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Reflection of the changes of the North Atlantic Oscillation Index and the Gulf Stream Position Index in the hydrology and phytoplankton of Võrtsjärv, a large, shallow lake in Estonia

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The North Atlantic Oscillation Index (NAO) was correlated with winter and spring air temperature in Estonia while wind speed dynamics were mediated by the position of the Gulf Stream. In the low-NAO years, the large (270 km^2), shallow (mean depth 2.8 m), polymictic lake, Võrtsjärv, was significantly shallower than in the high-NAO years. Phytoplankton biomass was higher in the springs after high-NAO winters, and it was inversely related with the depth of the lake in summer and autumn but not in spring. In Võrtsjärv, the North Atlantic Oscillation directly influences spring phytoplankton via its effects on the ice cover dynamics. The climate signal 'recorded' in the water levels results in lower summer/autumn phytoplankton biomass in the years when the water level remains high throughout the year. The effects of light and phosphorus limitation on phytoplankton at higher water levels are discussed.

Introduction

Studies on global climate have revealed that the northern hemisphere has increasingly become warmer; winters are becoming wetter and summers drier (Magnuson *et al.* 1997). These changes are reflected in the increasing trend of the North Atlantic Oscillation Index (NAO), which characterizes the variability of air pressure differences between Iceland and the Azores (Hurrell *et al*. 2001, 2003). Another climatic index, the Gulf Stream Position Index (GSI) characterizes the position of the north wall of the Gulf Stream (Taylor 1996). Southward movements of the Gulf Stream (lower GSI) are typically associated with stronger winds, whilst northward movements (higher GSI) are associated with stable conditions (George 2000). Climate change affects the balance of heat, water and substances in lake catchments resulting in changes of the hydrological regime and loadings. Taylor *et al*. (2002) have elegantly shown that biological systems can exhibit responses to subtle climatic signals and could be sensitive indicators of climatic processes. Hydrological changes have the strongest impact in shallow lakes where they cause large changes in the water volume and lake depth. In non-stratified shallow lakes the changes in depth affect light extinction of the mixed water column, sedi-

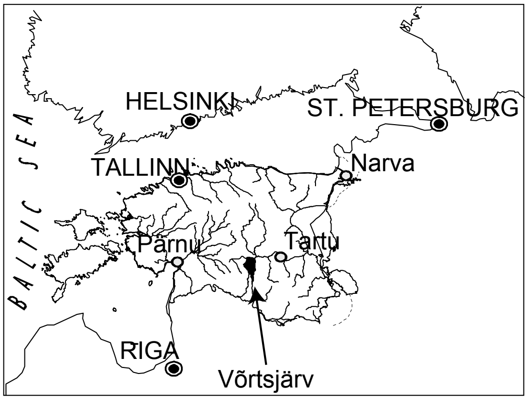

Fig. 1. Location of Võrtsjärv.

ment resuspension intensity, nutrient release, and denitrification rates. These factors are important as they control the growth and composition of phytoplankton that is the first link of the pelagic food web.

In Võrtsjärv, which has a mean depth of 2.8 m, the mean annual amplitude of water level fluctuations is 1.4 m, while the maximum range reaches 3.2 m. The latter corresponds to a 1.4-fold difference in the lake area, a 2.4-fold difference in the mean depth and a three-fold difference in lake volume (Nõges and Nõges 1999). Thus, changing water levels are considered to be the leading factor controlling the ecosystem dynamics of Võrtsjärv and impacting the phytoplankton (Nõges *et al*. 2003). This paper presents the relationships found in Võrtsjärv between the long-term changes of the water level and phytoplankton abundance and NAO and GSI as proxy indicators of climate forcing.

