TIME-SPACE CHANGES OF CLIMATE AND WATER SYSTEMS OF KARELIA

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ABSTRACT
The main aim of the present study is to estimate the regional climate change and response of water ecosystems of largest lakes of Europe and the White Sea. This study includes analysis of long-term data from multi-year records of basic climatic parameters (air temperature, precipitation, evapotranspiration, index of continentality, river runoff, etc.). Variability of the hydrological regime of individual rivers and lakes, as well as the study area at large related to the regional climate change is presented and discussed. As the result of statistical analysis of the climate, water balance and water level for the largest lakes of Europe (Ladoga and Onego) and the White Sea over the period 1880-2004, their noticeable changes were detected. It was found that time series of annual air temperature, precipitation and evapotranspiration over a 120-year period contain significant positive linear trends, and river runoff contains a negative trend for the given period. Considerable climate changes in the region in those years are manifest also in a shorter period of snow cover in the catchments and a longer ice-free period on the lakes. Potential changes (spatial and temporal) in the regional climate and hydrologic regime for the period 2010-2050 were estimated using the results of numerical experiments with the ECHAM4/OPYC3 model and for two IPCC scenarios of the global climate change.

KEYWORDS
Climate change; time series; river watershed; total inflow; ice-free period.

2. DATA AND METHODS

The source material was series of mean monthly and annual air temperature and precipitation values from 26 weather stations (WS) in Republic of Karelia and 12 WS in the Murmansk Region from 1999-2004, as well as annual discharge series from six largest river watersheds of Karelia (rivers Kovda, Kem, Nizhniy Vyg, Suna, Shuja and Vodla). The longest time series were available for weather stations in Petrozavodsk (since 1880), Padany (since 1890), Valaam (since 1874).
To estimate regional climate variability, 1880-2004 time series of data on air temperature, precipitation, total evaporation (evapotranspiration), potential evaporation, streamflow were statistically analyzed, and long-term instrumentally measured data were compared with calculations based on mathematical models. Potential changes in principal climatic characteristics and water balance elements (WBE) for the study area were estimated using the results of calculations based on ocean-atmosphere models. To this end, we employed the previously tested model ECHAM4/OPYC3 (Filatov et al., 2002; Climate of Karelia…, 2004; Filatov et al., 2005) designed for scenario calculations of potential climate change in the quite extensive area comprising Karelia, Arkhangelsk, Murmansk and Leningrad Regions, which contain the catchments and basins of the largest water objects studied: White Sea, Lakes Ladoga and Onego.

3. RESULTS

Analysis of principal tendencies in long-term climatic and hydrological time series from 1880 to 2004 revealed positive linear trends in annual air temperatures, precipitation, total evaporation in Karelia and the

Kola Peninsula (Climate of Karelia…, 2004; Salo Y., 2003). Total streamflow in the region shows a minor negative trend due to a faster increase in total evaporation within the study area compared to precipitation. In the second half of the 20th century, linear trends of annual air temperature were positive, equaling an average of 0.10 °C/50 yrs. in the Kola Peninsula and 0.60 °C/50 yrs. in Karelia.

Analyzing seasonal air temperatures based on data from the weather stations situated in the north of European Russia, we revealed a spatial and temporal differentiation of temperature change tendencies by seasons. Only the spring air temperature shows a positive trend (up to +3.5°C/100 yrs.) throughout the study area. In all other seasons, areas with positive trends are mostly situated in the southern part of the region, close to Europe's largest lakes – Ladoga and Onego.

Figure 1 shows how the climatic norm of annual air temperature was changing with time in Karelia at large. Mean temperature values over 30 years (climatic norm) refer to the middle of the period. Noteworthy is the quite smooth time series of mean multiannual temperatures during the 19th century, and a significant rise of the norm as the industrial period began. Among-year changes of mean annual air temperatures have reflected the warming of the 1930s, followed by a cooling event of 1960-1970, which was, in turn, superseded by a still continuing rise in air temperature in the late 1980s. Note also that the variance of surface air temperature fluctuations increased with time, indicating the climate in the region was growing somewhat less stable. Coefficients of the linear trend of among-year air temperature variations accurately reflect the prevalent directivity of the change. The most severe cooling events of the study period took place in the second half of the 18th and in the mid-20th century. The linear trend coefficient had only positive or zero values from the 1870s to the 1940s. In the 1980s, the sign of the linear trend coefficient changed from negative to positive, and the air temperature has been rising consistently since then.

