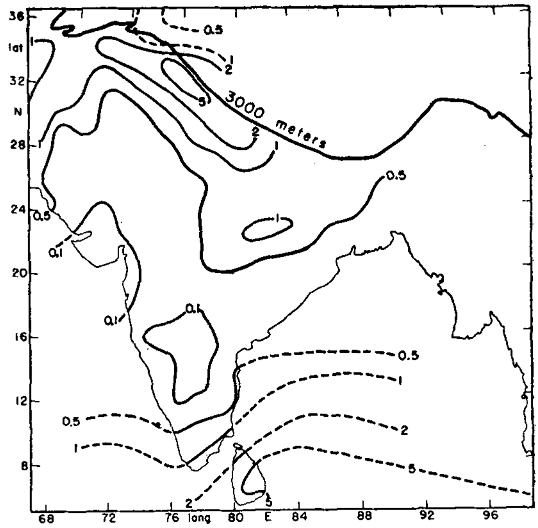

Fig. 10. Mean distribution of rainfall over Indo-Pakistan in January in inches.

Acknowledgment

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REFERENCES

BJERKNES V., 1910: Dynamic meteorology and hydrography. Tables 1M and 2M. Carnegie Institution of Washington, Washington.

BJERKNES, V., and COLLABORATORS, 1933: Physikalische Hydrodynamik. Berlin, J. Springer, 643—653.

CHAUDHURY, A. M., 1949: A theoretical analysis of upper-air circulation over Indo-Pakistan. To be published in *Quart. Jour. Met. Soc.*

CRESSMAN, G. P., 1949: Variations in the structure of the upper westerlies. To be published in *J. Meteor.*

HADLEY, G., 1735: Concerning the cause of the general trade winds. (London).

HESS, S. L., 1948: Some new meridional cross sections through the atmosphere. *J. Meteor.*, **5**, 293—300.

INDIA MET. DEPT., 1943: Climatological Atlas for airmen. 1—100.

NAMIAS, J., and E. CLAPP, 1949: Confluence theory of high tropospheric jet stream. To be published in *J. Meteor.*

PALMÉN, E., 1948: On the distribution of temperature and wind in the upper westerlies. *J. Meteor.*, **5**, 20—27.

— and K. NAGLER, 1948: An analysis of wind and temperature over North America in the case of approximately westerly flow. *J. Meteor.*, **5**, 58—64.

— and C. W. NEWTON, 1948: A study of the mean wind and temperature distribution in the vicinity of the polar front in winter. *J. Meteor.*, **5**, 220—226.

RIEHL, H, 1948: Jet stream in the upper troposphere and cyclone formation. *Trans. Amer. geophys. union* **29**, 175—186.

— 1945: Subtropical flow patterns in summer. *Dept. of Met., University of Chicago, Miscellaneous reports,* Met., University of Chicago, Miscellaneous reports, No. 22, 1—64.

— 1949: Unpublished studies.

ROSSBY and COLLABORATORS, University of Chicago, 1947: On the general circulation of the atmosphere in the middle latitudes. *Bull Amer. Met. Soc.*, **28**, 255—280.

SOLBERG, H., 1936: Le mouvement d'inertie de l'atmosphère stable et son rôle dans la theorie des cyclones. *Proc.-Verbaux de l'assoc. de météor., U. G. G. I., Edinburg*, 66—82.

WILLETT, H. C., 1944: Descriptive Meteorology. New York, Academic Press, 131—135.