Regime Shifts in Marine and Lake Ecosystems: Teleconnection Patterns

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Abstract

Climatically induced regime shifts in aquatic ecosystems can re-organize plankton communities and thus alter structural and functional system properties. These changes may be synchronized over large spatial scales and across different types of aquatic ecosystems. We studied the timing and type of long-term changes for several indicators of abiotic and biotic system components. The synchrony of regime shifts was analyzed with regard to system type (marine, freshwater), season (spring, summer) and geographic location. We choose two marine systems (North Sea, Baltic Sea) and two lakes (Müggelsee, Lake Washington). We hypothesize coherent shifts of all physical system components in spring during the late 1980s in Europe – possibly synchronized by NAO dynamics - regardless of system type and location, but out of phase with the North American system. Further, biological responses were expected to be less coherent but still obvious shifts in ecosystems. In contrast, responses of all system components are expected to be more variable during summer.

Introduction

Shifts in the climate have been observed regularly, the most recent occurred in the mid 1970s and the late 1980s, associated to changes in the North Atlantic Oscillation or the El Nino Southern Oscillation (Hare and Mantua 2000; Philander 1990). Those changes have been identified as the main drivers of drastic changes in aquatic ecosystems (Alheit et al. 2005; Blenckner et al. 2007; Gerten and Adrian 2000; Winder and Schindler 2004). Consequently, several regime shifts in marine (Alheit 2009; Alheit et al. 2005; Beaugrand et al. 2008; Hare and Mantua 2000; Weijerman et al. 2005) and lake (Blenckner et al. 2007; Blenckner and Hillebrand 2002; Wagner and Adrian 2009) ecosystems have been reported within the last years, and several of them have been attributed to changes in the NAO in the late 1980s (Alheit et al. 2005; Blenckner et al. 2007; Edwards and Richardson 2004; Lehodey et al. 2006).

The term regime shift has no universal definition, but is used to describe the transition between two periods of more or less stable equilibria of climate, physical or biological system states (Lees et al. 2006). However, there is consensus on some properties of regime shifts,
such as a relatively abrupt occurrence on large spatial scales, persistence of the system before and after the shift (deYoung et al. 2004).

In this study, we addressed the issue of regime shift occurrence by analyzing four aquatic ecosystems, two marine systems – the Baltic Sea and the North Sea – and two lake ecosystems – Lake Washington and Müggelsee. With respect to system level, we calculated indices for the different abiotic and biotic system components for each system and season and determined the timing of regime shifts for these indices.

The European systems are expected to be teleconnected with respect to climatic regime shifts. Thus, we hypothesized synchronous and coherent shifts in the physical system components in spring in the European systems during the late 1980s (NAO driven), but an out of phase shift in the physical state of Lake Washington. Furthermore, we assume a chronology of change from physics to phytoplankton and zooplankton, i.e., a possibly lagged response in the biota compared to the physical system state, regardless of system type. Regime shifts in spring and summer may not correlate in any system and region, and we expect high seasonal variability for lakes as well as marine systems.

Materials and Methods

Study Sites

We examined two marine and two lake ecosystems: the Baltic Sea and the North Sea, Müggelsee and Lake Washington, respectively. The first three systems are located in the Northern part of Europe, Lake Washington, by contrast, is situated in the western part of the United States (see Fig. 1). An overview of morphological characteristics is given in Table 1. The marine systems are heterogenous environments with respect to physical and biological properties, thus, we concentrated on specific subregions within these systems. Those are the German Bight for the North Sea and Central Baltic Sea. The study period is the longest overlapping period with existing data for all considered ecosystems, 1980 – 2007.

Fig. 1: Location of the studied ecosystems North Sea, Baltic Sea, Müggelsee and Lake Washington.
Data collection

Profile measurements (0.5m steps) of physical and biological variables of Müggelsee were recorded in weekly to biweekly intervals between 1980 and 2007. Thermal stratification was defined to occur when the temperature difference between surface and 5m depth exceeded 1°C. Plankton was determined to species level for the zooplankton and to genus level for the phytoplankton (detailed information on sampling methodology and processing in (Gerten and Adrian 2000). Sampling frequency of the Lake Washington monitoring programme is monthly (until March) and weekly to biweekly during stratification (April to November). Profile measurements of physical and biological variables have been recorded in 1m steps (above the thermokline) and 5m steps (below the thermokline) between 1962 and 2007 (phytoplankton until 2000 only). Plankton was determined to species level (Edmondson and Litt 1982).

