On the Global Balance of Water Vapor and the Hydrology of Deserts

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Abstract

An attempt is made to measure the horizontal divergence of the vertically integrated moisture flux over the northern hemisphere for the calendar year of 1950. This is done through the evaluation of daily data for some 90 upper air stations at several levels up to 500 mb. The final map obtained indicates strong maxima of divergence not only over certain oceanic regions, but also over three separate arid regions. Such a result implies an unexpectedly large excess of evaporation over precipitation in these latter areas, which must be balanced by convergence of liquid water on and below the ground surface, unless the year studied was rather completely different from normal, this not being so likely, however.

1. Introduction

With the advent of more plentiful observations concerning the troposphere from stations distributed over the northern hemisphere, it has become feasible to treat many problems associated with the terrestrial hydrological cycle on a hemispheric basis. Previously many such questions could be approached, if at all, only on a regional basis with corresponding limitations in the significance of results when the general circulation processes and other global questions are at issue. Even when more local investigations are intended the simultaneous consideration of hemispheric conditions imparts a sense of perspective not otherwise obtainable. The importance of the last remark is illustrated by various features of the material which follows.

Probably one of the first truly hemispheric attempts to measure directly from winds and humidities the effect of atmospheric motions in transporting water vapor across latitude circles was that of WHITE (1951), in an effort to include the contribution of latent heat to the earth's energy balance. These efforts were much amplified by STARR and WHITE (1954), again especially from the viewpoint of the energy balance of the general circulation. Oceanographical and climatological aspects were later touched upon in some still further extensions of this work by STARR and WHITE (1955).

All of the papers referred to involve the assessment of the net vapor flux across latitude circles, following the pattern of tech-

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niques evolved for the similar evaluation of the momentum flux in general circulation studies. In the case of these latter endeavors, BUCH (1954) has shown that air data for the northern hemisphere are sufficient not only for the calculation of zonal averages of the momentum flux, but also for the drawing of reasonable hemispheric yearly and seasonal maps of a number of quantities involved in the observational treatment of this flux. It was therefore decided that the comparable maps for the water vapor flux problem should be drawn for the same time interval as was used by Buch, namely the calendar year 1950. The feasibility of this plan was also suggested by the studies of moisture flux over North America made by BENTON and ESTOQUE (1954). This aim necessitated extensive recomputation and augmentation of data tabulations previously compiled by the General Circulation Project at the Massachusetts Institute of Technology.

At the present writing this task has been accomplished, and the results will be published *in extenso* as soon as time permits. In the meantime, a survey of the material is being presented by PEIXOTO (1958). Also, certain special aspects are treated by STARR, PEIXOTO and LIVADAS (1958), and by PEIXOTO and SALTZMAN (1957). The present paper is still another such discussion dealing with the hydrological significance of the results, especially for some of the principal desert areas of the hemisphere.

2. Procedures and results

The zonal and meridional components of the horizontal total flux of water vapor above a point on the earth's surface may be represented by the expressions

$$Q_\lambda = \frac{1}{g}\int\int qu\, dp\, dt; \qquad Q_\varphi = \frac{1}{g}\int\int qv\, dp\, dt, \quad (1)$$

where g is gravity, q specific humidity, p pressure, t time and u and v are the zonal and meridional wind components counted positive eastward and northward. Use has here been made of the hydrostatic relation. The pressure integration extends from zero to the value of pressure at the surface, while the time integration extends for a period of one year, in the present instance. It is clear that the expressions (1) are the components of a vector, conveniently denoted by $\vec{Q}$, which defines a two-dimensional vector field over the earth's surface. It follows that one may take the (horizontal) divergence of $\vec{Q}$ and express it in terms of a convenient system of coordinates—spherical polar in our case. We thus have

$$\nabla \cdot \vec{Q} = \frac{1}{R\cos\phi} \times \left\{\frac{\partial}{\partial\lambda}(Q_\lambda)\frac{\partial}{\partial\phi}(Q_\varphi \cos\phi)\right\} \quad (2)$$

Here R is the earth's radius assumed constant, λ is longitude and ϕ latitude.

