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WATER VAPOR BALANCE OF THE ATMOSPHERE FROM FIVE YEARS OF HEMISPHERIC DATA

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The atmospheric balance of water vapor for the northern hemisphere is investigated through entirely automatic data processing and objective analysis procedures, in order to assess the potentialities of these methods for the present purposes by examining a large sample of results. The present study is based on five years of daily observations taken at about 800 meteorological stations. The final maps of the distribution fields of mean precipitable water content and of zonal and meridional transports of water vapor in the atmosphere are presented and discussed. The structure and the implications of the water vapor divergence map for hydrology are treated. Finally the water vapor balance on a planetary scale is discussed and the results are compared with evidence obtained from climatological and hydrological sources. The five-year averages of the various fields appear to give consistent results and mainly agree with previous findings.

The water balance at the earth's surface has been the subject of many investigations during the past decades. Until very recently most of the research has been focused on the earth-bound branch of the hydrological cycle. Over land areas the balance of precipitation, evapotranspiration, run-off, above and below the ground, and the change in ground-water storage formed the subject for investigation, using the so-called classic equation of hydrology. However, progress along these lines has been seriously hindered by the difficulty in obtaining reliable measurements of evaporation, change of storage, and, to some extent, of precipitation.

Over the oceans the situation is even more precarious through the lack of basic quantitative measurements of evaporation and precipitation. Estimates of evaporation based upon theoretical considerations involving assumptions as to the character of the eddy diffusion and transfer processes in the boundary layer differ very widely. The same uncertainty arises when evaporation is estimated by the energy-budget approach (not to mention the inadequacy of the values obtained from evaporimeters on board ships). Precipitation data over the oceans are still rather scarce and difficult to interpret. Furthermore, the values of precipitation measured at island stations are poorly representative of the surrounding ocean regions.

A new approach to the study of the hydrological problems, which tries to bypass some of these difficulties, has recently started to emerge with the realization that it is possible to evaluate with fair accuracy the atmospheric water vapor transport fields, and thus to evaluate the divergence of water vapor flux directly from meteorological observations. In this manner the difference between evaporation and precipitation is inferred from continuity requirements and a knowledge of the atmospheric branch of the hydrological cycle.

The water which falls as rain or snow upon a given point on the earth's surface is not necessarily that which has recently been evaporated from the same locality. Although local evaporation may add appreciably to the moisture supply for precipitation, as is the case in occasional heavy snows along lake shores, essentially the needed water vapor to feed the precipitation processes is transported from distant sources in subtropical ocean regions. This transport is accomplished by the large wind systems that form the components of the general circulation of the atmosphere. Actually the amount of water vapor contained in the atmosphere is rather small. In the mean it amounts to about 0.3 per cent of the total mass of the atmospheres. In fact, if all of it were condensed as precipitation *in situ,* only a very moderate amount of precipitation would result. Any more substantial amount depends upon the convergence of larger quantities of water vapor from distant areas. We are thus led to the expectation that over large areas of the globe there is an excess of precipitation over evaporation. On the other hand, there are other regions of the earth's surface where the evaporation predominates, as is quite common over subtropical oceans.

The evaporation due to solar heating and the subsequent condensation of the water vapor mainly in the atmosphere constitutes a gigantic distillation process of water over the globe. In this process the general circulation of the atmosphere plays a fundamental role in carrying the water vapor away from the source regions and in providing the dynamic and thermodynamic mechanisms which finally lead to precipitation. Thus, the study of the various fields which characterize the water vapor distribution in the atmosphere and its transport is essential to a better understanding of the hydrological cycle considered *in toto*. This explains the "raison d'être" of the present paper which constitutes a natural extension of previous work published by the writer. On a regional scale and for shorter intervals of time, various studies of water vapor transport in the atmosphere, with applications to hydrology, have been made (among others) for the United States by Benton & Estoque (1954), Rasmusson (1966, 1967), and most recently by Malhotra (1969); for the Baltic Sea by Palmén & Söderman (1963); for southern Sweden by Nyberg (1965); for Australia by Hutchings (1961), and for the African continent by Peixoto & Obasi (1965). By-and-large the results are reasonable when the meteorological network is sufficiently dense and the area is large.

The present paper deals with the calculation of those quantities which are already most familiar in water vapor balance studies, since it was thought best to investigate in this way the properties of the new data and the computing processes which are now mostly automatic, as is practically necessary for deriving results from the very large amount of data contained in the MIT General Circulation Data Library.[1]

BALANCE REQUIREMENTS FOR WATER VAPOR FLUX IN THE ATMOSPHERE

The general formulation of the balance requirements for water vapor in the atmosphere and its relation to the hydrological cycle have been discussed on various occasions and published elsewhere (see, e. g., Starr & Peixoto 1958, 1965). Thus, it appears sufficient to give in the present paper only a general review of the approach followed.

