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Convergence of Horizontal Flux of Water Vapor in the General Circulation of the Atmosphere[1]

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Abstract. An evaluation of the evaporation (E) over the North Atlantic Ocean has been made using recent data; this draws attention to the limitations of the turbulent flux method of estimating evaporation when applied to climatological data. Precipitation amounts (P) for a similar area and period are obtained using a recently developed technique. The resulting $P - E$ distribution corresponds to the total convergence of water vapor brought about by atmospheric motions. The advective convergence (due to the mean monthly flow pattern) is subtracted from the total convergence to obtain the effect of the eddy motions on a smaller scale. The patterns of horizontal convergence due to advective and eddy transports are shown to differ appreciably from one another.

Introduction. During the last ten years, observational studies of the general circulation of the atmosphere have been largely concentrated on balance requirements on a global scale. The necessity for fluxes of various quantities in the vertical direction and in the horizontal direction across lines of latitude, and the study of the mechanisms whereby these fluxes occur, have contributed much to the understanding of flow patterns and their dynamics. An increase in the frequency of observations and in the number of reporting stations has led to a natural development of this line of approach —an attempt to study the divergence of the horizontal fluxes. In the same way that horizontal flux is divided, in general circulation studies, into the flux due to the mean flow (advective flux) and the eddy flux, so can flux divergence be similarly and conveniently treated.

To illustrate this type of study of divergence fields the parameter chosen as an example is water vapor, and the work described here involves two aspects of atmospheric turbulence: the first concerns small-scale turbulence in the lowest layers of the atmosphere, and the concept of uniform vertical flux in these layers; the second involves turbulence on a larger scale, and the horizontal transport and divergence brought about by atmospheric motion with a time scale of about a month.

After evaporation, condensation, and precipitation have been taken into account, water vapor is conserved in the atmosphere. Also, both the horizontal transport of the water content in clouds and the change in the precipitable water content of the atmosphere in any given region are relatively small from month to month. Therefore a balance between the horizontal divergence of water vapor and precipitation minus evaporation ($P - E$) is a necessary phenomenon. The $P - E$ pattern is therefore the pattern of the horizontal divergence of water vapor and is important for defining one part of the energy sources for the maintenance of the general atmospheric circulation.

Evaporation and precipitation. Three treatments of the evaporation from ocean to atmosphere on a global scale have been given, by *Jacobs* [1951 and other papers], *Budyko* [1955 and other papers], and *Privett* [1960]. These authors obtain the areal distribution of evaporation over the oceans by applying the equation

$$E = au(e_s - e_a)$$

where E is evaporation, a is a coefficient of proportionality (assumed constant), u is the scalar mean wind speed, e_s is the saturation mixing ratio (or vapor pressure) at mean sea surface temperature, and e_a is the saturation mixing ratio at the mean dew point of a layer of air close to the surface. u and the mean dew

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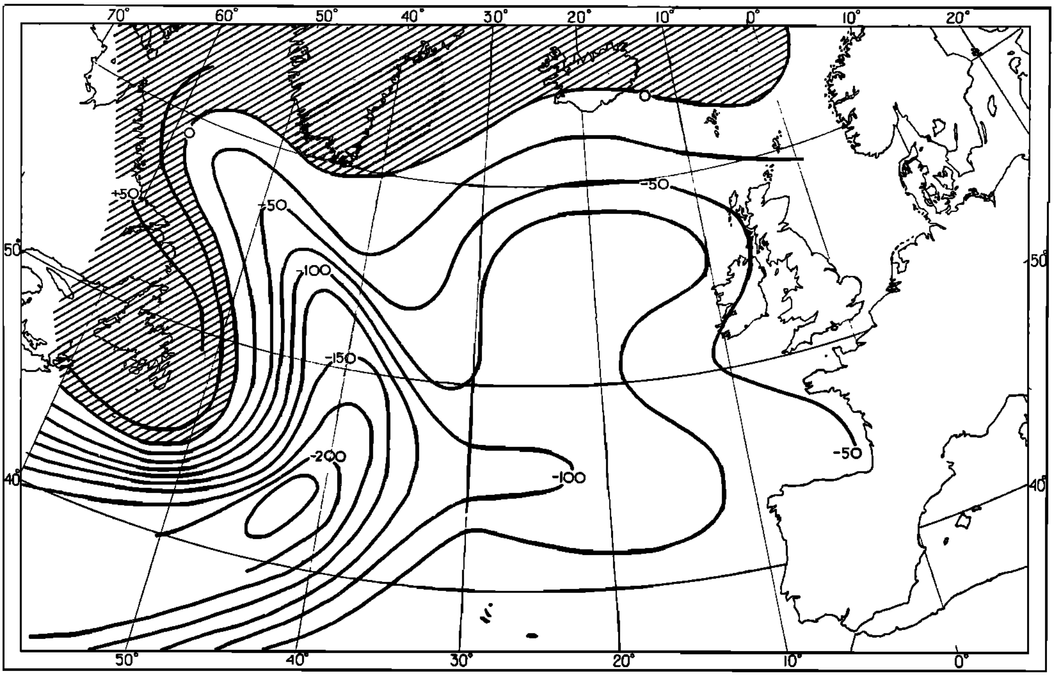

