THE CHANGE OF THE HYDROLOGICAL CYCLE UNDER THE INFLUENCE OF GLOBAL WARMING

A.G. GEORGIADI
Institute of Geography of the USSR Academy of Sciences, Staromonethy per. 29, Moscow 109017, USSR

ABSTRACT The impact of global warming on the water cycle can be extremely complex and diverse. The results of research summarized below illustrate the scale and the geography of the components' possible changes on a global, regional and local level due to global warming. The changes of air temperature, precipitation, river runoff, evapotranspiration and soil moisture are analyzed on different stages of warming. The results are a base for estimating the reaction of the hydrological regime of large river basin-large inner reservoirs systems. The different reactions of large river basins and of large inner reservoirs on different stages of warming and in different parts of the world are demonstrated.

INTRODUCTION

Climate warming is a phenomenon of a global scale. It may well be that the world is at the threshold of an extremely rapid change of climate in the nearest decades. There is no doubt that warming will greatly influence the water cycle - a powerful process regulating natural freshening of water resources, distribution of water on the continents, supply of fresh water to plants, animals, and man, greatly influencing erosional and geochemical processes.

The impact of climate warming on the water cycle is extremely complex and diverse. Different stages of warming will be characterized by different degrees of hydrological changes, although of the same general direction. The warming will be accompanied by an increase in the intensity of hydrological cycle, while the components of the cycle will change irregularly in time and space. The warming will cause considerable changes in the hydrological regime in large river basins but in different parts of the world the effect will be opposite.

The results of research summarized below illustrate the scale and the geography of the changes on a global, regional (including large river basins), and local levels due to global climate warming. In many instances the estimates are quite close to each other, but sometimes they differ much. Many aspects have so far been poorly studied. Among such aspects, a special place is occupied by the influence of changes in the vegetation cover on the process of hydrological cycle.
CLIMATE CHANGES CAUSED BY THE GREENHOUSE EFFECT

Peculiarities of the water cycle on the Earth reflect the current natural climatic situation that has in the main evolved during recent millenia and has underwent a considerable anthropogenic influence in recent decades.

The predicted climate warming will bring significant changes not only in the thermal regime of the Earth, but also in the regime of its atmospheric moisture cycle as well as in the zonal structure and biophysical properties of the vegetation cover. All this will lead to substantial changes in the hydrological cycle of the Earth.

The change of the thermal regime

In the early stage of warming, the mean global temperature will rise by half a degree. In the following stages it may be 1 or 2°C higher than at present by the year 2000, 2 or 3°C higher by 2025, and 3 to 5°C higher by 2050 (Antropogenic Changes of Climate, 1987).

In each stage temperature changes are extremely irregular from place to place. And with that contrasts between the high and low latitudes grow and reach maximal values when the concentration of CO₂ doubles (Hansen et al., 1987).

It should be mentioned that different climate models produce different results in a number of largely varying cases (Rind, 1987). For instance, with twice as much of CO₂ the model of the Goddard Institute of Space Research gives 9.4°C change in the polar region and 3.8°C in the equatorial one, while the model of the Laboratory of Geophysical Hydrodynamics of Princeton University gives 14°C and 2.5°C and the model of the National Centre of Atmospheric Research of the USA gives 7°C and 3°C respectively. Note here that even a greater uncertainty is present in the assessments of atmospheric moistening variations.

By the present time, on the basis of global climate models (Schlesinger et al., 1984), empirical models of climate changes (Vinnikov, 1986) as well as on the basis of geological analogs of future climatic conditions (Vinnikov, 1986; Velitchko & Klimanov, in press) maps were made of possible changes of the mean air temperature of the Earth, which give the most complete notion on the character of changes of the thermal regime of the Earth.

Estimations made by the global climate models also allowed to reproduce seasonal changes of air temperature (Schlesinger, 1983).

The change of humidification regime

In the early stages of warming, annual precipitation increases, but not greater than by 10%, predominantly in high and low latitudes of the northern hemisphere and decreases in middle latitudes - regions of an intensive agricultural production (Vinnikov, 1986).

