Pole to pole divergence of water vapor

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ABSTRACT

A study of the mean divergence of the water vapor transport on a planetary scale from pole to pole during the IGY is presented. The fields of the mean precipitable water content, of the total vertically integrated water vapor transport and of its divergence covering all the globe are included. Some implications of the water vapor divergence field in connection with the oceanography, hydrology and with the energetics of the general circulation of the atmosphere are discussed. The actual analysis is compared with the previous work obtained from aerological data and with studies of other authors obtained from a different and independent approach, such as the analyses based upon classic climatological procedures.

1. Introduction

The present study is an extension of the work published by the writer (Starr, Peixoto & Crisi, 1965) on the water balance for the IGY for the Northern Hemisphere. Although the aerological network in the Southern Hemisphere is not yet sufficiently dense in large oceanic areas and over the central part of South America it appears that the IGY data, being the best available, are fairly adequate to obtain a global representation of the divergence field of water vapor from pole to pole on a planetary scale. These studies are essential to acquire a better comprehension of the basic aspects of the water balance of the atmosphere as a whole. More detailed new balance studies on a regional scale and for shorter intervals of time would require much more data, as was the case for those already made over the United States and Southern Canada by Benton & Estoque (1954) and Rasmusson (1967), over the Baltic Sea by Palmén (1963) and for the African Continent by Peixoto & Obasi (1965). When sufficient data are available for such purposes the divergence of water vapor can be evaluated accurately enough to give useful estimates of the mean difference between evaporation and precipitation, provided the region is not too small and the time interval not too short.

In studying the transport of water in the atmosphere the required basic quantities for each instant t and at different pressures p at each vertical are the following: the specific humidity q, the eastward component u and the northward component v of the wind field $\mathbf{V}$, defined by

$$\mathbf{V} = u i_\lambda + v i_\phi. \tag{1}$$

For a unit column of air extending from the earth's surface to the uper boundary of the atmosphere, the water balance equation can be written as shown by the writers in previous work (Starr & Peixoto, 1957) as follows:

$$\frac{\partial W}{\partial t} + \operatorname{div} \mathbf{Q} = \sum, \tag{2}$$

where the symbols have the meaning:

$W(\lambda, \phi, t)$ denotes the precipitable water at a point of longitude λ and latitude ϕ and is given by

$$W(\lambda, \phi, t) = \frac{1}{g}\int_0^{p_0} q\,dp \tag{3}$$

assuming that the atmosphere is in hydrostatic equilibrium, so the pressure p is taken as the vertical coordinate. Gravity is denoted by g, and p_0 is the surface pressure. $\mathbf{Q}$ given by

$$\mathbf{Q}(\lambda, \phi, t) = \frac{1}{g}\int_0^{p_0} o\mathbf{V}\,dp \tag{4}$$

is the two-dimensional vector field of the total horizontal water vapor transport:

