EXCHANGES OF WATER IN THE HYDROSPHERE

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Contents

Summary

Historical development of the notion of "hydrosphere" is discussed. In this Theme the hydrosphere is treated as a continuous sphere of the Earth containing water in all aggregations within World Ocean, the cryosphere, lithosphere and atmosphere, and taking a direct part in the planetary hydrological cycle. We can conveniently present the hydrosphere as a system of four interrelated global reserves (ocean, continents, cryosphere, atmosphere) between which a continuous process of circulation and re-distribution of water takes place. The general classification of hydrosphere waters is discussed. General characteristic and estimation of water storage are given for each of the reserves.

It is shown that variations of the world ocean level (WOL) may serve as an integral indicator of global water exchange between reserves. Variations of level in the twentieth century and their possible reasons are discussed. Approximated estimations of inter-annual variability of water storage in individual reserves are given.

1. General information and classification of hydrosphere waters

1.1. The notion of hydrosphere

Literally “hydrosphere” means a water coating. The notion of the hydrosphere was first introduced to the scientific literature in 1875 by E. Zyuss who considered it as an integral water coating of the planet consisting mostly of the World Ocean. Wider treatment of this notion was given by J. Merray in 1910. According to Merray the hydrosphere “consists mostly of the World Ocean and lakes and rives as well. Part of the water may be in solid and gaseous condition in the form of ice, snow, hail and water vapors of atmosphere. Water also percolates deeply into the stony crust of the Earth where it performs hydration of minerals and also forms a significant part of the biosphere”.

However, such broad treatment of “hydrosphere” has not received full recognition among investigators. Up to the middle of the twentieth century different definitions of the concept were used. Most experts agreed that it was necessary to include the World Ocean and land surface waters in the hydrosphere but there were differences in opinion with regard to atmospheric moisture, glaciers and underground water. Should the water in gaseous and solid conditions be included in hydrosphere, and what part should be included? For example, A. Chebotarev’s (“Hydrological vocabulary”, 1978) understanding of hydrosphere was “interrupted water sphere of globe situated on the surface and in the thick of the crust. It is a combination of oceans, seas and terrestrial water bodies (rivers, lakes, underground waters), including water accumulations in the solid phase (snow cover, glaciers)”. In this definition atmospheric moisture is not included in the hydrosphere, and there is no mention of which specific types of underground waters (free or connected) are included. Many American scientists take the same view as Chebotarev. In the “Ocean and Atmospheric Sciences” encyclopedia, all types of waters in liquid and solid condition are included in the hydrosphere, and a depth of 4000 m is considered as the lower boundary of underground waters.

There is another point of view, however, according to which atmospheric moisture is a composite part of the hydrosphere. Natural water exists in three phases (liquid, solid and gaseous) and if we include the solid phase in the hydrosphere, it is logical to include the gaseous phase as well, i.e. atmospheric moisture. Hydrogeologists have had even more disputes about the lower boundary of the hydrosphere and which types of underground waters belong to it and which don’t. In particular, R. Klige (1998) considered that all types of water, including the ones in chemically and biologically connected conditions, may be referred to as the hydrosphere. This notion of hydrosphere seems to be inexcusably broad since connected (especially chemically) natural waters do not participate in the global hydrological cycle of moisture.

The next definition given by Fedoseev is sufficiently full: “In a broad sense, a continuous coating of the globe, stretching downwards to the upper mantle, where in conditions of high temperature and pressure not only molecules dissolve but their synthesis continuously occurs, and upwards, nearly to the height of the tropopause, above which molecules of water are exposed to photo-dissociation, is understood by *hydrosphere*”. The waters of the World Ocean, cryosphere, lithosphere and atmosphere are all included in the hydrosphere, but water of the biosphere is not. When including biosphere moisture in the composition of the hydrosphere, the water coating ceases to be continuous and, moreover, the water consistence in biosphere (1120 km^3) is negligibly small as compared to other coatings, even the atmosphere. Therefore, the hydrosphere may be considered as the surroundings of the biosphere, without it the existence of the latter is impossible. The significance of the biosphere consists of the fact that transpiration, i.e. the process of water evaporation by vegetative cover, makes up to 12% of total evaporation from the land surface.

