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Historical Changes of the Regional and Global Hydrological Cycles

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ABSTRACT: The gradual accumulation of the Earth's hydrosphere, the land-to-water ratio, the periodic change of orogenesis and peneplanization stages, the timely and spatial change of the incoming solar energy determined the periodic changes of the major global hydrological cycles with the development of continental glaciations and permafrost of great pluvial epochs of a global warming in the geological past.

Within a relatively short historical period various reasons for periodic and non-periodic heat and water transfer have led to changes in the hydrological cycle and to land moisture fluctuations.

At present global hydrological processes are going through quite drastic changes as a result of the fluctuations of a number of geophysical processes (natural energy factors, in the first place). The global warming of the climate has resulted in the increase in the intensity of surface water exchange, in the drying up of continents and in the filling of the World Ocean. These changes are accompanied by an increase in the anthropogenic impact on water balance by the strenghthening of hydrologic exchange and the slowing down of river water exchange.

Water on the Earth is continuously interacting with the lithosphere and atmosphere, and is permanently migrating and changing its physical state. It is all the time consumed and regenerated in the process of cycling. Water cycling in nature, or the socalled hydrological cycle – is a continuous closed process of water circulation on the globe lead by the inflow of solar radiation and the force of gravity. Water evaporates from the ocean and land surfaces and goes to the atmosphere, wherefrom it precipitates back to the surface of the Earth. Water precipitation on the land surface feeds rivers and underground aquifers, and the river runoff supplies water to seas and oceans.

Besides the annual water cycles involving about 1 million km^3 of water, there are also the multiyear cycles of water availability on lands characterised by alternation of water-deficient and water-surplus periods of different duration and different magnitude.

On a whole, despite the gradual increase of the volume of hydrosphere, in the process of the past geological evolution of land gradual dessication of the continents took place mostly due to deepening of the oceanic basin and increase of the mean height of the orogenic structures. Over this background the cycles of 190–200, 50–55, 17–18 million years and other cycles can be identified (Klige 1980) (Fig 1).

The land-ocean ratio, periodical alternation of the epochs of orogenesis and peneplanation, time-space changes of solar influx determined the periodical changes of the global hydrological cycles with development of the continental glaciations and permafrosts, or large pluvial epochs of general warming.

As disclosed by studies of the hydrological cycles, in the geological past the water regimes could be significantly different. Thus, the Mesozoic rivers had much higher runoff (Razumikhin 1976). As compared to the Early Cretaceous, in the Late Pliocene runoff from the territory of Central Asia was nearly 10 times lower, and 3–4 times lower, than in the Late Oligocene.

According to the levels and areas of lakes fixed by numerous fragments of sediments and specific features of geomorphology, in the Middle Jurassic there were many lake systems (in Kazakhstan, Central Asia, Tuva, Kuznetsk basin, Mongolia, China, and other regions). At the same time, humid and moderately humid climatic regimes favoured abundant growth of vegetation and formation of the Carboniferous sedimentary strata (Martinson 197; Sinitsyn 1980). The hydrological cycles with development of lake systems are peculiar for the Lower and Upper Cretaceous.

Vast lakes of the lagoon type and intracontinental seas are known, their connections with the ocean were