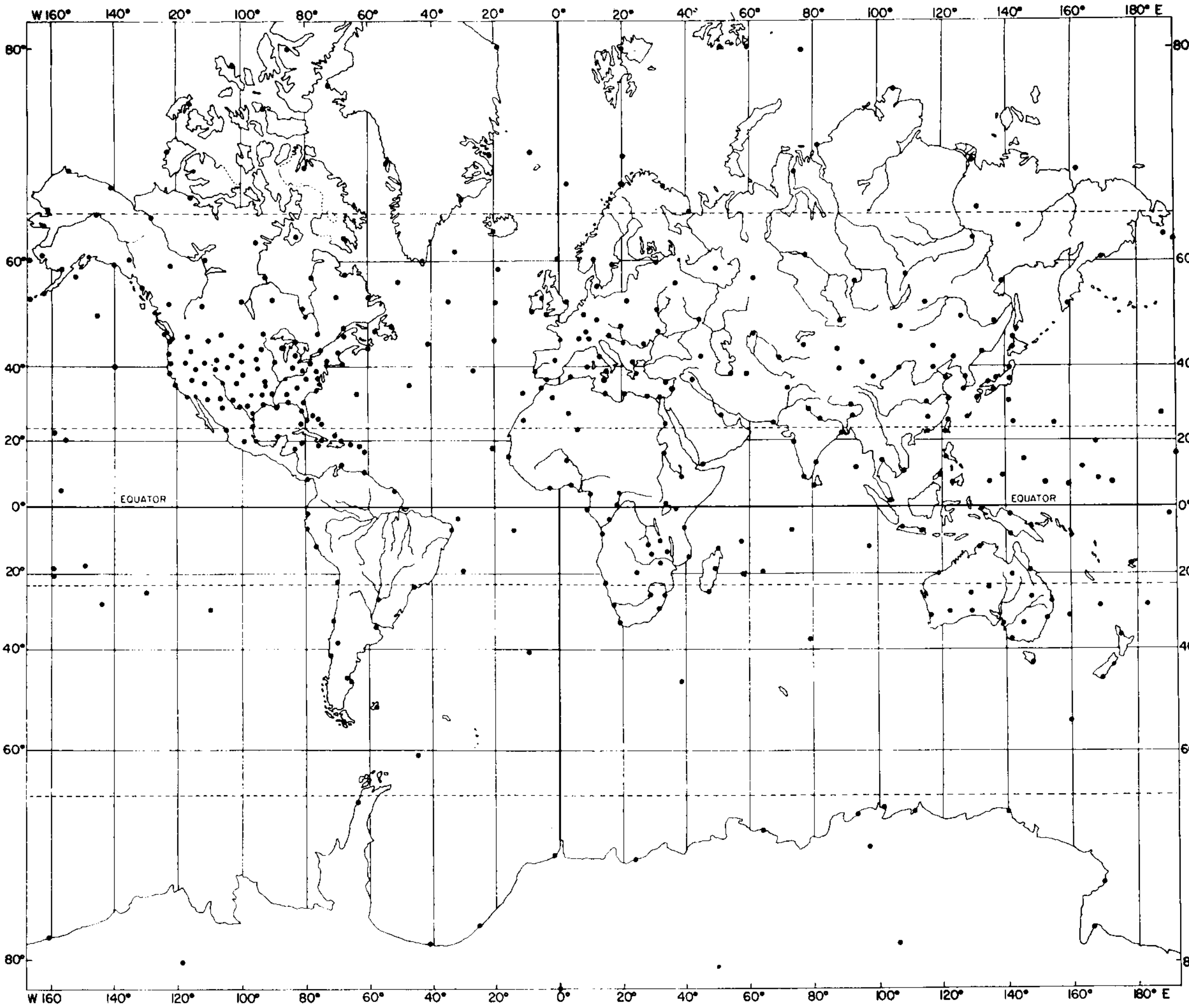

Fig. 1. Distributions of the stations used in the investigations of the atmospheric water vapor conditions during the IGY.

$$\mathbf{Q} = Q_\lambda i_\lambda + Q_\phi i_\phi, \tag{5}$$

where the zonal and meridional components Q_λ and Q_ϕ, respectively, are given by

$$Q_\lambda = \frac{1}{g}\int_0^{p_0} qu\,dp, \tag{6}$$

$$Q_\phi = \frac{1}{g}\int_0^{p_0} qv\,dp. \tag{7}$$

In (2) Σ represents the net sources of water substance in the atmosphere column. As was discussed on various occasions (see, e.g., Starr & Peixoto, 1965) for all practical purposes, Σ is given by the excess of evaporation over precipitation, $E-P$, as measured at the earth's surface.

Taking the time average for a time interval τ the balance eq. (2) becomes:

$$\overline{\frac{\partial W}{\partial t}} + \overline{\operatorname{div}\mathbf{Q}} = \overline{\sum} = \overline{E-P}, \tag{8}$$

where the bar denotes the time mean operator

$$\overline{(\ )} = \frac{1}{\tau}\int_0^{\tau} (\ )\,dt. \tag{9}$$

For periods long enough (e.g., one year) $\overline{\partial W/\partial t}$ may be taken as zero. Thus, positive values of divergence show areas where evaporation exceeds the precipitation, whereas negative values of the divergence (convergence) show areas where precipitation exceeds the evaporation.

2. Data and procedures

The basic data used in this study were taken directly from aerological observations made during the calendar year 1958 for the stations indicated in Fig. 1. The general formulation of the problem and the computational approach used in the present study are the same as those used and discussed on previous occasions by the writers (Starr *et al.*, 1965) and therefore only a general review will be given now. Also, in another study (Starr, Peixoto & McKean, 1969) the representativeness of the actual basic data, the network coverage, the data processing, the procedures followed and the methodology of the several computations are presented and analyzed. Hence these topics are not discussed here.