Material and methods

Study site

Võrtsjärv (Fig. 1) is a large shallow non-stratified eutrophic lake located in central Estonia (58°05´–58°25´N, 25°55´–26°10´E). Its area is 270 km^2, catchment basin 3374 km^2, mean depth 2.8 m, and maximum depth 6 m. Water renewal averages about 1 year and ice cover lasts from mid-November until mid-April (on average 135 days). Võrtsjärv is highly eutrophic, characterised by a mean total nitrogen concentration of 1.6 mg l^{-1}, total phosphorus of 54 μg l^{-1} and chlorophyll *a* of 24 μg l^{-1} (Haberman *et al*. 1998). Secchi depth during the ice-free period is < 1 m.

Data

Data on the North Atlantic Oscillation Index in 1886–2002 were obtained from the website http://www.cru.uea.ac.uk/cru/data/nao.htm, and data on Gulf Stream position in 1966–2001 were obtained from the website http://www.pml.ac.uk/gulfstream. For calculating seasonal indices, a year was split into 3-month periods, the winter beginning in December of the previous year. The winter NAO (NAOw) and the annual average GSI (GSIy) were used in the present analysis. Data on air temperature (1894–2001), precipitation (1866–2000), daily average wind speed (1992–2000), water temperature (1947–2000), water level (1923–2002), ice-on and ice-off dates (1924–2000) for Võrtsjärv were routinely measured during meteorological and hydrological surveys by the Estonian Institute of Hydrology and Meteorology. Phytoplankton biomass (1964–2002) was measured using different counting methods at the Võrtsjärv Limnological Station. In 1964–1993, concentrated phytoplankton samples were fixed with formaldehyde and counted in the blood counting chamber (Goryajev's chamber) until reaching the total number of 400 counting units (Nõges and Laugaste 1998). A minimum of 60 individuals of the dominating species and all met individuals of other species were measured in every sample. The volume of the individuals were counted using common geometrical equations (Edler 1979). Since 1994 Lugol's iodine fixator and the Utermöhl (1958) counting technique were applied (Nõges *et al*. 2003). Intercalibration revealed no significant differences between these counting methods (P. Nõges unpubl. data). The magnification of 400× was used in all cases.

Statistical analysis

As the first step, the normal distribution of all variables was checked with Shapiro-Wilk's *W*-test (STATISTICA FOR WINDOWS version 6.0).

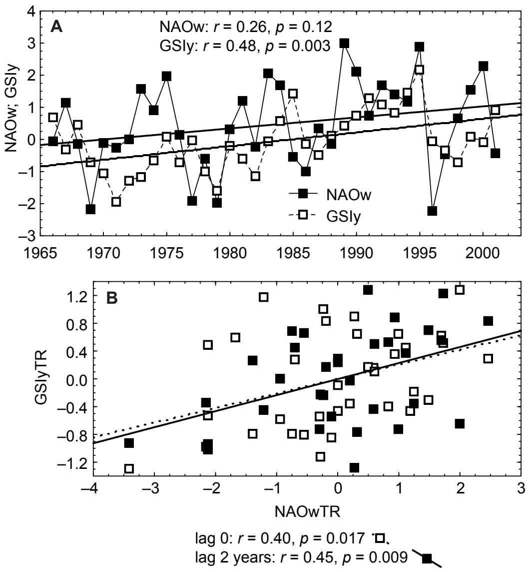

Fig. 2. — **A**: Long term dynamics and trends of the North Atlantic Oscillation Index in winter (NAOw) and the annual averages of the Gulf Stream Position Index (GSIy). — **B**: Correlation of the transformed time series (NAOwTR and GSIyTR) from1966–2001.

Time series of NAOw, GSIy, seasonal average air and water temperature, precipitation (except for autumn), and average lake depth were normally distributed ($p > 0.05$). The variables, without normal distribution were ln-transformed. Prior to this, a constant was added to air temperature series of winter months to eliminate negative values precluding ln-transformation. Before correlation analysis, the original (or ln-transformed) data series of the same length were 'cleaned' from trends and autocorrelations with the Time Series Analysis module of STATISTICA 6.0.