Since we may assume that, to a high degree of accuracy, the atmosphere is in hydrostatic equilibrium, we shall take the pressure p as the vertical coordinate and use a (λ, Φ, p, t) coordinate system, where λ denotes the longitude, Φ the latitude, and t the time. The basic quantities used in the present study are the specific humidity, q, u the eastward, and v the northward wind component. The horizontal wind vector is $\vec{v} = u\,\vec{i_\lambda} + v\,\vec{i_\Phi}$, where $\vec{i_\lambda}$ and $\vec{i_\Phi}$ are the eastward and the northward unit vectors. If we consider at each point of the earth's surface a unit column of air which extends to the top of the atmosphere, the

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[1] These tapes are available at cost of reproduction for all users desiring to have them.

total horizontal flux of water vapor above that point, for a given instant of time t, defines a two-dimensional vector field

$$\overrightarrow{Q}(\lambda, \Phi, t) \equiv \int \overrightarrow{qv}\,\frac{dp}{g} \equiv Q_\lambda \overrightarrow{i_\lambda} + Q_\Phi \overrightarrow{i_\Phi} \tag{1}$$

where g is the acceleration of gravity and Q_λ and Q_Φ are the zonal and meridional components of the vector $\overrightarrow{Q}$, respectively, and expressed by

$$\begin{cases} Q_\lambda \equiv \displaystyle\int qu\,\frac{dp}{g} \\ Q_\Phi \equiv \displaystyle\int qv\,\frac{dp}{g} \end{cases} \tag{2}$$

The integrations along the vertical extend from the earth's surface, where the point on the earth's surface is given by

$$W(\lambda, \Phi, t) = \int q\,\frac{dp}{g} \tag{3}$$

The integrations along the vertical extend from the earth's surface, where the mean pressure is p_0 to the top of the atmosphere where the pressure is zero.

Expressions (1), (2), and (3) may be averaged with respect to time over the interval τ leading to the corresponding mean values $\overline{\overrightarrow{Q}}$, $\overline{Q_\lambda}$, $\overline{Q_\Phi}$ and $\overline{W}$, where the bar denotes the time-average operator

$$\overline{(\ \ )} \equiv \frac{1}{\tau}\int_\tau (\ \ )\,dt \tag{4}$$

At a given point of the atmosphere at an instant t, the balance requirement of the water vapor for the unit mass can be expressed formally by a generalized balance equation, as follows:

$$\frac{\delta q}{\delta t} + \nabla \cdot q\overrightarrow{v} + \frac{\delta q\omega}{\delta p} = \frac{dq}{dt} \equiv \sigma(q) \tag{5}$$

where $\omega = \frac{dp}{dt}$ is the individual rate of change of pressure, $\nabla \cdot$ the horizontal divergence operator, and $\sigma(q)$ represents the rate of generation or destruction of water vapor in the unit mass by phase changes. The balance equation (5) may be integrated with respect to pressure and the resulting equation is:

$$\frac{\delta W}{\delta t} + \nabla \cdot \overrightarrow{Q} = \Sigma(q) \tag{6}$$

In the (λ, Φ, p, t) system this equation assumes the form:

$$\frac{\delta W}{\delta t} + \frac{1}{a \cos \Phi} \left[\frac{\delta Q_\lambda}{\delta \lambda} + \frac{\delta}{\delta \Phi} (Q_\Phi \cos \Phi) \right] \equiv \Sigma (q) \tag{7}$$

since $\int_0^{p_0} \frac{\delta (q\omega)}{\delta p} dp \equiv 0$. The constant a denotes the mean radius of the earth and Σ (q) the total rate of generation or destruction of water vapor in the unit column of the atmosphere as already mentioned. The main sources and sinks of water vapor in the atmosphere are due primarily to the evaporation E from the earth's surface and to precipitation P, falling from the air column. The condensation associated to the formation of clouds and the evaporation resulting from its dissipation are of negligible importance, since the water content of clouds in liquid and solid phases is small. Thus, the rate of generation of water vapor within the unit column of the atmosphere may be taken accurately enough as the excess of evaporation over precipitation:

$$\Sigma (q) \equiv \int \sigma (q) \frac{dp}{g} \equiv E\text{-}P \tag{8}$$

As noted before (Peixoto 1958) the water transports in solid and liquid phases by the clouds are negligible when compared to the transport of water in the vapor phase, except possibly in the tropical regions where the southward transport of water in the liquid phase may be of some importance.

Therefore, in using the above assumptions for the water vapor balance equation, we are led, in fact, to an equation of balance for the total water substance in the atmosphere, which reads as follows

$$\frac{\delta W}{\delta t} + \nabla \cdot \vec{Q} \equiv E\text{-}P \tag{9}$$

or

$$\frac{\delta W}{\delta t} + \frac{1}{a \cos \Phi} \left[\frac{\delta}{\delta \lambda} Q_\lambda + \frac{\delta}{\delta \Phi} (Q_\Phi \cos \Phi) \right] \equiv E\text{-}P \tag{9a}$$

If balance equation (9) is applied to a region of area A of the atmosphere bounded by a closed vertical wall (e. g., a river drainage basin, etc.), the equation may be transformed by the Ostrogradsky-Gauss theorem into

$$< \frac{\delta W}{\delta t} > + \frac{1}{A} \int (\vec{Q} \cdot \vec{n_c}) \, dc \equiv <E\text{-}P> \tag{10}$$

where $\vec{n_c}$ denotes the outward normal vector at any point on the boundary [c], and $< >$ denotes the space average over the area A.