The vertical integrations required to compute the time mean values of W, Q_λ and Q_ϕ, as given by expressions (3), (6) and (7) respectively, were performed numerically applying the trapezoidal rule. Contributions to the vertical integrals above 500 mb and between surface and 1000-mb level were disregarded. Thus the various integrated fields are in most cases slightly underestimated. The contribution of higher layers, which might be of some importance in the tropical and equatorial regions and over extensive areas of high terrain has been studied on a regional scale (Peixoto & Obasi, 1965). The yearly mean values of $\overline{W}$, $\overline{Q}_\lambda$ and $\overline{Q}_\phi$ evaluated for each station of Fig. 1 were plotted and the corresponding fields analyzed using standard procedures, as indicated in the above-mentioned paper (Starr *et al.*, 1969).

From the five degree grid values the total mean horizontal vector field of water vapor transport $\overline{\mathbf{Q}}(\lambda, \phi)$ was read off and the horizontal divergence in the λ, ϕ, p coordinate system,

$$\operatorname{div} \overline{\mathbf{Q}} = \frac{1}{R\cos\phi}\left[\frac{\partial \overline{Q}_\lambda}{\partial \lambda} + \frac{\partial}{\partial \phi}(\overline{Q}_\phi \cos\phi)\right] \quad (10)$$

was evaluated using finite differences methods. R denotes the mean radius of the earth. The computations were carried out in the M.I.T. Computation Center using an IBM 7094 digital computer.

3. Analysis of the results

The field of the mean precipitable water content in the atmosphere, $\overline{W}$, is shown in Fig. 2. The actual analysis agrees with the previous analysis presented by Starr & Peixoto (1965) for the Northern Hemisphere.

On the whole the amount of precipitable water is higher over the oceans, with the exception of the Amazon Basin where the world mean maximum value was obtained. The departures from zonal symmetry are associated with the physiography of the globe. These effects are evident over both hemispheres. Since the Northern Hemisphere features were presented previously by Starr & Peixoto (1965) and a detailed analysis for the entire globe is given in the 1968 paper, we confine ourselves here to the most important general features of the $\overline{W}$ field. The water vapor content attains its maximum values over the equatorial regions and decreases towards the poles with a practically zonal symmetry, as anticipated. There are, however, a few exceptions worth mentioning.

The observed low center of precipitable water over central Australia is similar to that found by Hutchings (1961). Its presence can be associated with the Great Victoria Desert and the corresponding dryness of that region.

Over the continent of Africa, there is a center of minimum precipitable water over the central portion of the southern part of the continent, as observed by Peixoto & Obasi (1965). This is the region of the Kalahari Desert, and dry conditions are to be expected there. The effects of topography are also evident over the Andes, the high lands of Ethiopia and the mountains of Kenya. The areas of highest water vapor content are found over the equatorial region of South America, the equatorial eastern and western Pacific Ocean, the Indian Ocean and Equatorial Africa, where the evaporation is more intense.

In general, the observed values of precipitable water for the Southern Hemisphere are slightly higher than the values for the Northern Hemisphere during the same period (Peixoto & Crisi, 1965). Peixoto & Obasi (1965) likewise found higher values over southern Africa than over the

