DIRECT MEASUREMENT OF THE HEMISPHERIC POLEWARD FLUX OF WATER VAPOR

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ABSTRACT

The average meridional flux of water vapor in the atmosphere is evaluated for the northern hemisphere from suitably distributed daily observations of wind and moisture during the year 1950. Zonal averages for five latitude circles are presented, and these are compared with the corresponding requirements calculated from estimates of zonally averaged precipitation and evaporation given in climatological literature. Considering the nature and scope of the work, the extent of the agreement obtained is considered noteworthy.

INTRODUCTION

For several years the writers have been engaged in a long-term program of systematic compilation and analysis of hemispherically distributed observations of wind, temperature and moisture in order to elucidate the manner in which certain basic integral requirements of the general circulation are fulfilled in the atmosphere. As the studies proceeded, many of the results were published elsewhere (e.g., Starr and White 1951, 1952 a, b, c, 1954). However, the measurements relating to the poleward flux of water vapor have been completed only recently and have not been reported in their entirety save for some partial results contained in Starr and White (1954). The final outcome of the computations for the one complete year used (1950) is therefore presented herewith.

Since the divergence or convergence of the zonally averaged meridional flux of water vapor during a period of one year must reflect an excess or deficit of evaporation as compared to precipitation aside from minor secondary considerations, the present subject offers for the first time an independent means of checking the global precipitation and evaporation balance elaborated by various workers in the science of climatology during the past several decades. The importance of this entire field of endeavor for a number of oceanographic considerations hardly needs to be dwelt upon here.

PROCEDURE FOLLOWED

Water may be transported by atmospheric circulations in the solid, liquid and vapor form. For the purposes of our study, the transport in vapor form only is considered, the probability being that contributions from the solid and liquid forms are small in comparison, except as noted later. The flow of water vapor northward across a conical vertical wall along a complete circle of latitude from the surface to great heights and for any desired time period may be expressed as an integral of the form

$$\frac{1}{g}\int\int\int q\, v\, dx\, dt\, dp\,, \tag{1}$$

where g is the acceleration of gravity, q the specific humidity, v the northward component of velocity, dx an element of linear eastward distance, dt an element of time and dp an element of pressure taken vertically. The assumption of hydrostatic equilibrium is made use of in formulating this expression.

In recent years it has become feasible to evaluate the water vapor flux integral by using direct wind and moisture observations from a hemispheric network of upper air stations. While the quantity and quality of these observations are not yet adequate for reliable evaluation of the instantaneous transports on individual days, the mean flux over a large number of days can be approximated rather satisfactorily. This situation is comparable to the success with which the meridional flux of other quantities, notably of angular momentum, was measured by us in previous work to which reference has already been made. Certain details of the technique common to these studies, together with discussions of specific questions concerning the data used and other pertinent matters, are also to be found there. In view of this circumstance, only a brief statement of the methods is entered here.

The geographical distribution of the key stations is shown in Fig. 1 and is substantially the same as that used for the investigation of the hemispheric angular momentum balance (see Starr and White, 1954). This station network was again divided into five latitude zones centered in the vicinity of 13°, 31°, 42.5°, 55° and 70° N, as indicated.

The measurements of specific humidity were obtained from the reported dewpoints and temperatures. Because of the low moisture