Equations (5), (6), (9), and (10) may be averaged with respect to time. Since the bar operator and the divergence are permutable, we can write the balance equation as follows

$$\overline{\frac{\delta W}{\delta t}} + \frac{1}{a \cos \Phi} \left\{ \frac{\delta}{\delta \lambda} \overline{Q_\lambda} + \frac{\delta}{\delta \Phi} (\overline{Q_\Phi} \cos \Phi) \right\} \equiv \overline{E\text{-}P} \tag{11}$$

and

$$< \overline{\frac{\delta W}{\delta t}} > + \frac{1}{A} \oint \overline{\vec{Q} \cdot \vec{n}_c \, dc} = \overline{<E\text{-}P>} \tag{12}$$

For a latitudinal belt bounded by parallels of latitudes Φ_1, and Φ_2, Equation (12) can be written in the form

$$\left[\overline{\frac{\delta W}{\delta t}} \right] + \frac{1}{2\pi a \, (\sin\Phi_2 - \sin\Phi_1)} \int \left\{ (\overline{Q_\Phi} \cos \Phi)_{\Phi_2} - (\overline{Q_\Phi} \cos \Phi)_{\Phi_1} \right\} d\lambda = [\overline{E\text{-}P}] \tag{13}$$

where the brackets [ ] indicate the mean zonal value computed over the latitudinal belt. Equation (13) can also be derived from Equation (11) by noting that

$$\int \frac{\delta Q_\lambda}{\delta \lambda} \, d\lambda \equiv 0 \tag{14}$$

Equations (11), (12), and (13) may be regarded as equations of hydrology, based upon the atmospheric branch of the hydrological cycle. In fact, they show that any difference between the average rate of evaporation minus precipitation $<E\text{-}P>$ within a given region must be balanced by a change in the amount of water vapor stored in the atmosphere $< \overline{\frac{\delta W}{\delta t}} >$, or a net transfer out of the area, or both.

The quantity $\overline{\frac{\delta W}{\delta t}}$ is in general very small compared with the other terms in Equations (11), (12), or (13), except, perhaps, when short periods of time are considered and the region is under the influence of a severe storm. For long enough periods (e. g., one year), the rate of change of water vapor storage by the atmosphere may be taken as zero in these equations. Thus, generally speaking, positive values of divergence shows areas where evaporation exceeds precipitation, whereas negative values of divergence (convergence) show areas where precipitation is larger than the evaporation.

COMPUTATION AND ANALYSIS

As already mentioned, the basic quantities necessary to compute the fields $\overline{W}$, $\overline{\vec{Q}}$ ($\overline{Q_\lambda}$, $\overline{Q_\Phi}$), and $\overline{\nabla \cdot \vec{Q}}$ are the instantaneous values of the specific humidity q and the wind components u and v. The computations of those fields were made from 0000 GMT observations taken daily at about 800 stations located mostly in the northern hemisphere with some southern hemisphere stations included in order to improve the analysis of tropical regions. The five-year period extended from May 1958 through April 1963. These data, conveniently organized after extensive checking to eliminate, as far as possible, erroneous and garbled reports form one part of the MIT General Circulation Data Library.

For the present study the mean values $\bar{u}$, $\bar{v}$, and $\bar{q}$ were computed separately at each station and level as were also the mean products $\overline{qu}$ and $\overline{qv}$. The distributions represented by the station data were subjected to objective analysis by machine.

Since meteorological data are recorded and transmitted in terms of pressure as the vertical coordinate, the evaluations and the analyses were made in such a system. The standard pressure levels used in this study range from 1000 mb (near the surface) to 200 mb (about 13 km), at intervals of 50 mb. The vertical integrals were evaluated by applying the trapezoidal rule to data at 50-mb intervals up to 200 mb, beginning with the first standard pressure level above the surface and adding the contribution from the surface layer. The latter contribution was evaluated using surface values of q, qu, and qv and considering the mean monthly surface pressure to be the pressure at the bottom of the layer. In order to exclude undue influence from stations having an excessively small fraction of the possible number of observations, a cut-off criterion was incorporated in the machine analysis program for the horizontal map at each of the levels. This criterion for the present study was set at 30 per cent, so that any station having less than this fraction of possible observations was dicarded. Further details are given by Starr, Peixoto & Gaut (1970).

The results of vertical integration of q, qu, qv, etc., at various meteorological stations were used to generate the necessary maps. The computerized numerical analysis used was essentially based on iterative interpolation, which satisfies Poisson's equation in finite difference form. As a first guess use was made of previous results for hemispheric moisture analysis published by Starr et al. (1965). The calculations were made on a UNIVAC 1108 computer. Further details concerning the formulation of an objective analysis scheme and the description of the highly complex computer program are given by Harris, Thomasell & Welsh (1966, 1968, see ref. Welsh 1969). The divergence $\nabla \cdot \overrightarrow{\overline{Q}}$ was evaluated by machine from the grid point values of $\overline{Q_\lambda}$ and of $\overline{Q_\Phi}$ at a regular 5° gridwork of latitude and longitude using spherical coordinates (7) and finite difference methods. The final map was obtained by objective analysis techniques.

In addition to the values for the entire five-year period, results were computed for four composite 15-month seasons, the winter including the months January, February, and March, etc. Actually all the quantities were accumulated by months, then added together to obtain the results for the seasons, as well as for the 60 months. However, in this study we shall discuss only the five-year results.

RESULTS AND DISCUSSION

The results of the present study are shown graphically mainly in the form of hemispheric maps. These were obtained by automatic computing untouched, in a certain sense, by human hands. The isolines were drawn automatically as a contoured print out by the computer.