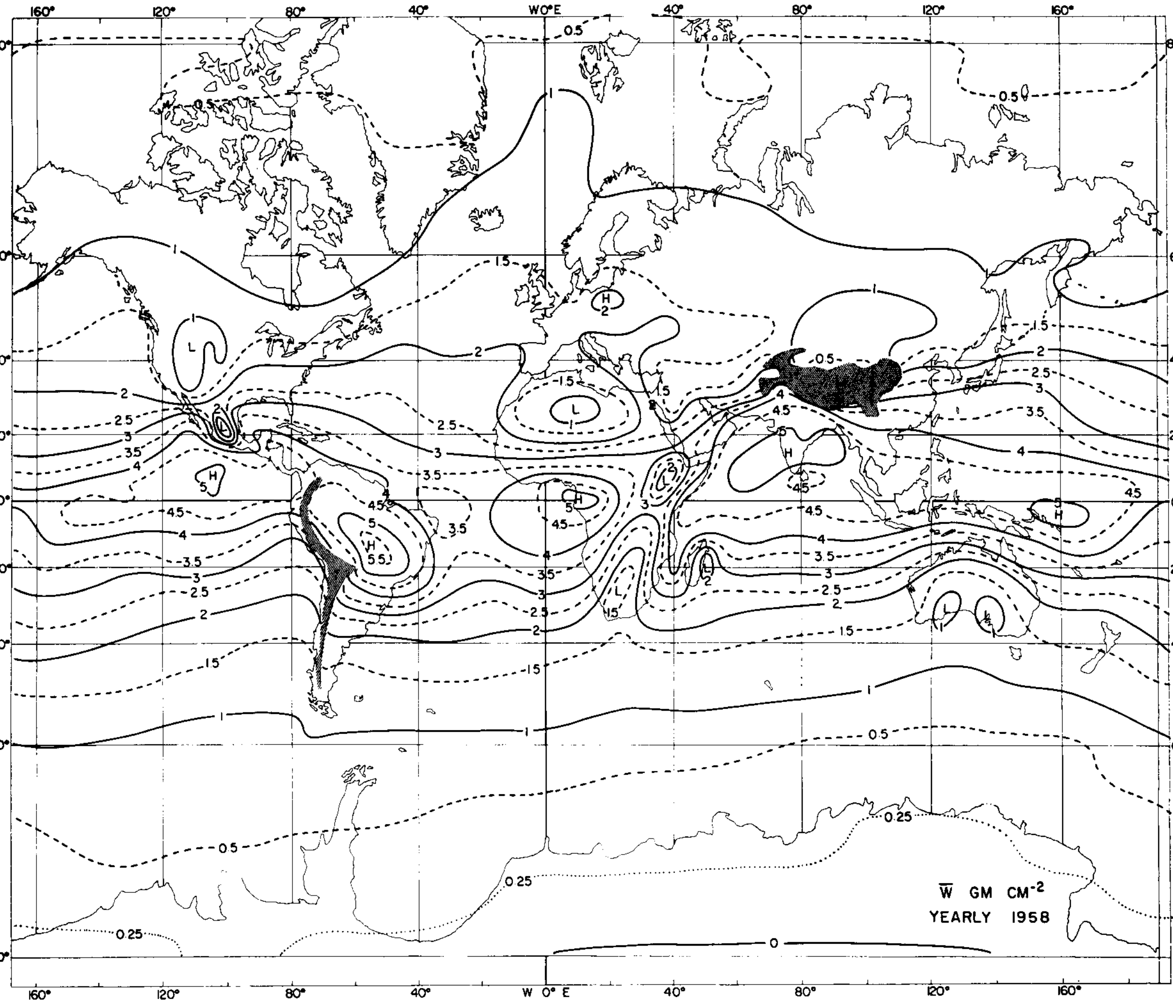

Fig. 2. Time average of the vertically integrated values of specific humidity (precipitable water), $\overline{W}$, in g cm^{-2} for yearly data. Isoline spacing (*full curves*) 1 g cm^{-2}.

northern part of that continent and attributed this to the effect of the trade winds. It now seems likely that higher mean temperature values for the Southern Hemisphere associated with a larger predominance of the oceans contribute to the higher observed values of precipitable water.

Since a discussion of the total $\overline{Q}_\lambda$ and $\overline{Q}_\phi$ fields has already been presented in the author's 1968 paper, only a few comments concerning the mean integrated flow of moisture are made here. Contrary to the analysis presented previously by Starr, Peixoto & Crisi (1965), there is, in the actual analysis, a net northward flow of moisture across the equator. The easterly flow over the equatorial region alternates with the westerly flow in the middle latitudes. Again the regularity of the distribution of the precipitable water and of the moisture transport fields over the Southern Hemisphere as compared with the Northern Hemisphere is associated with a larger predominance of the oceans.