A "narrower" notion of the hydrosphere may be given as well. The hydrosphere can be considered as a continuous Earth coating containing water in all aggregations within the World Ocean, cryosphere, lithosphere and atmosphere, and taking a direct part in the global hydrological cycle. The main difference between this definition and the preceding one is in the fact that those types of underground waters which are found in connected condition in the crust and are not drained by rivers and cannot independently move like runoff, are excluded from the hydrosphere. In general the hydrological cycle (HC) is a continuous process of circulation and redistribution of all types of natural waters between the separate components of the hydrosphere. It determines certain relations between them in different averaging scales. The narrow definition of hydrosphere which we use in this article makes it possible to represent all natural waters as an integral self-organizing system, and it is the hydrological cycle which creates the interconnection and unity of hydrosphere waters.

It should be also noted that there is no single point of view on the notion of cryosphere. The term was first used by the Polish scientist A. Dobrovolsky in 1923. According to the "Glaciological Dictionary" (1985), the cryosphere is an Earth coating of irregular form in the area of atmosphere, hydrosphere and lithosphere interaction distinguished by negative and zero temperatures and presence of water in the solid phase. This definition of cryosphere extends from the frozen rocks under the surface of the Antarctic Continent at depths of 4 to 5 km, to a height of 100 km, including the very cold mesopause, with silvery clouds. However, this interpretation of "cryosphere", in our view, seems to be too broad. Firstly, the cryosphere itself is a part of the hydrosphere, and secondly, using temperature as a defining criterion creates problems. Overcooled rocks, and the upper layers of the atmosphere can hardly be included in the cryosphere, since they contain virtually no water in solid phase. Therefore, the narrower definition of cryosphere as an Earth coating characterized by presence of water in solid phase, is more expedient.

1.2. Model of global hydrosphere reserves

The hydrosphere is conveniently considered as a system of four interconnected reserves (ocean, continents, cryosphere, atmosphere), between which continuous process of circulation and redistribution of natural waters occurs (see Figure1).

In Figure 1 moisture flows between individual reserves are shown by pointers, where P – precipitation, E – evaporation, M – continental runoff to the ocean, A – iceberg flow, and numbers indicate their intensity in 10^3 km^3/year. Naturally, the biggest reserve is the World Ocean, containing 13.38 x 10^8 km^3 or 96.5% of total storage of natural waters. The smallest reserve is the atmosphere which contain 13x10^3 km^3, or 0.001% of total storage of natural waters. Despite such a small value the significance of atmospheric moisture for the HC is extremely great as shown below.

Unlike the World Ocean and the atmosphere, a great variety of types of natural waters are observed on the continents and in the cryosphere. Continental waters may be divided into rivers, lakes, swamps, soil, underground (including gravitating and capillary water) and biological waters. Their total amount is estimated to be 34.137 x 10^6 km^3, or 2.475% of total Earth water storage. Continental ice shields, mountain glaciers, permafrost ice, seasonal snow cover and sea ice comprise the cryosphere, and the total mass of ice in the cryosphere is estimated at 24.4 x 10^6 km^3, or 1.76% of total storage of natural waters.