The maps showing the two-dimensional distribution of the vertically integrated fields of the mean precipitable water content, $\overline{W}$, the mean zonal transport $\overline{Q_\lambda}$, and the mean meridional transport $\overline{Q_\Phi}$ are reproduced in Figs. 1, 4, and 5, respectively. Figs. 2 and 3 show the mean meridional distribution of the specific humidity q in the vertical through the atmosphere, and the meridional profile of the mean zonal precipitable water content $[\overline{W}]$, as obtained by machine analysis. The map of the divergence of the mean total transport field is shown in Fig. 6.

In regard to the methods of analysis, materials, and results shown in this paper some general points are worth noting.

(1) One of the main purposes of the research that led to the results of the present study was to evaluate the potentialities of automatic processing and objective analysis schemes in studying the various fields which are relevant for the water vapor balance. This is a problem that we have to face and will be-

come more acute, if we are to use in full all the information contained in the accumulated record during recent years. It seems that automatic processing constitutes the only possibility to obtain improved knowledge of the behavior of the general circulation and of the workings of the atmosphere.

The actual results are encouraging, and in fact they appear to be remarkably good. However, there are shortcomings inherent in the unavoidable smoothing and other approximations that are involved. Some of these drawbacks are also shown in the present output. In order to reduce these effects, independent analyses will first have to be made for purposes of comparison. This is being planned for the near future.

(2) The analysis of the mean precipitable water content $\overline{W}$ presented in Fig. 1 shows, perhaps better than any other, the essentials of the mean water vapor distribution in the atmosphere. Generally speaking there is a continuous decrease of the water content from the equator to the pole, as might be expected, since the atmospheric capacity to retain water vapor is a function of the temperature. The departures from zonal symmetry are associated with the physiographic characteristics of the earth's surface. On the whole the precipitable water is larger over the oceans than over the continents. Over land the effects of physiography are particularly evident, as can be seen from the dry conditions (less than 1.0 g cm^{-2}) that prevail over the desert areas (e. g., the Sahara, Arabia, Iran, North Tibet, etc.), and over regions of high topography (e. g., the Rocky Mountains in the western United States, Central Mexico, Himalyan Mountains, plateaux of Tibet and Central Asia, Highlands of Ethiopia, etc.).

The areas of highest water vapor content are shown over the equatorial regions of South America, eastern and western Pacific, the Indian Ocean, and equatorial West Africa. The region of lowest precipitable water (less than 0.5 g cm^{-2}) is found over the Arctic.

Fig. 2, the vertical meridional cross-section through the atmosphere of the mean specific humidity $[\overline{q}]$, reveals that the largest value is observed over the equatorial region near the surface and decreases rapidly with latitude and almost exponentially with height. There is thus a strong vertical gradient in the lower layers of the atmosphere. About 50 per cent of the water vapor is contained in the lowest 15 per cent of the atmosphere and more than 90 per cent in the lower half (approximately below 500 mb).

Fig. 3 shows the meridional profile of the mean zonal precipitable water content of the atmosphere $[\overline{W}]$. The profile obtained by Starr, Peixoto & Crisi for the IGY is included for comparison. The agreement is good. The values of $[\overline{W}]$ decrease monotonically from the equator to the pole with the steepest gradient

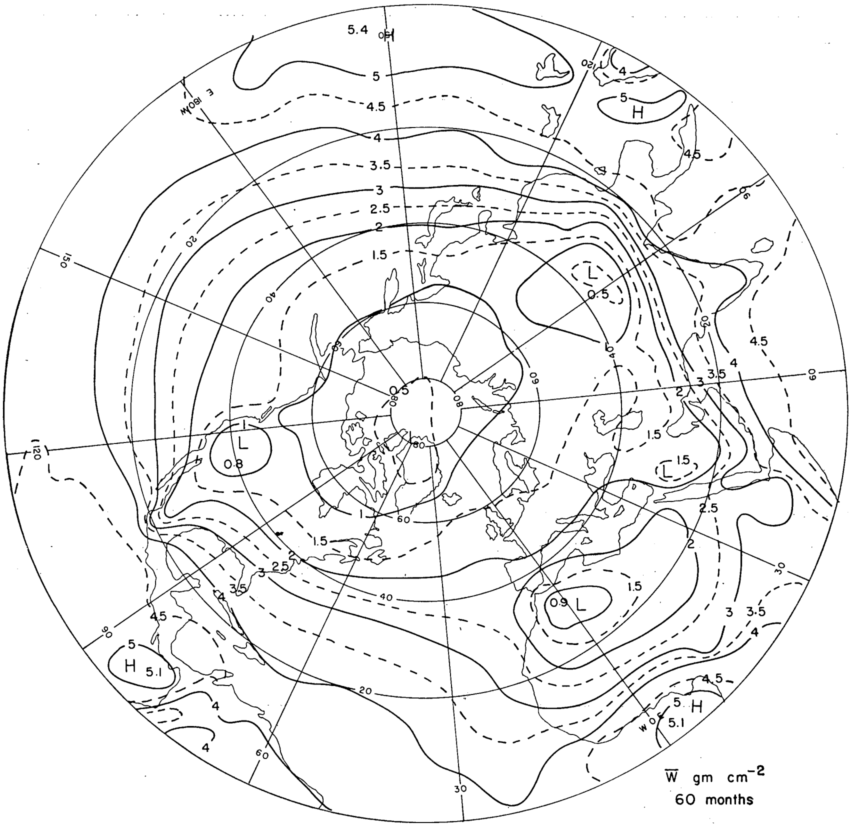

Fig. 1.

