Hemispheric water balance for the IGY

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ABSTRACT

A study of the hemispheric water balance over the northern hemisphere during the IGY covering the mean conditions for the calendar year 1958 is presented. The study includes analyses of the amount of precipitable water, of the vertically integrated water vapor transport vector field and of the divergence of water vapor transport for the hemisphere. Some implications of the water vapor divergence field are deduced which are important for hydrology and oceanography. Finally, the water vapor balance is discussed in the light of various meteorological considerations.

1. Introduction

The impetus of the modern approach to studies of the general circulation of the atmosphere as outlined for example by STARR (1951) resulted *inter alia* in a number of extensive investigations of the northern hemisphere water balance and its relation to the general circulation. The more important of these are STARR & WHITE (1955), STARR, PEIXOTO & LIVADAS (1958), STARR & PEIXOTO (1958), PEIXOTO (1958, 1960) and STARR & PEIXOTO (1964). All these studies were based upon aerological data for the year 1950 and included various evaluations from 90 daily upper-air sounding stations at several levels up to 500 mb over the entire northern hemisphere. Encouraged by the results and by the continuing growth of the hemispheric network of upper-air sounding stations, the authors of this paper have extended the studies for the IGY year 1958.

2. Formulation of the problem

Since the formulation of the problem and the procedures followed in the present paper are the same as those described in the previous study by STARR & PEIXOTO (1958), it seems sufficient to present only a general review of the approach followed. The basic quantities used in this study are the specific humidity, q, the eastward wind component u and the northward component v, the total wind being $\mathbf{V}$.

To a high degree of accuracy the atmosphere may be considered in a state of hydrostatic equilibrium so the pressure p is taken as the vertical coordinate. Thus a coordinate system (λ, ϕ, p, t) is used in which λ denotes the longitude, ϕ the latitude and t the time. The precipitable water contained in a unit column of air at a given instant above a point on the earth's surface is expressed by

$$W(\lambda, \phi, t) = \frac{1}{g}\int_0^{p_0} q\,dp, \qquad (1)$$

where g is the acceleration of gravity and p_0 the mean value of the surface pressure. The total horizontal transport of water vapor above a point on the earth's surface defines a two-dimensional vector field, $\mathbf{Q}(\lambda, \phi, t)$, expressed by

$$\mathbf{Q}(\lambda, \phi, t) = \frac{1}{g}\int_0^{p_0} q\mathbf{V}\,dp. \qquad (2)$$

The zonal and meridional components of the vector field are given by

$$Q_\lambda = \frac{1}{g}\int_0^{p_0} qu\,dp, \qquad (3)$$

$$Q_\phi = \frac{1}{g}\int_0^{p_0} qv\,dp. \qquad (4)$$

Expressions (1), (2), (3) and (4) may be averaged with respect to time over the interval τ, leading