Analysis of empirical and calculated data has demonstrated that according to IPCC scenarios, not only annual values of climatic and hydrological characteristics but also their distribution among seasons and within a year will change under new climatic conditions. The greatest warming in Karelia is likely to happen in autumn and winter months, whereas the rise in air temperature during spring and summer months will not be so significant.

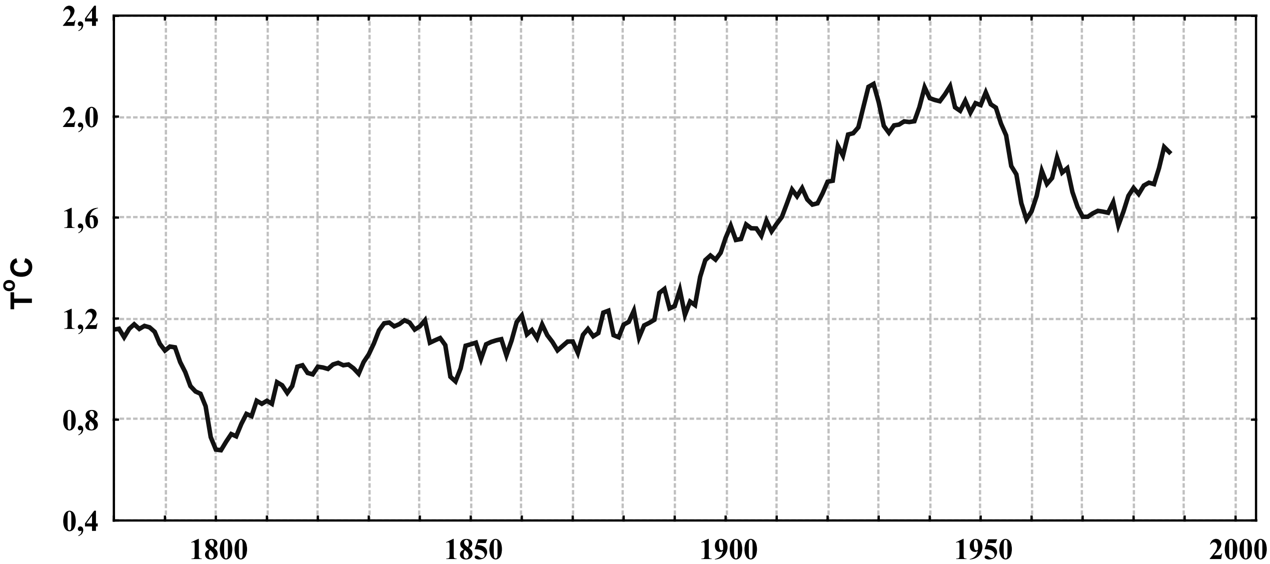

Figure 1. Dynamic of climatic norm of annual air temperature for territory of Karelia region in 1752 -2000. (30-years moving average values).

According to studies of the past two decades (Koronkevich et al., 2003; Shiklomanov et al., 2004), streamflow is increasing in Russia at large, but decreasing somewhat in Karelia (Figure 2), which tells on the water balance of the waterbodies and, hence, on their ecosystems. Where climate changes have been studied quite thoroughly by now, knowledge about the response of aquatic ecosystems to the changes is still insufficient. In our study, we relied both on data from long-term observations over climate and aquatic ecosystems, and on modeling the change of ecosystems of Karelia's largest waterbodies – White Sea, Lakes Ladoga and Onego (Kondratyev et al., 2002; Climate of Karelia…, 2004; Meleshko et al., 2004).

