Changes in some elements of the water cycle in the easternmost part of the Baltic Sea Drainage Basin between 1945 and 2010*

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Abstract

Soil moisture and evaporation are the most important elements of the terrestrial water cycle. In situ data from 14 stations with soil moisture observations, 13 stations with pan evaporation and 200 stations with precipitation measurements are used to analyse temporal changes in these elements of the terrestrial water cycle over the Russian part of the Baltic Sea Drainage Basin.

It was determined that soil moisture, pan evaporation and visible evaporation have exhibited significant changes during the past 45 years. These changes reflect the non-uniform character of moistening changes over the Russian part of the Baltic Sea region.

1. Introduction

In most publications on the problems of global and regional models applied to the analysis of climate system changes, data from various reanalyses (The ERA-40 Project 2000, Kistler et al. 2001, Kanamitsu et al. 2002) have been used to validate model results. But such data are somewhat artificial because they are interpolated onto the nodes of a regular grid, and the results of such an interpolation depend to a great extent on the interpolation methods used. Moreover, not all meteorological variables

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(in particular, such elements of the land water cycle as evaporation, soil moisture, and moisture fluxes into the soil) are simulated with sufficient reliability (IPCC 2007). Thus, for example, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change notes that 'evaporation fields from the ERA-40 and NRA are not considered reliable because they are not well constrained by precipitation and radiation'. For this reason, the direct use of in situ data for model results validation is more reliable.

Moreover, such data are already available for analysis. The Global Soil Moisture Bank (http://climate.envsci.rutgers.edu/soil_moisture/) (Robock et al. 2000) exists, where data on in situ records of soil moisture have been gathered for Russia, Ukraine, USA, China, Mongolia, Brazil and some other countries for more than 30 years.

Pan evaporation is measured worldwide. In some countries (e.g. Russia and the United States) the time series of this variable span more than 40–50 years. It seems appropriate to set up a World Centre for the accumulation of pan evaporation data (as well as lysimeter data used for monitoring actual evaporation) to make them available to the scientific community (similar to the Global Soil Moisture Bank). The value of this information has already been tested in climatic change assessments (see Golubev et al. 2001).

These variables are not simulated in the reanalyses: soil moisture, potential evaporation and evapotransporation are the most important elements of the terrestrial water cycle. Furthermore, soil moisture characterizes the amount of water accumulating within the active (1 m) soil layer, pan evaporation can be accepted as a potential evaporation estimate, and lysimeter measurements from natural surfaces (unfortunately, from a very sparse network) can be used as estimates of evapotranspiration. This paper assesses the changes in the first two characteristics – soil moisture and pan evaporation – as recorded by the network of long-term meteorological stations of the former USSR and subsequently of the Russian Federation, Belarus and the Baltic States.

2. Data and methods of analysis

Quite a large area of the drainage basin of the Baltic Sea lies in Russian territory. Soil moisture observations (from the 1970s to 2000/2001) are currently available from 14 long-term stations in this region. As far as pan evaporation is concerned, there are 4 stations in Russia with observations from the 1950s to 2008 and 8 stations in the former Soviet republics with observations from the 1950s to the mid-1990s; these data are used in this analysis (Figure 1).

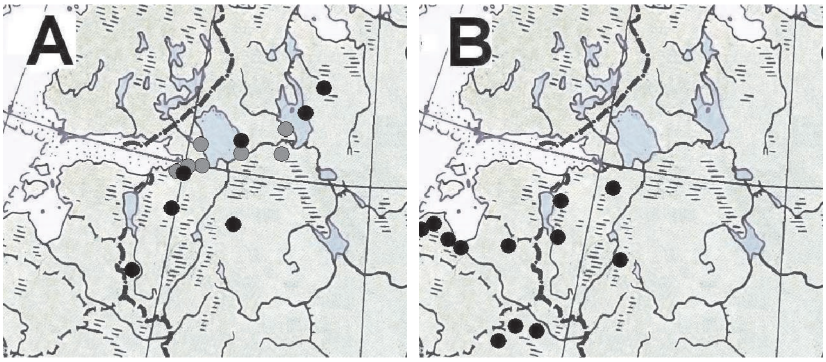

Figure 1. Stations with soil moisture (A) and pan evaporation (B) records. In Figure 1A the black circles are the most complete data time series, and the grey circles represent time series with periods from which data are missing