Results

The NAOw and the GSIy were significantly correlated ($r = 0.40$, $p = 0.017$). A time lag of about two years was detected in the covariation of NAOw and GSIy (Fig. 2), but the difference of the correlation coefficients of NAOw with a 2-year lag and a non-lagged GSIy was not significant ($p = 0.4$). The annual average air temperature and the amount of precipitation in central Estonia were positively correlated with the NAOw. The NAOw correlated negatively

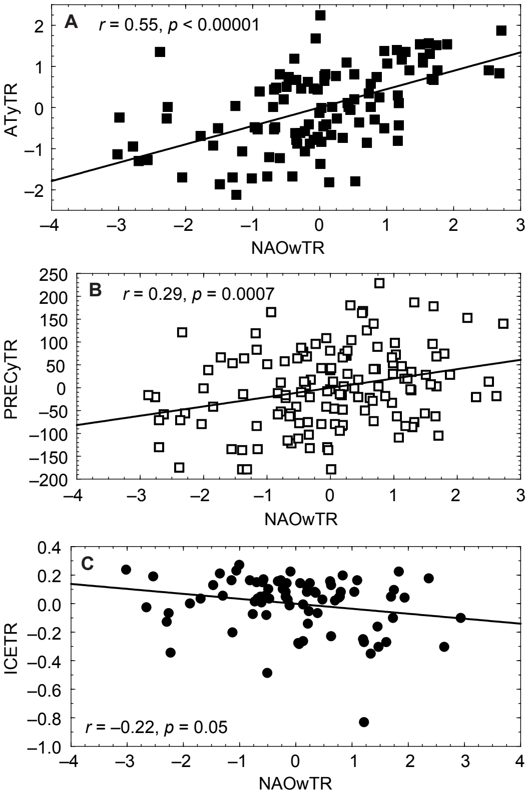

Fig. 3. Correlations of the transformed time series of (**A**) the air temperature in central Estonia (ATyTR) in 1894–2000, (**B**) the annual average amount of precipitation in Estonia (PRECyTR) in 1886–2000, and (**C**) the duration of ice cover on Võrtsjärv (ICETR) in 1924–2000, and the North Atlantic Oscillation Index in winter (NAOwTR).

with the duration of ice cover on Võrtsjärv (Fig. 3). The correlation of air temperature with the NAOw in 1895–2001 was the strongest in winter ($r = 0.66$, $p < 0.00001$) and also significant in spring ($r = 0.50$, $p < 0.00001$). There was no significant correlation between seasonal air temperatures and the GSIy in 1966–2001.

From April until November, water temperature in Võrtsjärv was significantly correlated with air temperature (Fig. 4). Water temperature in spring was significantly correlated with the NAOw ($r = 0.37$, $p < 0.03$). On a monthly basis, average water temperature and the NAOw were significantly correlated in April ($r = 0.48$, $p = 0.004$), July ($r = 0.34$, $p = 0.047$), and September ($r = 0.36$, $p = 0.036$). The only significant correlation between water temperature and the GSI occurred in September ($r = 0.37$, $p = 0.033$).

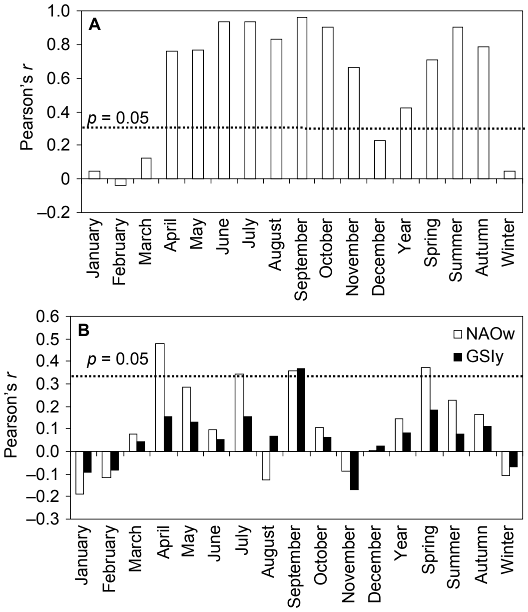

Fig. 4. Seasonal course of Pearson's correlation coefficient (*r*) between transformed time series of (**A**) the air temperature in central Estonia and the water temperature in Võrtsjärv, and (**B**) the water temperature in Võrtsjärv with the North Atlantic Oscillation Index in winter (NAOw) and the annual average Gulf Stream Position Index (GSIy) in 1966–2000.