The change of the thermal regime in the study area is manifest in an increase in the duration of the ice-free period on Lake Onego. The ice-free period in the Petrozavodsk Bay of Lake Onego has grown longer due to an 8-day shift of the spring ice break dates. Analysis of changes in precipitation volumes in the study area over the second half of the 20^{th} century has demonstrated that although linear trends of total monthly precipitation have different directions during a year, total annual precipitation in the Lake Onego catchment has increased over the study period (45 mm/50 yrs. on average). An upward tendency in precipitation volumes is observed at all stations from October to June. From July to September, directions of the trends vary.

Correlations between streamflow and climatic characteristics were determined to assess the effect of climate change on streamflow from Lake Onego catchment. The dependence of temporary storage of water in a basin on mean annual air temperature over the catchment and total annual precipitation was found. Figure 2 shows the values of total influx to Lake Onego observed in 1950-2000 and results of total influx calculations based on the proposed formulae.

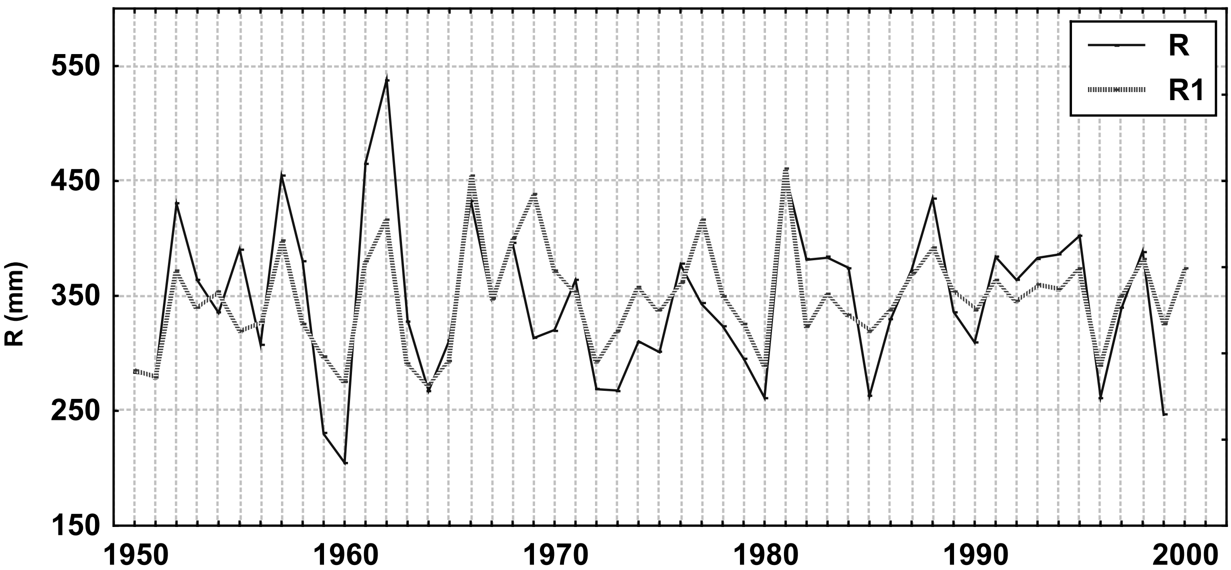

Figure 2. The values of total inflow to Lake Onego observed in 1950-2000 (R) and results of total influx calculations (R1).

It follows from the graphs that the calculated results agree quite well with the measured values. According to the hypothetical scenarios of climate change, a rise or fall in air temperature by 1-2 ^{o}C and a simultaneous in total annual precipitation by 10 and 20% compared to modern values would result in a change in streamflow to Lake Onego as drawn in Figure 3. If the air temperature increases by 1^{o}C, streamflow to the lake may remain unmodified given that total annual precipitation increases by about 3%; a warming of 2 ^{o}C would be compensated by a precipitation rise on 6 %.