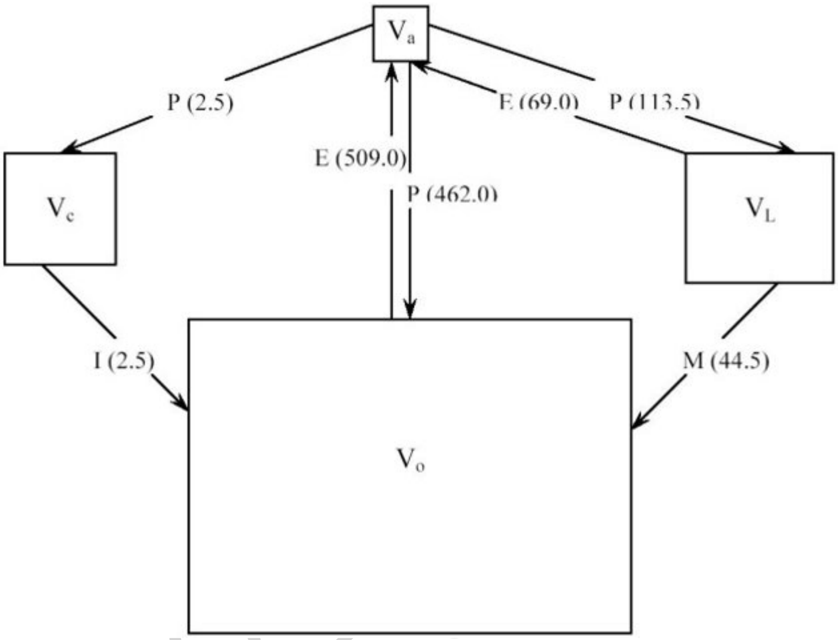

Figure1. Model of global hydrosphere reserves

According to modern thinking, the total storage of natural waters over a very long period of time (measured in geological epochs) remains at a constant level, i.e. input of water to the Earth surface from within the core of the Earth and from cosmic space is very small and is almost compensated for irrevocable loss of water as a consequence of water vapor dispersal in the upper layers of the atmosphere to the cosmos. This means that the hydrosphere, which connects each of the four reserves, is a quasi-closed system and, consequently, the following equation may be written:

$$V_0 + V_C + V_L + V_A = \text{const} \tag{1}$$

Here V_0, V_C, V_L и V_A are summary water storage in World Ocean, cryosphere, continents and atmosphere, respectively. Although the system is effectively a closed one, the redistribution of water is continuously occurring between individual reserves, and, consequently, water storage changes in time in each of the reserves. These oscillations are of different scales: short-term, seasonal, long-term, secular and long-secular. The most powerful are seasonal and long-secular oscillations.

1.3 General classification of hydrosphere waters

The structure analysis of Figure 1 makes it possible to formulate a general classification of hydrosphere waters, based on the following criteria: aggregation, geographical unity, physical and chemical composition, morphometric peculiarities, conditions of expansion, etc. (see Figure 2). The classification is hierarchical; the first level is made of four main reserves. Each of these is subsequently divided into composite parts, which also may be divided to smaller parts, and so on.