Soil moisture data are represented by 10-day observations on soil plots with natural (mostly meadows) vegetation and on fields with winter crops during the warm period (from April to August/September). In the cold season, these observations are made on the 18th or 28th day of each month. The soil plots at each station are representative of the main soil type and landscape of the region and do not differ significantly from the prevailing soil type and landscape of the climate zone. The mean depth of the water table at the plots and its seasonal variations are typical of a larger surrounding area. The unique thermostat-weight method (when 10-cm long soil samples are weighed, oven-dried, and weighed again) allows soil moisture to be estimated very accurately. With this method, both the total and plant available soil moisture values can be estimated (*Guidance for hydrometeorological stations...* 1973). A suite of agrophysical constants for the site soil type, including its volume density, is also determined on each observational plot. Multiplying the soil moisture by this density gives the soil moisture measured in mm (see Robock et al. 2000).

Plant available soil moisture is the amount of water that can be extracted by the vegetation cover and evaporated (for more details, see Robock et al. 2000).

Pan evaporation data are monthly sums for the warm season (May–September). Pan evaporation measurements are performed using an evaporimeter (GGI-3000) system inserted into the soil. It consists of an evaporation pan and rain gauge. The ground water depth on the observation plot should not be more than 2 m, and the soil composition and the soil freezing/thawing regime at the water-evaporation plot should not differ from those at the meteorological site (*Guidance...* 1985).

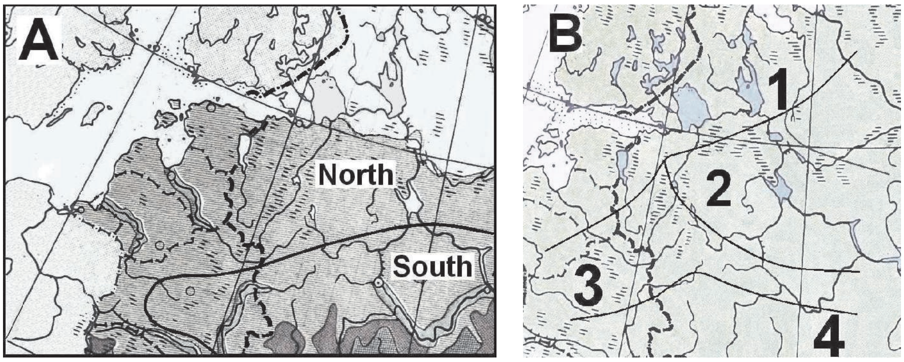

Figure 2. Regions for which soil moisture data (A) and pan evaporation data (B) were averaged

Precipitation data from 200 stations of the archive created in the RIHMI-WDC were used to analyse visible evaporation. These data were combined into monthly sums for the warm season (May–September) from 1966 to 2009.

The changes in soil moisture over the Russian part of the Baltic Sea Drainage Basin were analysed for three layers: 0–20 cm, 0–50 cm, and 0–100 cm. Data on plant available soil moisture were used in order to eliminate the factor due to multifarious mechanical compositions of soil. Thereafter, data on soil moisture from separate stations were averaged by soil types taking soil texture into account (Figure 2A).

Precipitation data (both monthly and daily) are available at the Russian Research Institute for Hydrometeorological Information at http://meteo.ru/climate/sp_clim.php and at the US NOAA National Climatic Data Center at http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html. Data on soil moisture are available from the International Soil Moisture Bank (http://climate.envsci.rutgers.edu/soil_moisture/). Data on pan evaporation are available on request from the author.

Changes in pan evaporation and visible evaporation were assessed using sums of monthly pan evaporation and precipitation data for the warm season (May–September). Data on pan evaporation were averaged over regions characterized by the specific features of the temporal changes of this parameter (Figure 2B).