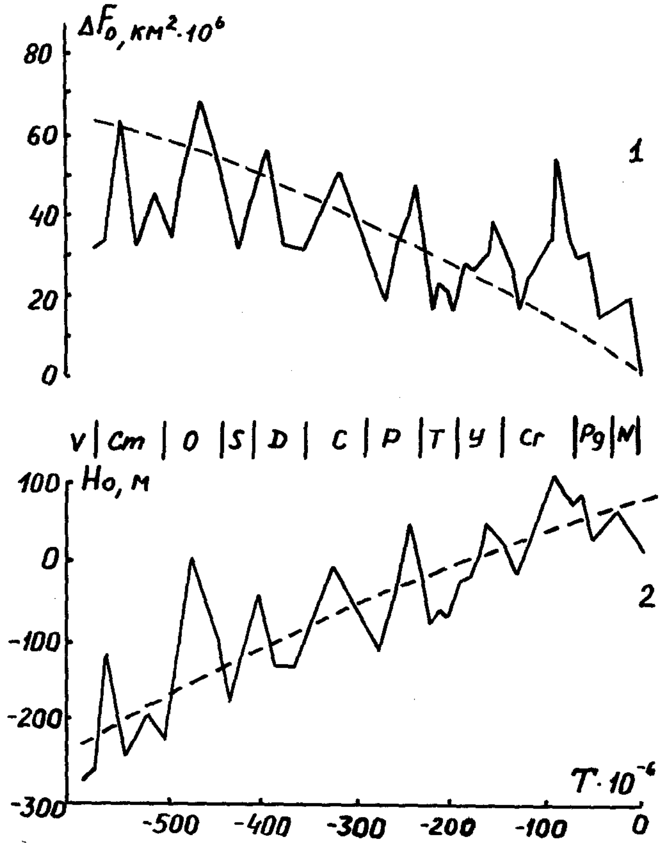
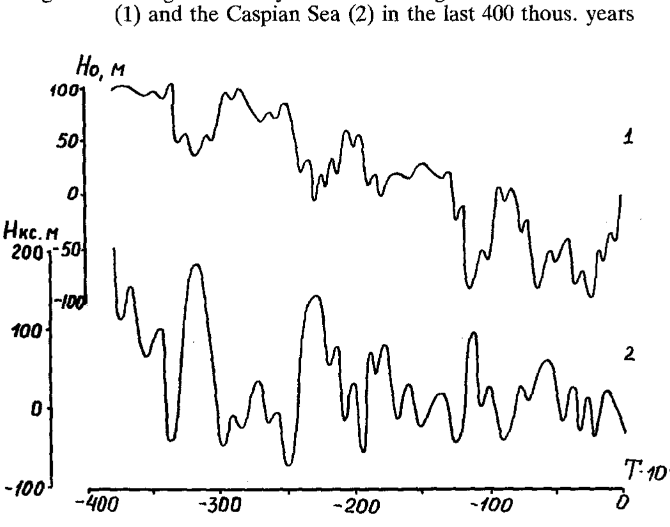


Fig 1 Global changes of the cycles of submergence by the ocean (1) of land in the phanerozoic and (2) oscillations of the sea level

periodically interrupted, and this produced changes in the regimes of these water bodies from oceanic to typically lacustrine ones. The driving factors could be both tectonic processes, and important changes of the sea levels.

Fig 2 Changes of the cycles of water regime of the world ocean (1) and the Caspian Sea (2) in the last 400 thous. years



During individual large hydrological cycles vast inner seas were also emerging. A case of such gigantic sea nearly fully isolated from the ocean was the Sarmatian Sea in the S of Eastern Europe about 17–8 million years BP, and probably, connected to the ocean in the end of the Miocene. It stretched from the Carpathians to the mountains of Central Asia covering the S of Ukraine, the territories of the Black, Caspian, and Aral Seas, and was over 3 million km^2 in area.

Important influence on the water regimes on land and on formation of the specific features of the hydrological cycles was produced by development of the continental glaciations, their impacts being traced in the Lower Proterozoic, Upper Riphean, Vendian, Ordovician, Silurian, Carboniferous, Permian, and several other geological periods (Kotliakov 1968; Monin, Shishkov 1979, etc.).

In the best studied Quaternary period the glacial sheets were spread over up to 45 million km^2 of land and 25 million km^2 ocean area, correspondingly (under maximum glaciation). That means, that 30% of land or about 14% of the Earth's surface was covered by ice of total volume of about 62.4 million km^2 (Suetova 1968).

In the period of development of the continental glaciations, large-scale development of the periglacial lakes took place; they were covering vast territories (Kvasov 1975).

The most sensitive to changes of the global water circulation were the closed reservoirs. According to studies of the paleogeographical regimes, of evolution of the hydrological cycles on the Earth's surface, and of their relationships with the sea levels and with levels of the largest closed water bodies, the epochs of large transgressions of the ancient lakes, the epochs of glaciations, and the planetary regressions of the World Ocean were practically synchronous (Fig 2).

About 40 thous. years ago in the Kalinin phase of the Valdai Ice Age in Europe and the Tillit-Mogador phase of the Wisconsin Ice Age in North America when the air temperature was, apparently, 5–10° C lower than today, the level of the Caspian Sea was more than 75 m higher than now, corresponding to larger area – up to over 900 thous. km^2 of this sea (Varushchenko; Klige 1987), and to over 130 thous. km^3 of the water volume (about 78 thous. km^3 now).

The level of the Bonneville Lake reached up to 1609 m about 40 thous. years BP (Eardley et al. 1973) (contemporary level – 1260 m), its area was about 60 thous. km^2 (contemporary – 2500 km^2) and its volume was more than 14 thous. km^3 (now – 11 km^3).

The Lake Lahontan that has nearly disappeared at present, reached the maximum level of about 1350 m 40000 years ago (now – 1150 m) and overflowed the area of 22442 km^2, its water volume approached 3000 km^3 (Larry 1978).

