**Meeting report**

**Comparative analysis of European wide marine ecosystem shifts: a large-scale approach for developing the basis for ecosystem-based management**

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Abrupt and rapid ecosystem shifts (where major reorganizations of food-web and community structures occur), commonly termed regime shifts, are changes between contrasting and persisting states of ecosystem structure and function. These shifts have been increasingly reported for exploited marine ecosystems around the world from the North Pacific to the North Atlantic. Understanding the drivers and mechanisms leading to marine ecosystem shifts is crucial in developing adaptive management strategies to achieve sustainable exploitation of marine ecosystems. An international workshop on a comparative approach to analysing these marine ecosystem shifts was held at Hamburg University, Institute for Hydrobiology and Fisheries Science, Germany on 1–3 November 2010. Twenty-seven scientists from 14 countries attended the meeting, representing specialists from seven marine regions, including the Baltic Sea, the North Sea, the Barents Sea, the Black Sea, the Mediterranean Sea, the Bay of Biscay and the Scotian Shelf off the Canadian East coast. The goal of the workshop was to conduct the first large-scale comparison of marine ecosystem regime shifts across multiple regional areas, in order to support the development of ecosystem-based management strategies.

**Keywords:** climate change; ecosystem regime shifts; eutrophication; fisheries; trophic cascades

**1. INTRODUCTION**

Abrupt ecosystem shifts, commonly termed regime shifts, are changes between contrasting and persisting states of ecosystem structure and function. They are considered to be abrupt in the sense that the timespan during which the shift occurs is relatively short (1–2 years) in comparison to the duration of the different states (often decadal to multi-decadal) [1]. These events have been detected in terrestrial, freshwater and marine ecosystems [2]. At present, the mechanics behind marine ecosystem regime shifts have been varyingly explained as a result of multiple causes, involving both abiotic and biotic processes. Abiotic factors include climate-induced changes such as temperature and salinity as well as nutrient changes. Biotic drivers have included hypothesis that includes the restructuring of food webs owing to overfishing (e.g. trophic cascades) and internal population dynamics. However, both categories of drivers include natural and anthropogenic contributions, which may operate synergistically, making it difficult to disentangle the various influences.

The growing literature in the field shows that the rapid and major reorganizations of marine ecosystem can have significant impacts at the ecological, social and economic levels. Globally, major ecosystem shifts were collectively observed in the late 1980s, with many large- or small-scale ecosystems experienced quasi-synchronous shifts following an overall period of high variability (e.g. the North Sea, the Baltic Sea, the Mediterranean, the Black Sea, the Bay of Biscay, the western North Atlantic and the Scotian Shelf, and the North Pacific).

These studies of climate–human ecosystem interactions have accumulated substantial regional knowledge about ecosystem structure and function, and assembled comprehensive long-term data series of abiotic as well as biotic variables across multiple trophic levels. To implement an ecosystem approach to management and to have a degree of predictability (i.e. anticipate these rapid shifts), there is first a need to perform comparative studies of ecosystem dynamics, taking systems experiencing similar external forcing and/or having a comparable ecosystem structure into account. Only by performing an in-depth analysis of synchronies between major ecological changes in various ecosystems, can direct and indirect effects of climatic and anthropogenic drivers as well as mediator mechanisms be identified and disentangled.

Ultimately, the goal of the workshop was to compare ecosystem regime shifts in a multitude of different marine ecosystems from various regional areas in the North Atlantic, with an emphasis on comparing changes on multiple trophic as opposed to single trophic levels. Furthermore, a set of standardized statistical techniques were applied to all systems avoiding variability in results owing to the use of different numerical methods. Eventually, this analysis will yield background information on the effects, additive or multiplicative, of different external, natural and/or anthropogenic drivers needed for the further development of ecosystem-based management.