Sampling in the Baltic Sea was carried out at irregular intervals since 1959 and data were provided as monthly means. Data include water temperature (surface and 60m depth), biomass of phytoplankton groups (diatoms, cyanobacteria, and dinoflagellates) and of zooplankton species (mainly copepods) (Mollmann et al. 2000; Wasmund and Uhlig 2003). Water temperature data for the North Sea since 1980 were taken from the ICES database (http://www.ices.dk/ocean), plankton data on species level were extracted from the CPR survey (Batten et al. 2003).

Seasons

As marked changes were observed in the seasonality of lake plankton communities (Adrian et al. 2006; Winder and Schindler 2004), season onset was defined by physical and biological lake properties. In particular, the onset of the spring season in Müggelsee was defined as the ice-off date, the start of the summer season was defined as the date of the clear water phase. End of summer was set as week 40 (Wagner and Adrian 2009). For Lake Washington, the onset of the spring season was defined when lake temperatures began to rise after winter (i. e. the date of the water temperature minimum), summer season was defined as the stratified period. For the marine systems, it was not possible to adjust seasons due to the lack of appropriate data, thus, seasons were defined according to months (spring = March to May, summer = June to September).

Aggregation level of data

All variables were calculated as yearly averages and assigned to the spring season or the summer season, respectively. Temperature variables were compiled as monthly and seasonal averages; plankton variables were compiled as seasonal averages. Phytoplankton was categorized as cyanobacteria, diatoms, dinoflagellates, cryptophyceae, and chrysophyceae; zooplankton was included as copepods (on species level), rotifers and cladocerans (content of categories differed between systems).
<table>
<thead>
<tr>
<th>System</th>
<th>location</th>
<th>mean depth (m)</th>
<th>area (km²)</th>
<th>ice</th>
<th>ice-out</th>
<th>mixing regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Washington*</td>
<td>47° 36’N, 122° 15’W, 52° 26’N, 13° 39’E, USA</td>
<td>32.9</td>
<td>87.6</td>
<td>no</td>
<td>dimictic</td>
<td></td>
</tr>
<tr>
<td>Müggelsee**</td>
<td>German Bight*** 6°25’E (western boundary); 54°59’N (northern), Germany</td>
<td>4.9</td>
<td>7.3</td>
<td>mostly yes</td>
<td>various</td>
<td>polymictic</td>
</tr>
<tr>
<td>North Sea</td>
<td>(northern)</td>
<td>22.5</td>
<td>24.500</td>
<td>no</td>
<td>stratified in summer</td>
<td></td>
</tr>
<tr>
<td>Baltic Sea</td>
<td>Central Baltic Sea**** (54° - 59° N; 12° - 27° E) (northern), Northern Europe</td>
<td>62.1</td>
<td>211.069</td>
<td>no</td>
<td>stratified in summer</td>
<td></td>
</tr>
</tbody>
</table>

**Winder and Schindler 2004**

**Driescher et al. 1993**

***Beddig et al. 1997**


Table 1: Location, morphological and thermal characteristics of the studied ecosystems
System component state indices

Variables were classified as a function of system level, i.e., as physical, phytoplankton or zooplankton variables, respectively. To compare temporal trends between systems and seasons, we separately calculated a system state component index for each system, system level and season. This index included all associated variables and was calculated as described in Hare and Mantua (2000), modified by Wagner and Adrian (2009). This resulted in a total of 24 systems state component indices (4 systems x 3 levels x 2 seasons). Assuming rather abrupt shifts from one more or less stable state to another, the timing of regime shifts was analyzed by using the sequential t-test method implemented by STARS (Rodionov 2004; Rodionov 2006). We set the length of the regimes to 7, the Huber parameter to 1, and the significance level to 0.05.

<table>
<thead>
<tr>
<th>System Component</th>
<th>Lake Washington</th>
<th>Müggelsee</th>
<th>North Sea</th>
<th>Baltic Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zooplankton</td>
<td>-</td>
<td>1995</td>
<td>1990</td>
<td>1990</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Timing of regime shifts according to the STARS method (see Method section), classified by seasons and system component for the studied aquatic ecosystems. Please note that the Baltic Sea physical and phytoplankton system components showed two distinct regime shifts in spring.