In the period of interstadial warming (about 25–23 thous. years BP) the hydrological cycle was changing, and the closed water reservoirs were characterised by

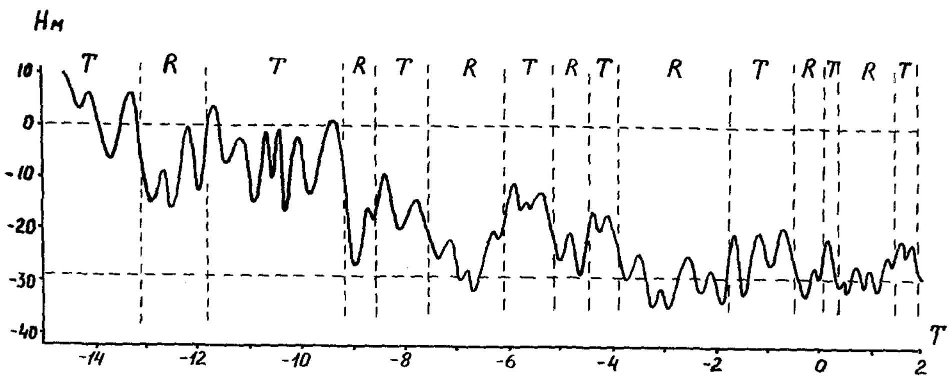


Fig 3
The cycles of water abundance (transgressions and regressions in the regime of the Caspian Sea in the Post-Glacial Period

profound regressions. In that period the levels of water reservoirs could be close to the contemporary ones, or even lower.

About 20 thous. years BP a new wave of cooling emerged, and the next stage of the Valdai Ice Age started (the Bologoe stage) in Europe and of the Wisconsin Ice Age (the Late Wisconsin, the Woodford) in North America. The closed lakes showed a nearly simultaneous response to this lowering of temperatures by the transgressive rise of levels, the maximum took place about 16 thous. years BC (the Caspian – 15 m, Bonneville – 1594 m (Eardley et al. 1973), Lahontan – 1320 m (Larry 1978). Starting from that time the continental ice sheets started to gradually degrade, air temperature was rising, and the lake levels showed gradual decline. Over the background of the major hydroclimatic cycle of the decline of moistening over continents, several lower-rank cycles took place.

Thus, in the period of degradation of the recent continental glaciation – the past 17 thous. years – the largest intracontinental water body – the Caspian Sea – underwent a series of oscillations asynchronous to the oscillations of the Ocean's level, showing a general trend towards decline at a mean rate of about 3 mm/year; this gives evidence of an overall gradual reduction of precipitation over the continents (Fig 3).

In this period at least eight rather significant transgressions and regressions of the Caspian Sea level can be identified. The changes of similar character took place in other closed lakes, located in Africa, as well as in North America. Using data on oscillations of the lake levels, glacial dynamics, humidity of peat areas, archeological data, and some other parameters, one can isolate in the hydrological cycle the periods of precipitation oscillations of different duration – from 3–4 years to 1850 years and more.

The factors of different origin that were changing the heat-water cycles in the past, both of the periodical and non-periodical directed character, produced in a relatively brief historical period changes of the hydrological cycle and fluctuations in precipitation over land that are often devoid of clear periodicity. This can be easily traced taking, for example, the changes of several parameters characterising precipitation over Europe in the recent 2 thous. years (Fig 4), mean multi-annual totals of precipitation for 50-year periods for summer and winter seasons in England (Lamb 1977), deviations of the totals of summer rainfall in Estonia from the present-day values (Klimanov et al. 1985), deviations of the depths of lacustrine deposits of the Pert-Lake from the average for 1.5 thous. years in the south of Karelia (Schostakowitsch 1931); depths of the varved clays in the Saki Lake in the Crimea (Schostakowitsch 1934), inflow of the surface runoff to the Caspian Sea (Klige 1988), reconstructed runoff of the Dnieper (Shvets 1978).

This climates of the recent millenia are described by rather abundant historical data, and are characterised by three major trends: warming of the 8th–13th centuries, or the so-called "little climatic optimum"; the subsequent cooling that occurred nearly everywhere till the middle of the XIX-th century with some deviations (Little Ice Age); and another warming since the second half of the 19th century reaching its relative maximum in the 1930–1940-es of the 20th century.

