Comparison of several climate indices as inputs in modelling of the Baltic Sea runoff

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Using Transfer function (TF) models, we have earlier presented a chain of events between changes in the North Atlantic Oscillation (NAO) and their oceanographical and ecological consequences in the Baltic Sea. Here we tested whether other climate indices as inputs would improve TF models, and our understanding of the Baltic Sea ecosystem. Besides NAO, the predictors were the Arctic Oscillation (AO), sea-level air pressures at Iceland (SLP), and wind speeds at Hoburg (Gotland). All indices produced good TF models when the total riverine runoff to the Baltic Sea was used as a modelling basis. AO was not applicable in all study areas, showing a delay of about half a year between climate and runoff events, connected with freezing and melting time of ice and snow in the northern catchment area of the Baltic Sea. NAO appeared to be most useful modelling tool as its area of applicability was the widest of the tested indices, and the time lag between climate and runoff events was the shortest. SLP and Hoburg wind speeds showed largely same results as NAO, but with smaller areal applicability. Thus AO and NAO were both mostly contributing to the general understanding of climate control of runoff events in the Baltic Sea ecosystem.

Introduction

Regional climate indices (ACIA 2005, Eisenreich 2005, BACC author team 2008) have proved useful in modelling relations between large scale climate changes (as reported e.g. by the International Panel on Climate Change, Solomon et al. 2007) and their regional consequences. Using transfer function (TF) models, we have previously presented a chain of events between changes in the North Atlantic Oscillation (NAO), westerly winds, runoff, and subsequent oceanographical and ecological changes; first in the Baltic Sea salinity (Hänninen et al. 2000), and later in mesozooplankton (e.g., Hänninen et al. 2003, Vuorinen et al. 2003, 2004). These we have, finally, connected with herring growth and reproduction (Rajasilta et al. 2006). In this paper, we compare several alternative indices as basis for models of general runoff regulation. Basically the approach we use is to figure out the process, or processes that lead to changes in Baltic Sea oceanography. Instead of comparing several indices covering one region and period we wanted to make a stepwise analysis starting from very local, and weather related environmental parametres such as wind, then expanding the point of view into a correlating, still very...
local but more comprehensive parameter such as air pressure (taken from the area where prevailing wind conditions over the Baltic Sea catchment are actually born). One question posed was: While the North Atlantic Oscillation (NAO) index is the most widely used, could the Arctic Oscillation index (AO) expanding the areal coverage give a more comprehensive view of the circumstances that control Baltic Sea runoff? On the other hand, we wanted to see whether simply focussing on local time series would give comparable results as the widely used regional indices. To conduct the study we compared several indices, which all are related to NAO but represent different areal coverage. Arctic Oscillation (AO) indicates the dominant pattern of non-seasonal air pressure variations at sea level north of 20°N, thus representing a northern half-global coverage (Fig. 1). When surface air pressure is low in the polar region, the arctic air is kept in the north (this also brings westerly weather towards Scandinavia, as does the positive mode of the NAO), but when a high pressure prevails in the north, cold polar air is moving southwards from the arctic. The NAO index is defined as the normalised sea-level air-pressure difference between the Azores (Ponta Delgada) and Iceland (Stykkisholmur). When the index is positive, south-westerly winds dominate in the North Atlantic. In these conditions winters tend to be mild and rainy in the catchment area of the Baltic Sea. Such circumstances have been dominant during our study period since late 1960s up to the present day (e.g. BACC author team 2008).

**Fig. 1.** The Baltic Sea with total and sub-river catchment areas (thick lines with grey areas), and HELCOM subdivisions used in modelling exercises (see the legend in the insert). BB + BS = Gulf of Bothnia, and NBP + WBP + EBP = central Baltic Sea. Reference localities of NAO (1 = Iceland and 2 = Azores), AO (20°N latitude) and a monitoring station for wind speeds (3 = Hoburg, Gotland) are also shown.
As local indices, we included sea-level air-pres-
sures in Iceland (SLP). While the NAO index is
calculated as the difference in atmospheric air
pressures at sea surface (SLP) level measured at
Azores and Iceland, the SLP at Iceland repre-
sents the northern component of the index (often
referred to as the Icelandic low). Finally, we
used wind speed (given with direction informa-
tion at regular 3-h intervals) data from Hoburg,
Gotland (56°92′22″N, 18°14′71″E).