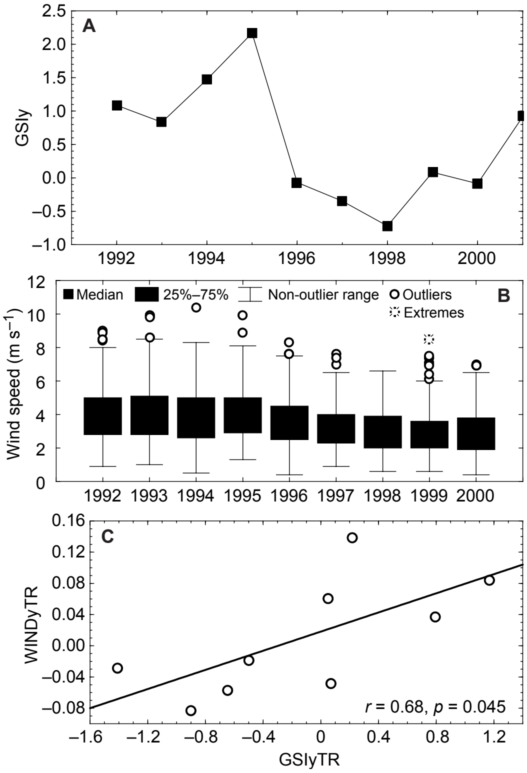

Fig. 5. (**A**) The annual average wind speed in central Estonia, (**B**) the annual average Gulf Stream Position Index (GSIy) in 1992–2000, and (**C**) the correlation of their transformed time series (WINDyTR and GSIyTR).

In 1866–2001, the amount of precipitation correlated with the NAOw in spring ($r = 0.29$, $p = 0.001$) and in winter ($r = 0.26$, $p = 0.002$) but, the correlation was lacking in other seasons. In 1966–2001, the GSIy was not significantly correlated with precipitation. There were higher wind speed events (> 8 m s^{-1}), and the average wind speed was higher in the high-GSI years (1992–1995) as compared with that in the low-GSI years (1996–2000) (Fig. 5). Yearly average wind speed was significantly correlated with the GSIy ($r = 0.68$, $p = 0.045$) while no significant correlation occurred with the NAOw.

In the low-NAO years, Võrtsjärv was significantly shallower than in the high-NAO years ($r = 0.29$, $p = 0.01$). The relationship between the mean depth of the lake and the NAOw was the strongest ($r = 0.37$, $p = 0.0009$) when the spring water level was considered (Fig. 6).

Phytoplankton in Võrtsjärv is dominated by filamentous cyanobacteria, representing 66% of the average phytoplankton biomass during the ice-free period. Diatoms constitute the majority of the remaining assemblage. Spring phytoplankton development starts in March/April when the ice becomes transparent and the fast-growing flagellates (*Mallomonas, Uroglenopsis, Rhodomonas, Cryptomonas, Gymnodinium*) appear. In addition, the under-ice bloom of *Aulacoseira islandica* may reach a biomass up to 10 g m^{-3} wet weight. Towards summer, filamentous blue-greens begin to dominate with a succession of *Limnothrix planktonica* (Wolosz.) Meffert and *L. redekei* (Van Goor) Meffert forming the majority (> 90%) of the biomass of cyanobacteria. In autumn a second peak of diatoms develops favoured by increasing of soluble reactive silicon, decreased water temperature and increased mixing at lower water depths. The growth of phytoplankton biomass continues up to late autumn reaching values around 30 g m^{-3} wet weight before ice cover (Nõges *et al.* 2003). Phytoplankton biomass was higher in the springs after high-NAO winters (*r*