During the Holocene optimum - an analog of possible warming by 1°C -
precipitation was more abundant in high and low latitudes: by 50 to 100 mm in high latitudes and by 200 to 300 mm further to the south, for instance, in the Sahara. In the middle latitudes of Eurasia (between 50° and 60°N) and of North America (between 30 and 60°N) there formed extensive regions with a decrease of annual precipitation (Velitchko & Klimanov, in press).

In the optimum of the Mikulino interglacial - an analog of warming by 2°C - the change of atmospheric humidification is of an essentially different character (Velitchko et al., in press). In this period, there is a considerable increase of the humidification of Europe and the northern margins of Asia.

Important peculiarities of the change of atmospheric humidification, that may come about with a global warming of between 3 and 5°C, have been detected on the basis of experiments with global circulation models of the atmosphere. These experiments have shown that global precipitation will increase by between 4 and 12% (Manabe & Stouffer, 1980). In the high latitudes (to the north of 40-50°N and to the south of 40°S) the increase of precipitation amounts averaged over the latitudinal belts is however much greater and may reach 40% (Manabe & Wetherald, 1985).

HYDROLOGICAL CONSEQUENCES OF A GLOBAL WARMING

The studies of possible hydrological consequences of climate change are developing in three main directions. Among them (1) experiments with global climate models. The results of experiments with different models differ much. As the temporal variations of the hydrological regime are very great, it is rather difficult to distinguish a response to the increase of CO₂ concentration from the natural hydrological changeability reproduced by the model (Manabe & Wetherald, 1985). Nevertheless, the modern models of the general circulation of the atmosphere are considered to be quite satisfactory as they reproduce the main features of the global distribution of such variables as runoff and soil moisture. Rapidly developing is also a research path (2) in which estimations of precipitation and air temperature calculated with the help of global climatic models are taken as input variables, while the components of the hydrological cycle are determined on the basis of models which describe hydrological processes with different degree of detail. Such an approach creates a basis for sufficiently reliable estimates of regional changes of the hydrological cycle. For this purpose physically based, empirical and water balance models are used. Note that in a number of cases physically based and empirical models yield similar results which fact in a way makes the assessments obtained on the basis of simplified models more trustworthy. The third path (3) also employs hydrological cycle models, but uses climate characteristics reconstructed for geological or historic periods - analogs of possible climate warmings.

River runoff changes

In these investigations priority is given to the influence of global warming on
river runoff which is the major source of fresh water needed by society. The growing interest to this problem is to a great extent due to the high sensitivity of the large river basins combined with large inner reservoir systems. This problem is most acute in the USSR. Examples of such systems are the Volga with the Caspian sea, the Aral with the Syrdarya and the Amudarya, the Don with the Azov sea, which are all in a critical latitude.

0.5°C rise

Even in the early stage of warming (with a mean global temperature rise of 0.5°C), changes in the heat and moisture regime will lead to a decrease of annual river runoff within large areas of the northern hemisphere. In the USSR, the most drastic decrease of river runoff is expected in its European part to the south of 60° N latitude, in most of Soviet Central Asia and Kazakhstan, in the north of East Siberia, north-east of the USSR and Primorie. In the rest of the country the runoff will increase (Lemeshko, 1988).

The runoff of the largest river systems of the USSR will change in the following way: Volga - a decrease of 6 to 20%; Don - a decrease of 15%; the upper reaches of Yenisei and Ob’ - an increase of 7 to 10%, and Amur - an increase of between 5 and 20% (Speranskaya, 1988).

In England and Wales the change of annual river runoff will not be greater than 10% (Palutikoff, 1987), while the runoff of the Thames will decrease by 7%. The seasonal distribution of the runoff will also change. The northern regions of England will be characterized by a decrease of the runoff in winter and spring and by an increase of it in the summer and autumn months (when there is an increase of precipitation). As for the western rivers - Ex and Why - the seasonal picture is expected to be much more complicated with the sign of runoff change very unstable. In the east of England rivers will have a decrease of runoff all-year-round. With increased warming, the inter-year changeability of runoff will fluctuate more, particularly in spring, summer and autumn, when on some rivers the many-year changeability may decrease or increase by dozens of percents.