Material and methods

Study area

Coastal areas support major part of the world’s
population, and economy of coastal states is
largely based on resources derived from the
sea, such as fisheries, shipping, and recreation.
Therefore, it is crucial to understand the factors
controlling coastal sea ecology. A typical exam-
ple of a coastal sea area, the Baltic Sea, receives
the impact of some 85 million people in nine
coastal nations. The semi-enclosed Baltic Sea
is one of the major brackish-water basins of the
world, with an area of 377 400 km² and a volume
of 21 200 km³. The size of the drainage basin is 1
729 000 km², which is about four times the area
of the sea itself (Fig. 1). The mean water depth is
only about 56 m, and the maximum depth is 451
m at Landsort Deep (e.g. Voipio 1981).

The Baltic Sea hydrology is generally con-
trolled by climate in the North Atlantic. The
North Atlantic Ocean is the origin of practically
all incoming water. Rivers provide the majority
of incoming freshwater, which originally evapo-
rates in the Atlantic (in the more or less constant
high pressure area between Azores and Ber-
mudas), then enters the catchment area via pre-
cipitation, and finally reaches the Baltic Sea as
freshwater runoff. This affects the surface water
hydrography especially in the northern parts of
the Baltic Sea. The largest river in the region,
the Neva, produces 18.2% of the total runoff
into the Baltic Sea (Dietrich and Schott 1974).
The measured record of total runoff into the
Baltic Sea spans about 100 years. For the period
1950–1990, the mean annual river discharge into
the Baltic Sea was 15 310 m³ s⁻¹ (Bergström and
Carlsson 1994). There was a substantial rise in
the 1970s (e.g. BACC author team 2008, Hän-
ninen and Vuorinen 2011). Salinity of the Baltic
Sea is maintained at an intermediary level by
seawater intrusions from the North Sea through
the Danish Straits. Saline water has a greater
effect on the southern Baltic and deeper water
layers. The restricted water inflow through the
Danish Straits and runoffs into the Baltic Sea
create a stratification of the water masses. For a
more detailed overview of the Baltic Sea oceano-
graphy (see e.g. Voipio 1981).

Data

The TF study was conducted for the period
1970–2000 by applying existing, already
reviewed, institutional time series from various
data sources. The period was chosen in order to
review the possible effects of increased runoff
in late 20th century, pointed out by e.g. BACC
Author Team (2008), making it an excellent
modelling period for the selected climatic indi-
ces. For the runoff regulation modelling analysis,
the monthly atmospheric forcing data from the
North Atlantic Ocean were provided by NOAA
(National Oceanic and Atmospheric Adminis-
tration) and from the Baltic Sea area by SMHI
(Swedish Meteorological and Hydrological Insti-
tute). The Baltic Sea was divided into HELCOM
conformed sub-drainage basin. For each of the
sub-basins the SMHI provided monthly total
freshwater discharges (km³), except for Kat-
tegat. The data comprised both monitored river
runoffs and estimates of non-monitored runoff
data. Monitored runoff consist altogether of
some 200 river flow stations, representing 86%
of the total area of drainage basin. Runoff areas
not covered by measuring, mostly coastal areas
located between major rivers, were calculated
using runoff from neighbouring stations consid-
ered as representative (according to Bergström et
al. 1994). The runoff data were originally com-
piled for the 1970s and the 1980s by Stålbacke
(1996) and completed for later years by several
organisations and projects operating in the Baltic
Sea area (the compiling system and data are
documented at http://nest.su.se/bed/river_inputs.
shtml).
Statistical analyses

TF models, also called dynamic regressions, were created using the Scientific Computing Associates statistical software (Statistical System Software release 8.0, Liu and Lattyak 2007). The advantages provided by TF models, in relation to regression models, are evident. In a traditional regression analysis the response of a dependent variable is related to values of potential explanatory variables. The drawback of a regression analysis stands out when the error terms of the model are serially correlated, which results in an ineffectual or incorrect model (e.g. Box and Newbold 1971). Autoregressive integrated moving average (ARIMA) models were introduced to account for such autocorrelated structure of time series data (e.g. Box and Jenkins 1976). Also comparison with ARIMA models renders TF models superior. ARIMA time-series analyses consist of an iterative procedure, including three main phases: identification of a time series, parameter estimation, and diagnostic checking. Once an appropriate model is determined, it can be used for forecasting, control, or simply to better understand the structure of the time series. The univariate ARIMA models are useful for the analysis of a single time series. In such a case, modelling is limited to the information contained in the series’ own past. In many cases, however, it may be possible to relate the response of one series to other time series. TF models were introduced as a particularly useful method for such applications. TF models can connect one series not only with its own past values, but also with past and present values of other, related, time series. This is done by merging the basic concepts of general regression models with those of (ARIMA) models. In our earlier studies we had applied TF’s in the Baltic Sea environmental data analysis by modelling relations between large-scale climate indices, and their regional or local ecological consequences (Hänninen et al. 2000, 2003, Vuorinen et al. 2003, 2004). More comprehensive presentation of the TF models is given by e.g. Box and Jenkins (1976), Liu and Hudak (1992), and Liu and Lattyak (2007).