From the magnitudes encountered in the atmosphere, such as that for the precipitable water vapor contained in a typical column of air, it must be concluded that the storage effects are sufficiently small so that the water lost in regions of positive divergence must be resupplied and that concentrated into regions of convergence must be removed. Since such corrections as the horizontal transport of liquid water are small, the divergence must, for all practical purposes then be numerically equal to the annual excess of evaporation over precipitation.

In the evaluations from data, the station network presented by STARR and WHITE (1955) was significantly extended especially in Africa and elsewhere. Some stations near to the equator in the southern hemisphere were used as an aid in the drawing of maps. The augmented key station distribution is shown in Fig. 1. Many of the procedures followed are the same as those described in the reference given. Thus, for instance, the advection was computed wherever possible from radio winds although a number of pilot-balloon stations again had to be resorted to. Unlike the previous study, the evaluation of the expressions (1) was carried out independently for each station, using wind and humidity data reported daily from the levels: surface, 1000 mb, 850 mb, 700 mb and 500 mb, except where elevation of the earth's surface interfered. Above 500 mb the moisture transports are much too small to be of practical concern.

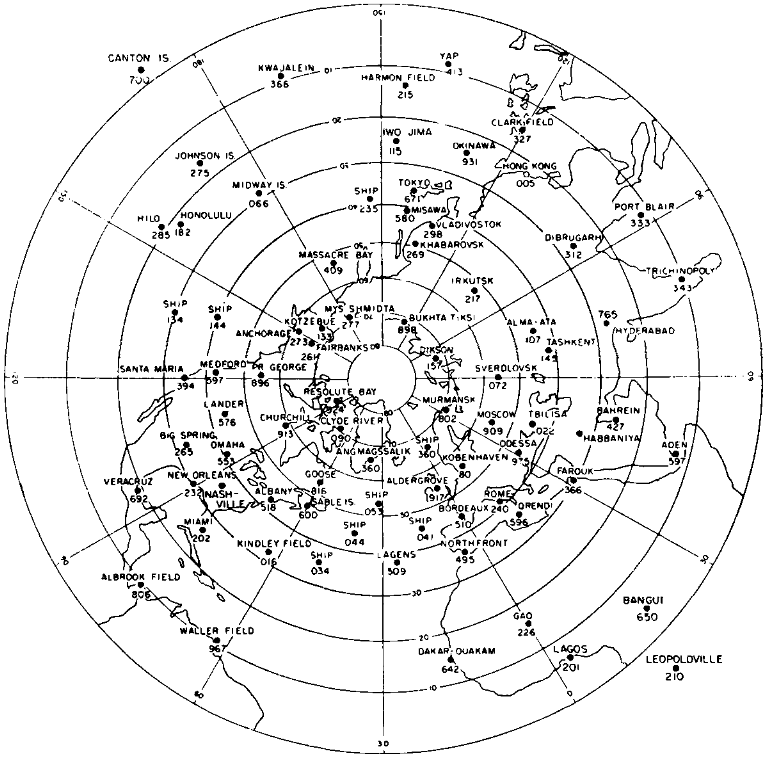

Fig. 1. The distribution of key stations over the northern hemisphere (and slightly beyond the equator) used in the investigation of the atmospheric water vapor transport. A few additional stations which are not shown were also used at times as alternates.

Two maps were then constructed and analyzed, one for each of the quantities Q_λ and Q_φ. Using data read off from these charts for every 10° of latitude and longitude, $\nabla \cdot \vec{Q}$ was computed through the use of equation (2), measuring the derivatives by finite difference approximations. In this way a value of the divergence was obtained for each 10° interval zonally and meridionally. These were plotted on a third map and analyzed, the resulting picture being that shown in Fig. 2. An approximate representation of the field of $\vec{Q}$ itself is given in Fig. 3.

3. General discussion

It is to be understood at the outset that the character of observations at our disposal, and the consequent methods which must be resorted to in performing calculations of the present kind, prevent the reproduction of a vast amount of detail which, without a doubt, is present in the true picture. Viewing the result then only as a general, first approximation to actuality, the writers have concluded that it nevertheless possesses much that challenges one's scientific imagination and raises many questions which deserve something more than mere facile answers. The following list of topics includes several such subjects.

a. By and large, the areas of divergence and convergence balance for the hemisphere so that there is but little net flow across the equator. Zonal averages along other latitudes agree with corresponding climatological estimates secured by independent means (see STARR, PEIXOTO and LIVADAS 1958).