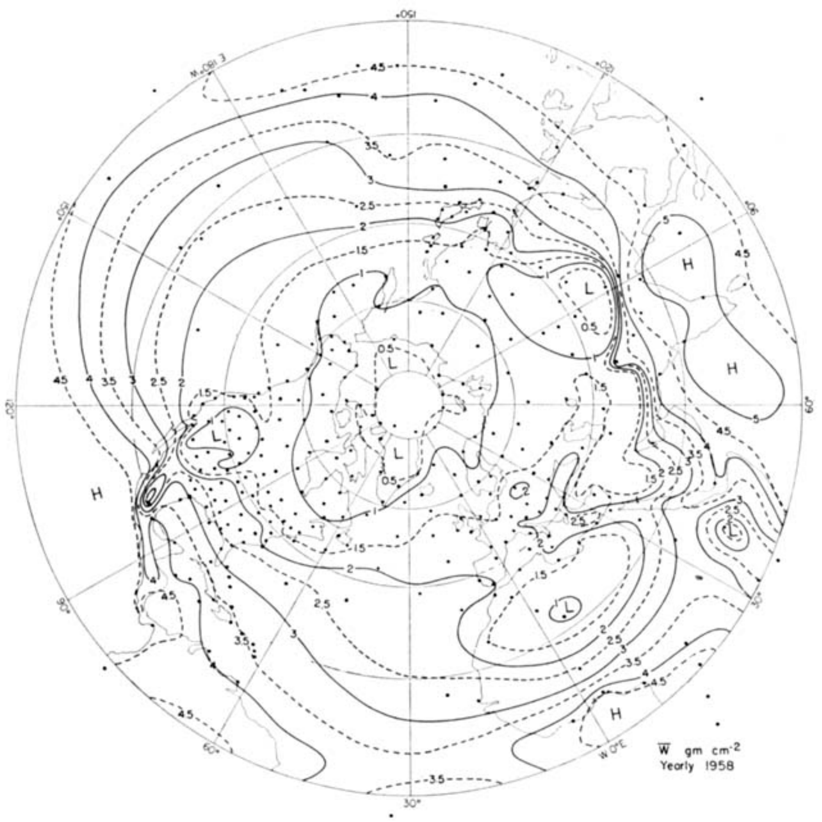

FIG. 1. Time average of the vertically integrated values of specific humidity (precipitable water) $\overline{W}$, in gm per cm^2 for the year 1958. Isoline spacing (full curves) 1 gm cm^{-2}. The dots indicate the distribution of primary stations used in the present investigation.

to the corresponding mean values $\overline{W}$, $\overline{\mathbf{Q}}$, $\overline{Q}_\lambda$, $\overline{Q}_\phi$, where the bar denotes the operator

$$\overline{(\quad)} = \frac{1}{\tau}\int_0^\tau (\quad)\,dt. \tag{5}$$

In this study τ represents the calendar year 1958. The divergence of the yearly mean field $\nabla \cdot \overline{\mathbf{Q}}(\lambda, \phi)$ is given in the (λ, ϕ, p) coordinate system by the expression

$$\Delta \cdot \overline{\mathbf{Q}}(\lambda, \phi) = \frac{1}{R \cos \phi}\left[\frac{\partial Q_\lambda}{\partial \lambda} + \frac{\partial}{\partial \phi}(\overline{Q}_\phi \cos \phi)\right], \tag{6}$$

where R denotes the radius of the earth.

For a unit column of air extending from the earth's surface (pressure, p_0) at each point to the top of the atmosphere (pressure, $p = 0$), the water vapor balance equation can be written

$$\frac{\partial W}{\partial t} + \nabla \cdot \mathbf{Q} = \Sigma, \tag{7}$$

where Σ represents the net sources of water substance in the atmospheric column. The sources and sinks of water vapor in the atmosphere are due primarily to evaporation, E, and to precipitation P. The transport of water in the solid or liquid phases is very small compared with the flux of water vapor in the atmosphere. For all practical purposes Σ is given by the excess of evaporation over precipitation, E–P. Thus, taking the time average for the given time interval (one year), the equation for atmospheric water vapor balance becomes,

$$\frac{1}{R \cos \phi}\left[\frac{\partial \overline{Q}_\lambda}{\partial \lambda} + \frac{\partial}{\partial \phi}(\overline{Q}_\phi \cos \phi)\right] = \overline{\Sigma} \equiv (\overline{E} - \overline{P}) \tag{8}$$

because for this time interval $\partial W/\partial t$ may be taken as zero. Positive values of divergence show areas where the total evaporation exceeds the precipitation whereas negative values show areas where the total evaporation is exceeded by the precipitation.

3. Data and procedures

The basic data used in this study were taken directly from aerological observations made during the calendar year 1958. An extensive coverage of 321 selected weather stations, indicated by dots in Fig. 1 provided the data over the northern hemisphere. Where a choice was possible, the most reliable and meteorologically representative stations were selected. In areas where observations were sparse, all available data were used. The total of 321 stations was separated into 285 primary and 36 secondary stations. The upper-air data for the primary stations were obtained on punched cards or magnetic tape, while the secondary ones were taken from IGY microcards. All these data were checked and processed by electronic means. All rawinsonde data available for each primary station were used; rawinsonde data for most stations were available at least once each day. A majority of these stations provided two soundings each day, some three and even four. Statistical computations were based upon all the data available at each station. The data handling and machine processing were accomplished by the Air Weather Service Climatic Center, at Asheville, North Carolina.

