TRANSFER OF ATMOSPHERIC MOISTURE

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Contents

Summary

This article discusses different types of horizontal water vapor transfer: net, advective, macro-turbulent and methods for its estimation from experimental data. Factors are considered for formation of water vapor flow, among which are primarily atmospheric circulation and its moisture content. Much attention is paid to geographical regularities in distribution of atmospheric moisture flows over the earth globe, including zonal average flows. Regional aspects are also considered, including water vapor transfer over the equator, and over the northern and southern polar areas.

1. Introduction

As is well known, atmospheric moisture transfer occurs simultaneously in vertical and horizontal directions. Vertical transfer involves the movement of evaporated moisture to higher atmospheric levels, mainly by vortex motion, its condensation, formation of clouds and fall out of precipitation. These matters are considered in *Formation of Precipitation*, and so our main task here is to analyze the formation and regularities of horizontal water vapor transfer—a process which dominates over the vertical. It is horizontal transfer that serves as a linking mechanism of the hydrological cycle (HC) between individual reserves and even between individual parts of one and the same reserve, ensuring redistribution of water vapor and its balance at a global scale. Moisture transfer is also one of the most important characteristics of atmospheric circulation, sustaining, along with potential energy, flows and enthalpy, the energy balance of the earth globe. We should remember that the atmosphere is the most dynamic reserve of the hydrosphere since the rate of water vapor transfer is an order of magnitude higher than the rate of stream water motion and two orders higher than that of ocean currents. As a consequence, the period of complete renewal of atmospheric moisture is 8 to 9 days, which is considerably less than the periods required for renewal of water in the other reserves. Also, in accordance with atmospheric water balance equation (AWB), horizontal moisture transfer determines the formation of sources and sinks of water vapor, moistening of the land surface and replenishment of terrestrial water resources, processes of atmospheric rotation, and so on.

2. Methodology for determination of horizontal moisture transfer components

From the point of view of regularities of moisture redistribution between the reserves of the hydrosphere, the most interesting is estimation of horizontal water vapor transfer integrated over the vertical. Its main characteristics in a fixed point are: F – total net flow; F_x and F_y – zonal and meridional components of the net flow; $\overline{F}$ – advective net flow; $\overline{F}_x$ and $\overline{F}_y$ – zonal and meridional components of advective flow; F'_x and F'_y – zonal and meridional components of vortex flow. The net transfer is a vector sum total of zonal and meridional components, i.e.

$$\mathbf{F} = F_x\mathbf{i} + F_y\mathbf{j}, \quad \overline{\mathbf{F}} = \overline{F}_x\mathbf{i} + \overline{F}_y\mathbf{j}, \; \mathbf{F}' = F'_x\mathbf{i} + F'_y\mathbf{j}\,, \qquad (1)$$

where **i** and **j** are unit vectors directed eastward and northward. Besides, the total flow consists of advective and vortex flows, i.e. $F_x = \overline{F}_x + F'_x$ and $F_y = \overline{F}_y + F'_y$. From here it follows

$$F_x = g^{-1}\int_{p_k}^{p_0}\overline{qu}\,dp = g^{-1}\int_{p_k}^{p_0}\overline{q}\,\overline{u}\,dp + g^{-1}\int_{p_k}^{p_0}\overline{q'u'}\,dp \qquad (2)$$

$$F_y = g^{-1}\int_{p_k}^{p_0}\overline{qv}\,dp = g^{-1}\int_{p_k}^{p_0}\overline{q}\,\overline{v}\,dp + g^{-1}\int_{p_k}^{p_0}\overline{q'v'}\,dp \qquad (3)$$

where q – specific humidity, u,v – zonal and meridional wind speed components, g – acceleration due to gravity, p_0, p_k – sea level pressure and pressure on such isobaric surface where humidity may be neglected. Taking into consideration the exponential character of humidity decrease with height, practically all moisture resources are concentrated within the troposphere—the lower atmospheric layer which extends upwards to 11 km on average. In low latitudes the boundary of the troposphere rises to 16 to 18 km, and in polar latitudes it goes down to 8 to 9 km. In numerical calculations the upper tropospheric layers with low moisture content are often neglected, and consideration is restricted to $p_k = 300$ hPa (hector Pasqal: 1hPa=1mbar).

