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К ОЦЕНКЕ ТРЕНДОВ В КОМПОНЕНТАХ ВЛАГООБМЕНА ОКЕАНА С АТМОСФЕРОЙ

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Приводятся оценки линейных трендов компонентов влагообмена между океаном и атмосферой (испарения, осадков и их разности — эффективного испарения), температуры воздуха, температуры поверхности океана по данным архива Reanalysis-2 и интегрального влагосодержания атмосферы по данным спутникового архива REMSS PMWC за период 1988—2016 гг. Отмечается интенсификация роста компонентов влагообмена начиная с 2012 года. Показано, что количество выпавших осадков над Мировым океаном растет быстрее испарения на 1.1 мм/год, что составляет 35 % от фактического тренда уровня Мирового океана (3.1 мм/год). На основе анализа безразмерных трендов установлено, что тренд во влагосодержании атмосферы почти в два раза превышает тренд в температуре воздуха над Мировым океаном. Это означает, что долговременные (трендовые) изменения влагосодержания зависят, прежде всего, от вертикального влагообмена океана с атмосферой, а не от глобального потепления. С 2012 года рост влагосодержания опережает рост температуры воздуха на 1 год. Поэтому влагосодержание атмосферы является не только ключевым следствием процесса глобального потепления, но и фактором, его формирующим.

Ключевые слова: испарение, осадки, влагосодержание атмосферы, Мировой океан, тренды, глобальное потепление.

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TO THE EVALUATION OF TRENDS IN THE COMPONENTS OF OCEAN-ATMOSPHERE MOISTURE EXCHANGE

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The linear trends in the components of ocean-atmosphere moisture exchange (evaporation, precipitation and their difference — net evaporation), air temperature, and sea surface temperature are estimated based on the data of the archive Reanalysis-2 and the data from the REMSS satellite archive on integral atmospheric total precipitable water for the period of 1988—2016. An intensification of growth of moister exchange components has been observed since 2012. The results showed that the amount of precipitation over the global ocean is growing faster than evaporation by 1.1 mm/year, which is 35 % of the actual global sea level trend (3.1 mm/year). The analysis of dimensionless trends showed that the trend in total atmospheric precipitable water is almost twice as high as the trend in air temperature over the global ocean. This means that the longterm (trend) changes of precipitable water depend primarily on the vertical air-ocean moisture exchange and not on the global warming. Since 2012 the growth of amount of precipitable water is 1 year ahead of air temperature. Thus the characteristics of atmospheric total precipitable water is not only a key consequence of the global warming process, but is also its forming factor.

Key words: evaporation, precipitation, atmospheric total precipitable water, global ocean, trends, global warming.

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Introduction. Vertical moisture exchange between the ocean and the atmosphere, representing the two opposite moisture fluxes (evaporation and precipitation), until now remains the most difficult element of the hydrological cycle [1, 2]. The difference "evaporation minus precipitation" (E-P) is the link between the water balance of the atmosphere and the freshwater balance of the upper ocean layer. Let us write the equation of atmospheric water balance in the integral form [3]:

$$\frac{\partial W}{\partial t} + \mathrm{div}F + \frac{\partial W_w}{\partial t} + \mathrm{div}F_w = E - P. \tag{1}$$

Here W — total precipitable water of atmosphere ("precipitated water"), $\boldsymbol{F}$ — vertically integrated horizontal total flux of water vapor. W_w — atmosphere moisture content (in clouds), $\boldsymbol{F}_w$ — horizontal flux of liquid-drop moisture. Value of W_w is at least one order of magnitude less than W, thus it can be neglected together with div$\boldsymbol{F}_w$ without a significant loss of accuracy. The value of div$\boldsymbol{F}$, based on the Ostrogradsky—Gauss theorem, is interpreted as the difference between the transfer of atmospheric moisture beyond the considered water area (territory) and the introduction of moisture inside. For the global ocean as a whole, the outflow of water vapor predominates over its introduction, and for a long period of time the value of div$\boldsymbol{F}$ corresponds to the total inflow of fresh waters (rivers, ground and glacial waters) to the sea.