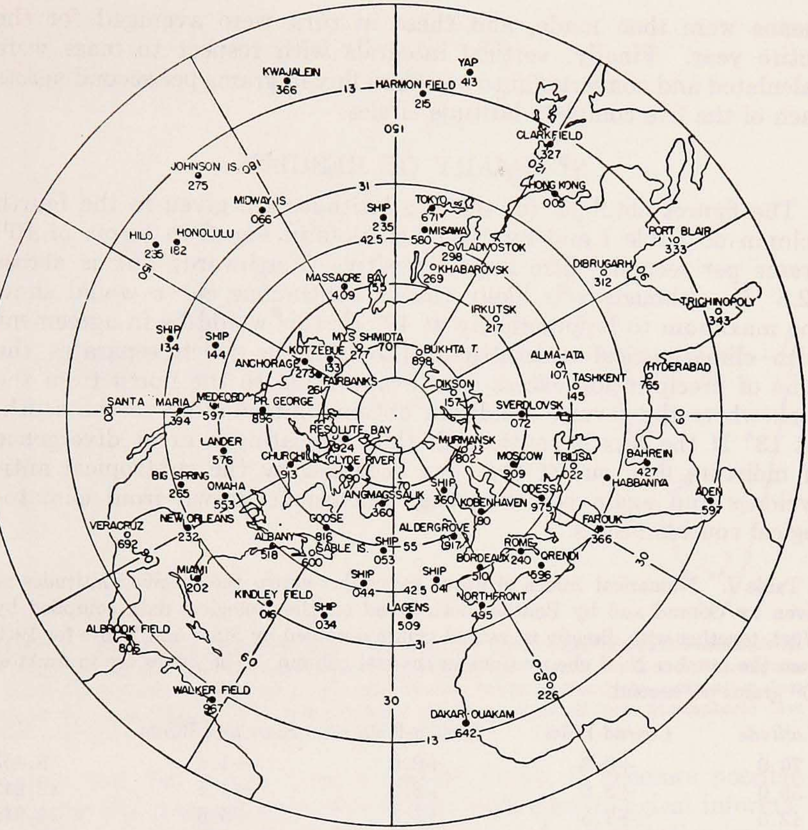

Figure 1. The distribution of key stations over the northern hemisphere used in the investigation of the atmospheric water vapor flux. Pilot-balloon wind stations shown by open circles, radio wind stations by dots.

content above 500 mb, the computations were restricted to the four standard pressure levels, 1000, 850, 700, 500 mb.[1] The flux of water vapor was evaluated at each latitude and level by first forming the product of the northward component of the wind and the specific humidity at each station for each day. Simple longitudinal daily

[1] In the processes of making radiosonde observations of humidity, an instrumental phenomenon known as "motorboating" occurs under certain definite atmospheric conditions. It indicates in general that the moisture content is too low to be measured and takes place at quite low temperatures ordinarily. An upper limit to the moisture amount may still be specified, however, and such values were used in these cases (see appropriate instructions for observers).

means were then made, and these in turn were averaged for the entire year. Finally, vertical integrals with respect to mass were calculated and converted into moisture flux in grams per second across each of the five complete latitude circles.

SUMMARY OF RESULTS

The figures obtained for the five latitudes are given in the fourth column of Table I and by the black dots in Fig. 2 in terms of 10^{11} grams per second. The largest positive (northward) flux is across 42.5° N, although it is likely that a continuous curve would show the maximum to be practically at 40° N; this would be in agreement with climatological estimates of the latitude which separates the zone of precipitation excess over evaporation to the north from the zone where the reverse condition obtains immediately to the south. At 13° N the flux is southward, thus indicating a great divergence of moisture flow out of the zone occupied by the subtropical anticyclones and again corroborating conclusions drawn from climatological considerations.

Table I. Numerical values of water vapor flux across the specified latitudes as given by Conrad and by Benton, both based on climatological data compiled by Wüst, together with directly measured values obtained by Starr and White for 1950 from the number N of observations in the last column. The fluxes are in units of 10^{11} grams per second.

Latitude	*Conrad-Wüst*	*Benton-Wüst*	*Starr and White*	*N*
70.0	+0.8	+0.5	+1.4	8,463
55.0	+3.6	+3.2	+4.4	12,845
42.5	+7.5	+5.5	+5.6	14,916
31.0	+6.2	+3.5	+4.6	20,748
13.0	−4.0	−4.6	−2.9	12,729

Numerical estimates of the water vapor flux requirements have been given by Conrad (1936) and by Benton and Estoque (1954), both of these being based on original data concerning precipitation and evaporation presented by Wüst (1922); these are shown in the first two columns of Table I and by the two curves in Fig. 2. Perhaps with some reservations relative to the situation in the tropics, which will be treated further below, it appears that agreement of measurements with requirements as portrayed by the curves is all that could reasonably be expected.