1°C rise

In the next stage of global warming, when the mean global temperature has risen by 1°, the expected changes of river runoff will be similar to those of the Holocene optimum. At that time river runoff formed in accordance with the natural climate and, as compared to the present, was characterized by areas of relatively low and high values (Belyaev & Georgiadi, 1989). The calculations were based on empirical zonally relations between annual runoff and the dryness coefficient and between evaporative capacity and air temperature and were made for the main natural zones of the northern hemisphere.

In the Holocene, in the main agricultural zone of Europe river runoff was lower than at present by no more than 50 mm. Only one rather extensive area of a greater decrease of runoff was found in the non-chernozem belt of the Russian Plain. The runoff of the southern part of Europe (the zone of steppes and hard-
leaved forests) was close to the present one. In the narrow northern strip of modern forest-tundra and tundra, runoff was much greater - by between 50 and 100 mm.

Within the broad west-east belt of taiga through West and East Siberia, runoff in the Holocene optimum was lower than at present by 50 mm and more. An insignificant decrease of runoff also took place in the north-eastern margin of the Asiatic continent and in the regions abutting the Sea of Japan.

The greatest increases - between 50 and 100 mm - were detected along the Polar Ocean coast as well as in natural zones of forest-steppe, broad-leaved and mixed humid forests of East Asia. In the rest of the temperate belt, river runoff was close to the present values with only a very insignificant excess. Similar deviations are also characteristic for North America. The area of the most considerable runoff decrease, up to 50 mm and over, embraced the south-east of the temperate belt within the zone of mixed and broad-leaved forests, forest steppe, and the east of the subtropical belt (the zone of humid mixed forests). To the north and south of this area, runoff was higher than at present, but no more than by 25 to 50 mm.

In the same period, the zone of zero runoff in Africa was much smaller. Runoff in the Sahara was much greater than at present, although absolute values are not so impressive. To the south of 15° N latitude, along the present territories of Senegal, southern parts of Mali, Niger, Chad, and Sudan, runoff was higher by 50 mm and over. Considerable positive deviations were also characteristic for the north of Africa and along the Mediterranean coast.

If Holocene-like climate conditions come, the annual runoff of one of the largest rivers of the USSR - Volga and of its tributaries will decrease, as compared to the present, by 10% (Belaya and Vyatka rivers) to 24% (Oka), while the decrease of Volga itself in its different parts will range from 15 to 22% (Velitchko et al, 1988). The process of runoff drop on the North Dvina (-17%) is the same. As runoff on the Visla and the Dnieper is dropping just a little - by 5% and 3%, respectively, - on the Don the tendency is towards a runoff increase: the rise in runoff is 6% (Georgiadi, in press).

2°C rise

In the optimum of the Mikulino interglacial, which might be taken as an analog of climate warming by 2°C, the character of heat and moisture relationship and, correspondingly, of river runoff, was quite different (Belyaev & Georgiadi, 1989).

In Europe, river runoff significantly surpassed the present values. It is especially true of the runoff which formed within East and West Europe as well in the western part of the European USSR, where it has been between 100 and 200 mm above the present level. At the same time in most of the Russian Plain its excess over the present-day runoff was not greater than 50 mm. An extensive area of a lower run-off was located within the same limits as found with the 1°C rise.

Almost in all of Asia, runoff was greater during the Mikulino interglacial than at present. Most prominent was the excess to the north of the polar Circle,
in the north-east and in a small area of wet mixed forests of east Asia. In an extensive area, occupying a latitudinal belt in the north of the continent and the eastern regions of the temperate and subtropical belts, runoff was 50 mm and over higher as at present.

In Africa, the area of zero runoff for the most part coincides with the present one. Only in the north the runoff was greater than at present by 25 to 50 mm and more.