In present, a significant number of reanalysis archives are known, containing estimates of evaporation and precipitation over the ocean surface. Naturally, the question of evaluating the accuracy of the calculated characteristics is of fundamental importance. In foreign studies, the estimation of their accuracy is carried out mainly at a qualitative level by calculating the divergences of the moisture exchange components from different archives with each other. However, comparison of the calculated characteristics of one archive with unknown errors with the characteristics of another archive, but also with unknown errors, can hardly allow to reliably estimate the quality of the product and reveal its disadvantages. Obviously, for this purpose some physical criteria should be applied. The simplest equations are the equations of freshwater (2), thermal (3) global ocean water budgets which for a long time period in the stationary approximation have the form [3]:

$$E^* - P^* = Q_{gl}, \tag{2}$$

$$R^* = LE^*\left(1 + Bo^*\right), \tag{3}$$

where Q_{gl} — global fresh water inflow to the ocean (river, ground and glacial waters); R — radiation balance at the sea surface; LE — heat losses on evaporation; Bo — the Bowen ratio ($Bo = H/LE$); H — turbulent air-sea exchange; and the index "*" means the average over the global ocean water area. Note, that in equation (3) heat fluxes at lateral boundaries with land and sea bottom are equal to zero. Since H is an order of magnitude smaller than LE, even marked errors in the values of H can not significantly affect the accuracy of LE. In equation (2) Q_{gl} is determined with the highest accuracy, and in equation (3) all parameters are determined much more accurately than evaporation.

So, the system of simple balance criteria allows to easily control the components of moisture exchange in the global ocean-atmosphere system. Unfortunately, for regional scales and shorter time periods, the accuracy of the moisture exchange components can only be controlled at a qualitative level. It is much easier to achieve accuracy of the estimates of atmospheric total precipitable water (TPW), which is directly measured from satellite data with an average error $\sigma = 1.0$ mm, which does not exceed several percent of TPW values [4].

The paper [3] presents the following "reference" estimates based on climate data in the early 1990s: net evaporation — 13 cm/year, evaporation — 140 cm/year, precipitation — 127 cm/year. In present, these estimates can be adjusted on the basis of modern data on global ocean heat balance. The paper [5] provides the estimates of the global ocean heat balance components calculated for 43 climate models of the CMIP5 project and averaged over a five-year period (2000—2004). The average estimates for the whole complex of models are $R^* = 120.3$ W/m^2, $LE^* = 104.8$ W/m^2, $H^* = 13.6$ W/m^2. Proceeding from this, from the Eq. (3) we get $E^* = 133$ cm/year, which almost coincides with the direct estimate of evaporation $E^* = 134.4$ cm/year. Taking up $Q_{gl} = 12$ cm/year [6], we get from (2) $P^* = 121$ cm/year. Thus, new "reference" estimates are: net evaporation — 12 cm/year, evaporation — 133 cm/year, precipitation — 121 cm/year.

A comparison of data for global ocean evaporation and precipitation for 2002—2008 for eight different types of reanalyses presented in [7] showed that the estimates of net evaporation are very low. Moreover, they are negative for four reanalyses types (MERRA, R2, ERA-40, CFSR), i.e. precipitation is greater than evaporation, which is absurd from the physical point of view. According to ERA-40 precipitation exceeds evaporation by 38 000 km^3/year, or by 10.5 cm/year. Given the relatively short calculation period these estimates can only be considered as approximate. More accurate estimates of evaporation and precipitation were obtained in [8] where they were calculated for 12 types of reanalyses for a 35-year period (1979—2014). Evaporation and precipitation means are 129 and 118 cm/year, which is somewhat lower than their "reference" values. The data on evaporation and precipitation from the MERRA (115 and 104 cm/year) and JRA55 (146 and 134 cm/year) archives have the largest deviations from the "reference" estimates, although the difference E^* - P^* in both cases almost corresponds to the Q_{gl} value. Only for one archive — ERA-40 the difference E^* - P^* was negative. This means that given the significant extension of the evaporation and precipitation time series, their mean annual values for most reanalysis archives approach the physical accuracy criteria. But this does not mean high accuracy of the interannual variability of moisture exchange components. There is a significant dispersion for various archives even in linear trends: from overestimated positive to negative values [2, 7, 9, 10]. In this regard, the main goal of this paper was to analyze the trends in components of the atmospheric water balance over the global ocean.