The secondary stations were used principally in critical areas not covered by the primary station network and also a few of them were chosen to fill in gaps at the equatorial border. The data from these stations were obtained with either radiosonde, radio-wind, pilot balloon, rawinsonde or a combination of these methods. Although only seven pilot balloon stations were used, in general the corresponding data were not so reliable as those from the primary stations.

In spite of generally excellent coverage over the northern hemisphere and near the equatorial border in the southern hemisphere, there were some areas of little or no data; the Amazon River Basin in South America, the eastern Pacific Ocean from Central America to the Hawaiian Islands and the Indian Ocean.

The over-all coverage of reliable data over the Arctic and middle latitudes in the northern hemisphere was excellent. The data from arctic stations were fairly complete up to 80 degrees latitude. The coverage over North America was especially dense over the United States; all stations in this area were used except a few superfluous ones. The good coverage over China, Mongolia and especially the Tibetan plateau was most helpful.

The procedures and the methodology of the several computations were presented and discussed on several occasions by the writers. Briefly, the yearly mean values $\bar{q}$, $\overline{qu}$, and $\overline{qv}$ were computed for each station at the four standard pressure surfaces of 1000, 850, 700 and 500 mb. The vertical integrations required to compute $\overline{W}$, $\overline{Q}_\lambda$ and $\overline{Q}_\phi$ were performed numerically applying the trapezoidal rule. Contributions to the vertical integrals were disregarded above 500 mb and between 1000 mb and the surface and the various integrated fields are in some cases underestimated.

The values of specific humidity are, in general, small above 500 mb over middle and high latitude regions. Although the wind speeds are generally high, the water vapor transports remain relatively small. However, these contributions are likely to be greater in the tropical and equatorial regions and over extensive areas of high terrain. The contribution of higher layers has already been taken into consideration by the writers in studying the humidity conditions over Africa.

As mentioned the lower boundary was set at the 1000-mb pressure surface whenever possible. In cases where the mean surface pressure, p_0, for the yearly period is greater than 1000 mb, this procedure underestimates the total vertically integrated values. It was found in previous studies that, with the exception of tropical areas, the contribution of the thin layer between 1000 mb and the surface was of little relative significance for the total integrated values. The largest differences probably occur over the trade wind regions, where low-level humidities are high. In cases where the mean surface pressure is less than 1000 mb or where the surface topography normally extends above the 1000-mb surface, the actual surface values of humidity and wind were used.

The yearly mean values of $\overline{W}$, Q_λ, and $\overline{Q}_\phi$ for each station were plotted on separate charts

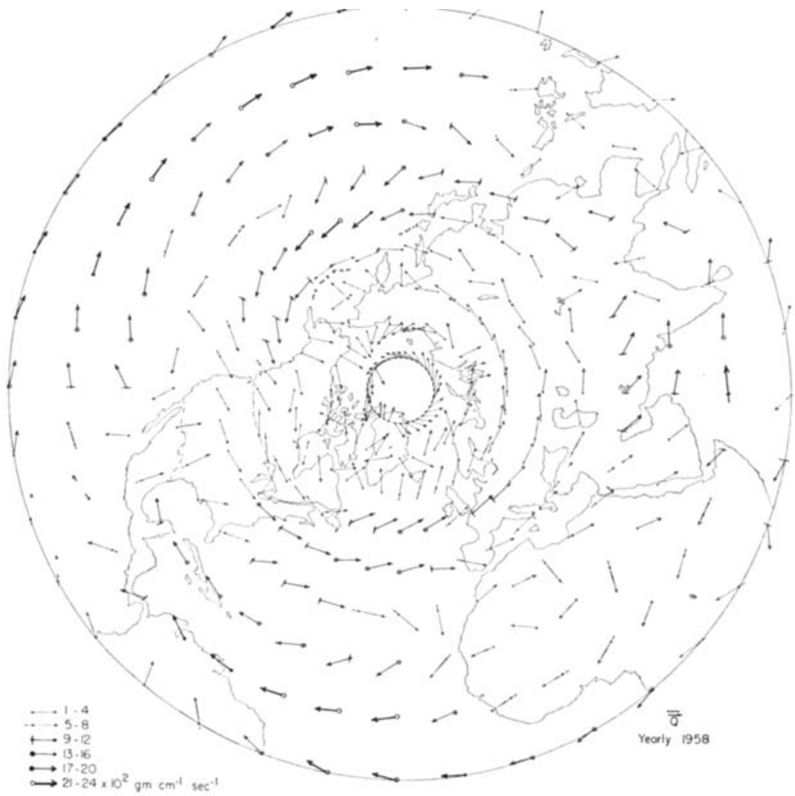

FIG. 2. Distribution of the vertically integrated moisture transport vector field averaged for the year 1958.