The workshop was held on 1–3 November 2010 in Hamburg, Germany and was attended by 27 invited scientists from 14 countries. Participants included a careful blend of specialists from the regional ecosystems under study and more general specialists in marine ecosystem dynamics. The workshop was mainly funded by the EUR-OCEANS consortium.
2. COMPARATIVE ANALYSIS OF REGIME SHIFTS

(a) Methods
The workshop began with an introduction into the numerous statistical methods suitable for the detection of ecosystem regime shifts. The resulting discussion highlighted the advantages/disadvantages of the various univariate and multivariate methods that have been used in the past to detect discontinuities in time-series data. For the purpose of the workshop, a standard set of procedures for the comparative analysis of marine ecosytems was agreed. This set of statistical techniques and guidelines was developed in the framework of the ICES/HELCOM Working Group on Integrated Assessments of the Baltic Sea (WGIAB; [3]). It contains principal component analysis (PCA) to identify main trends in the multivariate matrices of time series as well as a multivariate (constrained/chronological clustering, CC) and a univariate (sequential regime shift detection method—STARS; [4]) technique for identifying discontinuities in time series. A description of the methods and the necessary code to conduct the analysis in R (www.r-project.org) can be accessed from the workshop’s website (www.uni-hamburg.de/ihf/ForesightWorkshop.html).

(b) Ecosystems
A large variety of Northern Hemisphere marine ecosystems were represented during the workshop and were introduced by the participants in a series of short presentations. Multi-trophic level information was also available for areas of the Western North Atlantic, namely the Scotian Shelf, the Gulf of Maine, Georges Bank the Southern New England area. Eastern Atlantic Shelf Seas were represented by the Central Cantabrian Sea and the Bay of Biscay. More northeast Atlantic ecosystems were represented by the Barents Sea and the North Sea, the latter split into the Wadden Sea, the German Bight and an open sea area. Semi-enclosed seas were represented by the Black Sea, the Baltic Sea and the Mediterranean Sea. The latter two larger areas were additionally represented by a number of sub-ecosystems. Baltic systems included from west to east the Kattegat, the Sound, the Central Baltic Sea, the Gulfs of Riga and Finland as well as the Bothnian Sea and Bay. Furthermore, three coastal Baltic Sea sites were studied. For the Mediterranean Sea, the focus was on the Adriatic Sea, where slightly restricted information (i.e. not covering all trophic levels) was available for the Gulf of Lions and the Aegean Sea.

In total, time series for 24 marine bioregions were assembled during the workshop. These systems are situated along a number of gradients. Beside the geographical setting causing different influences of large-scale atmospheric phenomena and hence thermal differences, ecosystems differed in, e.g. terms of the average salinity level (e.g. low salinity Baltic versus high salinity Mediterranean Sea ecosystems), species diversity (e.g. low in the Baltic compared with the other areas) and anthropogenic impact (e.g. fisheries and eutrophication). Overall, an impressive collection of time-series information on European and Northeast American marine ecosystems was collected and analysed for the first time during the meeting.

(c) Observed ecosystem regime shifts and the importance of external drivers
For all the systems described above, PCA, CC and STARS were conducted to extract dominant ecosystem trends and potential regime shifts. The first results of these analyses displayed large-scale changes in ecosystem structure during the end of the 1980s/early 1990s, as described earlier for single systems in the literature. For some ecoregions, smaller changes were identified for the mid-1990s and early 2000s.

The predominance of changes in the late 1980s/early 1990s over the whole Northern Hemisphere indicates the importance of large-scale climatic changes in inducing ecosystem regime shifts. In this respect, the connectance of various Northern Hemisphere climatic patterns leading to the observed large-scale change was discussed. Furthermore, the importance and potential interaction between North-Atlantic atmospheric patterns such as the North-Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) were reviewed. A consensus on the meeting was that more work involving climate scientists needs to be conducted to resolve the effect of climate in inducing the observed large-scale Northern Hemisphere ecosystem changes.