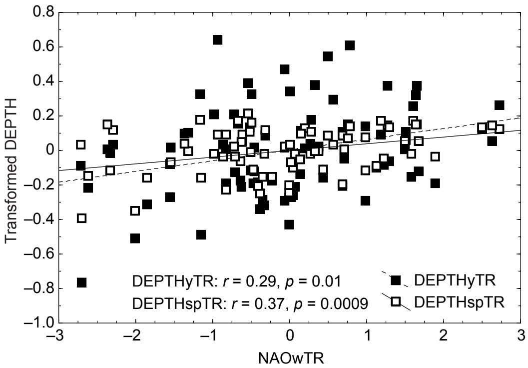

Fig. 6. Correlation of the transformed time series of the annual average and spring (March–May) depths of Võrtsjärv (DEPTHyTR and DEPTHspTR), and the North Atlantic Oscillation Index in winter (NAOwTR) in 1923–2001.

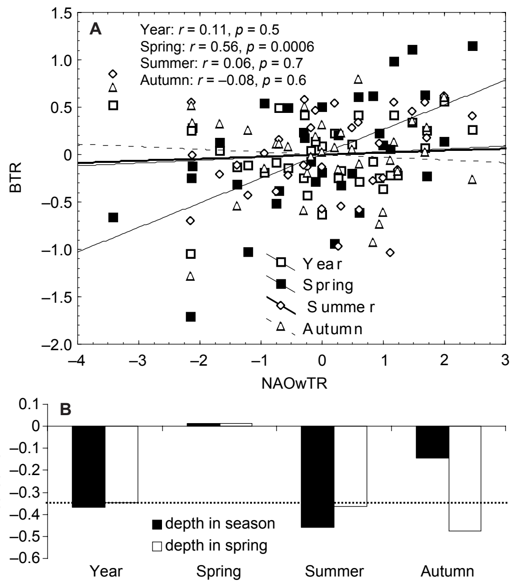

Fig. 7. Correlation of the transformed time series of the annual average, spring (March–May), summer (June–August) and autumn (September–November) phytoplankton biomass (BTR) in 1966–2001 with (**A**) the North Atlantic Oscillation Index in winter (NAOwTR), and (**B**) average depth of Võrtsjärv.

= 0.56, p = 0.0006) (Fig. 7A). In summer and autumn, phytoplankton biomass was inversely related with lake depth (Fig. 7B).

Factor analysis revealed that spring phytoplankton biomass clustered together with the NAOw and with winter and spring air temperatures. On the graph of factor weights (Fig. 8) spring phytoplankton biomass was positioned on the opposite side of the axis in respect to ice cover duration. Summer and autumn phytoplankton biomasses were oppositely positioned in respect to the GSIy, precipitation and the lake depth (Fig. 8).

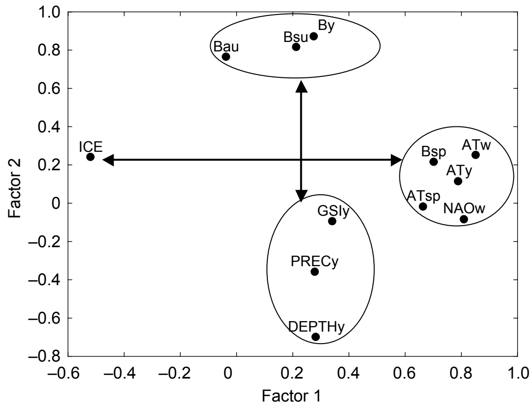

Fig. 8. Results of factor analysis of the transformed time series of the North Atlantic Oscillation Index in winter (NAOw); annual average Gulf Stream Position Index (GSIy); yearly average, winter (December–February) and spring (March–May) air temperature in central Estonia (ATy, ATw and ATsp, respectively); annual average precipitations in Estonia (PRECy); duration of ice cover on Võrtsjärv (ICE); annual average depth of Võrtsjärv (DEPTHy); phytoplankton biomass in Võrtsjärv in 1966–2000: By = annual average, Bsp = spring (March–May), Bsu = summer (June–August), Bau = autumn (September–November). The factor weights of the first two factors are presented; these factors explain 64% of total variability of the considered data set.