Map showing the distribution of the vertically integrated mean specific humidity (precipitable water), $\overline{W}$, obtained by automatic computing from 5 years of daily data in the northern hemisphere for a 60-month period. The units are gm cm^{-2}. Isoline spacing (full curves) 1 gm cm^{-2}.

over the subtropical regions. The grand average precipitable water content is about 2.7 g cm^{-2}. Thus, the storage in the atmosphere of water vapor is relatively small and the actual amount could be completely removed by the average precipitation acting alone within a period of ten days (Starr et al. 1965). Albeit small, the total precipitable water for the entire atmosphere is still comparable to the water content of the rivers of the earth.

(3) Fig. 4 shows the analysis of the vertically integrated mean zonal transport

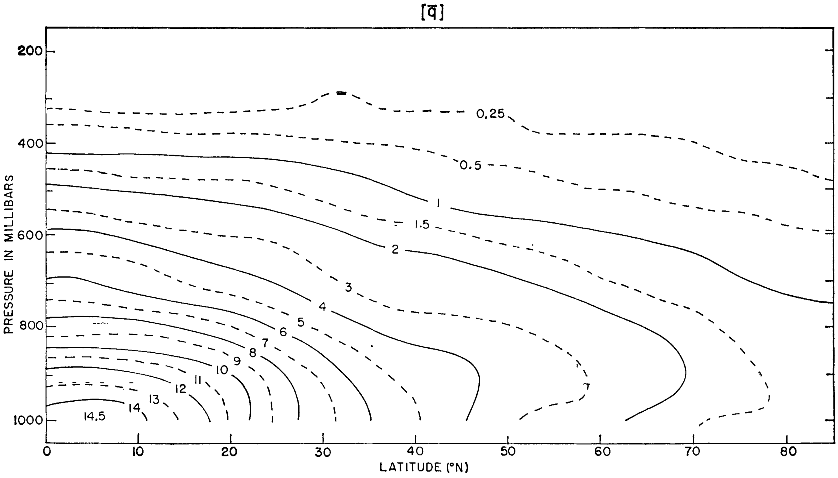

Fig. 2.

Vertical meridional cross-section through the atmosphere showing the distribution of the mean zonal specific humidity, $\overline{[q]}$, obtained by automatic computing from 5 years of daily data in the northern hemisphere for a 60-month period. The units are g kgm^{-1}, and the vertical coordinate is pressure in millibars.

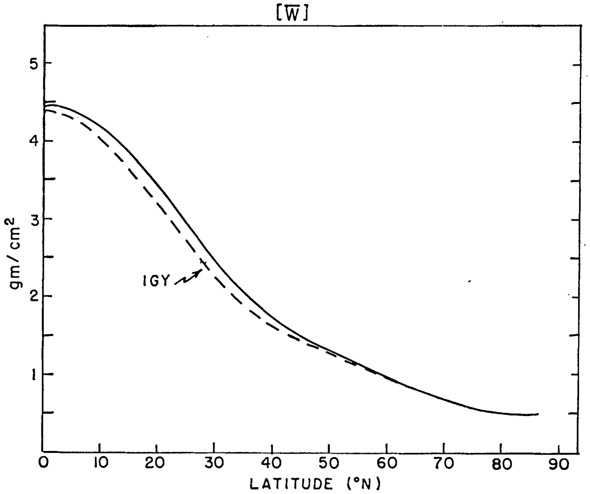

Fig. 3.

Meridional profile of the mean zonal precipitable water $\overline{[W]}$ obtained by automatic computing from 5 years of daily data in the northern hemisphere for a 60-month period. The dotted curve represents the yearly profile of $\overline{[W]}$ computed by Starr, Peixoto & Crisi (1965) for the IGY. The units are g cm^{-2}.