3. Results and discussion

3.1. Soil moisture

The derno-podzolic soil of the taiga zone is the main soil type in that part of the Baltic Sea Drainage Basin lying within our study region. Only the southernmost part of this region is covered by mixed forest with the same soil type. Analysis of data from separate stations showed that there are two areas in the study region where the temporal soil moisture changes are quite different.

Soil moisture changes in the upper 20 cm are caused by the interaction of two opposite processes: seepage and evaporation (Rode 1965). Precipitation water quickly infiltrates into the soil and as soon as seepage stops, the process of evaporation starts. This explains why only 'rapid' moisture fluctuations occur within the upper soil layers, blocking the formation of evident directional tendencies.

Below the top 20 cm layer, moisture seeps only slowly into the underlying layers. Moisture movement from the deeper layers back up to the soil surface is also a relatively slow process (Rode 1965). This explains why systematic common features of temporal soil moisture changes can be documented only for the 0–50 cm and deeper layers.

Soil moisture changes during spring (April–May) in the 0–50 and 0–100 cm layers are shown in Figure 3. At the beginning of the growing season the soil water content is sufficiently high as snowmelt leads to saturation of the soil.

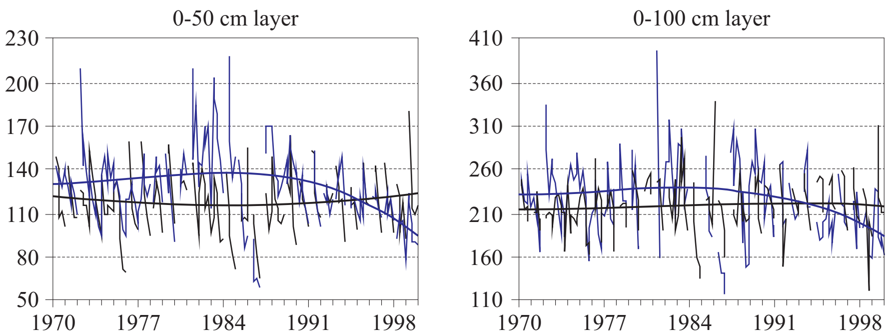

Figure 3. Soil moisture changes (in mm) at the beginning of the growing period (April–May) in the 0–50 and 0–100 cm layers (black line – north, grey line – south) in the easternmost region of the Baltic Sea Basin

Within the 0–50 cm layer an increase in soil moisture is observed over most of the northern part of the taiga zone, whereas in the south of this zone, this parameter decreases. Furthermore, in the south of the zone soil moisture increased slightly before the mid-1980s and then decreased rather sharply from the end of the 1980s. Similar tendencies were also noted in the 0–100 cm layer. This soil moisture decrease since the 1980s appears to have been caused by a reduction in snow depth and snow cover duration in the Russian sector of the Baltic Sea Drainage Basin (see Bulygina et al. 2009).

Reductions in soil water storage in spring are closely related to winter changes in the NAO index, which strongly affects the climate of the Baltic Sea region (BACC 2008). Since the 1990s, there has been an intensification of the zonal circulation type (with prevailing westerly winds), leading to a greater frequency of milder winters (Hagen & Feistel 2005, 2008). In such conditions there are more days with winter thaw (Groisman et al. 2010), when thawed soils absorb moisture, and surface water downloads into the groundwater. As a result, there is a decrease in spring soil water storage.

In summer (June–August) soil moisture values are smaller than in spring owing to the consumption of the thaw water accumulated in the soil in winter and early spring. The main tendencies of soil moisture changes remain the same as in spring (Figure 4) and become more apparent in both the 0–50 cm and 0–100 cm layers. Before the mid-1980s, the soil moisture increase became especially obvious in the north of the zone, and the rates of this increase and subsequent soil moisture decrease were also higher (by an absolute value) than in spring. Furthermore, all changes in the 0–100 cm layer were more evident than in the 0–50 cm layer.