using polar stereographic projection maps and the corresponding fields were analysed using standard procedures. A five-degree latitude longitude grid was used to extract the corresponding gridpoint values. From these the total mean horizontal vector field of water vapor transport $\bar{\mathbf{Q}}(\lambda, \phi)$ was computed. The horizontal divergence $\nabla \cdot \bar{\mathbf{Q}}(\lambda, \phi)$ was calculated by finite difference methods using the expression (6).

4. Analysis and interpretation of results

The spatial distribution of the mean precipitable water vapor content, $\bar{W}$, is represented in Fig. 1. In general, there is a continuous decrease of precipitable water vapor content from the equator to the north pole. The maritime and continental influences are evident. The Sahara, the desert areas of the Middle East south of the Caspian Sea, and north of Tibet are dry. In addition, the effects of high terrain are illustrated by the very dry areas (less than 1.0 gm cm^{-2}) over the western United States, central Mexico, the Himalayas and the plateaus of Tibet and Central Asia and Central Africa.

Over the western portions of the subtropical oceanic anticyclones the water vapor content is generally higher than over the eastern portions, as is evident in the Pacific. This agrees with the concept of general convergence and divergence, respectively, in the western and eastern portions of these semi-permanent, large-scale features of the general circulation. The areas of highest water vapor content are the equatorial region of South America, the equatorial eastern and western Pacific Ocean, the Indian Ocean (especially south and east of India, including the Bay of Bengal) and equatorial West Africa. The driest area is in the Arctic, where the yearly mean precipitable water vapor content is less than 0.5 gm cm^{-2} north of 80°N. The 1.0 gm cm^{-2} isoline is found generally at or near 60°N. It dips south of 60°N over the regions of most frequent outbreaks of cold, dry polar continental air (eastern Siberia, the Bering Sea, Hudson Bay, etc.), and it extends slightly north of 70°N over Jan Mayen and northeast of Iceland, due to the Gulf Stream and the moist air masses frequently carried northeastward across the North Atlantic.

It must be pointed out that once again our analysis shows the mean water vapor storage in the atmosphere to be very small. The analysis of the mean precipitable water vapor content provides more detail and accuracy than heretofore available. Studies of the precipitable water vapor have important application to investigations of the radiation and heat balance in the atmosphere. Many specific applications of infrared radiation technology, however, require instantaneous information concerning atmospheric moisture.

A chart showing the total mean horizontal transport of water, $\bar{\mathbf{Q}}$, in vector form is given in Fig. 2. This chart gives a general idea of the main features of the mean total transport of water vapor in the atmosphere. It shows good agreement with a similar one published previously by Starr & Peixoto (1958) and also supports their conclusion that the net moisture flow across the equator for the year is practically zero.

5. Water vapor balance

Starr & Peixoto (1958) calculated the mean E–P field over the northern hemisphere for the year 1950, inferred from the horizontal divergence of the water vapor transport using a ten-degree latitude-longitude grid. A similar procedure was used in this study to compute the mean E–P field for 1958. As mentioned before, in view of the greater amount of data available for this study, a basic five-degree, latitude–longitude grid was used. The analysis of the distribution of the mean total horizontal divergence for 1958 in cm per year is presented in Fig. 3.

This analysis shows the existence of divergence centers alternating with convergence centers and exhibits considerable detail. In the areas of dense and representative data coverage the detail obtained in the five-degree grid computations is undoubtedly justified. However, in areas of sparse data coverage some of it may not be reliable. In such doubtful areas the analysis was smoothed slightly. Otherwise the field of divergence was analyzed so as to fit the numerical values.