Discussion

Our results clearly demonstrate the relationship of global climatic indices like the NAO and the GSI with climate characteristics in Estonia. As reported earlier by Tomingas and Jaagus (1999), the western airflow from the Atlantic during positive NAO remarkably increases air temperature and precipitation in Estonia in winter, while in summer positive NAO tends to be associated with higher air temperature and less precipitation.

Taylor and Stephens (1998) documented the time lag between the dynamics of the NAO and the GSI. George (2002) explained the lagged response of the GSI as the time taken by the ocean to respond to atmospheric forcing. It appears that the meridional pressure gradient, which is reflected in the NAO and influences the strength of westerly winds transporting warm moist maritime air across Europe, can affect winter and spring air temperature in Estonia independently of the position of the Gulf Stream. However, the wind speed dynamics appear to be mediated by the position of the GSI and not directly influenced by the NAO.

Shallow lakes are principally different from stratified lakes in their ability to 'remember' climate signals. Because of thermal stratification, the climatic signal captured during spring turnover can persist in the hypolimnion of stratified lakes for several months afterwards (Livingstone 1993). In shallow non-stratified lakes, this signal persists for a shorter time (Gerten and Adrian 2000). Võrtsjärv represents a unique case regarding the 'memory' of climatic events. In spring a direct NAO signal is reflected in the water temperature (Fig. 4) and in the duration of the ice cover (Fig. 3), while in summer and autumn the winter NAO signal persists in the water level of the lake. This is caused specifically by the outflow conditions of Võrtsjärv. The Emajõgi, the outflow of Võrtsjärv, has a slope of only 0.03 m km^{-1}. In years with a high spring flood (high-NAO years), a water-rich tributary, the River Pede, which enters the Emajõgi five km downstream from its outflow from Võrtsjärv reverses the flow in the upper course of the Emajõgi (Järvet 1995). Therefore, the water level remains high for several months after flooding and the water level in spring determines the water level throughout the entire year.

Numerous studies referred to by Straile *et al*. (2003) documented the importance of the NAO to phytoplankton growth and species composition via the effects of ice cover dynamics. This probably is the case in Võrtsjärv, evidenced by higher spring phytoplankton biomass in the high-NAO years (Figs. 7 and 8), and an opposite relationship in summer. In years when water level remains high throughout the year, the summer/autumn phytoplankton biomass is lower (Figs. 7 and 8). This phenomenon has been explained by the reverse relationship between average light intensity and water depth in the polymictic water column bringing about light limitation and unfavourable growth conditions for phytoplankton (Nõges and Nõges 1999). According to Nõges *et al*. (2003), phytoplankton biomass in Võrtsjärv is significantly lower in years of high water level. The representation by filamentous blue-greens among phytoplankton follows the changes in the water level, and also the succession of dominant species can be partly attributed to it. *Planktolyngbya limnetica* reached its maximum in the low-water period in the middle of the 1970s; *Limnothrix redekei* and *L. planktonica* started to dominate in the high-water period in the 1980s while total phytoplankton biomass decreased substantially. During the low-water period in the 1990s, the role of the nitrogen-fixing species *Aphanizomenon skujae* increased. The succession was caused by changes in light and nutrient availability in the strongly mixed environment. During low-water periods, the mixed water column was better illuminated while the N/P mass ratio in the water decreased below 20. The latter was caused both by increasing phosphorus concentration because of higher resuspension rate, and decreasing nitrogen concentration because of higher denitrification rate at a lower water level. Dim light species like the filamentous *Limnothrix* spp. were most successful in competition for light and phosphorus in deeper water while nitrogen-fixing *A. skujae* was favoured by the low N/P ratio in shallow water. In Võrtsjärv N_2 fixation starts at N/P mass ratio about 20, which is much higher than the Redfield ratio 7 (Tõnno and Nõges 2003).

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