Analysis of the data has demonstrated that annual air temperature and total annual precipitation have increased in Lake Onego catchment over the second half of the 20^{th} century, but no change in total streamflow to the lake has so far followed. The detected patterns of change of the main characteristics of the regional climate and the consequences of potential change in the hydrological regime in Lake Onego catchment can be taken into account when planning sustainable water management and conservation of this waterbody, which offers unique possibilities for drinking water supply, transport, energy production and recreation.

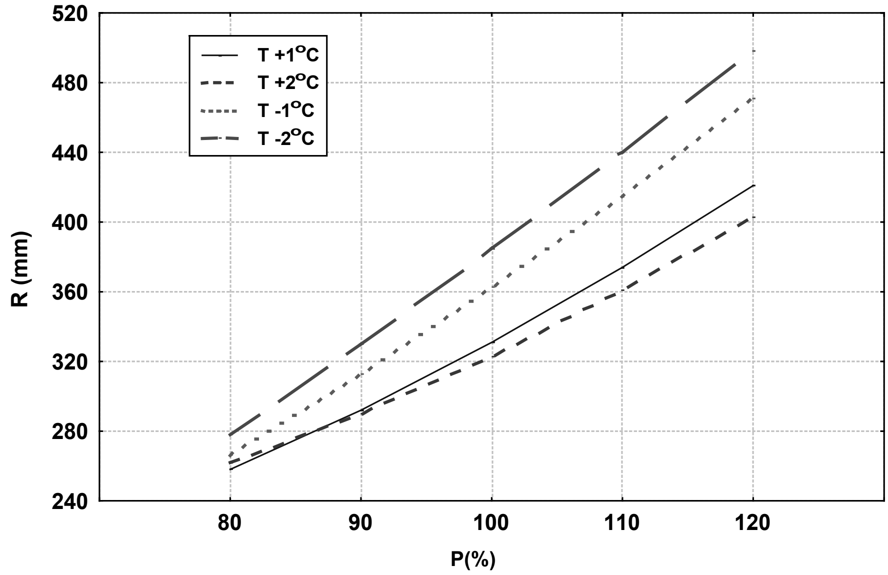

Figure 3. Dynamic of inflow to Lake Onego by different temperature and precipitation change scenarios. (100% - mean annual precipitation at present time).

The coupled thermohydrodynamic and ecosystem models have been applied to study the contemporary situation on water ecosystem of Lake Onego, to understand the main mechanisms of the ecosystem transformation and to learn what may happen in future. Some attention has also been paid to the present state of socio-economic development in the basin and its effect on the water quality of the lakes. The recommendations towards the sustainable development of the region are worked out, and the complex of measures required for rational use of its resources is formulated.

In addition to climatic circulation, the authors have constructed scenarios of Lake Onego circulations which may arise as global warming changes the climate in the lake catchment. The ecological model taking current status and condition into account was applied to these circulation scenarios to predict functioning of the Onego Lake ecosystem in relation to climate change. The main conclusion drawn from the calculations is that climate changes cause no significant changes in the functioning of the lake ecosystem.

The White Sea attracts continuously increasing attention of both researchers and users. This is due to a new stage of developing the resources of the White Sea itself and its catchment area (diamond and gold mining, fish catch, the growing of maricultures, transport of natural gas from the Stockmann gas deposit of the Barents Sea to Western Europe, and consequently, a major change in the entire infrastructure entailing creation of new enterprises). The above-mentioned problems, together with quite a few traditional ones (such as the use of marine bioresources, wood cutting in the catchment area, the impacts of pulp-and-paper industry and wastes discharge of cities and towns located on the sea-shores and in the catchment areas) will require working out scientifically substantiated recommendations for rational use and protection of marine resources.

In spite of the previous efforts, we still lack a systematic knowledge of intrinsic mechanisms of functioning of the White Sea ecosystem and its responsiveness to external forcing. The required sets of coupled thermohydrodynamic and ecosystem models have not been developed. The inherent processes of transport and transformation of the aquatic environment constituents, as well as the regularities in water exchange have not been adequately studied thus far. The same is true for studying the impacts of climate change and anthropogenic forcing upon the marine ecosystem.