Fig. 1*A*. Precipitation minus evaporation (mm), January. Plus signs indicate convergence; minus signs, divergence.

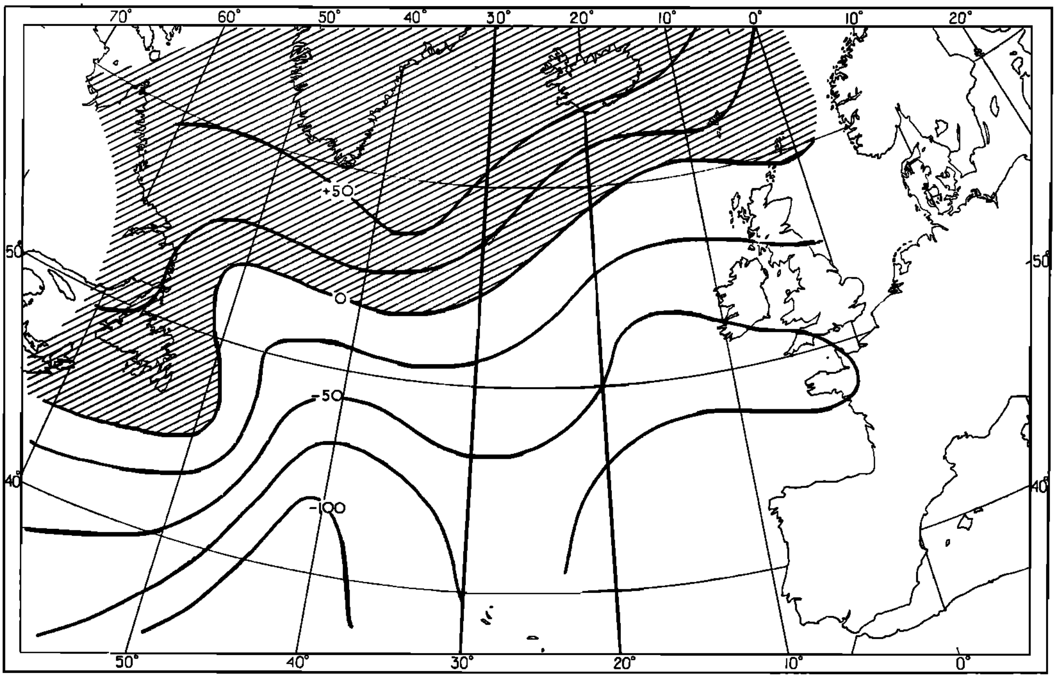

Fig. 1*B*. Precipitation minus evaporation (mm), July.