Results

Almost all analyzed system component state indices showed clear regime shifts (except for the phytoplankton and the zooplankton system components of Lake Washington and the physical system component of the North Sea in spring; see Table 1). However, we found marked differences in the chronology and seasonality between systems. Furthermore, the Baltic Sea physical and phytoplankton system component showed two regime shifts in spring.

Chronology of regime shifts

The physical system component state indices of Müggelsee and the Baltic Sea showed regime shifts in spring in the late 1980s (Fig. 2, Table 2), as well as the physical system components of the marine environments in summer (Table 2). Changes in the plankton communities of the European systems in spring and summer occurred usually in the early 1990s (Table 2). The physical system component of Lake Washington showed regime shifts in 2000 and 2001 in spring and summer, respectively. Changes in Lake Washington plankton components were only obvious in summer during the 1990s (Tab. 2).
**Teleconnection patterns**

The European systems showed coherent responses of the physical system components in the late 1980s (except for the North Sea in spring and Müggelsee in summer). The timing of regime shifts of the biological system components varied to a higher degree, however, observed changes occurred predominantly in the early 1990s (except for the North Sea phytoplankton, Table 2).

**Seasonal patterns**

Usually, the timing of regime shifts per system component did not differ much among seasons within systems. In all systems, the timing of regime shifts in spring and summer varied by two years maximum (except for changes in Müggelsee physics – Fig. 3 – and the North Sea zooplankton, Table 2).
Fig. 2: Regime shifts in system components in spring (physics, upper panel, phytoplankton, middle panel, and zooplankton, lower panel) for Müggelsee (left panel) and Baltic Sea (right panel). Given are yearly means of system component state indices with standard errors and estimated average states of regimes (green lines).
Fig. 3: Regime shifts in system components (physics, upper panel, phytoplankton, middle panel, and zooplankton, lower panel) in spring (left panel) and summer (right panel) for Müggelsee. Given are yearly means of system component state indices with standard errors and estimated average states of regimes (green lines).
Discussion

Regime shifts occurred on all system components within each of the studied ecosystems. The differences in terms of the timing of regime shifts between marine and lake ecosystems were less pronounced than expected. In general, the marine systems showed the most coherent changes throughout all levels and seasons. The most striking differences, however, were found between Lake Washington and the European systems.

As expected, only systems in Europe showed a regime shift in the physical system component state in the late 1980s (Fig. 2, Table 2), certainly connected to changes in the NAO, which is in line with the current understanding of changes in European marine and limnic ecosystems (Alheit 2009; Alheit and Bakun; Beaugrand 2009; Blenckner et al. 2007; Gerten and Adrian 2000). Additionally, the Baltic Sea and the North Sea also showed a regime shift in the physical system state in summer (Table 2, Fig. 2). By contrast, the North American lake did not show strong changes in the physical state before 2000.

In contrast to expectations, the marine physical system components in summer showed regime shifts in the late 1980s. This is surprising, as the climate induced summer warming of aquatic systems was expected to manifest itself later, as has been reported for several Northern hemispheric lake ecosystems (Adrian et al. 2006; Blenckner et al. 2007; Wagner and Adrian 2009). This may provide evidence that the timing of response to climate induced warming trends differed between marine and limnic systems. However, this difference might be also due to the fact that seasons were defined differently in this study; while we applied a phenology adjusted definition of seasons for the lakes (Adrian et al. 2006; Wagner and Adrian 2009; Winder and Schindler 2004), seasons for the marine systems had to be defined in the traditional manner according to months.

Except for Lake Washington, the biological system components changed subsequently to the regime shifts in the physical system components (Table 2) and may thus be driven by climate induced warming trends, at least in parts. However, we did not find a hierarchy of change from phytoplankton to zooplankton. We thus conclude that climate change and following bottom-up effects are not the only driver for changes in the plankton community, neither for lakes, nor for marine systems.

We conclude that regime shifts in the climate may be responsible for changes in the physical state of aquatic ecosystems. Those shifts in the physical state of aquatic systems can be teleconnected over large spatial scales via changes in climate phenomena (like the NAO shift in the late 1980s). Effects of changes in temperature may subsequently cascade up the food web, regardless of system type and season, and manifest in clear regime shifts in the biological system states. With respect to the timing of regime shifts, the difference between marine and lake ecosystems is unexpectedly small.

References


