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A statistical assessment of climate variability and ecosystem response in the German Bight

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Abstract We compiled homogeneous long-term time-series of data with 40 variables for the overall German Bight and for the period 1975 - 2004. A diverse set of variables was selected to cover multiple trophic levels and different environmental forcing.

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Previous studies have hypothesised the presence of regime shifts in observations extending over the entire North Sea. Focusing on a smaller spatial scale, and closer to the coast, we investigated the major modes of variability in the compiled time-series by using Principal Component Analysis (PCA). The results obtained confirm a previously identified regime shift in the North Sea in 1987/88 and suggest that the German Bight is dominantly characterised by long-term modes of variability.

We conclude that the shift of 1987/88 is driven by hydro-meteorological forcing (through temperature, Gulf Stream Index, frost days and Secchi depth). Phosphate and ammonium showed highly negative correlations with the documented long-term mode of variability. Diatoms and *Calanus spp.* did not show evidence of changes in concert to this mode.

The results also underline the need for ecosystem modelling and for the importance of maintaining long-term monitoring programmes.

KEY WORDS: Climate change, German Bight, PCA, Marine Ecosystem, Long-term trend, Helgoland Roads

1 Introduction

Global climate change is likely to affect the physical, biological and biogeochemical characteristics of the oceanic and coastal environments, modifying their ecological structure, their function, and the goods and services they provide (IPCC 2001). The analyses of long-term time-series can help to understand how ecosystems respond to natural climatic variability and to evaluate potential effects of anthropogenic perturbations.

Changes in several biological and environmental variables of the North Sea have been reported in recent years and attributed to a range of factors. Reid et al. (2001), for instance, were the first to suggest that a regime shift may be identified in the North Sea around 1988 based on a compilation of plankton data derived from the Continuous Plankton Recorder (CPR) and fish catchments. Beaugrand (2004) and Edwards and Richardson (2004) proposed that a regime shift covering the period 1982-1988 in the North Sea may be connected to changes in large-scale hydro-meteorological forcing. Weijermann et al. (2005) investigated the possibility of a connection between physical changes and ecosystem state in the North and Wadden Seas. They suggested that regime shifts occurred in 1979, 1988 and 1998, although results were less clear-cut in the latter case. More recently, also Kirby et al. (2007) documented some climatic impacts on the North Sea ecosystem.

We compiled a homogeneous long-term time-series of data for a limited part of the southern North Sea: the German Bight. The resulting dataset includes 40 different variables and spans over 30 years. By using Principal Component Analysis (PCA) we investigated the dominant modes of variability in the dataset and identified the variables most accountable for those modes. In particular, we addressed the following questions:

1. Can we identify regime shifts in the German Bight?

2. What is the time-scale of these events?
3. What are the variables dominating the these events?
4. Can causes and effects be clearly identified?

The novelty of our study is the focus on a restricted location of the southern North Sea (the German Bight). We provide for the first time a detailed understanding of climate variability in this region, not based on physical and biological data only but also on chemical variables. However, our results will be discussed also in the context of the overall North Sea variability.

2 Data and methods

In order to identify basic structures of variations, which reflect more clearly the influence of an external forcing, we compiled a diverse set of data including multiple trophic levels and several physical variables for the German Bight (6^o 30 E to 9^o 10 E and 53^o 30 N to 55^o 10 N), see Figure 1 for a map of the region.

Unbiased observations of nature are almost impossible, thus we selected data with the following criteria: 1) the time series had to be homogeneous, no obvious anthropogenic cause for sudden changes in the time-series and no or few missing values in the data set, 2) long-term diverse set of variables including multiple trophic levels and different environmental indicators and 3) different sites representative for the overall German Bight. The resulting data set comprises a total of 40 variables spanning over 30 years and divided into three major categories: atmospheric and hydrophysical variables (19), biological variables (15) and chemical variables (6), see appendix A and B for a full list and description. The biological variables were log-normalized and all time-series were normalized by calculating the anomalies (deviations from the mean for each data point) and dividing these by the standard deviations. No smoothing or filtering techniques were applied to the data. Following the approach of Hare and Mantua (2000), we used Principal Component Analysis (PCA) for our investigation. PCA has been used in many studies to objectively identify coherent patterns of variability among a number of time-series (Mantua, 2004). In brief, the PCA is an "ordination technique" that reduces the dimensionality and identifies the most important modes of joint variability in a multi-variable data set. Assuming that the data are linearly related, the PCA defines an orthogonal linear transformation that transforms the data to a new coordinate system such that the greatest variance by any projection comes to lie on the first coordinate (the first Principal Component), the second greatest variance on the second coordinate (the second Principal Component), and so on. This way one can capture the most important fluctuations in the data with a few components. A PCA generates three types of outputs: principal components (PCs), eigenvectors (or loadings) and eigenvalues. When plotted against time, PCs give the temporal variability of the most dominant patterns. Eigenvectors indicate which variable contributes most to the dominant patterns. Eigenvalues are used to determine the fraction of total data variance explained by each

PC.

For a detailed review of the PCA method see von Storch and Zwiers (1999). Once we computed the first Principal Component, we quantified the overall step magnitude of the regime shift by using the method of Ebbesmeyer et al. (1991).

For investigating correlations between subsets of time-series, we used Canonical Correlation Analysis (CCA). As with PCA, there may be more than one significant dimension (more than one canonical correlation), each representing an orthogonally separate pattern of relationships between the two subsets of variables. The first canonical correlation is always the one that explains most of the relationship. The canonical correlations are interpreted the same as Pearson's r.

