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Ecological forecasting in the presence of abrupt regime shifts

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ABSTRACT

Regime shifts may cause an intrinsic decrease in the potential predictability of marine ecosystems. In such cases, forecasts of biological variables fail. To improve prediction of long-term variability in environmental variables, we constructed a multivariate climate index and applied it to forecast ecological time series. The concept is demonstrated herein using climate and macrozoobenthos data from the southern North Sea. Special emphasis is given to the influence of selection of length of fitting period to the quality of forecast skill especially in the presence of regime shifts.

Our results indicate that the performance of multivariate predictors in biological forecasts is much better than that of single large-scale climate indices, especially in the presence of regime shifts. The approach used to develop the index is generally applicable to all geographical regions in the world and to all areas of marine biology, from the species level up to biodiversity. Such forecasts are of vital interest for practical aspects of the sustainable management of marine ecosystems and the conservation of ecosystem goods and services.

1. Introduction

Marine ecosystems around the world are currently undergoing dramatic changes because of the influence of human activity and/or climate change, resulting in a reduction in species diversity (Rockström, 2009; Steffen et al., 2007; Worm et al., 2006). Direct and indirect anthropogenic causes, such as overfishing, industrial and urban growth, pollution and eutrophication, habitat losses, and changes in coastal morphology, suggest ecosystem degradation (Goldberg, 1994). Inter-annual and inter-decadal variability in the components of the marine ecosystem can be attributed to climate and oceanographic variability, non-linear predator prey dynamics, and anthropogenic impacts. The marine ecosystem is extremely complex and its processes, such as trophic and non-trophic interactions, benthic–pelagic coupling, and species interactions, are only partly understood, which has led to the conclusion that it is inherently unpredictable. Major changes in species composition, species richness, and functional diversity, which affect the sustainability of biological resources, are caused by signals of climate variability such as the intensity of the trade winds, the El Niño, or the Atlantic Multidecadal Oscillation (Avaria and Muñoz, 1989; Binet, 1997; Carrasco and Santander, 1989; Russell, 1973). In general, investigations in different parts of the world have shown that signals of climate variability can be detected at various trophic levels, indicating that a major part of inter-annual and inter-decadal biological variability can be attributed to physical forcing (Aebisher et al., 1990; Cushing and Dickson, 1976).

For example, in the Atlantic sector, the North Atlantic Oscillation (NAO) index (Hurrell, 1995) has been widely used to identify the response of climate variability in marine ecosystems (Dippner, 2006; Drinkwater et al., 2003 and references therein). In the southern North Sea, winter NAO was confirmed as an optimal predictor to forecast the structure of macrofaunal communities in the following spring (Kröncke et al., 1998).

Using statistical downscaling method (von Storch et al., 1993; Dippner and Kröncke, 2003) developed forecast equations to predict macrofaunal community structure in spring based on the climate during the preceding winter. However, this linear relationship between NAO winter index and benthic macrofauna failed after 2000 with the consequence that NAO index is not any longer a suitable climate predictor. The reason is a climate regime shift (Swanson and Tsonis, 2009), which occurred parallel to an abrupt biological regime shift (Beaugrand et al., 2014; Dippner et al., 2010). A possible reason why NAO winter index is not suitable after 2000 as climate predictor might be the fact that after 2000 NAO index has loss autocorrelation causing a decrease in potential predictability (Dippner et al., 2014).

To overcome this disadvantage, two possibilities exist: the development of a "new" climate index, the application of other statistical forecast methods, or both. Using different non-linear methods such as "optimally pruned extreme learning machine" and "optimally pruned k-nearest neighbours" in combination with NAO winter index as

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climate predictor, predictions also fail in case of regime shifts (Junker et al., 2012).

Therefore, the focus of the paper is the construction of a new climate predictor that works. Recently, Dippner et al. (2012) have developed a multivariate environmental index for the Baltic Sea, which has a much better performance than all other existing climate indices for the Baltic Sea. Our scientific question is how can the prediction of ecological time series be improved in a situation when potential predictability decreases due to climate regime shifts? According to Dippner et al. (2012), we hypothesize that a multivariate climate index is the optimal way to answer this question.

2. Data and methods

2.1. Benthos data

Macrofaunal samples were collected using a 0.2-m^2 van Veen grab. Sampling was carried out every spring from 1978 to 2012 at five different stations in the sublittoral zone off the island of Norderney. The stations were located at water depths between 10 m and 20 m (Fig. 1) and a single grab was taken at each one. Samples from all stations were treated as replicates for the area, since a multivariate comparison had shown no significant differences between the macrofaunal communities (Dörjes et al., 1986). The samples were sieved over a 0.63-mm mesh and fixed in 4% buffered formaldehyde. Species number, abundance and biomass were determined (Fig. 2). After sorting, the organisms were preserved in 70% alcohol. The samples were dried for 24 h at 85 °C and burned for 6 h at 485 °C. Biomass was determined as ash-free dry weight per m^2. The study area is representative for a wider area, because the *Fabulina (Tellina) fabula* community present in the study area is found in the entire coastal area of the south-eastern North Sea on fine sands (Kröncke, 2011).