The equatorial regions of the Atlantic and Pacific oceans show a general convergence indicating an excess of precipitation over evaporation due to the convergence of the trade winds from both hemispheres. Marked centers of strong convergence are found just south of Panama and off the east coast of South America near the equator; both of these areas are known to have excessive precipitation. Although the data supporting the divergence south of the Gulf of Maracaibo in South America is sparse, this area does have rather scanty precipitation compared with the Amazon River basin and water shed farther to the south and east. Another area of very strong divergence is found over the Arabian Sea. Even though the data supporting the water vapor transport analysis in this area were peripheral and the analysis relied heavily on mean winds, this divergence area can be associated with the high salinity of the Arabian Sea caused essentially by the excessive evaporation.

Peixoto (1959, 1960), Lufkin (1959) and Jacobs (1948) have derived separately, in slightly different ways, empirical relations between the sea-surface salinity and the field of E–P for areas of the oceans where the effects of horizontal transport of surface water salinity are negligible. Earlier Sverdrup (1942) had established empirically a rather simple linear relation between surface water salinity and E–P. The simple relationship indicates that transport of salinity by ocean currents is of minor importance for average conditions over long periods of time, whereas, the difference between evaporation and precipitation is of primary importance. Since the field of E–P is intimately related to the general circulation of the atmosphere, it can be concluded that the average values of sea surface salinity are controlled by the atmospheric circulation.

Sverdrup (1942) includes a chart showing surface salinity of the oceans in northern summer; this chart shows excellent agreement with Fig. 3 over the oceans. More recently both Defant (1961) and Von Arx (1962) have emphasized the important relationship between atmospheric circulation and sea surface salinity.

Two areas of strong convergence bordering the equatorial and subtropical regions are worthy of special note. One extends from south-

FIG. 3. Distribution of the horizontal divergence of the vertically integrated total annual flux of water vapor $\nabla \cdot \overline{\mathbf{Q}}(\lambda, \phi)$ for the IGY in grams per cm² per year. The isopleths (full lines for divergence and dashed for convergence) are entered for intervals of 100 cm year^{-1}.

western Arabia near Aden generally westward and southward across equatorial eastern and central Africa and the other is over north-central India. The first area over Africa contains the headwaters of the Blue Nile and several tributaries of the White Nile; there are several rivers flowing southward from this area through Somaliland and Kenya. Upper parts of the Congo and Ubangui rivers are also in the area. The heavy rains over the areas referred to in India are well known. With more detailed data coverage close to and within the Himalayan mountains the water vapor transport analyses would undoubtedly support more accurately the location of the center, or possibly two centers of convergence, one further north and elongated along the mountain mass and one farther east over Assam. It seems very likely that even greater detail could be obtained in the divergence analysis over India if there were a high density of reporting stations located so as to delineate clearly the tremendous convergence of water vapor transport associated with the well-known summer monsoon. Nevertheless, the analysis shown on Fig. 3 appears to be consistent with the more general known facts of the earth's water balance over India. It is interesting to note the extension of this prominent convergence northward through Kashmir to the Pamirs and Altai Mountains west of Sinkiang where rain and snow provide the head waters of the Indus River and also several other smaller rivers flowing into the Tarim Basin of Sinkiang where they disappear. Actually there is a further extension of the convergence over the marshy west Siberian lowlands. It should also be noted that this entire large area of convergence over India covers the vicinity of the headwaters of several extensive river systems: Indus, Ganges, Brahmaputra, Salween, Mekong, and Yangtze.