The maximum warming in the period of the little climatic optimum (LCO) was observed in Europe at the turn of the 12th–13th centuries, and in individual regions – till the first decades of the XIV-th century (Lamb 1977). For example, in the centre of the Russian Plain – in the 14th century (Buchinskiy 1957; Liakhov 1984), in the Far East – in the 15th–17th centuries (Arakava 1975). The mean temperatures of the vegetation period in the LCO are assessed as exceeding the contemporary temperatures in Western and Central, as well as Eastern Europe by about 1° C (Le Roi Ladurie 1971; Klimanov & Serebriannaia 1985, etc.) or by 2° C (Liakhov 1984). According to H. Flohn (1975) the period from 900 till 1050 could be characterised by increase of the mean global temperature of air by 1° C and more frequent droughts in Europe. Higher aridity of the summer months, and higher precipitation in the winter months have also been observed (Lamb 1977; Borisenkov & Pasetskiy 1983). Decline of precipitation was also a feature characteristic of the Russian Plain (Kostin 1979) and the surrounding mountains (Turmanina 1979). But for the Baltic area and the northern regions of the European USSR there are data on about 50 mm excess of the annual precipitation totals in the LCO as compared to the modern ones (Klimanov & Yelina 1984; Klimanov; Koff; Punning 1985). In the opinion of S. G.

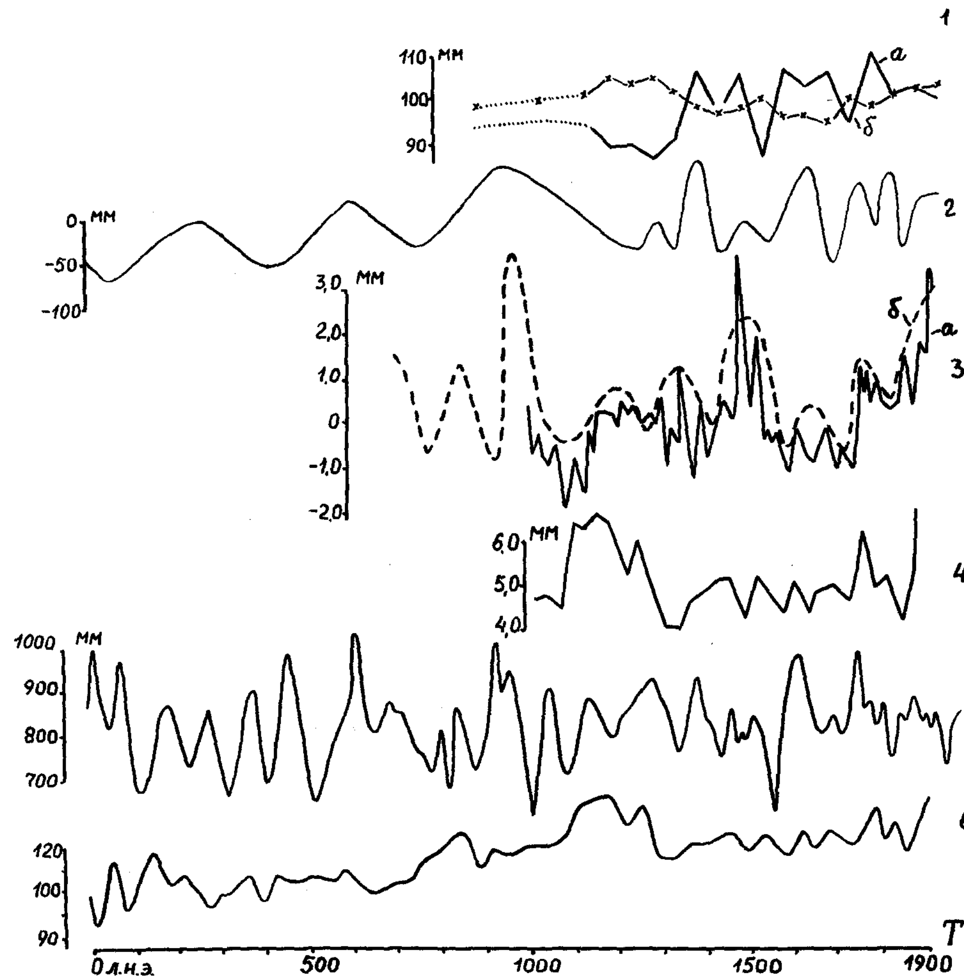


Fig 4
Changes of precipitation and river runoff in different parts of Europe in the last 2 thous. years: 1. Mean multi-year precipitation totals by 50-year summer (a) and winter (b) seasons in England (Lamb 1977); 2. Deviation of the values of summer precipitation of the modern ones, Estonia (Klimanov et al. 1985); 3. Deviation of depth of the Pert-lake deposits from the mean for 1.5 thous. years, S of Karelia (Schostakowitsch 1931); 4. Depths of varved clays of the Saki lake, Crimea (Schostakowitsch 1934); 5. Inflow of the surface waters to the Caspian Sea (Klige 1988); 6. Reconstructed runoff of the Dnieper river (Shvets 1978)