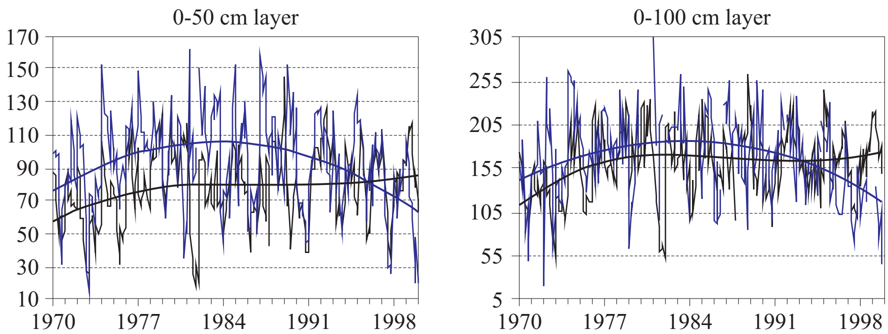

Figure 4. Soil moisture changes (in mm) during summer (June–August) in the 0–50 and 0–100 cm layers (black line – north and grey line – south of the easternmost region of the Baltic Sea Basin)

Some decrease in precipitation in summer over the Baltic Sea Drainage Area (possibly due to the dominance of the meridional circulation type) (see HELCOM 2007, Hagen & Feistel 2008, BACC 2008) may be responsible for such changes in soil moisture in the top metre of the soil.

In autumn (September–November) soil moisture values rise again owing to the greater precipitation (see HELCOM 2007) and the decrease in evapotranspiration once plant growth has stopped and/or slowed down (Figure 5). In the 0–50 cm layer, the soil moisture increase in the north

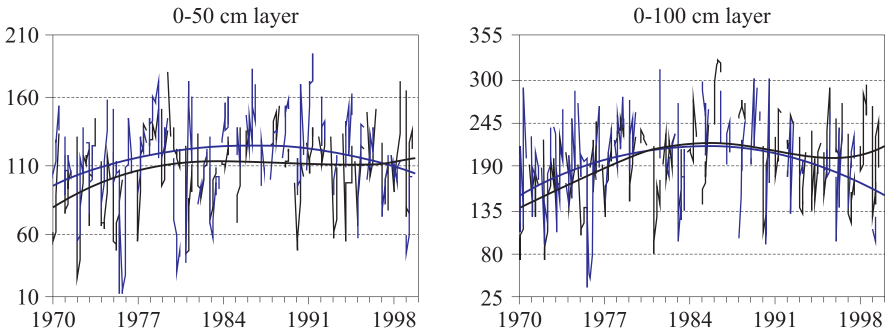

Figure 5. Soil moisture changes (in mm) during autumn (September–November) in the 0–50 and 0–100 cm layers (black line – north and grey line – south of the easternmost region of the Baltic Sea Basin)