The analysis of the distribution of the mean total horizontal moisture divergence for the IGY in cm per year is shown in Fig. 3. The approach and the techniques for obtaining the spatial distribution of the divergence field used in the current investigation were discussed in some detail previously by the writers. The present analysis agrees quite well with the one presented before by Starr, Peixoto & Crisi (1965) for the Northern Hemisphere. However, as was mentioned in the paper by Starr, Peixoto & McKean (1969) it is hoped that the actual analysis has improved over the equatorial regions. Since a detailed study of the divergence field for the Northern Hemisphere using the same data has already been presented (Starr *et al.*, 1965), we shall discuss here only the most prominent features of the field over the Southern Hemisphere.

It is of interest first of all to point out the excellent agreement on the whole, and in particular over the Southern Hemisphere, of the present analysis and that of Budyko (plates 54 and 68 in his atlas) which deal with evaporation and heat, gain by the atmosphere due to condensation of water vapor. Incidentally, Budyko's results were obtained by using a different approach from the one employed for the Southern Hemisphere by Privett (1960).

The equatorial regions of the Atlantic and Pacific Oceans show a general convergence of water vapor transport indicating an excess of precipitation over evaporation. This is a reflection of a mean convergence associated with the intertropical convergence zone. Marked centers of strong convergence are found just south of Panama, off the east coast of South America near the equator and over Brazil with high values in the headwaters of the Amazon River as would be expected. This belt of convergence extends through the Atlantic Ocean with a center over the Gulf of Guinea. In equatorial Africa the regions of convergence are found in the general vicinity of the headwaters and drainage basins of many large rivers. The areas of largest convergence are found in Ethiopia and the Somali Highlands, from which the Blue Nile river derives most of its water; in Northern Congo over the headwaters of the Ubangi and Congo rivers; in Southern Angola, Rhodesia and the eastern parts of southwest Africa where the Zambezi, Orange and Limpopo rivers originate. In Ghana and the Ivory Coast there is convergence and much of the excess of water associated with it is probably fed into the Niger, the Volta and perhaps the Snegal rivers. An extensive area of convergence extends from India, along which a complex of several rivers systems are found (Indus, Ganges, Brahmaputra, Salween, Meking, Yangtze). It extends farther through Southeast Asia, Indonesia and through the entire Central Pacific Ocean to the West Coast of Central America, with several intense centers. All these areas are known to have excessively high values of precipitation.

The midlatitude regions around the Southern Hemisphere show many areas of convergence, as in the Northern Hemisphere. The areas of convergence are related to the polar front associated with the extratropical storm tracks across the South Atlantic, South Indian and South Pacific Oceans. The extensive area of convergence which covers most of South America corresponds to the basins and headwaters of a large system of rivers (Magdalena, Orinoco Amazon Paraguay, Parana, Uruguay). There is a convergence center which extends along the eastern South Pacific and the Chilean Coast. In this region the convergence is in part associated with the topography of the region where thermal convection combined with orographic effects are responsible for strong thunderstorm activity which leads to heavy precipitation over the narrow band along the southwest Coast of the continent. Over the neighboring oceanic regions, the salinity content is very low.

The subtropical regions of the South Atlantic, Indian and South Pacific Oceans show rather strong and extensive areas of divergence of water vapor. In the Atlantic the divergence belt is elongated in a east-west direction without any interruption. The strong divergence of water vapor off the coast of central Brazil indicates an excess of evaporation over precipitation there. This should be reflected by correspondingly higher salinity values for that region of the Atlantic Ocean. Dietrich (1957) has reported such a region centered at 15° south latitude. The salinity of the ocean here has its highest values for the entire latitude band, being greater than 1.5 parts per thousand above the zonal average. By and large all the divergence regions over the oceans have a very high salinity. These areas and the corresponding ones over the Northern Hemisphere are areas where evaporation attains its maximum value. They are associated with the anticyclonic belt of the subtropical latitudes and are generally situated on the margins of the semipermanent high pressure cells, where subsidence and clear skies predominate. On land, areas of large divergence are found over the Northeast of Brazil associated with the periodic droughts found there; over Africa in Angola and the Kalahari desert, in Uganda, Kenya and South Africa; over most of Australia in agreement with the findings of Hutchings (1961). This last one is associated with the dryness of the Great Victoria Desert.

In the polar regions it seems that there is a small net divergence. With the presence of ice there is comparatively little evaporation. Its larger value is noted over the North Pole region.