Miagkov (1979), the LCO are in general characterised by reduction of precipitation over Europe. But in the 13th century precipitation was rapidly increasing over the background of relatively high air temperatures. This produced expansion of glaciers in the Alps and in Iceland: ice in the Northern Atlantic Ocean has become more abundant. On the basis of his reconstructions of the precipitation extrema in the past 4100 years, using data on reconstructed annual runoff of the Dnieper (Shvets 1978), Yu. L. Rauner (1981; 1985) concluded, that in the first phase of the LCO (750–950 years) there was a gradual increase of extremely humid years followed by reoccurrence of relatively arid regimes. In the main phase of the LCO (950–1250) global increase of temperature was, probably, associated with acute growth of precipitation (Bruks 1952). As compared to the mean level, increased incidence of extremely humid summer seasons and of the spring-summer floods in 1100–1300 has also been registered in Belgium.

The relative growth of total annual precipitation in the western and northern regions of the European USSR, increased depth of silty deposits, higher runoff in the Caspian basin can be taken as an evidence for more aboundant precipitation in the region in the middle of the 10th century and 12th–13th centuries. Correspondingly, aridity of climates could be more intensive in the 11th and at the turn of the 13th–14th centuries.

After the LCO practically everywhere there was a general decline of the temperature background with individual extrema of warming. Thus, in the Baltic area warmings took place about 600, 300–400 and 150 years ago, but at that time the mean annual air temperatures didn't exceed the modern ones up to the 1930–50-es of the 20th century (Klimanov; Koff; Punning 1985). The most clearly pronounced and spread practically everywhere was the warming at the turn of the 15th–16th centuries, it allows to divide the Little Ice Age (LIA) into two phases: 14th–15th and 17th–19th centuries. In the first phase of the LIA overall reduction of temperature went parallel to decline of precipitation (Miagkov 1979). In Europe transition to the Little Ice Age became clear between 1300 and 1450 with reduction of air temperature by 1.3–1.4° C, then again very well-pronounced in 1550–1700, the intermediate period was characterised by extreme variability of the hydroclimatic regimes (Lamb 1977; Borisenkov & Pasetskiy 1983).

In the second phase of the LIA the general decline of the temperature background was accompanied by growth of precipitation, of winter precipitation, as well. There was active expansion of glaciers, enforcement of the avalanche danger in the Alps. The maxima of this glaciation are timed to about 1600 and 1800–1840 (Le Roi Ladurie 1971). The Caucasian mountains, according to data of V. I. Turmanina (1979) had three periods of the glaciers' advancements in this epoch: 1640–1660, 1730–1750, and 1790–1840. The reduced temperature background is disclosed by the significantly higher frequency of severe winters (Dulov 1983), higher abundance of ice in the Baltic Sea, especially in the middle of the 17th century. For example, the port of Riga was annually freed from ice 6–10 days later than in the beginning and the end of the century (Betin & Preobrazhenskiy 1962). In E Europe the summer temperatures were by about 1.5° C lower than now (Klimanov et al. 1985). According to data of M. Ye. Liakhov (1984) in this period the lowest winter temperatures were also observed – by 2.5° C lower than today. The patterns of air temperature since the middle of the 17th century till the 1930–40s of the 19th century show nearly everywhere in Europe the intrasecular hydroclimatic oscillations. A. V. Shnitnikov isolated the following phases of increased humidity in this period: the 1980s of the 18th century, 1800–1815, 1940s of the 19th century. The latter is usually referred to as the end to the Little Ice Age. According to V. A. Klimanov, the extreme values of precipitation could be the periods between warmings and coolings. In the maximum phases of the LIA the frequency of summer seasons with heavy rainfall was increasing in the Baltic area and in Poland, and also in W Europe, while droughts could be more frequent in the more continental regions of European Russia (Drozdov 1980).

Growth of precipitation in the temperate latitudes agrees well enough with higher density of ice in the northern seas, and vice versa (Drozdov 1982).

At present, under the influence of several geophysical factors, natural energy fluctuations, first and foremost produced the climatic fluctuations, and the global hydrological cycle has undergone rather clear transformations (Klige 1985). According to calculations, starting from the end of the last century when the anomaly of the potential evaporation could reach about –40 mm, up to the 1940s of this century the dominating trend should be increase of the total evaporation from the ocean (Fig 5), resulting in its increase by 74 mm (nearly 27 thous. km^3), or by more than 5% of its multiyear mean of 507 thous. km^3 (1894–1975). By the 1960s the trend became somewhat downward (about 2%).

The multiyear pattern of precipitation over the oceanic surface showed a trend to its growth at a mean rate of about 500 km^3/year, that was afterwards replaced by the trend towards reduction of precipitation of about the same magnitude. The lowest values of precipitation over oceans correspond, probably, to 1882, 1908, 1912, and 1916, when they were by about 30–40 mm lower, than the multiyear average, and the highest values, exceeding the multiyear average by somewhat more than 40 mm corresponded to 1938 and 1941 – the maximum warming. Total changes of precipitation were rather small – of the order of ± 3% (Fig 5).