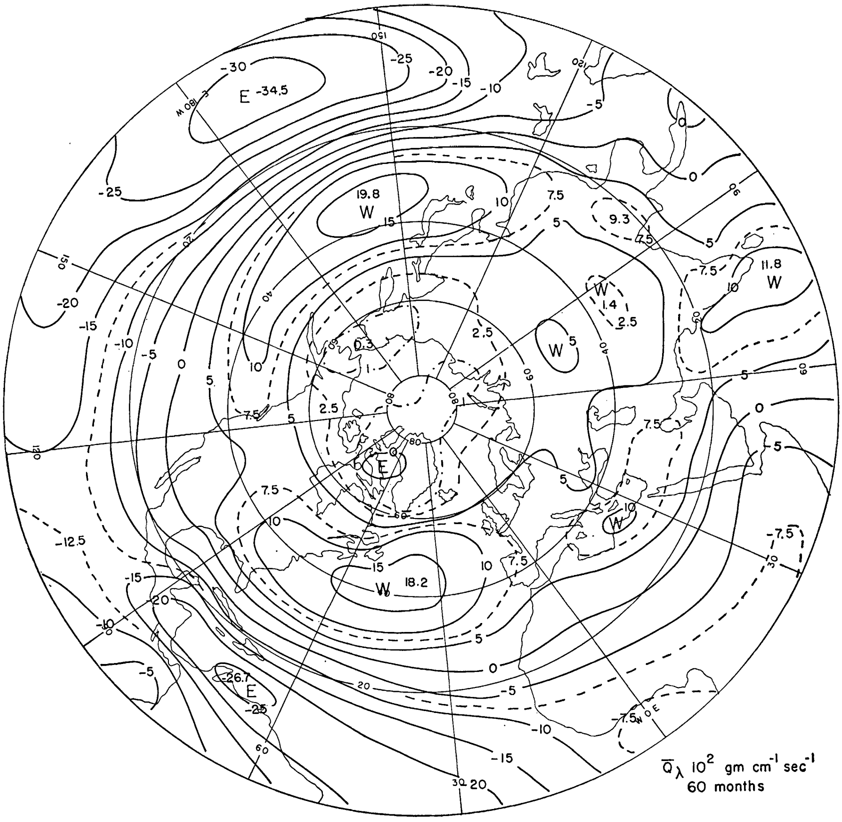

Fig. 4.

Similar to Fig. 1 but for the vertically integrated mean zonal transport of water vapor, $\overline{Q_\lambda}$, obtained by automatic computing from 5 years of daily data in the northern hemisphere for a 60-month period. The units are 10^2 g cm^{-1} sec^{-1}, Isoline spacing (full curves) 5×10^2 g cm^{-1} sec^{-1}. Positive values indicate westerly (west-to-east) transport.

of water vapor $\overline{Q_\lambda}$. Large positive (west-to-east) centers of zonal transport are found in midlatitudes, where westerly winds are predominant and stronger over the oceans. Large negative (east-to-west) belts of zonal transport are found in the tropical regions where strong and persistent easterly winds occur. The main centers are localized north of the equator over the Pacific Ocean, near the Marshal Islands, and over the Central Atlantic Ocean, extending from the African Coast to the northern part of South America and Puerto Rico. A negative area with easterly transport is also shown over the Arctic Archipelago of Canada and over portions of Northern Greenland.

(4) Fig. 5 shows the objective analysis for the mean meridional transport of water vapor integrated along the vertical, $\overrightarrow{Q_{\Phi}}$. There are several centers of northward (positive) flow, alternating with centers of southward (negative) flow, the most intense occurring over the oceans. This is to be expected, since by and large a net northward transport of water vapor prevails to the west of the semipermanent high pressure cells, localized over the subtropical regions (e. g., the Azores High, the Central Pacific High, etc.), whereas a southward transport is observed to the east of these cells. Similarly, associated with the mean positions of the baroclinic perturbations of the polar front several centers of northward and southward transport of water vapor are found in middle latitudes. Furthermore, these perturbations are very effective in transporting water vapor northward because the southerly winds are generally moister than the northerlies. In the tropical regions the transport is predominantly southward. Across the equator, however, there is a substantial net transport of moisture from the south, in agreement with previous findings (Starr, Peixoto & McKean 1969). This implies that on the average, over the northern hemisphere, the total precipitation exceeds the evaporation, which agrees with the results given by Budyko (1963). The transequatorial transport of water vapor constitutes a supply of moisture for the intertropical convergence zone, which on the average is located somewhat to the north of the equator.

As mentioned before, objective analysis tends to smooth out detail. In the present case the positive maxima in middle latitudes are probably reduced excessively, as may be noted from comparison with results of previous studies.

(5) Fig. 6 shows the two-dimensional distribution of the horizontal divergence of the vertically integrated total water vapor transport, $\overline{\nabla \cdot \vec{Q}}$. The analysis exhibits considerable detail and no attempt was made to introduce any adjustment of the printout map given by the computer. On the whole the machine objective analysis shows good agreement with the one presented by the writer (Peixoto 1970).

We shall discuss now the most prominent features of the divergence field. Convergence predominates over the equatorial regions of the Atlantic, Pacific, and Indian Oceans. This results in a strong belt of precipitation which characterizes the equatorial zone. The convergence of water vapor is mainly due to the equatorward transport of moisture by the lower branches of the mean meridional Hadley cells. Centers of strong convergence are shown over South America over the equator and over Brazil from which the Amazon River derives its waters; over equatorial West and Central Africa, where the headwaters and