b. Large centers of convergence are to be found in the general vicinity of the headwaters and drainage basins of many large rivers. Such convergence is found over the northwestern United States and western Canada (Columbia,

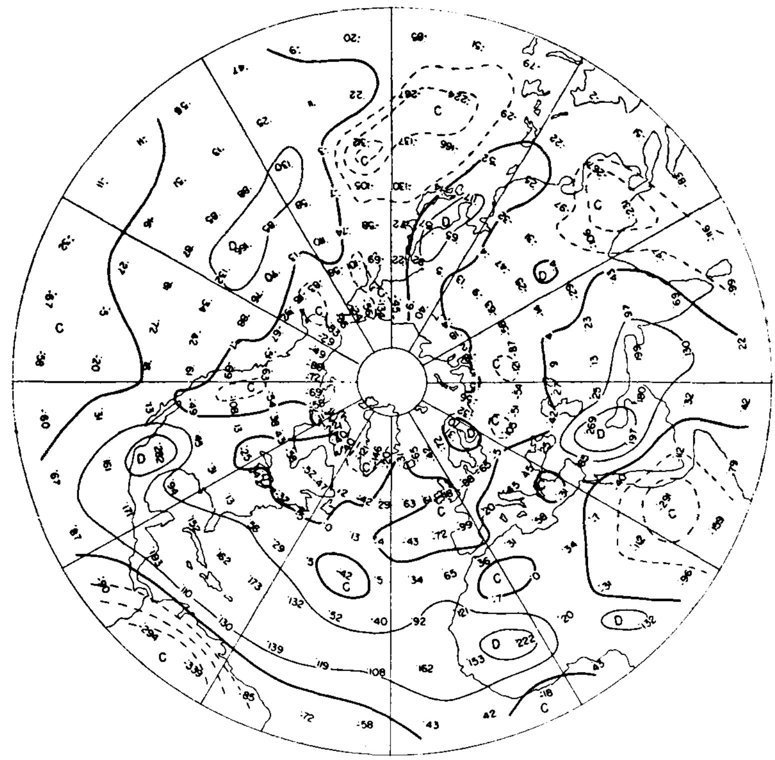

Fig. 2. Distribution of the horizontal divergence of the vertically integrated total annual flux of water vapor for the year 1950. The units are the equivalent depth of liquid water in centimeters per year. The isopleths (full lines for divergence and dashed for convergence) are entered for intervals of 100 cm per year.

Mississippi, Colorado, Mackenzi, Saskatchewan and Rio Grande rivers); over northern South America (Magdalena, Orinoco, and Amazon rivers); over eastern Africa (Nile, Congo, Juba and Scebeli rivers); over eastern India, Burma and Indo-China (Ganges, Brahmaputra, Irrawaddy, Salween, Yangtze, Si Kiang and Mekong rivers). In the case of some rivers of large size, no particularly marked convergence areas seem to manifest themselves; e.g., the Indus river—a quite possible result of deficient reports from central Asia where it rises.

c. Convergence centers are to be found over ocean areas as for example, the one in the western Pacific. Since the addition of such large amounts of fresh water are involved, the resulting dilution of the mineral salts in sea water is a matter of consequence in oceanographic studies.

d. Several areas of strong divergence are located over the oceans; notably, over the southern Atlantic and the Gulf of Mexico, and in the mid-Pacific. These then are major sources for atmospheric moisture as seems reasonable enough on general meteorological grounds. From the standpoint of oceanography, the effect of the resulting concentration of salinity in such locations has been considered.[2]

e. One of the more striking and puzzling features of Fig. 2 is the delineation of strong divergence centers over a number of (but not all) deserts. This is indicated over northern Mexico and the southwestern United States, over the western Sahara and over the general region of Arabia, Iraq and Iran. The eastern Sahara and the Gobi are exceptions, although the meager reports from central Asia may again be involved in the latter instance. Ac-

[2] From Fig. 2. by - and - large greater surface salinities should be expected in the North Atlantic than in the North Pacific. A more detailed study of this subject is now in progress.