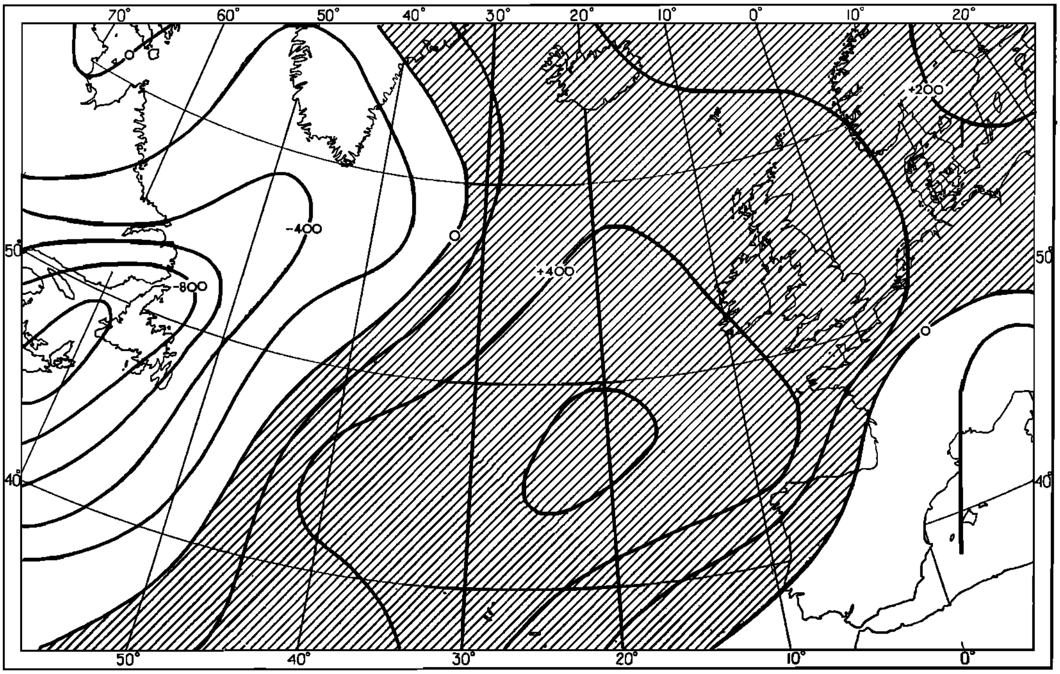

Fig. 2*A*. Advective divergence of water vapor (mm), January.

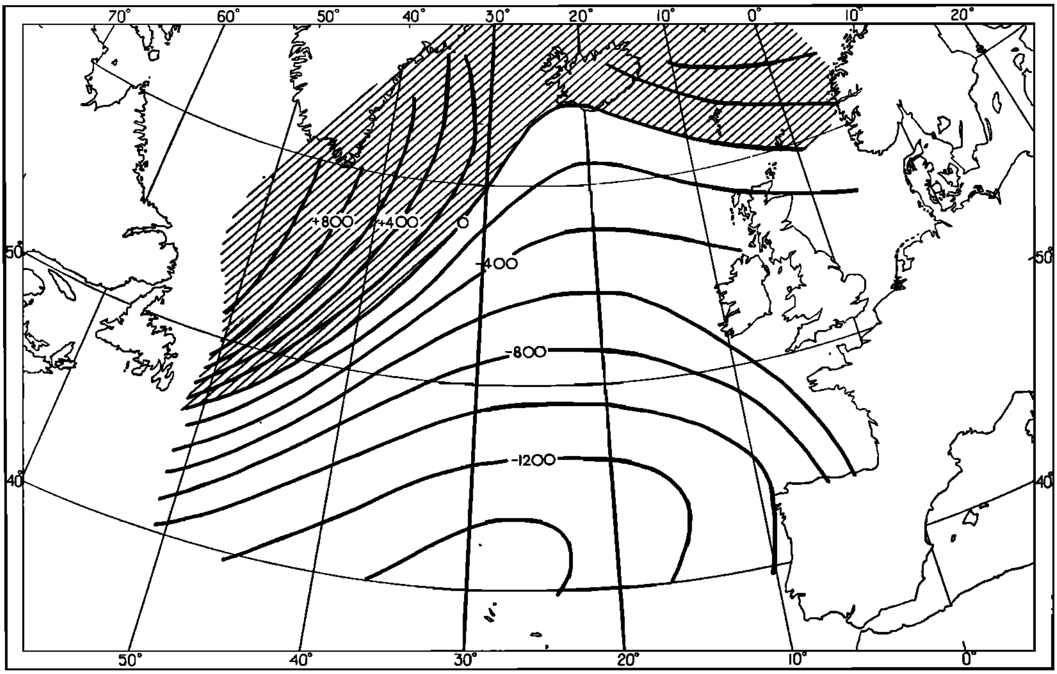

Fig. 2*B*. Eddy divergence of water vapor (mm), January. Plus signs indicate convergence; minus signs, divergence.