Results and discussion. The archive of atmospheric total precipitable water (TPW) was used, the data set is constructed using RSS Version-7 microwave radiometer total precipitable water (TPW) data (also referred to as total columnar water vapor). The input microwave data are processed by Remote Sensing Systems with funding from the NASA MEaSUREs Program and from the NASA Earth Science Physical Oceanography Program [11]. The archive (ftp://ftp.remss.com/vapor/monthly_1deg/) contains a series of average monthly TPW values since 1988 on 1×1° grid and is constantly updated.

Evaporation, precipitation and other characteristics of ocean-atmosphere interaction were determined using the archive data of NCEP-DOE Atmospheric Model Intercomparison Project (AMIP-II) reanalysis (Reanalysis-2) [12]. This archive is constantly supported and is among the most reliable. From this archive the average monthly values of the characteristics at nodes of a 2.5×2.5° geographic grid were selected for the open ocean. It should be noted that the preliminary averaging of all the mean monthly fields into the five-degree "squares" was performed. After that the values were averaged for 5-degree latitudinal zones of the ocean and the entire global ocean water area. It is important that the TPW values are independent of the characteristics from another archive.

The calculations showed that the average long-term values of E^* and P^* for 1988—2016 are 137.0 and 128.7 cm/year respectively, i.e. they are slightly higher, and net evaporation (8.7 cm/year) is slightly lower than the reference values. Fig. 1 shows the interannual variation of the global ocean evaporation and precipitation. Both time series have a pronounced positive trend. In this case, the trend for precipitation is 4.0 mm/year, and for evaporation — 2.9 mm/year (Table). Since the amount of precipitation over the sea grows faster than evaporation, the trend in net evaporation is negative. This means that a sea level rise by 1.1 mm/year corresponds to the decrease in net evaporation by 1.1 mm/year. Consequently, the contribution of net evaporation to the actual rise of sea level (3.1 mm/year) reaches 35 % and is comparable in its significance to the contribution of steric fluctuations [13].

We should note that in [1] according to the data of Reanalysis-1 [14] similar calculations were carried out for evaporation and precipitation over the global ocean for the period of 1980—2005. It was shown that the trend for precipitation is 4.2 mm/year, and for evaporation — 3.6 mm/year, i.e. net evaporation was — 0.6 mm/year. Obviously, in recent years an effect of ocean-atmosphere moisture exchange on the sea level has been intensified and at the same time an outflow of water vapor resulting flux from sea to land has been decreased.

Fig. 2 shows the interannual variation of net evaporation and atmospheric total precipitable water over the global ocean for 1988—2016, and their oppositely directed trends. Net evaporation (resulting moisture flux to land) decreases rapidly at a rate $Tr = -1.1$ mm/year. Thus, during the considered 29-year period net evaporation has decreased by 3.2 cm, which is over 25 % higher than the average Q_{gl}. In fact, this means a significant drying up of the land and an increase in water resources scarcity. As for TPW, it grows at a rate of $Tr = 0.57$ mm/10 years.