2.2. Climate data

The following monthly climate data sets were used for the construction of the multivariate climate predictor: (1) the Arctic Oscillation (AO) index from 1950 to 2011 (Thomson and Wallace, 1998), which describes the leading Empirical Orthogonal Function (EOF) of monthly geopotential height anomalies at the 1000 hPa level of the Northern Hemisphere poleward from 20°N. From reanalysis data sets of the National Centers of Environmental Prediction/National Center of Atmospheric Research (NCEP/NCAR; Kalnay et al., 1996), we used monthly values from 1948 to 2011 of (2) precipitation rate anomalies averaged over the area 50°–57°N, 4°W–9°E, (3) sea surface temperature (SST) anomalies (4) zonal, and (5) meridional wind anomalies, all

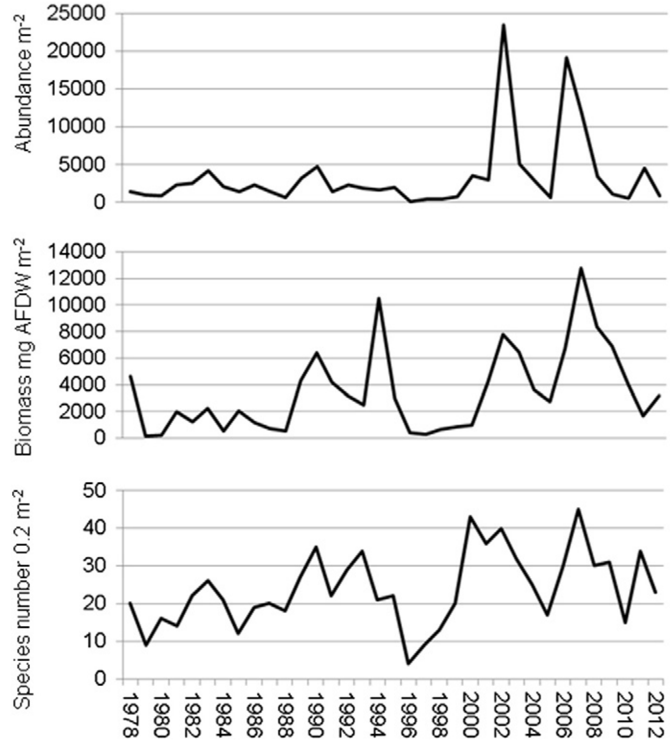

Fig. 2. Second quarter species number 0.2 m^{-2}, abundance m^{-2}, and biomass m^{-2} of benthic macrofauna.

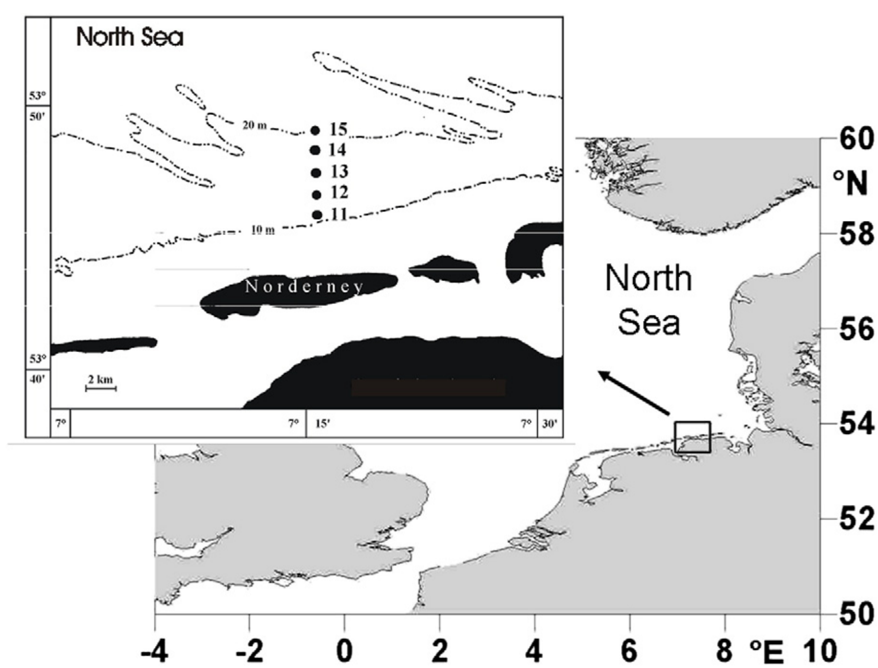

Fig. 1. Study area off the island of Norderney in the southern North Sea, with stations sampled from 1978 to 2011 modified after Kröncke et al. (2013).