Finally, all plausible models were compared and only one model for each analysis was chosen for presentation (for practical reasons we used the total Baltic Sea runoff for modelling also the sub areas). The following criteria of parsimony were sequentially used for selection of the models: (1) The smallest residual standard error among combinations of exploratory variables, (2) The simplest obtained model i.e. model with the lowest number of parameters, (3) The highest proportional decrease in error term when the TF model residual standard error was compared with those of the univariate ARIMA model of the same response variable (the decrease in error term was seen as due to inclusion of convenient exploratory variables into the model). There were no missing observations in climate, or runoff time series.

Results

Resulting TF models fit well with the observed series (Tables 1 and 2). All substantial parameters showed statistical significance, and coefficient of determination ($r^2$) values varied between 0.68 and 0.71, which is considered satisfactory in statistical time series analysis.

All climate indices had noteworthy correlations with the Baltic Sea runoff which, however, was very specific in each case; there also was a considerable areal variation (Table 1). There was, however, considerable areal variation (Table 2).

All the models resembled each other as their structures, and accuracy, proved to be very similar (Table 1). The most obvious difference between models was in time lags. A larger geographical area, in general, meant a delayed response between a weather effect and a subsequent change in freshwater runoff (Table 2). On the other hand, in the north-south direction, the northern areas showed lagged response. AO showed an inverse and relatively long regulation effect on runoff. This was, however, evident only when the total runoff area and the central areas of the Baltic Sea were included in modelling, but not concerning the Gulf of Bothnia. NAO was evidently the most suitable index for explaining general runoff regulation, resulting in, depending on the location, an immediate or very short response in the runoff. Iceland SLP indicated weaker and very similar regulation to
Table 1. Identified transfer function (TF) models between the total Baltic Sea runoffs and climatic indices used, initial estimates of the parameters with their standard errors, \( t \) and \( p \) are from one-sample \( t \)-test with which we tested whether or not the estimates differ significantly from 0. The parameters are: \( \omega B(1 – B^{12}) \) are the TFs between series \( y_t \) (output variable) and \( x_t \) (input variable(s)), where \( B \) is the backshift (or lag) operator, \( 1 – B^{12} \) is the non-seasonal differencing operator in the process, \( 1 – B \) is the seasonal differencing operator in the process, \( \omega \) values \( \omega = \omega_0, \omega_1, \omega_2, ... \) are the TF weights for the lags in the input series \( x_t \), \( \Theta \) is the seasonal moving average (MA) operator in disturbance term, \( \phi \) is the non-seasonal autoregressive (AR) operator in the disturbance term, and \( a_i \) is the error term in the disturbance. Coefficients of determination for the models are based on the sum of squares and are calculated as follows: \( r^2 = 1 – \frac{\sum(y – \hat{y})^2}{\sum(x – \bar{x})^2} \), where \( n \) is the number of observations and \( k \) is the number of estimated parameters. All presented time series are monthly means. For more detailed description, see text and e.g. Hänninen et al. (2000, 2003).

<table>
<thead>
<tr>
<th>(A) Total Baltic Sea runoff vs. NAO</th>
<th>Estimate</th>
<th>SE</th>
<th>( t )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>((1 – B^{12})\text{Runoff}_t = (\omega_0 + \omega_1 B^{12})\text{NAO}_t + (1 – \Theta^{12} B^{12})/(1 – \phi B)a_i )</td>
<td>( \omega_0 )</td>
<td>1.10</td>
<td>0.18</td>
<td>6.00</td>
</tr>
<tr>
<td></td>
<td>( \omega_1 )</td>
<td>0.76</td>
<td>0.18</td>
<td>4.19</td>
</tr>
<tr>
<td></td>
<td>( \Theta^{12} )</td>
<td>0.83</td>
<td>0.03</td>
<td>25.88</td>
</tr>
<tr>
<td></td>
<td>( \phi )</td>
<td>0.61</td>
<td>0.04</td>
<td>14.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(B) Total Baltic Sea runoff vs. AO</th>
<th>Estimate</th>
<th>SE</th>
<th>( t )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>((1 – B^{12})\text{Runoff}_t = (\omega_0 + \omega_1 B^{12})\text{AO}_t + (1 – \Theta^{12} B^{12})/(1 – \phi B)a_i )</td>
<td>( \omega_0 )</td>
<td>-0.55</td>
<td>0.26</td>
<td>-2.12</td>
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<tr>
<td></td>
<td>( \Theta^{12} )</td>
<td>0.81</td>
<td>0.03</td>
<td>25.20</td>
</tr>
<tr>
<td></td>
<td>( \phi )</td>
<td>0.60</td>
<td>0.04</td>
<td>13.88</td>
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</table>