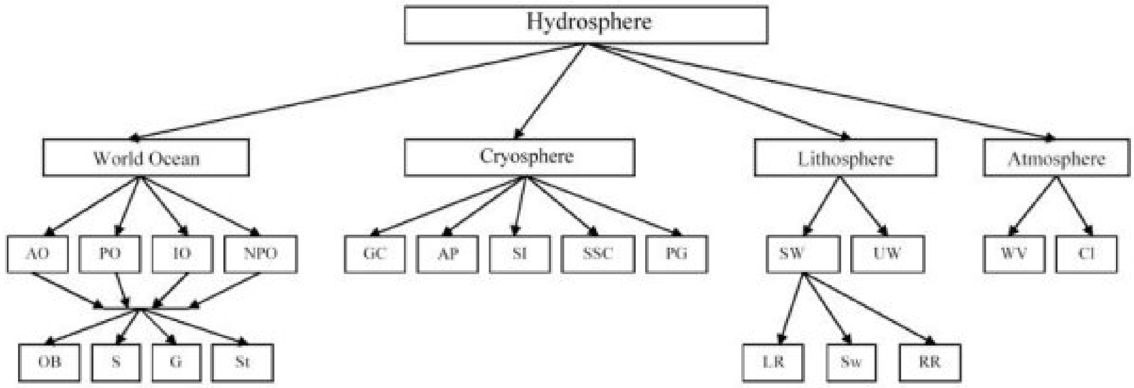

Figure 2: General classification of hydrosphere waters

In accordance with the classification, the World Ocean (WO) is divided into the Atlantic (AO), Indian (IO), Pacific (PO) and North Polar (NPO) oceans, each of which is divided into oceanic basins (OB), seas (S), gulfs (G) and straits (St). Cryosphere consists of glacial covers (GC), alpine glaciers (AP), sea ices (SI), seasonal snow cover (SSC) and permafrost glaciers (PG). Waters of lithosphere are divided into surface waters (SW) and underground waters (UW). In its turn surface waters are divided into lakes and reservoirs (LR), swamps (Sw) and river runoff (RR), and underground waters, to underground waters of aeration zone (UWaz) and of saturation zone (UWst). Finally, the atmosphere consists of water vapor (WV) and cloudiness (Cl). Lower levels of the classification for individual types of natural waters are not mentioned in Figure 2. These will be considered in appropriate chapters within this Theme.

Figure1 also provides a foundation for a classification of HC. All water flows within individual reserves and on their boundaries may be considered as independent links of HC. Thus, we have four links (branches) of HC: oceanic, lithospheric (continental), cryospheric and atmospheric. Let us consider them as the main structural units of the HC. A characteristic peculiarity of HC links is that on one side they are comparatively independent, and on another they are closely connected with each other, mainly by flows of evaporation and precipitation. Consequently, it is useful to consider interacting links as integral hydrological systems. As a result we have six such systems, which differ greatly in their significance.

Obviously, the ocean-atmosphere system should be considered the most important, not only in consequence of the large area it occupies, but because of the hydrological processes which take place in it. Thus, WO is the biggest reserve of natural waters, the main reason for the existence of the global hydrological cycle and the main provider of energy for atmosphere (through evaporation). The atmosphere is the only source of freshwater renewal in nature (through evaporation) and the main regulator of redistribution and enrichment of water storage (through precipitation) not only between individual reserves but between individual parts of each reserve.

Human civilization became possible only due to the fact that in the ocean-atmosphere system evaporation exceeds precipitation, leading to river runoff on continents, as well as ice runoff from Antarctica and Greenland. Another very important system, especially from a practical point of view, is the atmosphere-land system, involving a huge variety of hydrological processes and complex interactions.

The equation of water balance which expresses the universal law of substance conservation serves as a mathematical model for the hydrosphere and HC. It can be presented in algebraic form in the most general form:

$$\Sigma\Delta X_i = \Sigma\Delta X_{\text{штсi}} - \Sigma\Delta X_{deci} \qquad (2)$$

where $\Sigma\Delta X_i$ is the sum of water balance accumulation components which characterize water storage variations in time, $\Sigma\Delta X_{inci}$ is the sum of water balance natural components which mean the increasing of water value, $\Sigma\Delta X_{deci}$ – the sum of discharged components characterizing the decreasing of water value.

For a closed system like the hydrosphere $\Sigma\Delta X_i = 0$, the right part turns to the obvious identity $P_{gl} = E_{gl}$, from which equation, global estimates of precipitation (P_{gl}) and evaporation (E_{gl}) follow. All other hydrological systems are already opened, and for them the accumulation components can turn to zero only for average long-term conditions, but even not always. With decreasing spatial scales the water balance equation usually becomes more complicated, and sometimes quantitative values cannot be given to components of equation (2). This particularly concerns land, where a huge variety of natural scales is observed. On the basis of formula (2) we can write a system of four balance equations which will completely describe the variations of storage and water flows in reserves and their interchange.

$$\begin{aligned}
\Delta V_A &= E_{AO} + E_{AL} + E_{AC} - P_{AO} - P_{AL} - P_{AC} \\
\Delta V_O &= P_{OA} + M + I - E_{OA} \\
\Delta V_C &= P_{CA} - E_{CA} - I \qquad (3) \\
\Delta V_L &= P_{LA} - E_{LA} - M
\end{aligned}$$

This system of equations summarizes the global water balance. As noted by R. Satkliff in opening an International Symposium on Water Balance (Reading, England, 1970), global water balance cannot be considered a private problem of oceanology, meteorology or hydrology. It is a complex geophysical problem, and it is the geophysical approach, meaning joint analysis of all storage and flows of waters, that must serve as the main methodological principle of studying water balance at all scales, from global to local.