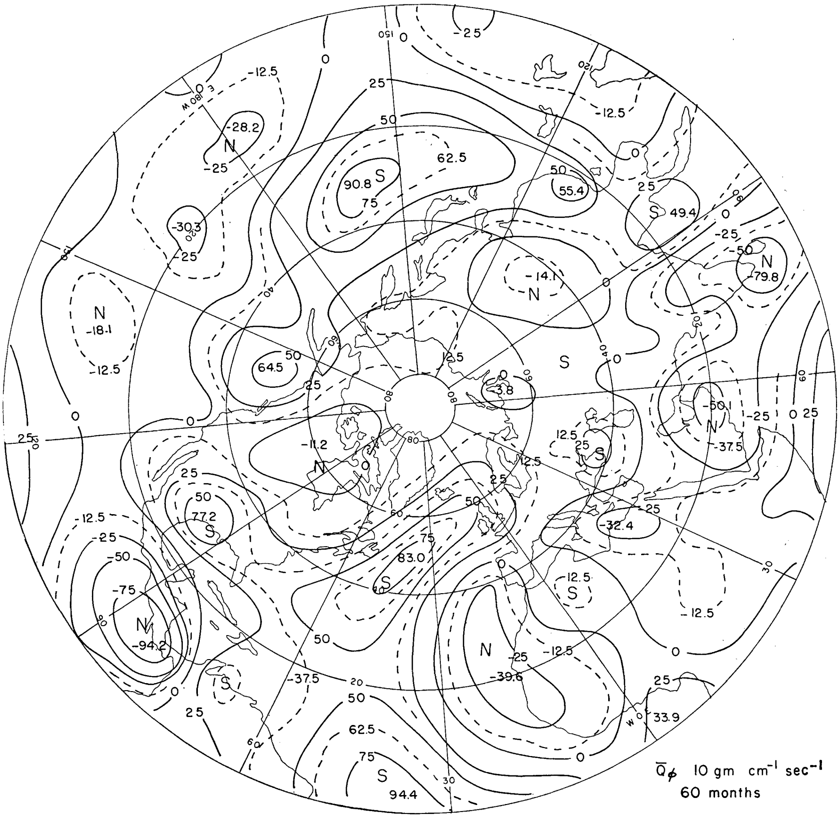

Fig. 5.

Similar to Fig. 1 but for the vertically integrated mean meridional transport of water vapor $\overline{Q_\Phi}$. The units are 10 g cm^{-1} sec^{-1}. Isoline spacing (full curves) 25 × 10 g cm^{-1} sec^{-1}. Positive values indicate northward (south-to-north) transport.

drainage basins of many large rivers are found (e. g., the Blue and White Nile, the Ubangi, the Congo, the Niger, the Volta, the Senegal, etc.); over the Bay of Bengal extending northward to the Pamir and Altai Mountains covering the headwaters of various important rivers (e. g., Indus, Ganges, Mekong, Yangtze, etc.).

The subtropical regions are dominated by an almost uninterrupted belt of divergence, with an excess of evaporation over precipitation. The most intense centers are localized over the Gulf of Mexico, Atlantic Ocean, North Africa,

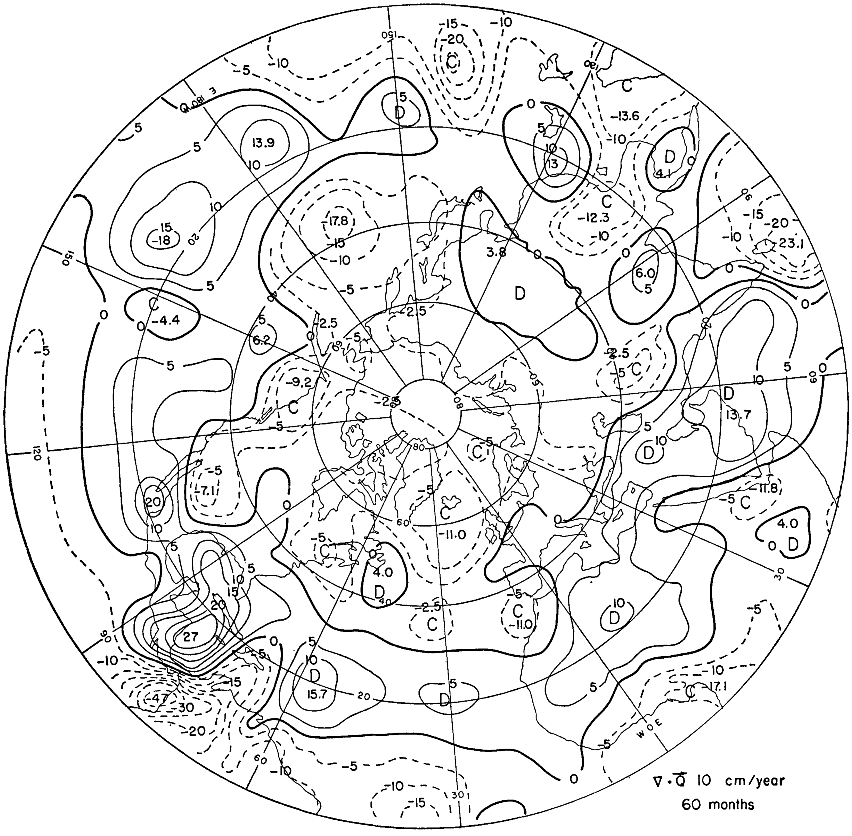

Fig. 6.

Map showing the distribution of the horizontal divergence of the vertically integrated total water vapor flux, $\nabla \cdot \vec{Q}$, obtained by automatic computing from 5 years of data in the northern hemisphere for a 60-months period. The units are g cm^{-2} year^{-1}. The isolines (full lines for divergence and dashed lines for convergence) are entered for intervals of 5×10 g cm^{-2} year^{-1} (or cm/year^{-1}).

Arabian Sea, eastern, central, and western Pacific, and extending into Mexico. The actual results agree with the fact that the oceanic belt at these latitudes exhibits a very high salinity content. Other less marked regions of divergence are found over the Mediterranean Sea with its high salinity, extending to the arid lands of Lybia, Algeria, Syria, Iran, Tibet, etc. This is the zone dominated by the large high pressure cells (Pacific High, Azores High, etc.) where subsidence of air leads to low relative humidity conditions under which evaporation fares best.