In principle, one way of an independent assessment of the accuracy of the global net evaporation trend is to compare it with the trend of «global» surface salinity. Unfortunately, this is currently impossible because of the absence of the time series of global salinity annual values. Trends in salinity are considered mainly at a qualitative level, i.e. in the form of maps [15—17], and the important regularity is the focal character of the

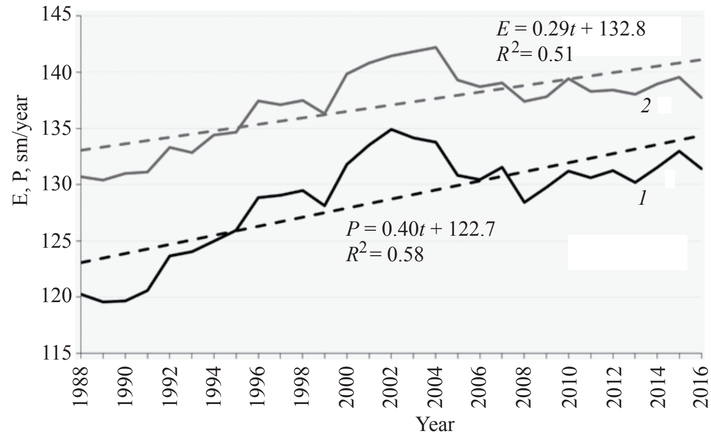

Fig. 1. Interannual variation of precipitation (*1*) and evaporation (*2*) over the global ocean according to the data of Reanalysis-2 archive for 1988—2016.

Рис. 1. Межгодовой ход осадков (*1*) и испарения (*2*) (см/год) над Мировым океаном по данным архива Reanalysis-2 за 1988—2016 гг.

Table 1

Trend equations, estimates of determination coefficients and trend index for the ocean-atmosphere system characteristics for 1988—2016

Уравнения трендов, оценки коэффициентов детерминации и индекса тренда для характеристик системы океан-атмосфера за период 1988—2016 гг.

Characteristics	Trend equation	Determination coefficient	Trend index, % 100 (a_1n/X_{mean})
TPW*	0.057 *t* + 27.095	$R^2 = 0.82$	5.91
AT*	0.018 *t* + 16.74	$R^2 = 0.72$	3.07
SST*	0.017 *t* + 17.19	$R^2 = 0.71$	2.83
*E**	0.286 *t* + 132.8	$R^2 = 0.51$	6.05
*P**	0.403 *t* + 122.7	$R^2 = 0.58$	9.08
*E**—*P**	−0.116 *t* +10.12	$R^2 = 0.62$	40.1

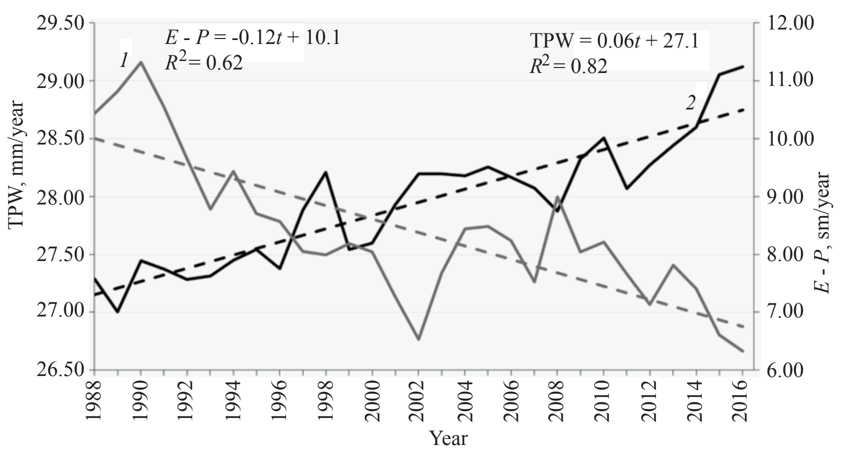

Fig. 2. Interannual variation of net evaporation (*1*), cm/year and atmospheric total precipitable water over the global ocean (*2*), mm/year for 1988—2016.