There are some features in the actual map of the divergence which are not easy to reconcile with the climatological maps obtained by the classical methods. In sampling some of the discrepancies we might mention among others, the following: over the dry region of the pampas of the southeastern part of South America east of the Andes (Patagonia, etc.), characterized by very low precipitation and active evaporation, the present analysis shows a region of convergence. In the southwestern and southern fringes of the African Continent the values of the mean annual precipitation are relatively high where the orographic uplift of moist air due to the presence of the Drakenstein Mountains causes heavy precipitation. However, the actual map does not depict this, since it indicates an area of divergence over the region. Similarly over Australia the present analysis fails to indicate the precipitation zones over the northern coast (York Peninsula) and the southeastern mainland and Tasmania, where two divergence centers dominate.

Some general comments

1. The principle of conservation of mass applied to the water substance led to the so-called concept of hydrological cycle which has been used in studies of water balance both on a local scale and on a hemispheric scale. Climatologists and hydrologists using the classic equation of hydrology, have long been concerned with precipitation, evaporation, runoff, and the storage of water in the terrestrial branch of the water cycle. Their efforts have been hindered, however, by (*a*) the necessity of assumptions regarding evaporation rates over varying surface conditions, and of subsurface storage, and (*b*) the lack of reliable information on precipitation especially over the oceanic regions and over unpopulated land areas.

Sverdrup (1951) has discussed the difficulties and uncertainties involved in evaluating evaporation rates over the oceans by the three usual methods, namely, (*a*) observations from evaporation pans on board ship; (*b*) computations from energy considerations (radiation and conduction of heat); and (*c*) computations of the vertical flux of water vapor from the sea surface assuming an eddy transfer mechanism at the surface. As he pointed out, the three methods lead to widely varying results, and the lack of adequate empirical data usually renders it impossible to determine which method is the best.

In considering energy transformations over the oceans, Jacobs (1951) discussed the lack of sufficient data on precipitation amounts for oceanic regions. Using available regional data with "correction factors" for each of the oceans, he was able to prepare a new chart of the precipitation over all oceans; but his method did not alter the fact that more observations of precipitation over the oceans are needed.

With the increased quantity and quality of aerological observations, it has become possible to study the water budget of the earth from the standpoint of the atmospheric in addition to the terrestrial branch of the cycle. With the good assumption that the flux of water through the top of the atmosphere is zero, any change in the water content of the atmosphere over a particular region must be effected by the processes of evaporation and precipitation and by the flux of water across the vertical boundaries of the region. This flux can be obtained once one has measured the wind field and specific humidity field at the boundaries. We are thus enabled to consider the implications of the atmospheric branch of the cycle.

2. Following a procedure previously discussed by the authors (Starr & Peixoto, 1958) the mean zonal divergence for various latitudinal belts was evaluated from the mean total meridional transport $[\bar{Q}_\phi]$. The values are presented in the author's 1969 paper. The results agree quite well with those obtained from independent previous estimates of the evaporation minus the precipitation estimated by climatological methods. Inspection of Fig. 3 verifies that on the average there is: (i) convergence $(\overline{E-P}<0)$ between 12° N and 8° S associated with the strong excess of precipitation over evaporation observed in the intertropical zone of convergence; (ii) convergence $(\overline{E-P}<0)$ northward of 40° N and southward of 40° S up to 75° S, in which the excess of precipitation over evapora-