Usually integrals (2) and (3) are found by means of numerical methods from the known vertical profiles of humidity (q) and wind speed components (u,v), i.e. with data from aerological sounding of the atmosphere. The simplest and the most widespread numerical method is that of trapezoids, which anticipate linear variation of moisture flow between individual estimated levels. But since wind speed variability considerably exceeds air humidity variability, computation of errors of the integrals depends to a greater extent on errors in wind speed. With a sufficiently high averaging period (e.g. one month) and twice-a-day sounding, random error decreases by a factor of approximately 60 and becomes very small. Therefore, when computing the integrals, the principal error becomes systematic, depending on the extent of non-linearity of the distribution of moisture flows with height, instrumental errors in wind speed and humidity, and a number of other factors. To obtain reliable estimates of integral flows of it is necessary to have several computation levels in the boundary atmospheric layer. Unfortunately quite often this is impossible, since the surface of 850 hPa located above the the boundary layer, is assumed by WMO as the lower near ground standard isobaric surface.

Since air humidity rapidly decreases with height, and wind speed, on the contrary, usually increases, maximum water vapor flow occurs at a height of 1 to 3 km. In low latitudes it rises to 3 km , and in high latitudes it goes down to 1 km. Approximately similar regularities are typical for the height of efficient rate of moisture transfer, which is determined as $U_{ef} = F / W$, where F is magnitude of the total net moisture flow, and W is atmospheric moisture content (AM). From here it follows, that the value of U_{ef} is a certain efficient wind speed with which atmospheric moisture is transported in the vertical air column. On average, it is observed near the height of the surface of 850 hPa, rising in low latitudes and falling in high latitudes.

We should note that while net and advective flows are computed directly from the above formulas, vortex transfer is usually estimated from the difference of the total and advective flows, i.e.

$$\overline{q'u'} = \overline{qu} - \overline{q}\,\overline{u}; \quad \overline{q'v'} = \overline{qv} - \overline{q}\,\overline{v} \qquad (4)$$

and then integrals F'_x and F'_y are taken. Taking into consideration that by their magnitude F'_x and F'_y are, as a rule, considerably less than the total and advective flows, they often are the difference of big values. Since it contains the sum total error of these components, the accuracy of estimation of vortex moisture flows is generally low.

Interpretation of individual terms in (2) and (3) from the point of view of physics depends on the time averaging period. For example, let’s assume $\tau = 1$ month. The advective component is traditionally interpreted as atmospheric moisture flow due to time average net circulation, and vortex one as moisture transfer due to macro-turbulence caused mainly by cyclones and anticyclones.

It is easy to demonstrate that for averaging over a latitudinal circle total integral zonal and meridional moisture flows may be written as follows:

$$[\, F_x \,] = [\, \bar{F}_x \,] + [\, F^*_x \,] + [\, F'_x \,] \qquad (5)$$

$$[\, F_y \,] = [\, \bar{F}_y \,] + [\, F^*_y \,] + [\, F'_y \,] \qquad (6)$$

where square brackets mean averaging over latitude. The first term from the right in (5) and (6) is mean (toroidal) moisture transfer caused by time and space average wind speed. Normally it manifests itself in low latitudes due to direct circulation Hadley cell. The second term from the right is stationary moisture transfer caused by large-scale quasi-stationary vortices, i.e. climatic centers of atmospheric action and orographical peculiarities of the underlying surface. Finally, non-stationary moisture transfer is caused by large-scale flowing vortices, among which there are cyclone and anticyclone formations.