The subtropical regions of the Atlantic and Pacific Oceans show rather strong and extensive areas of divergence. In the Atlantic the divergence pattern is elongated in an east-west direction and generally uninterrupted. In the Pacific the divergence extends westward from Mexico to Marcus Island; it shows several centers of marked divergence interrupted by areas of weak convergence or less marked divergence. This feature of the analysis may be due to a cellular structure in the Pacific anticyclone. Over the western portion of the Pacific anticyclonic belt the pattern is somewhat complex, but, in general, convergence predominates; the area south and west of Japan shows rather strong convergence as might be expected because the mean position of the polar front is in this region. Closely associated with the strong divergence of the subtropical oceanic anticyclones are three other interesting areas of divergence; one over the central Mediterranean Sea, another over Iran, and the third over Mauritania in west Africa. The central Mediterranean divergence extends southward over the desert areas of Libya and Algeria and actually joins to the east through the Syrian Desert with the divergence over Iran; this whole area is known for its dryness and is an important source of atmospheric moisture; also the Mediterranean is known for its high salinity, which is associated with high positive mean values of $E-P$. There are centers of convergence in southern and central Europe and in North Africa (Atlas Mountains, Tunisia). These centers are associated with the frontal perturbations and with the topography. The center over the Iberian Peninsula is somewhat displaced to the south. However, it is well known that the northern part of the Iberian Peninsula is one of the regions of highest mean rainfall in Europe, and is the source of important rivers: (e.g., Tagus, Douro, Ebro, etc.). The divergence over west and Central Africa coincides with scanty precipitation and with the cold Canary or North African Current. The dryness of the Cape Verde Islands is well known. It is not difficult to recognize and to accept that the subtropical ocean areas which show strong divergence of water vapor transport are, in fact, major sources of atmospheric moisture. But it is more difficult to conceive of deserts in West and Central Africa, Arabia, the Middle East, and Iran as contributing sources of atmospheric moisture. Nevertheless, the divergence of atmospheric water vapor transport shows this to be the case. STARR & PEIXOTO (1958) have already commented on this point, since their study of 1950 showed similar divergence over these same deserts. BARNES (1963) also has discussed atmospheric water vapor divergence and certain applications of such information for climatic modification. The strong, positive divergence of water vapor transport over dry, desert areas and the attendant interesting speculations aroused thereby are certainly worthy of further study from a climatic and hydrologic viewpoint.

The mid-latitude regions around the northern hemisphere show many areas of divergence and convergence. The most prominent are areas of convergence associated with the extra-tropical storm tracks across the North Atlantic and North Pacific oceans. The convergence between Iceland and Greenland, and the other rather strong and marked areas of convergence in the North Atlantic region are clearly related to polar front storms; this is especially evident over the eastern United States and over the Gulf Stream and also in the vicinity of the western and coastal regions of Norway and Sweden. A long and extensive area of convergence extends from the East China Sea northeastward over the Japanese islands and Sakhalin then eastward across the entire northern Pacific Ocean to the west coast of North America. Here, in the vicinity of the Queen Charlotte Islands off the coast of British Columbia, is found a strong area of convergence extending northward and southward along the coastal mountain ranges. This area is known to have copious and regular precipitation year after year. An area of weak convergence is found inland of the coastal mountains, and divergence is actually shown over the desert areas of Nevada and southern California including Death Valley and the Salton Sea; farther inland over the Rocky Mountains is found another area of moderately strong convergence. Within this general area of convergence are the headwaters of several large river systems: Columbia, Missouri, Colorado, Arkansas, and Rio Grande. The details of other small areas of weak convergence and divergence over the United States and Canada can be supported by excellent data coverage.

There are two rather strong and marked regions of divergence in the mid-latitudes that should be mentioned, although the over-all picture is one of general convergence. One area is found just south of Newfoundland and extends southeastward into the Atlantic; the other