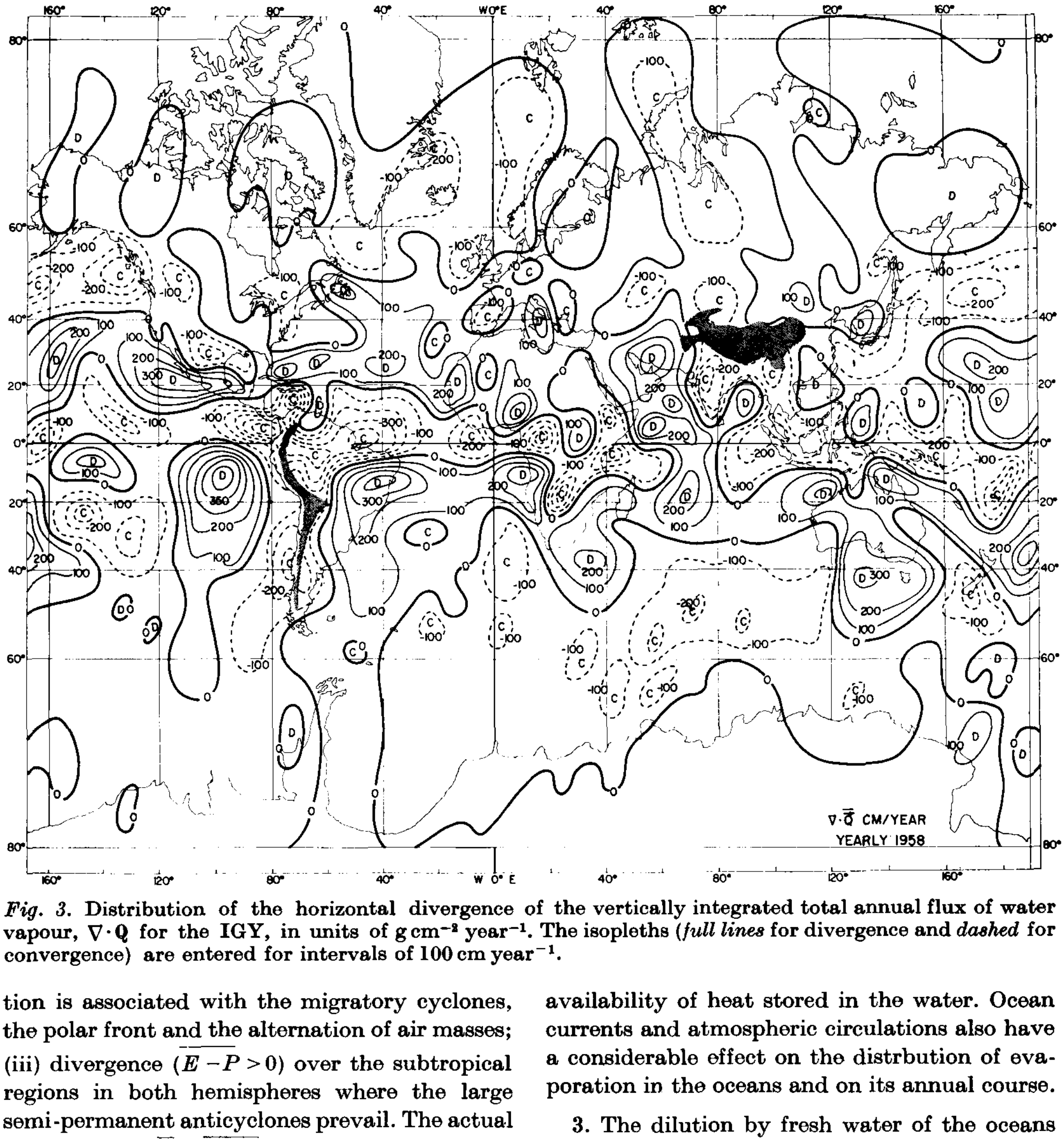

Fig. 3. Distribution of the horizontal divergence of the vertically integrated total annual flux of water vapour, $\nabla \cdot \mathbf{Q}$ for the IGY, in units of $g\,cm^{-2}\,year^{-1}$. The isopleths (*full lines* for divergence and *dashed* for convergence) are entered for intervals of $100\,cm\,year^{-1}$.

tion is associated with the migratory cyclones, the polar front and the alternation of air masses; (iii) divergence ($\overline{E} - \overline{P} > 0$) over the subtropical regions in both hemispheres where the large semi-permanent anticyclones prevail. The actual values of div $\overline{\mathbf{Q}} \approx \overline{E} - \overline{P}$ agree quite well with the values obtained by independent means, and compare well with the previous estimates from the aerological data fro the year 1950 (Starr & Peixoto, 1958) with the exception of the 40–50° N latitudinal belt. The difference might be real since over the region the network was rather reliable in both studies. However, a discrepancy over the 0–10 belt is due to the improvement of the present analysis.

Evaporation over the oceans exceeds that from land surfaces due to the different radiation balance of the water surface and also due to the availability of heat stored in the water. Ocean currents and atmospheric circulations also have a considerable effect on the distrbution of evaporation in the oceans and on its annual course.