Рис. 2. Межгодовой ход эффективного испарения (*1*), см/год, и влагосодержания атмосферы *W**(*2*), мм/год, над Мировым океаном за 1988—2016 гг.

trend spatial distribution. As a consequence, when they are averaged over the entire global ocean the global trend may become insignificant. A comparison of trends in salinity and *E* - *P* is also shown in the form of maps [17, 18], which does not allow for quantitative conclusions. Perhaps the situation will fundamentally change with the accumulation of satellite data on salinity. The newest version of the Aquarius satellite covers the period of weekly observations of global salinity from September 2011 to May 2015. The monthly salinity values from SMOS (*Soil Moisture and Ocean Salinity*) are available for 2010—2014. Obviously, these periods are too short for the trend estimation.

As follows from the Fig. 2 since 2008 there has been an acceleration in the growth of TPW. What are the reasons for TPW rapid growth? According to the IPCC experts [19], «*water vapor concentration rise is a key consequence, but not the reason of a global warming process and, therefore, is entirely due to a positive feedback between them*». Indeed, there is a high correlation between the air temperature (AT) and TPW. However, the correlation shows only the strength of the connection, but not the causal nature of the relationship between the variables. Obviously, the unilateral influence of AT on TPW can not be claimed based on their positive feedback. It is the water vapor that is the dominant greenhouse gas [20] that can influence AT through the greenhouse effect. Therefore, on the one hand, with an increase of global air temperature there is a certain TPW rise, on the other, the growth of TPW through the greenhouse effect leads to temperature rise.

Since a direct comparison of TPW and AT trends is impossible due to their different dimensionality, we reduce them to the dimensionless form [21]. This can be done with the trend index, representing a ratio of the trend span to its average value and is expressed in percent, i.e.:

$$I_{tr} = 100\, a_1\, n \,/\, X_{av}.$$

Here a_1 — trend value, n — length of time series, X_{av} — trend average. In fact, the trend index is a kind of analog of the coefficient of variation used to compare the variability of characteristics having different dimensions.

Table presents the trend equations, estimates of determination coefficients and the trend indices for various characteristics of the ocean-atmosphere system for the period 1988—2016. All the trends indicated in the table are significant according to Student's test at the significance level $\alpha = 0.05$. TPW has the maximum coefficient of determination, and for the evaporation it is the lowest. When the net evaporation (for which a high value of I_{tr} to a certain extent is due to the low mean value) is not considered, then the trend index is the highest for precipitation (9.0 %), almost the same for evaporation and TPW (6.0 and 5.9 %) and is the lowest for SST and AT (2.8 and 3.1 %). In fact, this means that the long-term (trend) changes in TPW depend first of all on the vertical ocean-atmosphere moisture exchange, and not on global warming. In this regard, the weight of evidence suggests that TPW is not only a key consequence of the global warming process, but is also its forming factor.

Conclusions. The calculations showed that the growth of global ocean moisture exchange components has accelerated. The trend for precipitation and evaporation for the period of 1988—2016 was 4.0 and 2.9 mm/year. Consequently, in recent years the effect of the ocean-atmosphere moisture exchange on the global ocean level has intensified and at the same time the outflow of the resulting water vapor flux from ocean to land has decreased. The contribution of net evaporation to the actual increase in global sea level (3.1 mm/year) reaches 35 %.

Analysis of dimensionless trends showed that the trend index is the highest for precipitation (9.0 %), almost the same for evaporation and total precipitable water (6.0 and 5.9 %) and is the lowest for SST and AT (2.8 and 3.1 %). In fact, this means that the long-term (trend) changes in TPW depend, first of all, on the vertical ocean-atmosphere moisture exchange, and not on global warming. In this regard, the weight of evidence suggests that TPW is not only a key consequence of the global warming process, but is also its forming factor.

The research results (trend assessment for some characteristics of air-ocean interaction, Table) were obtained in frames of the Government order of Federal Agency for Scientific Organizations of Russia (Theme № 0149-2018-0014).

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