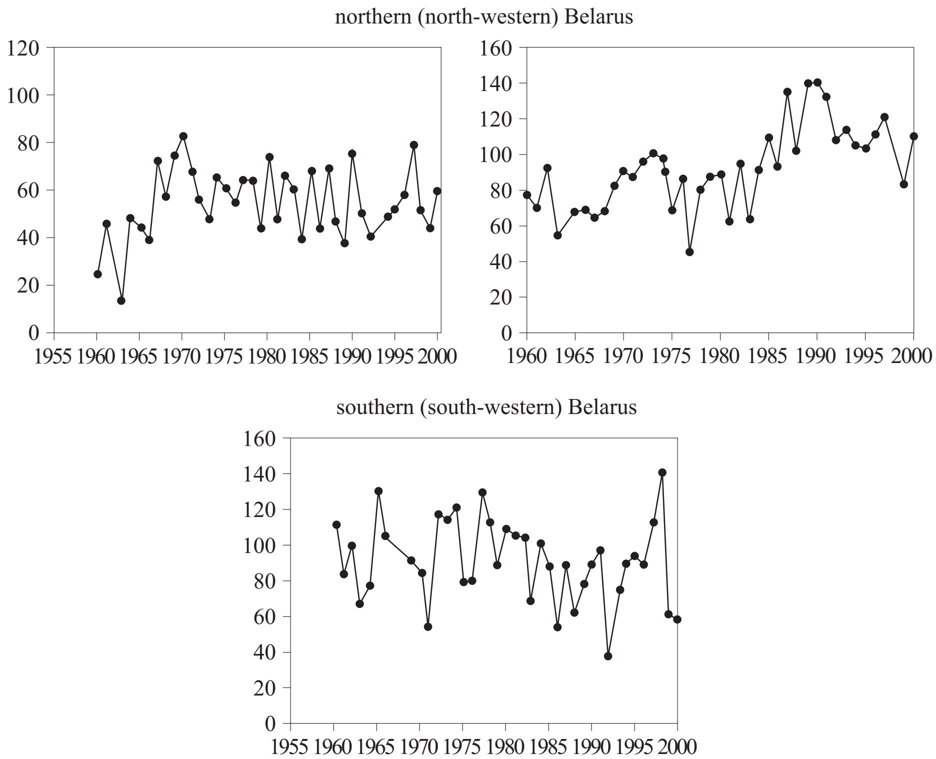

Figure 6. Soil moisture changes [mm] in the 0–50 cm layer in northern and southern Belarus during the growing season (May–August) (adapted from Loginov 2006)

peaks, while its decrease in the south is smaller than in other seasons. In the 0–100 cm layer, the soil moisture changes in the south are nearly the same as in spring, and the upward trend of soil moisture in the north reaches a maximum (as in the 0–50 cm layer).

Thus, over the easternmost region of the Baltic Sea Drainage Basin, soils have become more humid. Despite the relatively sharp decrease in soil moisture in the south after the mid-1980s, the overall downward trend in soil moisture during the entire 1970–2000 period was small (<5–7%).

Tendencies of opposite sign in soil moisture changes are observed in May–August in the 0–50 cm layer across Belarus (Figure 6). Thus, our analysis corresponds well to earlier findings by Loginov (2006).

3.2. Pan evaporation

The trends of changes in pan evaporation (or estimates of potential evaporation) during the warm season (May–September) vary over the different regions of the Baltic Sea Basin considered in this study. Pan evaporation increases over most of the Basin (Figure 7).

The rate of its increase and interannual variability after the mid-1980s exceeded the rate of its changes and interannual variability in the previous period. The total increase in pan evaporation in Region 1 from 1952 to 2008 was about 8%.

Pan evaporation decreases over the other easternmost regions of the Baltic Sea Drainage Basin (regions 2 and 3) and in the adjacent area (region 4) (Figure 8). Moreover, there is a regular similarity of changes in these three study regions (2, 3, and 4). Up to the end of the 1970s, a significant decrease in pan evaporation occurred, but thereafter the trends were less clear-cut. The mean values of pan evaporation for the 1981–2000 period were smaller than for previous decades. In each of these regions, however, the changes in pan evaporation have some peculiarities. Whereas a slight increase in pan evaporation has occurred in region 2 in the past two decades assessed (the 1980s and 1990s), pan evaporation has continued to decrease in regions 3 and 4. Furthermore, the interannual variability of pan evaporation in the mixed forest zone (region 3) remained nearly the same during the entire period assessed, whereas in the south of the taiga zone (region 2) and in the broadleaved forest zone (region 4) this variability in the second part of the study period became less. Pan evaporation decreased in these three regions by 40–50% during the entire period analysed.

According to Loginov (2006), a decrease in pan evaporation has been recorded over the entire territory of Belarus during the May–October period in recent decades (i.e. since 1980).