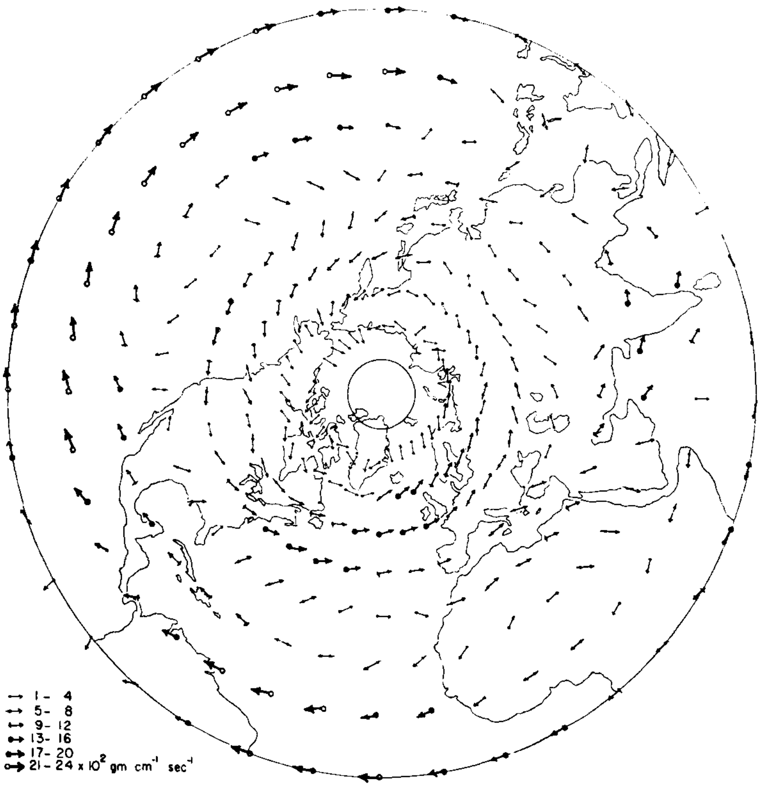

Fig. 3. Approximate distribution of the net moisture transport vector averaged for the year 1950. It should be stressed that the interdiurnal variability of this quantity is large and that because of this large standard deviation the rough streamlines suggested by this map cannot be regarded as being also the trajectories of individual water vapor particles. It is of pertinence to note the good agreement of this map with the analogous one drawn by Benton and Estoque (1954) for the North American sector from data for the calendar year 1949.

cepting the magnitudes shown, it is tempting to draw the somewhat startling conclusion that desert areas are on a par with oceans as major sources of moisture for our hemispheric regime of precipitation. Many questions are however raised immediately, and several of these will be enumerated in the following section.

f. The divergence pattern is most directly related to the difference between the evaporation and precipitation, as has already been explained. On the whole, some relation should exist with the (annual) precipitation itself, nevertheless. It follows that a better analyzed set of isopleths might have been drawn in Fig. 2 by making explicit use of a precipitation chart for the hemisphere. This was not done for several reasons, the lines having been sketched without at least deliberate deference to the rainfall distribution. Since the grid-point values are given, this allows each reader to make such adjustments as seem reasonable to him, the process being inherently subjective. In such attempts, it should be kept in mind that the divergence pattern for 1950 need not be exactly normal, and likewise that the precipitation for this one year may depart from the longer term average values at many points. The large area of convergence in the western Pacific may not, for example, be a normal feature.

g. To the extent that Fig. 2 resembles the long term mean pattern, it must be accompanied by an equal and opposite divergence of water substance below the base of the atmosphere in the hydrosphere and lithosphere, since continuity must be maintained and secular changes in long term storage are, no doubt, slow. Liberation of juvenile and connate water and other such effects are to be reckoned with here, but the sum total of their contributions is doubtless small.

This compensatory lower circulation cannot be determined from a knowledge of its divergence alone. At best, the only component of it which can so be determined is an irrotational part, which might nevertheless be of some interest. This could be accomplished by inserting derivatives of a velocity potential for Q_λ and Q_φ in an expression of the form (2) and solving the resulting Poisson equation by finite difference procedures or otherwise. The stipulation of a given flow across the equator completes the specification of a Neumann type problem. The resulting flow would, of course, be indeterminate to the extent of a quite arbitrary additive divergence-free transport.