The Volga basin runoff was greater than in the Holocene optimum, but still it remained lower than at present (Velitchko et al., 1988). For instance, in the upper reaches it was lower than at present by 15 to 20%, in the basin of the main tributary - the Oka river it was higher than in Holocene by 20%, but lower than at present by 8 to 10%, while in the left-bank part of the Volga basin it was close to the present value.

On the whole, the total volume of Volga runoff in this period was 5% lower as at present. On the North Dvina runoff also decreased just a little (-3%). But during this period there was a great - more than a 40% - runoff increase in the basins of the rivers Dnieper and Don (Georgiadi, in press).

3-5°C rise

A number of important features of the expected changes of hydrological cycle, if global warming is 3 to 5°C, have been established on the basis of experiments with global models of atmospheric circulation. A significant increase of runoff is expected in Arctic and Subarctic regions up to 45% to the north of 55° N latitude (Manabe & Wetherald, 1985).

Scenarios of the greatest climate warming and models of hydrological cycle were used to evaluate regional effect of river runoff changes. Annual runoff variations in Western Europe can be quite irregularly distributed about the territory (Schnell, 1984). In its northern part (Great Britain and Ireland, the north of France and Germany and further to the north) deviations can amount to 100 mm and more. In the southern part an abrupt runoff fall of 200-300 mm can occur. In the north (up to 58-60° N latitude) of the USSR European territory the annual river runoff increases by 2-3 times (Budyko, 1980), comparatively insignificant changes will occur in the south, and some decrease of the runoff in the Dnieper and Don basins.

With this kind of warming there may be considerable changes in the seasonal distribution of runoff. For instance, in the zone of mixed forests of the Russian Plain, the intensity and duration of spring floods will decrease by several dozens of percent, while the maxima of rain floods during winter thawing will increase (Kuchment et al., 1990). The total annual runoff will decrease by 20 to 25%.

In California there will also be significant changes in the seasonal distribution of runoff (Gleick, 1987). Runoff will decrease in the spring-summer-autumn season and will increase in winter. In some months the decrease of runoff may reach 40% and over.
The change of evaporation

With the warming of climate there will be considerable changes in evaporation regime, first of all, due to the change of inflow of heat and moisture to the land surface. According to estimates by climate models, with the 2-fold increase of CO\textsubscript{2} in the atmosphere the global evaporation increases by 4 to 7\% (Manabe & Stouffer, 1980; Hansen et al., 1984).

In different regions of the USSR, with a two-fold increase of CO\textsubscript{2} evaporability will undergo considerable changes (Budyko, 1980). For instance, in the west of the European USSR it will increase by 200 mm/year, in the central and north-eastern parts of this region its growth may comprise 300 mm/year, and in the south-east - between 400 and 500 mm/year.

The above estimates do not take into account changes in the vegetation cover which might take place with climate warming. Yet a global climate warming can greatly affect the character of a geographical distribution of vegetation (Emanuel et al., 1985) as well as some biophysical characteristics of plants, which will, first of all, bring about changes of transpiration and other water cycle components. Considerable changes will take place in of the types of forests and the structure of ecosystems.

As a result of climate warming there will be great regional changes in the size of lands occupied by forests and in the intensity of the annual growth of arboreous vegetation (Kauppi & Posch, 1986).

There will be a considerable change in the time and duration of plant growth and in the yields of agricultural plants while the areas of the cultivation of many of them will also change (Parry & Carter, 1980; Wilks, 1988).

The increase of CO\textsubscript{2} content may lead to a considerable growth of stomatal resistance of plant leaves bringing about a decrease of transpiration. With a two-fold increase of CO\textsubscript{2} concentration, the stomatal resistance may increase 2.5 times (Idso & Brazel, 1984).