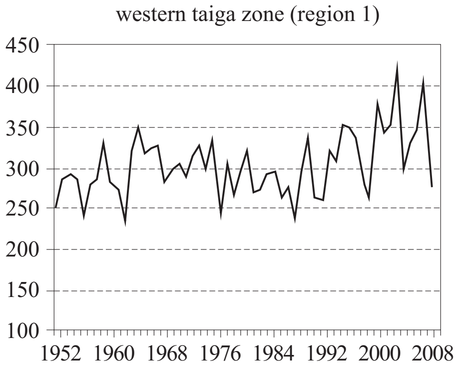

Figure 7. Pan evaporation changes (in mm) during the warm season (May–September) over Region 1 (see also Figure 2B)

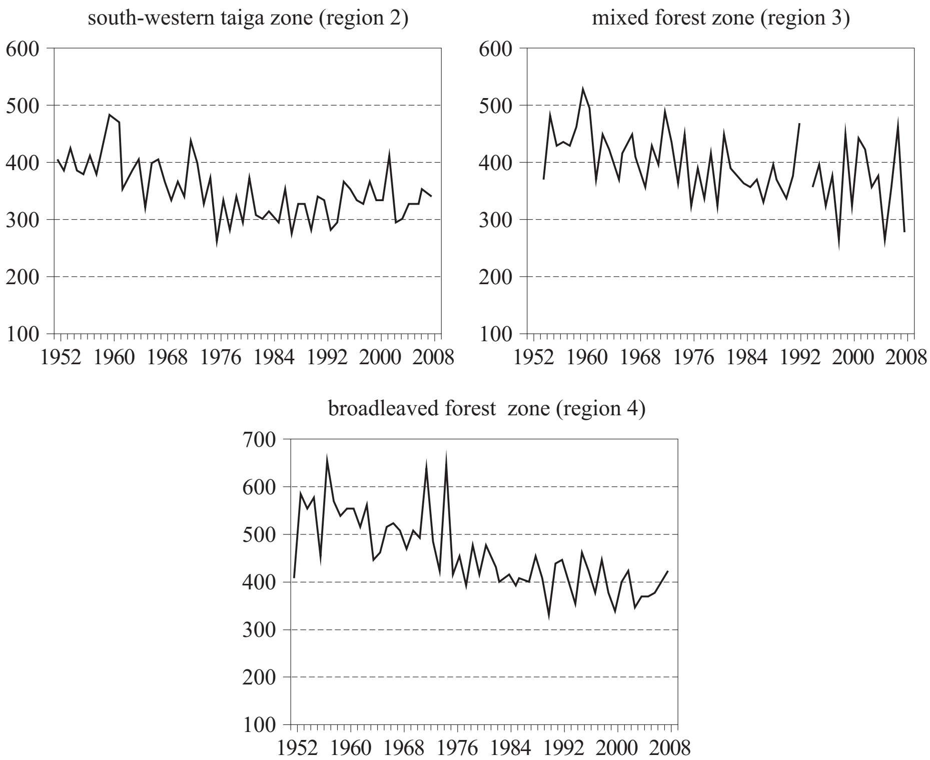

Figure 8. Pan evaporation changes (in mm) during the warm season (May–September) in the three easternmost parts of the Baltic Sea Basin (see also Figure 2B)

Such a decrease in pan evaporation, known as 'the evaporation paradox' (IPCC 2007) can be partially explained by changes in the wind speed (the near-surface wind is one of the main forcing factors). It was found that in the wet areas of the western former USSR (where our study region lies) the near-surface wind speed decreased by a factor of 1.6 between 1961 and 1990 (Meshcherskaya et al. 2004). According to our updated analyses, a reduction in wind speed was observed up to the 2000s, but the rates of its changes were reduced compared to pre-1990 decades. Over Belarus, the mean wind speed prior to 2004 was almost 20% less (Loginov 2006).