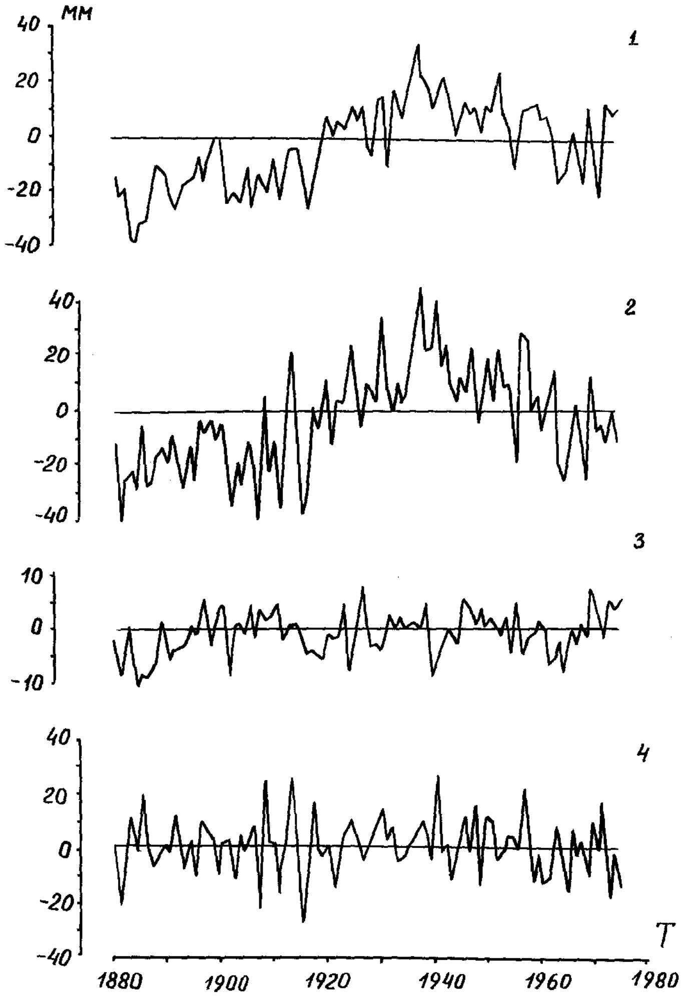


Fig 5 Changes of the components of water budget of the World Ocean in the anomalies: of evaporation (1), of precipitation (2), of river and glacial runoff (3), and annual increment of the ocean's waters (4)

Assessments of water budget demonstrate several specific features in the pattern of multiyear changes of precipitation in this century.

Thus, growth of precipitation (over 2%) took place over the ocean in the end of the 1930s – beginning of the 1940s (Fig 6) in the period of warming; and over continents (except for Antarctica and islands) there was sharp reduction of precipitation and of the meridional gradient (about 1° C) in this period.

The time variability of precipitation in Antarctica was studied by Schwerdtfeger (1976), N. V. Petrov (1975) and others with data on the annual layers of snow accumulation averaged for one decade. It was found that the rate of accumulation of the Antarctic ice sheet was increasing since the end of the 19th century to the 1930s of the 20th century, but around the 1940–50s it started to decline.

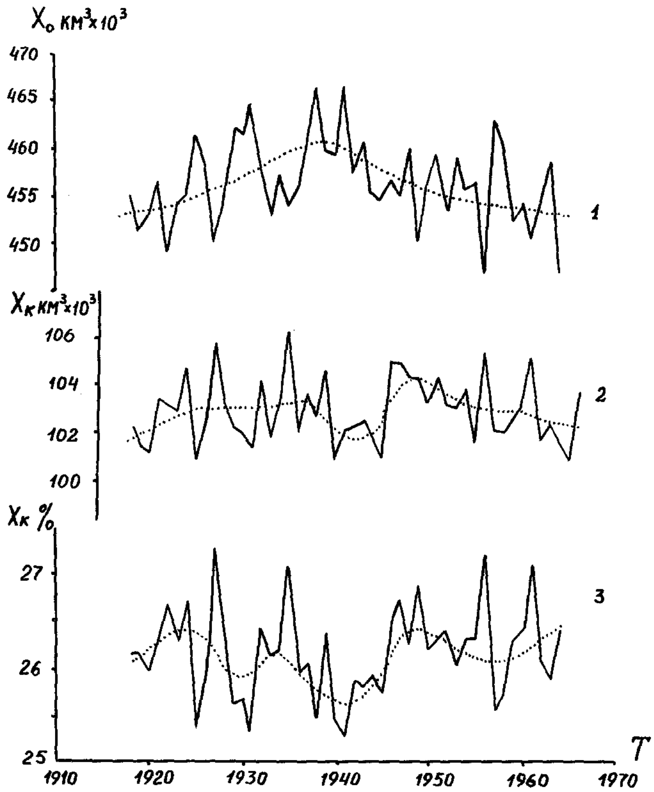


Fig 6 Changes of precipitation over the World Ocean (1), and over continents (2), and percentage of the continental precipitation in the oceanic ones (3)