Since only five latitudes were sampled in making the computations, values of the flux at regular ten degree intervals cannot be interpolated without a certain subjectivity. Nevertheless, when this is done as

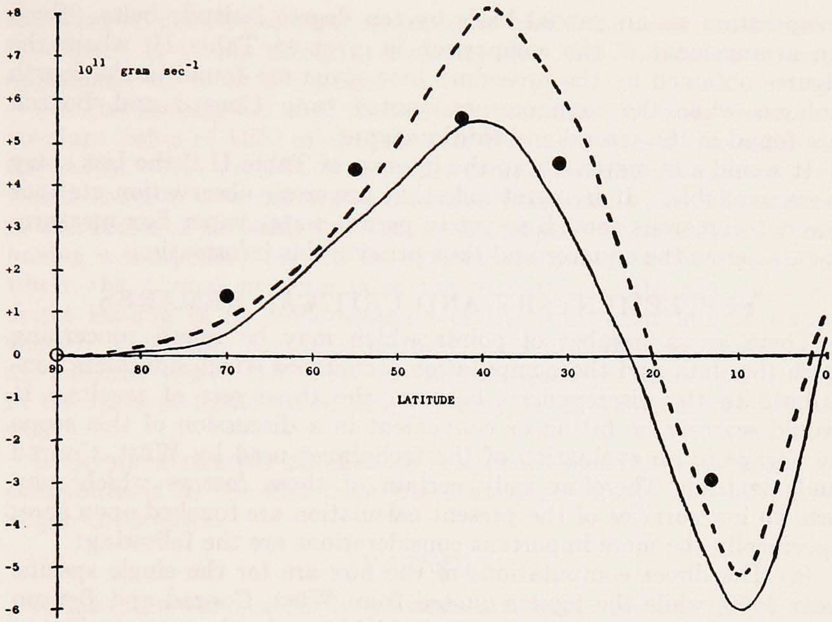

Figure 2. The meridional distribution of the poleward water vapor flux in the atmosphere. The dashed curve and the solid curve represent estimates of this flux deduced from evaporation and precipitation by Conrad (1936) and Benton (1953) respectively, both after data compiled by Wüst (1922). The dots represent the flux computed from atmospheric data for the year 1950. The units are 10^{11} gm sec^{-1}.

best one can, let us say from a smooth curve, it becomes possible to express the comparison of the results with climatological information in terms of the depth in centimeters of precipitation minus

Table II. The meridional distribution of the zonally averaged difference between precipitation minus evaporation by ten degree latitude belts for the northern hemisphere. The figures according to the indicated investigators are given in terms of cm per year.

Latitude Belt	*Conrad-Wüst*	*Benton-Wüst*	*Starr and White*
90–80°	+ 8	+16	—
80–70°	+22	+14	+27
70–60°	+25	+25	+35
60–50°	+32	+22	+19
50–40°	+32	+19	+ 7
40–30°	−19	−24	−11
30–20°	−48	−35	−30
20–10°	−37	−34	−34
10– 0°	+43	+46	—

evaporation on an annual basis by ten degree latitude belts. Such an arrangement of the comparison is given in Table II, where the figures obtained by the procedure here given are found in the fourth column while the requirements quoted from Conrad and Benton are found in the second and third columns.

It would add materially to the interest of Table II if the last entry were available. It is regrettable that upper air observation stations are not numerous enough as yet to permit water vapor flux measurements across the equator and thus provide this information.

SUPPLEMENTARY AND CRITICAL REMARKS

There are a number of points which may be raised concerning both the data and the computation techniques which doubtless contribute to the discrepancies between the three sets of results. It would scarcely be fitting or convenient in a discussion of this scope to engage in an evaluation of the techniques used by Wüst, Conrad and Benton. Therefore only certain of those factors which may lead to inaccuracies of the present calculation are touched upon here; specifically the more important considerations are the following:

(a) The direct computations of the flux are for the single specific year 1950, while the figures quoted from Wüst, Conrad and Benton represent long-term normals. It is highly probable that significant departures from normal do occur in individual years, although it is unlikely that the essential character of the meridional distribution of the water vapor flux changes radically from year to year. On the whole it would be highly coincidental if the flux distribution for 1950 were exactly normal.

(b) Fig. 1 shows the distribution of key stations used. In addition to these, numerous alternate stations were added as is described in the references already given. Since a certain fraction of the wind reports were obtained from pilot-balloon soundings, it is to be expected that some bias might thus be introduced because of the impossibility of making such soundings when cloudiness obscured the balloons. At least in middle latitudes this factor might lead to fluxes which are spuriously small, since the cloudiness is more prevalent on the eastward (more moist) sides of cyclones. Actually it is rather easy to overstress the importance of this circumstance, because the factors involved do not possess sufficient regularity. From an examination of the computations for various stations while the work was in progress, the impression is gained that not much error results from this source for the station network actually employed.