4. Visible evaporation

Visible evaporation (the difference between pan evaporation and precipitation) is an important characteristic of the regional water cycle. Indirectly, it indicates the total energy losses due to evaporation over the region. A positive value of visible evaporation indicates a deficit in the regional water budget, and the water demand by the atmosphere exceeds precipitation (so-called 'dry' conditions are perceived). When precipitation

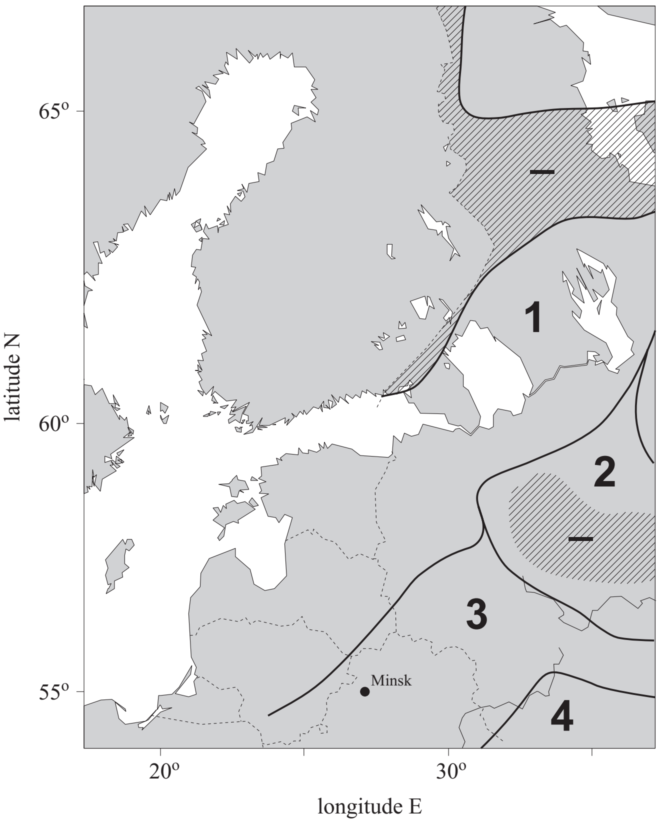

Figure 9. Spatial patterns of linear trends in precipitation for the warm season (May–September totals from 1966 to 2008) over the easternmost region of the Baltic Sea Basin (the regions are the same as in Figure 2B)

exceeds pan evaporation, visible evaporation is negative (which corresponds to 'humid' conditions). The more negative the visible evaporation, the wetter the region, and the excess water remains for runoff and for replenishing soil moisture.

To analyse visible evaporation changes, temporal changes in precipitation were studied first (Figure 9). Over most of the study region, there was a sizeable precipitation increase during the warm period (May–September) with small areas of decreasing precipitation. The absolute values of these decreases were much smaller than those in the areas of precipitation increase, and the region-wide precipitation estimates show increases of 8–14% during the 1966–2008 period for the regions in question (see also HELCOM 2007, BACC 2008).

Over the entire Baltic Sea Drainage Basin, long-term mean values of visible evaporation are negative, i.e. this region is located in the zone of sufficient moistening. Like pan evaporation, the mean visible