<table>
<thead>
<tr>
<th>(C) Total Baltic Sea runoff vs. Iceland SLP</th>
<th>Estimate</th>
<th>SE</th>
<th>( t )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>((1 – B^{12})\text{Runoff}_t = (\omega_0 + \omega_1 B^{12})\text{NAO}_t + (1 – \Theta^{12} B^{12})/(1 – \phi B)a_i )</td>
<td>( \omega_0 )</td>
<td>-0.17</td>
<td>0.05</td>
<td>-3.45</td>
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<tr>
<td></td>
<td>( \omega_1 )</td>
<td>-0.15</td>
<td>0.05</td>
<td>-3.02</td>
</tr>
<tr>
<td></td>
<td>( \Theta^{12} )</td>
<td>0.81</td>
<td>0.03</td>
<td>25.01</td>
</tr>
<tr>
<td></td>
<td>( \phi )</td>
<td>0.62</td>
<td>0.04</td>
<td>14.40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(D) Total Baltic Sea runoff vs. Hoburg winds</th>
<th>Estimate</th>
<th>SE</th>
<th>( t )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>((1 – B^{12})\text{Runoff}_t = (\omega_0 + \omega_1 B^{12})\text{NAO}_t + (1 – \Theta^{12} B^{12})/(1 – \phi B)a_i )</td>
<td>( \omega_0 )</td>
<td>1.64</td>
<td>0.38</td>
<td>4.37</td>
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<tr>
<td></td>
<td>( \omega_1 )</td>
<td>1.86</td>
<td>0.37</td>
<td>4.97</td>
</tr>
<tr>
<td></td>
<td>( \Theta^{12} )</td>
<td>0.78</td>
<td>0.03</td>
<td>22.96</td>
</tr>
<tr>
<td></td>
<td>( \phi )</td>
<td>0.64</td>
<td>0.04</td>
<td>15.35</td>
</tr>
</tbody>
</table>

Table 2. Summary of time lags (months) of transfer function models between total runoff and various climate indices for two sub-areas and the entire Baltic Sea basin. All time series were monthly series, except quarterly in the Gulf of Bothnia. ns = model not significant.

<table>
<thead>
<tr>
<th>Runoff vs.</th>
<th>Gulf of Bothnia</th>
<th>Central Baltic Sea</th>
<th>Entire Baltic Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAO</td>
<td>1–3</td>
<td>0</td>
<td>0–1</td>
</tr>
<tr>
<td>AO</td>
<td>ns</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Iceland SLP</td>
<td>ns</td>
<td>0</td>
<td>0–1</td>
</tr>
<tr>
<td>Hoburg winds</td>
<td>1–3</td>
<td>0–1</td>
<td>0–1</td>
</tr>
</tbody>
</table>
that of NAO, but inversely. Furthermore, Hoburg wind speeds very much resembled the NAO regulation (Fig. 2 and Table 1).

Discussion

Climate indices have proved useful in regional exercises in the arctic (ACIA 2005), Baltic Sea catchment (BACC author team 2008), and also European freshwater environments (Eisenreich 2005) to explain changes in local hydrological parameters that also are important for aquatic ecology, such as runoff or salinity. Here, we compared several climate and weather indices as the basis for modelling runoff changes in the Baltic Sea catchment area. We used as predictors a selection of related indices from northern-global air pressure (AO), to Atlantic and equatorial air pressure (NAO), further to north Atlantic air pressure at Iceland (SLP), and finally just local wind speed at a Baltic Sea island. We found that the Arctic and North Atlantic climate effects can generally be detected in the Baltic Sea runoffs, and changes in runoffs can even be modelled for Baltic sub-areas using various climate indices as predictors. However, including more local indices, such as sea-level air-pressure or local wind

Fig. 2. Modeled (filled circles, based on the identified TF-models) and observed changes (circles) of Baltic Sea runoffs for the period of 1970–2000. Predictors in modeling were: (A) NAO, (B) AO, (C) Iceland SLP, and (D) Hoburg winds (the letters refer to corresponding models in Table 1). Smooth lines are drawn with distance-weighted least squares method. Model fit scatterplots (observed vs. estimated values) are shown in the inserts.
speed in the exercise, did not produce any further improvement in the general understanding of the climate control over the Baltic ecosystem.