Of a certain interest is the multiannual pattern of the ratio of precipitation over continents to that over the oceans (Fig 6); it demonstrates, that with warming the role of continents is declining and reaches the minimum (within the limit of 2%) in the period of highest temperatures and their lowest gradients.

On a whole, the current century was characterised by a weak trend towards increase of precipitation over continents (without Antarctica) of the magnitude of about 0.25 mm (31 km^3) per year or about 0.03% over the background of the general gradual warming. The specific features of the multiannual patterns of atmospheric precipitation are most densely correlating with the multiannual changes of the mean air temperatures and of their meridional gradients. With increase of the air temperatures evaporation from the surface of the World Ocean increased, too. Owing to transportation of this moisture towards the continental areas, there was higher precipitation there in the beginning of warming, too. At the same time, together with the temperature increase, one could observe a clear anomaly of the meridional gradient of air temperature reaching its minimum in the period of maximum warming in the 1940s. Changes of the latitudinal temperature gradient were influencing the intensity of transportation of the water vapour from the ocean to continents.

Reduction of the meridional temperature gradient has lowered the intensity of atmospheric circulation, and in the final run – the inflow of the water vapour to the intracontinental areas and the amount of precipitation over a significant portion of land. An opposite situation has developed in the 1950–60s.

Important changes could be expected in this century in the processes of evaporation that were influenced by heat-moisture relationship in different regions.

According to studies of the potential evaporation (L_m) over continents in the period 1881–1975, being proportional to oscillations of the mean air temperature it could fluctuate within the range of from 1083 mm (1884–1885) to 1141 mm/year (1938) (± 2.5%) and mean multiyear values – about 1110 mm (Zubenok 1976). From 1881 to 1938 a trend towards increase of the maximum potential evaporation was observed, at a rate of about 0.7 mm/year, that was later substituted by the trend towards its reduction in the order of 0.55 mm/year (Fig 7).

The calculations of the multiannual patterns of the total evaporation from continents excluding Antarctica (area about 125.1 mln km^2) have explicated its oscillations (±6.5%) within the anomalies from −39 (1805) to 22 mm/year (1938) with a multiyear average of 526 mm (65800 km^3). The multiyear pattern of the potential evaporation from the continents demonstrates several peculiar periods (Fig 7). Thus, increased evaporation was charateristic of the years: 1897–1901, 1921–1954, 1970–1975, reduced – in 1881–1896, 1902–1920, 1955–1969, with an average periodicity of about 16 years. Evaporation was also characterised by a trend to growth by about 0.3 mm/year (0.07%). These changes of total evaporation from the land were determined by the relationship of the heat and moisture resources on land in individual periods.

One of the important components of the global hydrological cycle is the river runoff. As disclosed by the studies of its fluctuations, the general changes of the runoff and of total precipitation over continents are rather closely correlating with fluctuations of air temperature.

Usually in large regions increase of temperature to a certain limit is associated with increase of precipitation and runoff. But this pattern may differ in some physical-geographical regions, especially in the intracontinental regions located within the zones of insufficient moistening (Klige 1979; Mirovoi vodny balans . . . 1974).

Reduction of runoff over continents can in some cases take place in the periods of cooling, when evaporation from the ocean surface declines, inflow of moisture to land reduces, too, as it was observed in 1884–1888, 1917–1921, and 1962–1967.

On a whole over land areas (without the Antarctic islands) including the closed basins, too, the surface and underground runoff ranged from 276 (in 1925) to 317 mm/year (1897, 1976) with amplitude of 40 mm (5 thous. km^3) or within the limit of ±6.5% of its multiannual average of 300 mm, or 37.6 thous. km^3; the underground runoff accounting from about 12 mm of that, or 1.6 thous. km^3.

In the recent one hundred years the total runoff from the continents didn't show a clear trend of change despite a singificant rise of the global temperatures and increase of evaporation by about 8.8 km^3/year. Compensation of the runoff losses for evaporation was on account of increased runoff of the mountain rivers thanks to more intensive melting of glaciers (this increase amounted to about 0.4 km^3/year), and also of increased runoff from the coastal oceanic slopes thanks to higher precipitation.