Another feature of the station network is that, generally speaking, it is more dense over land areas. This could lead to an insufficient sampling of conditions over ocean areas where the moisture content is larger. It is not thought, however, that this factor has a very appreciable effect on the results.

(c) The assumption that the surface pressure has everywhere the constant value of 1000 mb is probably the most serious one made in the study. However, it is not unremediable, although its removal would involve a considerable increase in labor. The importance of this factor is probably greatest in the tropics, where surface winds having a component toward the equator are found in the mean and where the normal pressure is in the vicinity of 1010 mb, thus no doubt leading to an underestimate of the southward flux of water vapor. This same condition in the tropics probably represents also an instance where the effect of the transport of water southward in the form of liquid cloud droplets may be of some importance as well.

In terms of relative significance it appears that the neglect of the contributions to the flux from the atmosphere above 500 mb is of minor importance.

APPENDIX

It has been our custom in previous articles to present the results of flux calculations of various quantities in the form of a special table giving various details as to the classification of the atmospheric eddies which accomplish the transport. In the case of the flux of water vapor, such a table has been presented for each of the four latitudes 31°, 42.5°, 55° and 70° N by Starr and White (1954). In order to complete the series, the appropriate corresponding information for 13° N is here given in Table III. For a complete discussion of the terminology and symbols appearing in the column headings, see Starr and White (1954). For the purpose at hand it suffices to indicate that square brackets signify averaging with respect to longitude, a bar signifies averaging with respect to time, curly brackets indicate averaging over the total number of observations N, while n is the number of days with available observations and r is the coefficient of linear correlation between the northward component of wind velocity v and the specific humidity q. Primes denote the deviations from time or longitude averages, depending on the quantity to which they are affixed.

Note that, in the case of water vapor transport, the contribution of the so-called meridional cell component as given in column 6 at 1000 mb (due to net southward air motion) is large enough to give dominant importance to the vertical integral at the foot of the column. This is apparently due to the large concentrations of water vapor

Table III. Numerical analysis of water vapor flux data for year 1950 at latitude 13°N. All velocities are in m sec^{-1}, humidities in gm kg^{-1}. The levels are in mb.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Level	$\overline{[q]}$	$\overline{[v]}$ *	$\overline{[q]\,[v]}$ *	$\overline{[qv]}$ *	$[\bar{q}]\,[\bar{v}]$	$\overline{[q]'\,[v]'}$	$\overline{[q'v']}$ *	n	$\{q\}$	$\{v\}$	$\{qv\}$	$\{qv\} - \{q\}\,\{v\}$	r	N
500	+ 1.6	−0.15	− 0.0	+ 0.4	− 0.2	+0.2	+0.5	365	+ 1.6	−0.16	+ 0.4	+0.7	+0.14	2873
		±0.18	± 0.3	± 0.3			±0.2							
700	+ 5.0	−0.06	− 0.1	+ 0.4	− 0.3	+0.2	+0.8	365	+ 5.1	−0.08	+ 0.6	+1.0	+0.10	3461
		±0.14	± 0.7	± 0.7			±0.3							
850	+ 9.5	−0.12	− 0.5	+ 0.7	− 1.1	+0.6	+1.2	365	+ 9.6	−0.11	+ 0.7	+1.8	+0.15	3171
		±0.14	± 1.3	± 1.4			±0.4							
1000	+15.6	−1.08	−15.7	−13.8	−16.9	+1.1	+2.0	365	+15.7	−1.05	−13.4	+3.1	+0.22	3224
		±0.19	± 2.8	± 2.9			±0.5							
Integral (10^{2} CGS units)				− 0.7	− 1.6	+0.3	+0.6				− 0.7	+0.8	Sum	12729

* Confidence limits are twice the standard error of the mean.

near the surface and is in striking contrast to the situation in regard to the flux of angular momentum where the corresponding integral accounts for only a small percentage of the total flux which is itself small when compared to latitudes a little farther removed from the equator (see Starr and White, 1952c).

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