Our results of AO suggests that a lag of roughly half a year between cause and effect is due to late winter events (indicating probably a longer lasting snow and ice melting period in the northern and eastern catchment area) in the sub-arctic catchment area of the Baltic Sea. The effects originating from AO are lagged about seven months, most probably due to the fact that ice is not melting simultaneously over the entire watershed area. The Neva River is the largest river flowing into the Baltic Sea. The mean annual discharge of the Neva River into the Gulf of Finland varies considerably from year to year (data exist from the year 1859, see Bergström and Carlsson 1993), ranging from 42 km$^3$ y$^{-1}$ (observed in 1940) to 115 km$^3$ y$^{-1}$ (in 1924). The high variation in the Neva annual discharge is evidently connected with snow and ice melting in the northern watershed areas of the river. That area includes three of the four biggest lakes in Europe: Lake Ladoga and Lake Onega in Russia (connected by the Svir River), and Lake Saimaa in Finland (running to the Lake Ladoga by the Vuoksi River), all are annually covered by ice. Our results are in accordance with Doganovsky and Myakisheva (2000) in that the characteristics of the ice cover on these lakes show a rather complicated correlation with climatic parameters. The time of ice break-up depends on a multitude of factors, but it coincides rather well with the changes in air temperature. In spring, for example, ice melting in Lake Ladoga proceeds in the south-north direction. The water in the shallower southern areas warms up faster; hence ice break-up occurs earlier in these areas. The average duration of the ice-free period for the Lake Ladoga area varies from 103 to 181 days. These variations are mainly due to the effect of latitude and local conditions. Normally melting starts in early April, and by middle-late May Lake Ladoga is completely ice-free. Lake Onega lies further north of Lake Ladoga, and therefore its annual ice cover persists for somewhat longer. Ice thickness in Lake Onega increases until mid-March, and depending on winter severity, the ice melts completely in the period from late April to early June (Kondratyev and Filatov 1999). Therefore the large north-south coverage of the lake’s watersheds, together with Lake Saimaa, constitutes a long-lasting continuum not only regulating considerably freshwater discharges from the Neva watershed into the Baltic Sea but stabilizing substantially the annual variation in freshwater runoffs, as well. This is also in accordance with Jevrejeva and Moore (2001), who showed AO to have a positive effect on the Baltic Sea ice.

In this comparison the NAO explained Baltic area climatic regulation very well. It has also been largely used both in the Baltic Sea and elsewhere (Hurrell 1995, Hänninen et al. 2000, 2003, Zorita and Laine 2000, Vuorinen et al. 2003, 2004). However, we think that the use of both AO and the NAO simultaneously would improve general understanding of climate regulation in the Baltic Sea catchment, because NAO mainly reflects changes in westerly weather, while AO can be considered to replace it in the importance in those circumstances when the role of westerlies over the Atlantic is smaller, i.e. in situations when continental climate type is found over the Baltic Sea. This kind of alternating between continental and marine climate types is typical for our study area, thus the explanation value of NAO and AO also alternates periodically. Including just the North Atlantic air pressure or local wind speed at Hoburg would result in fairly good and comparable TF models. The sea-level air-pressure at Iceland proved to be least meaningful in figuring out the regulation effects between the climate indices and the Baltic Sea runoff regulation. The inverse relations found between the indices can be interpreted as Icelandic SLP representing predominantly Icelandic low-pressure conditions, while the opposite (the Azores high-pressure area) is true for the southern sea level pressures, similarly NAO representing predominantly southern low-pressure conditions as compared to the AO which is usually dominated by polar high pressures. Negative AO estimate can be interpreted as high air pressures in the polar regions, which usually denote low rainfall in the Baltic catchment (indicating also negative mode of NAO), and vice versa. Similarly, we see that the Hoburg wind speeds are basically more or less a reflection of NAO, and therefore simply indicate the same phenomenon, a difference between areal air pressures.
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References