3. On interpreting advective and eddy flows of moisture

As shown above, it is traditionally assumed that under mean monthly averaging advective moisture transfer is caused by mean motion of the atmosphere, and macro-turbulent transfer is caused by large-scale synoptical vortices (cyclones and anticyclones). However, it is easy to show that this kind of interpretation is not quite correct. With this purpose let’s put down the integral AWB equation (analyzed in detail in *Water Exchange between Land and Atmosphere*), as follows:

$$\partial W/\partial t + \mathrm{div}(\, \bar{\mathbf{F}} + \mathbf{F}') = E - P, \qquad (7)$$

where E – total evaporation, P – precipitation. In winter evaporation and changes in WB for continental regions with snow cover may be neglected since they are small, giving:

$$\mathrm{div}\ \bar{\mathbf{F}} + \mathrm{div}\ \mathbf{F}' = -P \qquad (8)$$

From this equation it follows that precipitation formation takes place simultaneously due to inflow of moisture through both advective and vortex atmospheric motions. Results of multiple investigations testify that contribution of the first term to formation of precipitation in many geographical regions may be rather considerable. This can easily be checked by means of Table 1 where AWB components are presented for the Volga river basin. Samara has been chosen as the outlet below which intermediate inflow may be neglected. The Volga river basin (A = $1.2\text{x}10^6$ km^2) was approximated by a contour of 10 – 12 aerological stations. The average distance between the stations was 480 – 402 km. Computation of divergence values was made from the Ostrogradsky-Gauss formula through moisture currents normal to the contour. Precipitation was computed from data of 200 stations with due account for all the corrections. Evaporation was determined by closing the AWB equation.

Month	**div $\bar{\mathbf{F}}$**	**divF′**	**divF**	$\partial W / \partial t$	**P**	**E**
1	-22	-20	-42	0	45	3

2	-17	-21	-38	0	42	4
3	-10	-25	-35	2	43	10
4	-21	6	-15	4	42	31
5	5	13	18	5	56	79
6	13	13	26	5	69	100
7	10	14	24	1	76	101
8	-6	9	3	-4	71	70
9	-19	6	-13	-5	61	43
10	-10	-24	-34	-4	58	20
11	-11	-23	-34	-3	50	13
12	-37	-17	-54	-1	60	5
Year	-125	-69	-194	0	673	479

Table 1. Atmospheric water balance components over the Volga river basin for a long-term period, in mm/month

From Table 1 it follows that in the cold period (October to March) the sum of $\text{div}\bar{F}$ values makes up 107 mm, and the sum of $\text{div}F'$ values is 130 mm. From here it follows that the contribution of $\text{div}F'$ to the total inflow of moisture determined by the ratio $\text{div}F'/\text{div}F$ is equal to 0.55, and it is even less for annual averaging ($\text{div}F'/\text{div}F = 0.36$).

However, it is well known that most precipitation is of cyclonic origin. Therefore, a contradiction arises which, to our mind, is caused by the not quite correct physical interpretation of factorization of the total flow of atmospheric moisture into advective and vortex components.

According to Van Migem, resolution of motion into mean and vortex is totally dependent on the choice of space and time averaging area for which mean values are determined. Clear separation of motion into mean and vortex ones will be reliable only when the space and time averaging area includes many small eddies (with sizes less than the averaging area) and a few big eddies (with sizes more than the averaging area). In the course of description of large-scale turbulence (cyclonic and anticyclonic vortices) such breaking down is rather conventional since there is no objective criterion for sampling.

Besides, direct separation of vortices from one another also depends on space and time averaging scales. Really, such separation may be reliable if the space and time area between neighboring synoptic vortices (cyclones) exceeds the sizes of the vortices themselves. It is quite natural that in practice this condition is far from being always met. Therefore, cyclones rapidly following one another are inseparable and will, in fact, be described within mean atmospheric motion.

Finally, the role of air mass transfer rate should be kept in mind. If the rate of cyclone motion is very close to the average rate of water vapor transfer, the advective component in this case will also characterize moisture transfer for such cyclones.

What was said above brings us to the conclusion that reliable separation of the total flow into average and vortex flows for actual synoptical conditions is a stubborn problem. It is rather arbitrary since the major part of vortex moisture transfer may serve a constituent part of the general atmospheric circulation and its average motion, in particular. Unfortunately, to date there are no accurate methods available for separation of the net moisture transfer into average and vortex transfer.

4. Factors for water vapor flow formation

If a fixed point of space is considered, as a result of considerable variations in wind speed as compared to air humidity, intensity of integral moisture flow depends mainly on the intensity of air mass motion, i.e. circulation factors. At the same time, under zonal averaging, moisture transfer is to a greater extent affected by MC, inter-latitudinal variations of which are considerably higher than intra-latitudinal variations of air mass motion rate.