The above changes in the vegetation cover will have quite a diverse influence on the process of evaporation from the land surface. So far no correct estimates have been made taking into account the above factors on global and regional level. There are only chance attempts to estimate the scales of the impact of some factors which sometimes are operating in opposite directions. For instance, a two-fold increase of the stomatal resistance of leaves in the steppe and forest-steppe zones of the Russian plain leads to a corresponding decrease of evaporation by winter wheat (with the warming of climate) by 15 and 28\% (Kuchment et al., 1990). In its turn, the decrease of evaporation may lead to an increase of runoff.

The problem of the impact of changes in vegetation cover on evaporation needs further study.

The change of soil moistening

Even in the early stages of climate warming there will be changes in the moistening of soil of large regions. In many humid agricultural regions spring and
summer reserves of moisture in the soil will decrease (Lemeshko, 1988). The area of the greatest decrease of spring moistening of soil within the USSR is situated on the Russian plain to the south of 60° N latitude, within the Asiatic part of the USSR it will spread out up to the Ob’ river basin including the northern and central areas of Kazakhstan. In the south of the Russian plain the spring moisture of soil will increase by 10 percent.

The area where there is a decrease of summer moistening of soil is somewhat broader than in spring, but it is characterized by a less intensive drop in the humidity reaching 10 or 15%.

Further decrease of soil moisture will take place after the content of CO$_2$ in the atmosphere doubles. Most intensive decrease will be observed in the principal agricultural regions of the world: in Europe, steppes of Kazakhstan, in the south of West Siberia, and in North America (Manabe & Wetherald, 1986). On the other hand, in many regions of the world soil humidity will greatly increase (the central part of Africa, India, the southern part of Australia, the north coast of Siberia and most of South America). The global distribution of soil moistening reconstructed with the help of climatic models does not take into account the above changes in the vegetation cover - hence the results need to be corrected.

Assessments of regional changes in soil humidity according to different climate models considerably differ from each other, but the trends of such changes coincide (Gleick, 1987).

The change of hydrological regime of lakes and inland seas

Climate warming will cause considerable changes of the levels and reserves of water in large water basins. At the same time the reaction of the large reservoirs on the different stages of warming and in different parts of the world can be different. It is evident that in some cases the coming changes can appear critical for the ecological situations.

During the Holocene optimum (the 1°C warming analog) and the Mikulin interglacial periods (the 2°C warming analog) the supply and level of water of the largest inner reservoir in the world - the Caspian sea - exceeded their present values (Velichko, Klimanov, Belayev, 1988).

The main feature of the Caspian sea water balance under the conditions of a 1 or 2-degree global warming is quite a significant increase of atmospheric precipitation over the sea: correspondingly by 40 and 60% resulting in the increase of their share in the income part of the water balance of the Caspian sea from 24 to 40%. Would such an increase not lead to a sea level rise in the Caspian sea it should be compensated either by a considerable increase of evaporation, or by a considerable decrease of river runoff (or by both simultaneously). Neither of the above tendencies is observed; with the rising of the mean global temperature the volume of the formed runoff will increase, while evaporation will decrease. As a result, the following changes will take place in the Caspian sea: its level will rise and, correspondingly, the area will increase; the expansion of the area will bring about, on the one hand, an increase of the total volume of
evaporation, on the other hand - a relative decrease of the surface inflow. As long as these tendencies do not level out the increased precipitation, the level of the Caspian sea will rise up to the point corresponding to the level of equilibrium.

Thus, during the optimums of the Holocene and the Mikulino interglacial the level of the Caspian sea was higher. It is noteworthy that the higher the average global temperature was, the larger was the aquatory of the Caspian sea. This means that the level of the Caspian sea did not react in the same way to different-scale climate changes: while during a short period of warming, as it was in the twentieth century, the level of the Caspian sea went down, in the periods of warming during the interglacial the level went up.

On the Great Lakes of the USA and Canada climate warming with a two-fold increase of CO₂ will bring about an opposite effect (Cohen et al., 1988). The level of Lake Superior will drop by 0.3 m, that of the Michigan-Guron system by 0.83 m and of Lake Erie by 0.68 m.

REFERENCES