h. During the preparation of the vast amount of data which went into the end product shown in Fig. 2, averages were also made for shorter time periods. Such seasonal maps are not reproduced here, since it is thought that the annual mean condition already presents a sufficient array of problems without now considering less reliable short term pictures. Plans are now in progress to treat additional years of record, especially the Geophysical Year. Upon the completion of such longer period averages, it may be feasible to return to the consideration of seasonal means.

i. We may pause but briefly here in order to ask philosophical questions concerning our material. The ramifications of the subject are well nigh endless as even slight reflection will confirm. Evaporation fares best under low relative humidities effectively produced by descent of air. Why do we have some of the hottest air on the earth's surface descending? Why, in other places such as southeast of Japan does the warm air ascend so vigorously but not elsewhere over certain other ocean areas with seemingly similar air properties? Why does the moisture evaporate so intensely in the middle of the Pacific south of the Aleutians? Why over northern Korea and eastern Siberia?

Answers to these questions and others exist. In many cases, simple statements of considerable pertinence can, no doubt, be made. But, more generally, the subject is part and parcel of the general circulation problem; to be elucidated fundamentally not otherwise than through a better understanding of the whole system. Fortunately, more sophisticated approaches to general circulation theory are at length gaining popularity, and worthwhile results are forthcoming at an increasing rate.

4. Comments on desert hydrology

It has long been recognized that evaporation far exceeds rainfall in most deserts. What is surprising is the magnitude in Fig. 2 of the evaporation from those arid regions already enumerated. How does the water balance at and below the surface maintain itself in order to permit this large annual loss? Unfortunately, the state of our information here is such that it is possible only to speculate about the processes which may furnish the answer to this and other related questions. The following notes may, it is hoped, at least be suggestive, pending the corroboration of our results from independent data and through other means.

a. Desert areas generally contain evidence of evaporation processes. Thus, residues of salt, gypsum and other deposits left behind are common. Presumably, these materials were leached out from ground substances during the passage of water over or through the lithosphere, although at least occasional contributions from sea water cannot be ruled out. Special phenomena such as the deposition on exposed rock surfaces of "desert varnish" indicate the accumulation of a mineral coating, again through the agency of evaporation (see, e.g., Holmes 1945).

b. A considerable amount of water is transported by surface flow from surrounding territories of more copious rainfall, since deserts tend to have an internal drainage. Various gorges and wadis mark the sites of ephemeral rivers which on occasion carry torrential streams into the central parts of the depressions formed by wind erosion. Such low areas often are below sea level. In some instances, permanent rivers like the Volga and the Jordan never find their way to the sea, their waters being eventually evaporated in toto. In other cases, as with the Nile and Rio Grande, a sizeable fraction of the flow is evaporated before the remainder is drained into the ocean.

c. The flow of ground water into deserts through aquifers and other means (underground rivers and such) can and, no doubt, usually does take place. If in a circular region one thousand kilometers in diameter, one meter of water is to be evaporated annually, the required inflow through porousmedia, distributed uniformly through a depth of one kilometer around the periphery would be much less than one millimeter per second.

That underground waters are abundant in deserts is commonly recognized because of the presence of oases and the fact that many wells have been constructed. It is said that the Nile receives water from such sources on its way across the arid portions of its course.

d. The problem of how underground water might rise from the water table to the surface either as a liquid or vapor is not known. In places where erosion by the wind has lowered the floor of depressions sufficiently, this question does not occur. Elsewhere, great thicknesses of sand intervene, and studies would have to be made in order to provide an answer. Much might perhaps be learned in this regard from laboratory experiments.

e. Since much remains to be verified as to the manner in which large evaporation in these arid regions may take place, it would be highly instructive to make extensive direct measurements of the vertical water vapor transfer near the ground by the standard methods. Even though these procedures involve questions as to the absolute accuracy which may be obtained, still the order of magnitude of the vertical transport can be determined. Due to the extremes of temperature and relative humidity likely to be encountered, special instrumental problems might have to be considered in some detail in order to achieve success.

f. Without further information it would seem from what has been said that if such intense inflows of water into certain deserts really do take place, some potential economic significance should be involved. The flow might thus be strong enough in order to make it profitable to install additional irrigation stations to intercept it at strategic places depending upon hydrological factors.

Also, it would appear that if a strong vertical flow of water in some form takes place through the ground from the water table, some means might be found for arresting it at or near the top surface. This might result in somewhat improved soil moisture conditions for plant growth.

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