During the discussion resulting from the conducted analyses, different opinions were expressed on the relative importance of external drivers for the observed regime changes. For some ecosystems like the Scotian Shelf, fishing-induced trophic cascades were considered to be the prime agent of change [5], while for other systems climate was considered to be the most important driver (e.g. [6]). Again, for other systems like the Baltic and the Black Sea the importance of the interaction between climate, fisheries and eutrophication in inducing the observed ecosystem changes was highlighted [7–10].

As to the internal mechanism leading to ecosystem regime shifts, changes in trophic control were also discussed. For example, overfishing has been shown to change the dominance of the control pattern from bottom-up to top-down [5]. Furthermore, the vulnerability of ecosystems to experiencing such a change in control may depend on its geographical location and hence the associated mean thermal conditions and/or species diversity [11]. Here, as in other heavily exploited regions, both climate change and fishing effects may interact in leading to ecosystem regime shifts. However, some other studies suggest that trophic control oscillates depending on climatic conditions alone [12]. The datasets assembled for the first time during the workshop will allow these hypotheses to be tested over a wide range of different marine ecosystems and eventually provide an integrative view on the importance of external drivers and their interactions with internal mechanisms in inducing marine ecosystem regime shifts.
3. FUTURE DIRECTIONS

The workshop was intentionally designed to contain both ‘hands-on’ data analyses and presentations on the ecology of the different ecosystems and theoretical questions related to ecosystem regime shifts. The data analysis will eventually not only lead to the first comparison of marine ecosystem regime shifts (which continues to date) on such a large geographical scale, but will also stimulate a number of new ideas for follow-up analyses and initiatives. During the workshop, the question of the definition of regime shifts and the existence of alternative stable states was frequently raised and this will be further explored. Furthermore, more data analyses are needed, not only to identify discontinuities in multivariate time series as indicators of regime changes, but also to identify the nature of the change, if linear, threshold-like or discontinuous. It was, however, acknowledged that proving the existence of real alternative stable states with hysteresis is still a difficult task, with the rarity of longer and multi-decadal time series being a major obstacle.

One obvious theme when thinking of the incorporation of abrupt shifts in ecosystem-based management strategies is the development of early warning indicators [13]. A presentation introduced different techniques that could be applied to the empirical data assembled for the various ecosystems. Future collaborations have been decided to pursue this field of research.

Eventually, the datasets collected will allow a variety of further analyses. One large advantage mentioned is the possibility of investigating ecosystem change on different scales. Variability on smaller scales, e.g. among the Baltic Sea sub-systems, can be compared with the large-scale change between ecosystems on both sides of the North Atlantic. Furthermore, more detailed analyses can be done on comparing ecosystem types along the abovementioned gradients of environmental settings, species diversity and anthropogenic impact.

The majority (if not all) of the participants finally felt that the approach of comparing a multitude of ecosystems based on a simple, common set of statistical techniques is a worthwhile approach and could be expanded to other marine areas. If similar data are available even freshwater and terrestrial ecosystems could be combined in a meta-analysis of ecosystem change. Such an analysis would then contribute to integrated ecosystem assessment activities on the local, e.g. the Baltic Sea [14], as well as the worldwide level such as the Millennium Ecosystem Assessment [15]. The datasets and knowledge derived from these analyses additionally provide valuable information for modelling and model validation, crucially needed for predicting the fate of ecosystems under global change scenarios. Hence, they would contribute to developing reliable strategies for the sustainable development of the world’s ecosystems.

We thank all participants of the workshop for their contribution (a list of workshop participants and additional data contributors can be found on the workshops website; www.uni-hamburg.de/IHF/ForesightWorkshop.html). The workshop represented a FORESIGHT WORKSHOP funded mainly by the EUR-OCEANS consortium (http://vds1719.sivit.org/eoc). Additional funding was provided by ‘KlimaCampus’ of Hamburg University (www.klimacampus.de).

10 Oguz, T. & Velikova, V. 2010 Abrupt transition of the large-scale change between ecosystems on both sides of the North Atlantic. Furthermore, more detailed analyses can be done on comparing ecosystem types along the abovementioned gradients of environmental settings, species diversity and anthropogenic impact.

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