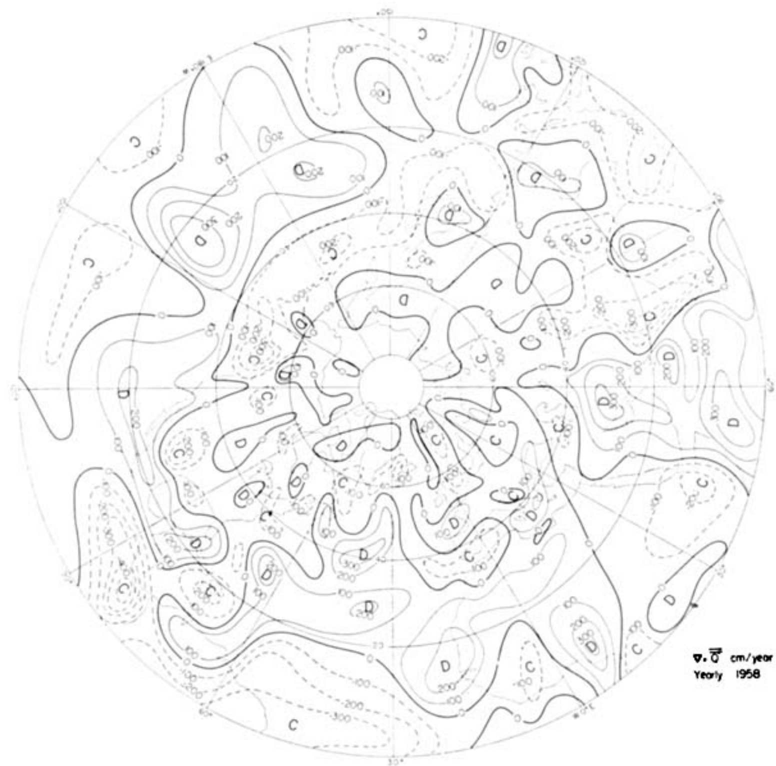

FIG. 4. Distribution of divergence for 1958 similar to preceding figure, but prepared by an equal weighting of summer and winter conditions especially over India with free use of climatological information over that region.

area is found over the northern portion of the Yellow Sea, northern Korea, and the western portion of the Sea of Japan. The divergence over northern Korea was also found by STARR & PEIXOTO (1958); it may be associated with the long winter monsoon carrying cold, dry air across this region and increasing its moisture at the expense of the underlying surfaces, especially over the Sea of Japan. It should be noted that the pattern abruptly changes to one of convergence along the western shores of the Japanese islands. The rather strong divergence near Newfoundland is more difficult to justify as a semi-permanent feature of the general circulation; it again may be possible that the outbreaks of cold, dry Canadian air masses over this region are responsible for it.

The arctic regions north of 60° N show a patchwork of small areas of weak convergence and divergence. Nevertheless, the data coverage north to 80° N was good, and at least the divergence pattern, complex as it may be, should represent conditions in 1958. It appears that there is a southward transport across 80° N, as is also the case across 70° N.

6. Final comments

The analysis was performed as objectively as possible and the use of preconceived ideas from climatology was avoided.

It should be noted, that except for differences already mentioned and various smaller details, the major features of the divergence analysis in this study agree quite well with those of the study made for 1950 by STARR & PEIXOTO (1958). We may consider the similarities between the two studies. The strong region of convergence over northern South America in 1950 is repeated in 1958 with more detail. The convergence center is associated with the heavy rainfall in the Amazon Valley. The divergence region, splitting northern South America on the 1958 map, was subsequently found to be associated with a dry region over Venezuela. This detail was not picked up on the 1950 map, although the zero is found along the northern coast of the continent. The strong convergence over the source region of the Nile was found for both years but with more detail in 1958. Divergence over the Mediterranean and over the western Sahara is found on both maps, although details are different.

Differences over India and Southeast Asia have not been completely reconciled. Supplemental stations used for the 1958 map altered the analysis significantly and made us question the representativeness of some of the mean values used in the 1950 analysis. Because of monsoonal effects over India, more numerous observations in one season than the other could greatly bias the transport vector field, and hence also its divergence.

As an experiment designed to investigate this last possibility somewhat further, our colleague Mr. E. RASMUSSON kindly prepared an alternate map of the divergence for 1958. The distribution shown in Fig. 4 was obtained independently, through the analysis of the zonal and meridional transports for summer and winter separately. The seasonal distributions were then weighted equally and combined into the chart for the year. In the preparation of Fig. 4 general climatological information was used as an aid in the analysis over the region in question. It is clear that the hydrological phenomena of India such as the boundary of the Thar desert and the high rainfall inland along the Malabar coast and over the Western Ghats region are reflected to better advantage.

The divergence region present in both years along the east coast of Siberia and China is consistent with the dry air coming off the Asian continent as already mentioned.

The presence of the divergence in both 1950 and 1958 over the Mississippi-Missouri Valley, continuing up into Saskatchewan, indicates a *significant item of agreement.*

On the whole where the data are adequate, the main features of the divergence field seem to be repeated for the two years. Reasons for differences may be due to inadequate data to define the divergence field, and to differences between the mean state of the circulation and moisture content for the two years, such as the action of hurricanes and typhoons. The annual total precipitation can sometimes be dependent on just one such storm. Finally, differences may be due to the finer gridwork used for the 1958 study.

The present study indicates the necessity of extending the analysis throughout the southern hemisphere. It seems also desirable at this point to pursue equivalent studies on the water balance on a regional scale so that in performing a more detailed analysis physiographic influences and local factors can be taken more fully into consideration.

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