3. The dilution by fresh water of the oceans under an area of convergence or the increase in salinity under a divergence center can alter the density of the surface water, possibly so as to establish shallow thermohaline convective currents. Divergence and convergence fields are in fair agreement with salinity distribution as presented by various authors.

Studies of the present type suggest a means of determining the salinity of areas of the oceans, as has been stated by Von Arx (1962) and others. The field of $E - P$ is intimately related to the general circulation of the atmosphere through the divergence field of water vapor transport. Thus, it can be inferred that the average values of sea surface salinity and consequently some of the thermohaline currents are controlled by the atmospheric circulation. Since the atmosphere and the oceans are in fact two components of a coupled system, studies of the present type constitute a tool in studying the sea-air exchange processes. Across the interface there is a considerable exchange of mass, energy and perhaps momentum through the changes of phase of water substance.

The energy cycle of the sea-atmosphere thermodynamic system is dominated by the solar energy. However, both the oceans and the atmosphere are fundamental in the redistribution and the transport of the energy, through the general circulations of the atmosphere and of the oceans (sea currents) and through the absorption and the reradiation of energy in the long-wave domain.

Although the energy cycle is basically dominated by the radiation energy processes, other processes are of importance in establishing the energy balance for all the earth, the globe and the atmosphere. In particular through the evaporation and the subsequent condensation and precipitation there is a huge exchange of energy across the air-sea interface and within the atmosphere and oceans due to atmospheric circulation directly in the form of latent heat. Evaporation acts also indirectly through the cooling of the surface of the globe (oceans and continents) and thus influencing the direct exchange of energy in the form of sensible heat between the globe and the atmosphere.

4. Again it is found that, by and large, the desert regions of the Southern Hemisphere are covered by large positive divergence centers. In such case, as was discussed previously (Starr & Peixoto, 1958), the excess of evaporation over the precipitation has to be made up by underground drainage from less arid sections that supply the water. The study of the flow of water beneath the surface in desert areas is an extensive and difficult subject, although one that has increasing practical importance.

Mention should be made of some of these studies. First we will mention one made by Prof. B. Hellstrom, reported some years ago, dealing with the easter Sahara near the Nile. It seems, from historical and archeological evidence that the Kharga Oasis in the Libyan desert was more abundantly supplied with water from springs in ancient times than it is today. The decline apparently was rather sudden and attributable to the puncturing through erosion and subsequent leakage of a subterranean water bearing rock stratum in the bed of the Nile. This had the effect of decreasing the hydrolic pressure head of the underground waters over the entire region and thus reducing the discharge of the Kharga springs. Hellstrom suggests that the erection of a high dam at Asswan would in effect repair the damage, since the higher head of the impounded waters would then prevent the leakage from the break which is located just upstream from Asswan.

In a more recent study based upon geological evidence and hydrological considerations Ambroggi (1966) also analyzed the problem of water under the Sahara. He reaches the conclusion that there are several internally drainage areas beneath the surface of the Sahara, which indicate the existence of large sources of underground water, that may become "the key to any development effort in the Sahara".

5. Since the actual results were obtained for only one year, they are not directly and quantitatively comparable with the results achieved by the conventional climatological and hydrological approaches. However, the usefulness of present study is obvious, and it must be regarded as a pilot study for further work already planned upon 5 years of data from pole to pole which is currently being analysed by the M.I.T. Planetary Circulations Project under the auspices of the National Science Foundation. These studies will no doubt lead to more stable representations of the divergence fields and will allow seasonal comparisons with climatological maps on a much firmer basis.

Acknowledgments

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ГЛОБАЛЬНАЯ ДИВЕРГЕНЦИЯ ВОДЯНОГО ПАРА

Представлено изучение средней дивергенции переноса водяного пара в планетарном масштабе от полюса до полюса по данным МГГ. Рассмотрены поля средних осадков, переноса полного вертикально проинтегрированного количества водяного пара, его дивергенции по всему Земному шару. Обсуждаются некоторые следствия распределения дивергенции водяного пара в связи с океанографией, гидрологией и общей циркуляцией атмосферы. Настоящий анализ сравнивается с предыдущими работами, основанными на аэрологических данных, а также основанными на независимом подходе, таком как анализ, основанный на классических климатологических методах.