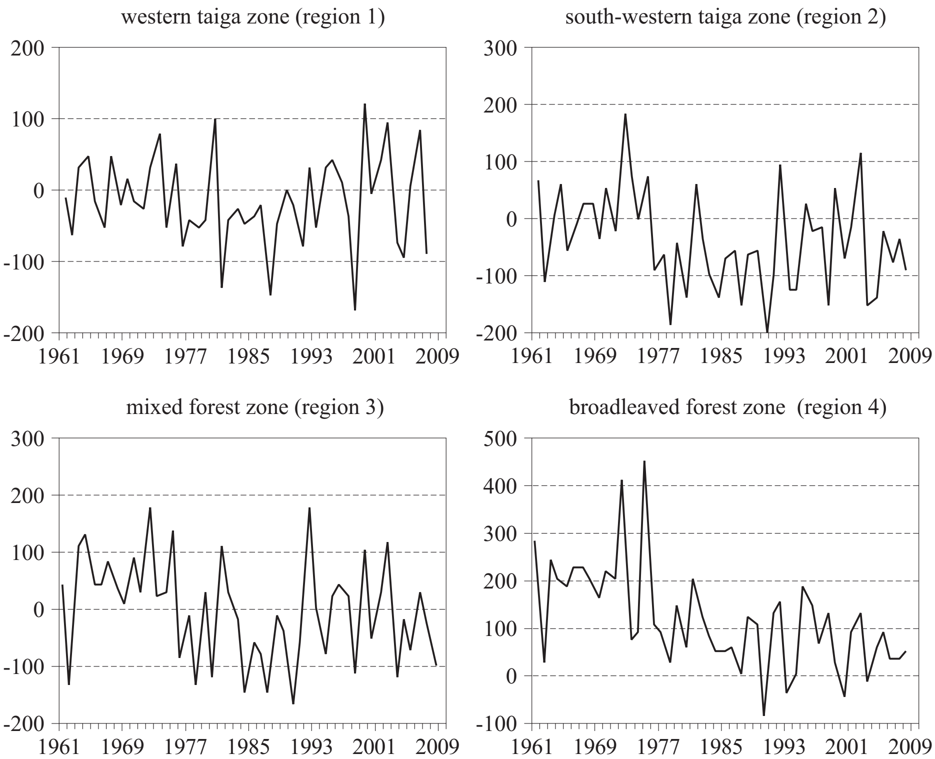

Figure 10. Visible evaporation changes (in mm) during the warm season (May–September) in the three easternmost parts of the Baltic Sea Basin and its south-eastern part (region 4)

evaporation after the 1980s became smaller than that in the previous two decades (Figure 10). Over the largest study region (region 1), where both precipitation and pan evaporation increased, variations in visible evaporation during the 1961–2008 period did not have a systematic component, but its interannual variability did increase sharply after the mid-1980s. In the south of the taiga zone (region 2) and in the mixed forest zone (region 3), the features of the visible evaporation changes are similar: after the mid-1980s visible evaporation fluctuations occurred mainly in the negative range, i.e. the region's soil moisture content increased.

In the adjacent area (broadleaved forest zone, region 4) visible evaporation values were positive during the whole study period, indicating regions of insufficient moistening. In this region the downward trend in visible evaporation was the strongest compared to the other regions. Here the mean value of visible evaporation for the 1980–2008 period was nearly three times less than its mean value for the previous two decades. During the second half of the study period the interannual variability of visible evaporation also increased, and sometimes its values became negative. Thus, the wetting conditions of this region significantly improved.

These changes in the moistening regime over the Russian part of the Baltic Sea Drainage Basin have inevitably led to significant changes in the runoff regime of the main rivers of the region since the 1980s (Vuglinsky & Zhuravin 2001, Shiklomanov & Georgievsky 2002). Winter and summer (low) runoff have increased practically everywhere, whereas in spring decreasing runoff trends are typical. These changes are explained mainly by changes in soil moisture (especially in spring) and potential evaporation. Similar changes have occurred in most of the rivers in Belarus and the Baltic States (BACC 2008). As a result, annual runoff and, consequently, inflow into the Baltic Sea have increased (Baumgartner & Reichel 1975, Mikulski 1982, BACC 2008).

5. Summary

Soil moisture within the top 1-metre soil layer increased during the entire growing season as well as in autumn over the north of the easternmost part of the Baltic Sea Drainage Basin but decreased in the southern part.

A small increase in pan evaporation in the warm season over the main part of the easternmost area of the Baltic Sea Basin and its significant downward trend in the east and south-east parts of this area as well as in the adjacent south-eastern areas beyond the Basin indicate a complex spatial pattern of changes in this characteristic property of the terrestrial water cycle during the past 50 years.

The lack of any apparent systematic changes of visible evaporation in the warm season over most of the easternmost part of the Baltic Sea Drainage Basin and its evident decrease in the east and south-east of the Basin and in adjacent areas reflect the non-uniform character of moistening changes over the Baltic Sea region during the past 45 years.

These moisture regime changes are closely related to variations in annual river inflow into the Baltic Sea: an increase in winter and summer runoff and a decrease in spring runoff.

None of these spatial features of changes in the terrestrial water cycle have been reproduced by the various reanalyses. That is why the use of in situ data is preferable for model validation and for checking the reliability of assessments based on these models.

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