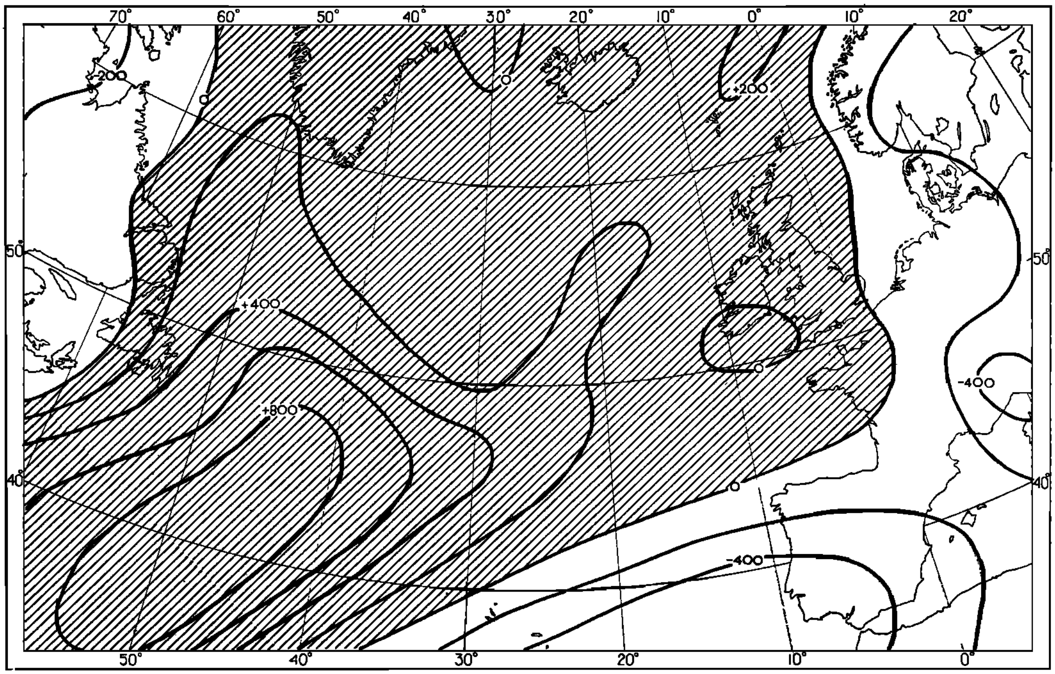

Fig. 3*A*. Advective divergence of water vapor (mm), July.