Therefore, along with an integrated system approach to the investigation of the whole marine ecosystem, a comprehensive study is required of numerous bays and estuaries of the White Sea because they play a very essential role in the formation of the marine ecosystem, as well as in its functioning. It should be emphasized that only a truly comprehensive research, encompassing multifaceted studies addressing the pool formation of organic matter, production-destruction processes, all forms of nutrients, phytoplankton, etc., can be really effective.

A thorough study of responsiveness of the White Sea ecosystem to anthropogenic impacts is also required. The White Sea is of great scientific significance within the frames of the programme of studying the Arctic seas because it is a rather small semi-closed waterbody, for which it may be much simpler (in comparison with other Arctic seas) to

- estimate the balance of matter and energy;
- investigate energy fluxes and matter flows at the main interfaces;
- work out (obtain) a set of models for diagnostics of the current status and prediction of future variations of the Arctic seas ecosystem;
- assess the ecosystem changes caused by natural and anthropogenic factors.

As a result, some scenarios have been formulated for the estimation of possible changes in the White Sea (WS) ecosystem in response to external impact variations, and certain recommendations have been elaborated for rational utilization of the resources of both the White Sea and its catchment. Development of recommendations concerning optimization of environmental management will make it possible to increase the efficiency of measures aimed at the improvement of the aquatic environment quality and diminish the risks from extraordinary man-induced ecological situations. It will be a significant step towards the revival of the region.

Several numerical models have been developed and exploited to this end, including the ones accounting for the atmosphere-ocean interactions. The employed climate change and marine ecosystem dynamics models have revealed that in the event of both possible climate warming in the region (the scenarios suggested by IPCC) and socio-economic changes in the strand area (several scenarios have been assumed) would not bring about any serious/far-reaching consequences. The pollution level and present status of water quality in the White Sea remain mostly fairly stable. Although, in estuaries of the Severnaya Dvina, Onega and Mezen' Rivers a substantial anthropogenic forcing is going on, this process has not yet resulted in major man-driven alterations to the aquatic ecosystem. In spite of a semi-Arctic geographical location, relatively cold water with enhanced salinity, high dynamic activity (strong tide-ebb currents), the White Sea is characterized by a number of specific hydrophysical features, low level of eutrophication and pollution, high rates of water exchange with the Barents Sea, and some others. The unique data assembled in the course of this study, and their multifaceted analyses constituted a solid base for pursuing a sustainable management of marine resources.

Utilization of these tools will make it possible to achieve science-based decisions aimed at pursuing efficient use and preservation of marine living resources. Because the White Sea models were constructed only for the lowest links of the ecosystem they cannot reflect complex processes of the interactions between plankton, benthos, fishes and seals. Consequently the fulfilled investigation should be considered as the necessary step for the construction of a more complex and complete model of the White Sea ecosystem. On the basis of the investigations it can be stated that:

In the given period of time the White Sea ecosystem state is stable. Average annual temperature will rise on average by 2°C in 50 years as the result of which fluvial run-off to the White Sea waters diminishes by 10-15%. In scenario models increase or decrease of inorganic nutrients by 20% in the river load into the White Sea did not show any notable effect on the phytoplankton succession. Decrease of freshwater input by 20% and increase of air temperature by 2°C resulted in a decrease of the thickness of the ice cover by 0.1 m, a decrease of the mean salinity by about 0.4‰, and intensify the formation of thermocline. That prevents the vertical mixing and leads to a decrease of inorganic nutrients in the surface layer suppressing autumn bloom of the phytoplankton. On the basis of our expert estimation behavior of phyto- zooplankton abundance is likely to correspond to the results obtained by the modeling experiments according to the following reasons:

A water contamination decrease leads to the optimal conditions for zooplankton and phytoplankton communities where human and other unfavorable impacts are minimal.

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