2. Water exchange and water balance of ocean

2.1 Circulation of ocean waters

Unlike from continents, the World Ocean contains individual oceans and seas which are connected to each other and which form an integral connected system. Unity of ocean waters is mainly provided by their continuous circulation (motion). This is realized not only horizontally (horizontal circulation), but also vertically (vertical circulation). Horizontal circulation may be surface, deep or bottom. Vertical circulation is divided into upwellings (raising of deep water to the surface) and downwellings (descent of surface water to the depths). Horizontal and vertical circulation are interconnected between each other and they form an integral system of currents—the general circulation of World Ocean. Essentially, it is this circulation which controls the intensity of water exchange processes. Ocean circulation, which realizes the transfer of water masses, on one hand contributes to close interaction of physical, chemical and biological processes, and on the other, it creates variety and differences of processes, which in their turn contribute to the eternal motion of water masses. From the unity of ocean waters and the continuity of their vital surroundings, it follows that the World Ocean is an integral ecological system.

General circulation is usually considered as motion of oceanic waters averaged for a long period of time, on a global scale. It is provoked by thermohaline factors (heating, cooling, evaporation and precipitation) and mechanical factors (wind, atmospheric pressure), which affect the ocean surface. Circulation of the ocean, especially in its surface layer, is closely connected with circulation of atmosphere and they together form a whole. If direct contact with atmosphere did not exist, vertical equalization of thermal, salty and other gradients would occur. Consequently, rapid transformation (rebuilding) of water circulation with depth is observed. In this case not only the intensity of circulation weakens, but its character changes. While in the ocean surface layer the contribution of the wind component to the circulation makes up ~ 80% and only 20% is attributable to thermohaline (density) factors, at a depth of 200 m the contribution of the density component, according to some estimates, exceeds 70%. Currents create not only macro-circulation systems—the main links of the general circulation, but they also transfer mass, heat and salts, directly affecting the water, heat and salt balances of the ocean.

The most powerful current and the only one that crosses three oceans is the Antarctic circumpolar current (ACC), which encircles the Antarctic continent in a huge ring. It reaches its maximum width in the Indian sector (2400 km on average), and its minimum width is limited by the size of the Drake Passage, between Antarctica and Tierra del Fuego. Discharge of ACC in the Drake Passage makes up 110-130 Sv (1 Sv=10^6 m^3/s), increasing in the eastern part of AO to 170-190 Sv. Average speeds of ACC are equal to 25-30 cm/s, sometimes increasing to 50 cm/s. Other very powerful currents are the Gulf Stream and Kurosio which play important roles in meridional transfer of heat from low latitudes to high latitudes.

The remarkable property of GOC is its high space-time stability. Although atmospheric conditions reflected on daily synoptic maps can differ from the long-term average picture of global circulation, the main currents of the global system always continues with little change in geographical position or intensity. Essentially, the macrocirculation systems continue throughout the whole year. Only small shifts of ocean circulation in a meridional direction, and strengthening of circulation intensity in consequence of thermal contrasts between tropical and polar latitudes, as well as between oceans and continents, are characteristic of seasonal variations.

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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 more of 100 printed works, including six monographs and five textbooks, including:

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- Sea Ice and Climate (co-author) (2000), St.-P Gydrometeoizdat, 91 p. (in Russian),
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His main scientific interests are connected with studying waters of the hydrosphere, hydrological cycle, climate variation, statistical methods of information analysis and methods of forecasting hydrological characteristics.