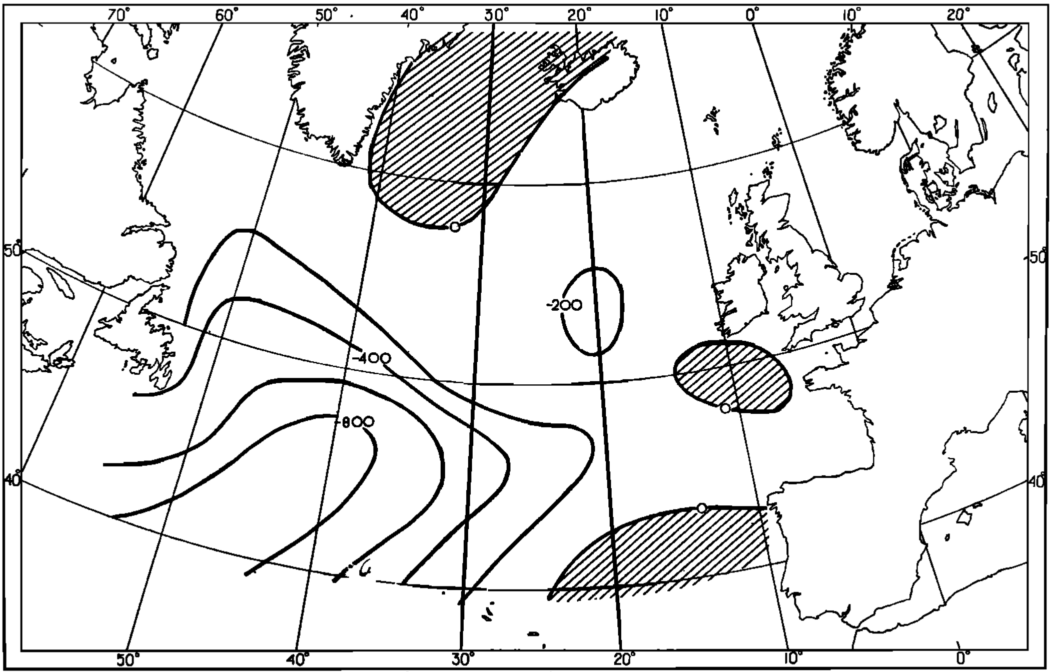

Fig. 3*B*. Eddy divergence of water vapor (mm), July.

point are measured from the observing platform of ocean vessels.

The use of this equation implies that observations are made in the surface layer in which turbulent fluxes are independent of height. A further assumption is that a fairly accurate distribution of the mean value of evaporation can be obtained by using mean values in the equation and establishing the value of the empirical constant by comparing the annual value of evaporation obtained over a selected area with a value obtained by a different method—using energy considerations applied to the ocean. Important assumptions and simplifications are therefore involved in this method, particularly as regards the distribution of meteorological parameters, mean values of which are based on a nonhomogeneous set of observations made at different heights from the sea surface and with the wind observation usually made some 30 feet above the dew-point observation. The ratio of the values for a obtained by Jacobs, Budyko, and Privett respectively is 1.0:0.9:0.8. However, this method is obviously not very satisfactory and has been adopted only because there is as yet none to replace it. It would be much better, for example, to assume a similarity between the velocity and humidity profiles over the sea and so obtain a via the surface drag coefficient. We would then require a reliable relation over the open sea between the surface drag coefficient, wind speed, and stability; this is at present being attempted (see the paper by E. L. Deacon in this symposium).

While awaiting information about the surface drag over the open sea, and because neither Jacobs' nor Budyko's charts extend much farther north than about 50°N, while Privett was concerned mainly with the southern oceans, Ocean Weather Ship data have been used to compute evaporation over the North Atlantic Ocean from mean values and Privett's value of a. Ocean Weather Ship data over the period 1953 to 1957 inclusive were employed here; they are more consistent than the marine data of the previous workers but in addition their present weather data have been used in an earlier investigation to obtain more reliable precipitation estimates than hitherto existed [*Tucker*, 1961]. The precipitation and evaporation figures for Atlantic Ocean Weather Ships for the period 1953 to 1957 were used to obtain mean charts of precipitation minus evaporation ($P - E$) for January and July (Figs. 1*A* and *B*).

Eddy convergence. Having the total divergence pattern in the form of the mean $P - E$ distribution, the relative importance of the advective flow (the mean monthly flow pattern) and eddies on a smaller scale can be shown by subtracting the horizontal divergence of water vapor due to the advective flux from the $P - E$ charts. The divergence due to the advective flux has been computed by *Bannon, Matthewman, and Murray* [1961]; their January and July charts for the North Atlantic (Figs. 2*A* and 3*A*) are reproduced above the residual charts showing the divergence of water vapor due to eddies smaller in scale than the mean monthly flow pattern (Figs. 2*B* and 3*B*).

The difference between Figures 2*A* and 2*B*, and between Figures 3*A* and 3*B*, is a quantitative assessment of a fact which although perhaps intuitively assumed has not been previously demonstrated, namely that in the general circulation of the atmosphere the patterns of horizontal divergence due to advective and eddy transports are completely different. It remains to be seen to what extent the patterns of eddy divergence of the various energy forms are similar, and whether they are related to the underlying geographical features or are entirely functions of other aspects of the flow pattern.

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