The intracontinental closed basins show a negative trend of the runoff: it is reduced at an annual rate of about 8.8 km^3 (Fig 7).

A weak trend is observed of increasing river runoff that goes directly into the ocean; a more pronounced positive trend is found on islands due to higher precipitation in the oceanic areas, the increase amounts to about 1.2 km^3/year.

An ever greater impact on the changes of the hydrological cycle is produced by human activities; on the one hand, there is a clear increase of water outflow through evaporation from the irrigated lands and artificial water reservoirs, on the other hand, thanks to hydrotechnical construction there is accumulation of water in the man-made reservoirs and reproduction of water on land. Thus, the ever increasing anthropogenic influence on the hydrological cycle produces intensification of the moisture cycling in the atmosphere, prolongation of duration of a water cycle on the surface of the globe, and changes in the qualities of natural waters.

As a result of the recent climatic warming the following processes take place: intensification of the hydrological cycle (about 4%), aridisation of the continents (the lake volume reduces by about 63 km^3/year), depletion of the ground waters by about 136 km^3/year and of glaciers (Antarctica – 315 km^3/year, Greenland – 82 km^3/year, the Arctic ilands – 12 km^3/year, mountain glaciers – 3 km^3/year). This process is somehow decelerated by construction of water reservoirs – 69 km^3/year. On a whole ocean gets over 540 km^3/year more, enforcing its gradual thermal expansion.

As a result of the anthropogenic impacts on the natural processes one can expect further warming of the global climate, that can further intensify the processes of water circulation in the hydrological cycle. What arouses the greatest concern is growing degradation of the glacial sheets, and the possibility of their partial decomposition. This can produce rather rapid rise of the ocean's level (by about 5 m) followed by submerging of about 1 mln km^2 of coastal areas.

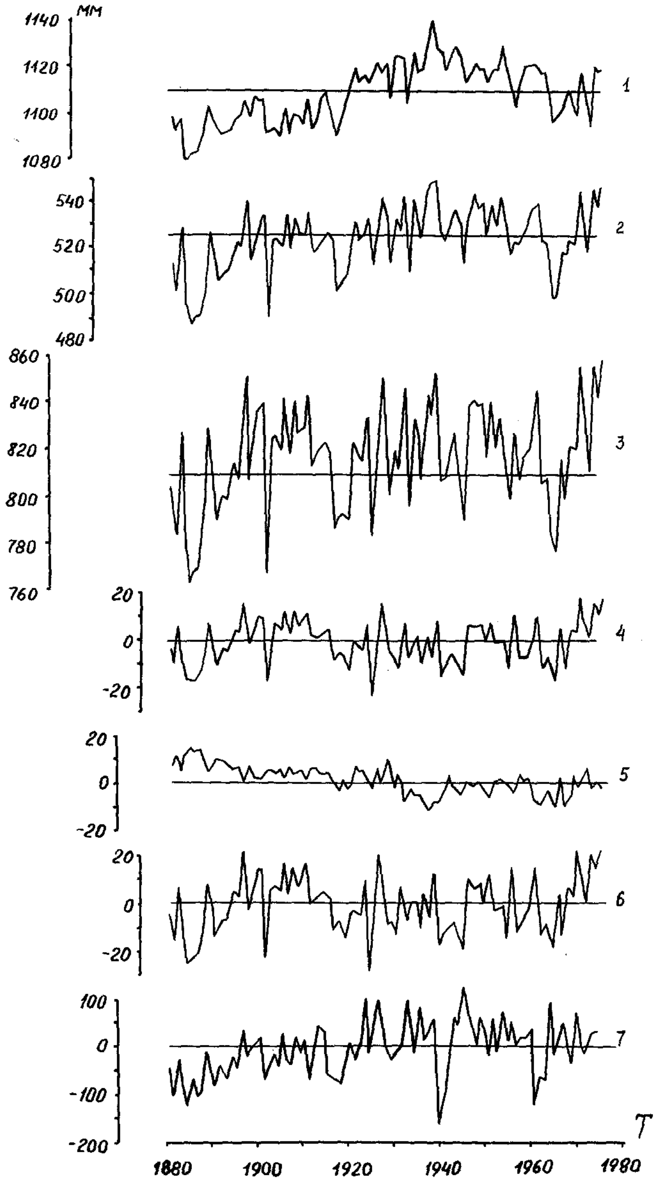


Fig 7 Changes on land of the potential evaporation (1), evaporation (2), precipitation (3), total surface runoff (4), runoff from inland areas (5), surface and underground runoff from continents (6), runoff from islands to the ocean (7)

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