4.1 Circulation factors for moisture transfer formation

Average (advective) air mass transfer is connected mainly with atmospheric circulation cells: Hadley, Ferrel and polar cells, that were considered in *Exchanges of Water in the Hydrosphere*. In low latitudes the most powerful mechanism of inter-zonal redistribution of moisture is IZC where maximum amount of precipitation falls out due to trade winds from the northern and southern hemispheres. However, as mentioned above, the main redistribution of heat and moisture, especially in extra-tropical latitudes, is performed due to large-scale atmospheric vortices—cyclones and anticyclones. Cyclones are characterized by low air pressure in the center and air circulation around the center counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. This results in intensive elevation of air masses in the central part of the cyclone. This leads to permanent condensation of moisture, cloud formation and precipitation fall out. Anticyclones, on the other hand, are areas of high pressure with concentric circumferences where air motion is contrary to that of cyclones. As a result of the descending motion of air masses particularly in the central part, anticyclones are associated with sunny weather, insignificant cloudiness and lack of precipitation.

Typical spatial sizes of cyclones and anti-cyclones are from several hundred kilometers to several thousand kilometers, and their lifetimes are typically from a few hours to tens of days. Anticyclones are usually larger and of longer duration, but they are less intensive. The spatial distribution of cyclones and anticyclones is rather non-uniform. This is seen especially clearly on near ground atmospheric pressure maps. For instance, a high-pressure belt extends in subtropical latitudes around the whole Earth in the northern and southern hemispheres. At the same time there is a low pressure belt in high latitudes in both hemispheres. Synoptical maps show stationary closed areas of high and low pressure being statistical results of prevailing baric systems in this region. Such areas are called atmospheric action centers (AAC). The most intensive AAC are the following:

- Azores maximum—located in the North Atlantic with its center around 35°N near the Azores Islands;
- Hawaii maximum—located in the North Pacific with its center north of the Hawaii Islands;
- Iceland minimum—a vast area of low pressure between Greenland and Europe with its center near Iceland;
- Aleutian minimum—the area of low pressure in the north of the Pacific Ocean with its center near the Aleutian Islands.

The pressure gradient between the Azores maximum and Iceland minimum has been called the North Atlantic Oscillation, and the one between the Hawaii maximum and Aleutian minimum, the Pacific Oscillation. If it is assumed that the value of this gradient characterizes the intensity of western transfer of air masses, it consequently characterizes amount of atmospheric moisture transferred.

In the southern hemisphere it is rather difficult to single out similar AAC, since areas of high and low pressure are not clearly spatially localized. At the same time there is a clear zonal pressure gradient between the city of Darwin (Northern Australia) and Tahiti Island that was suggested by D. Walker in 1920 and called the Southern Oscillation. This index primarily characterizes the intensity of trade winds circulation. Positive values of this index means intensification of moisture transfer from the shores of South America to the shores of Asia, and negative ones cause attenuation of these processes. Multiple investigations showed that this index is closely connected with such quasi-periodic phenomena as El-Nino, which occurs once every few years and is characterized by anomalousy warm waters near the shores of Ecuador and Peru.

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Biographical Sketch

Valery Nicolaevich Malinin was born in 1948. Having graduated from Sea Academy after adm. Makarov, he succeeded to the speciality of oceanologist. He worked in the Arctic and Antarctic Scientific Research Institute, and the State Hydrological Institute. From 1981 to the present he has been working in the Russian State Hydrometeorological University, where he progressed from teacher to professor. In 1978 he took a Ph.D (Geography) degree and in 1994 a D.Sci (Geography) degree. He has been a professor since 1996. He is the author of more 100 printed works, including six monographs and five textbooks, including:

- General Oceanology. Part 1. Physical Processes. (1997), RSHU Publ., 342 p. (in Russian),
- Vapor Exchange in the Ocean-Atmosphere System (1994), Gydrometeoizdat, 197 p. (in Russian),
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- The Hydrosphere of the Earth (co-author) (2004). St.-P., Gydrometeoizdat (in print) (in Russian).

His main scientific interests are connected with studying waters of the hydrosphere, the hydrological cycle, climate variation, statistical methods of information analysis, and methods of forecasting hydrological characteristics.