The midlatitudes show areas of divergence alternating with areas of convergence, these being by far predominant. Divergence is found over the south and central parts of the United States, to the east and south of Newfoundland and over Central Asia (Gobi Desert) extending to North Korea and part of Japan. The strongest centers of convergence in middle latitudes are found, as expected, over the Pacific and Atlantic Oceans. Other centers of convergence are localized over the Rocky Mountains, in the vicinity of the headwaters of various rivers (Columbia, Missouri, Colorado, Rio Grande, etc.); over the northwest coast of North America (Queen Charlotte Islands, British Columbia, etc.) a region known for its abundant and regular precipitation. A vast area of convergence extends from western Canada, to Greenland, where a net annual accumulation of snow and ice is observed. These centers of convergence are associated with the activity of the arctic frontal system. Convergence is also observed over a large area extending from Iceland to the Scandinavian Peninsula, penetrating deeply into Russia and Central Asia where a vast river system is also found (Volga, Don, Dnieper, Dniester, Onega, Duna, Ob, Lena, Amur, etc.). The convergence of moisture, which prevails over the middle and high latitude regions, is associated with the migratory perturbations that develop along the polar front and with the semi-permanent low pressure systems which are located in the sub-polar regions (Aleutian Low, Iceland Low, etc.).

(6) The divergence over the oceans is not difficult to interpret, since there is a permanent source of water available and a continuous evaporation taking place. In fact, the present field of divergence and convergence of water vapor agrees fairly well with the salinity distribution over the oceans. The regions under an area of convergence have low salinity content, mainly due to the dilution by fresh water produced by the excess of precipitation, whereas under an area of divergence the salinity is in general very high, as expected from the strong local evaporation. The correlation between the divergence of water vapor and the salinity is so definite that studies of the present nature may be useful in oceanography (Von Arx 1962).

The divergence from land areas where a surface storage of water is abundant (glaciers, lakes, rivers, etc.) is immediately accepted as natural. However, the present map of $\overline{\nabla \cdot \vec{Q}}$, shows, as in previous parallel studies, that over the continents the main areas of divergence occur over the arid and desert lands. Deserts generally contain evidence of evaporation processes. The occurrence of *evaporites* formed by residues of salts is very common in the Sahara, Algeria, and Tunisia where they occur in the "chotts". Special phenomena such as "desert varnish" are the result of a strong evaporation followed by an active oxidation of the mineral coating consisting mainly of iron components accumulated on exposed rock surfaces.

Considerable amounts of water are transported by surface flow from surrounding regions where rainfall is more abundant. The existence of various gorges and "wadis" indicates the importance of the run-off caused by occasional torrential streams into the central parts of the deserts. However, these sources are not intense enough, and the excess of evaporation over precipitation has to be aided by underground drainage from less arid areas that necessarily supply the deficit of water, as was discussed previously (Starr & Peixoto 1958). The study of the underground flow in desert areas is an extensive and difficult subject, although one of extreme economical importance (Lufkin 1959).

The existence of underground flow has been reported by Hellström (1940), who dealt with the eastern Sahara near the Nile (Peixoto 1970).Another example of the possible underground drainage has been suggested to take place in the Chad Basin. According to Drouhin (1954) although Claud Lake receives water from the Sahara and Lagone rivers, its area and salinity content remain constant. Without a sizeable subterranean drainage the salinity due to the combined effects of evaporation and the transport of salts by the rivers should increase. Hydrological observations indicate that there is a flow toward the north-northeast in an an aquifer which extends beneath the lake.

The existence of similar underground flows passing by the oases which are said to be connected with the Nile river were reported by Dr. F. Ali of the United Arab Republic Meteorological Department at the Symposium on Tropical Meteorology, held in Nairobi in 1960.

In a more recent study based upon hydrological and geological evidence Ambroggi (1966) reached the conclusion that there are several internal drainage areas beneath the surface of the Sahara. Malhorta (1969), in his study of the hydrological cycle of North America, found some indications of large sources of underground water in the desert areas of the United States.

(7) By-and-large the actual map of divergence shows the main features of the zonal distribution of $\overline{[E-P]}$ as obtained from climatological sources (Sellers 1965). In fact, it shows that on the average there is: (A) a net convergence ($\overline{[E-P]} < 0$) in the equatorial zone where heavy tropical rains occur; (B) a net divergence ($\overline{[E-P]} > 0$) in the subtropical regions, where a strong evaporation occurs; (C) a net convergence ($\overline{[E-P]} < 0$) in the middle and high latitudes, where precipitation predominates over the evaporation. Probably the objective procedure used here underestimates this convergence.

Thus, the primary and most important sources of moisture for the whole atmosphere are found over the subtropical regions, mainly in the oceans, where evaporation is taking place continuously. The moisture supplied to the atmosphere is afterward exported from the sources and carried by the atmospheric circulations into regions of prevailing convergence where it condenses and falls as precipitation. Therefore, the theory of formation of precipitation from evaporation *in situ* cannot be accepted. Although it would be of great hydrological interest to determine the mean path length of the water vapor transport between evaporation and condensation, the material at hand permits but a rough estimate. Judging from the present data, it is probable that the path-length of the atmospheric branch of the water cycle varies from one locality to another. However, taking as a criterion the distance between divergence and convergence centers, it appears that the path-length in north-temperate latitudes may be on the order of 1000 km.

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