Although the term "regime shift" is widely used in the literature, there is no universal definition for it. Lees et al. (2006) reviewed different criteria used to define a regime shift. Typically, common characteristics like speed and amplitude of the changes and the duration of quasi-stable states are used for defining climatic and ecological regime shifts. Lees et al. (2006) suggested that a standard definition should meet a number of conditions (like sudden, high-amplitude, infrequent events, number of trophic levels impacted by the shift and biophysical impacts) before a change in the data can be classified as a regime shift. Arguably, it is difficult to asses how useful these criteria are in universally characterising regime shifts.

We are interested in shifts that are not smooth or reversible. Therefore, we adopted the following defintions:

Regime = Quasi-stationary state of a system persisting for several years and characterised by low frequency variability.

Regime Shift = Transition period between two regimes that occurs within a year or two.

To prove the robustness of the results, we performed PCA with longer and shorter time-series. Because the zooplankton time-series did not start before1975, by excluding zooplankton we conducted PCA on longer time-series starting from1966 and up to 2004. Due to the expected regime shift in the late 1980s, we also performed PCA starting from 1983 so to examine this signal in more detail.

3 Results and Discussions

We used principal component analysis to reduce our dataset to new, fewer variables, called "Principal Components" (PCs), which account for the majority of the variability in the data. Eigenvalue analysis (see Figure 2) indicates that the first Principal Component (PC1) explains the most of the variability of our data set. The first and second principal components account for 26% and 13% of the total variance respectively. Since the interpretation of PCs higher than the first is problematic, because they are constrained to be orthogonal to each other and natural processes are not necessarily independent from each other (von Storch and Zwiers, 1999), we decided to focus our study on the first PC only.

Figure 3 shows the temporal variation of the first PC. The loadings (correlation coefficients between each time-series and the first PC) are illustrated in Figure 4. According to our definition, the temporal evolution of the first PC shows a pattern with two regimes: negative until 1987 and then positive until 2004, with an abrupt shift in 1987/88. The year 1996 appears to be anomalous, in that PC is temporarily reversed in sign. The first PC shows a minimum in 1979 and a maximum in 2000. Among the environmental variables, air temperature, SST, winter SST, Gulf Stream Index, Secchi depth and salinity show the strongest positive correlation with the first PC (see Figure 4). High negative loadings are found in nutrients like ammonium (NH4) and phosphate (PO4). Also fish (*Cod, Haddock* and *Saithe*) show high negative correlation with the first PC. In agreement with an increasing warming trend, frost days showed high negative correlation with the first PC. Temperature, through its influence on physiological processes, has the potential to affect ecosystems (Kirby et al. 2004). However, not all biological/ecosystem variables showed pronounced shifts in our analyses. Diatoms and *Calanus spp.*, for instance, did not show high correlation with the first PC, although other zooplankton species (sum of five small calanoid copepods, *Noctiluca scintillans*) showed slightly higher correlations (Figure 4).

Figure 5 shows the step magnitude in the temporal evolution of the first PC as given by the difference between the two regimes (see red dashed line in Figure 5). The marked step-wise increase in 1987 is about 1.1 standard deviation high. Figure 5 also shows that the two regimes are characterised by rather small inter-annual variations.

We also applied a t test and a resampling "bootstrap" test, to investigate the significance of the identified regimes. The results are not presented here, but they support the robustness of our analysis.

As proposed by Mantua (2004), in order to identify dominant ecosystem state variables and to better isolate ecosystem behaviour from other influences (like environmental changes), we separated the data into three categories: 1) biological, 2) climatic, and 3) chemical. In Figure 6 we show the results of PCA performed on each of these groups. The first PC of the chemical data, see Figure 6 (a), explains 39% of the total variance. Note that the second regime of PC1 for chemistry is not as smooth as the second regime of the first PC obtained with the global dataset (Figure 3). Ammonium (NH4) and phosphate (PO4) show the strongest negative correlation with PC1 of chemistry, while Secchi depth shows the strongest positive correlation with PC1 of chemistry. This may be connected to the fact that the German Bight waters changed over the last decade from a more coastal (fresher) dominated character to a more marine dominated character (clearer and saltier), see Wiltshire and Manly (2004).

The first PC of the climate variables in Figure 6 (b) shows pronounced inter-annual variability (because the physical variables respond much faster to atmospheric changes) and has a distinct peak in 1996. The variance explained is 39%. The highest loadings are given by the temperature data similarly to the results obtained with the global dataset (Figure 3) and the highest negative correlation with the first PC of climate includes frost days. Figure 6 (c) also shows the results of the PCA performed on the biological data. The PC1 of biology explains 28% of the total variance. The PC1 of biology time-series is the smoothest with respect to PC1 chemistry and PC1 climate and a more clear-cut increasing trend towards the latest years (2000-2004). Fish data (*Cod* and *Haddock*) show high negative correlation with the first PC similar to the results with the entire data set. Small calanoid copepods showed also high correlations.

In summary, the first PC obtained on the global dataset shows a regime shift in 1987/88. The PC1 chemistry, PC1 climate and PC1 biology are dissimilar from each other, highlighting the different modes of variability expressed by the three different categories.

Regime shift analysis

To further investigate our results, we plotted the first PC of all biogeochemical data against the first PC of all hydrophysical data (see Figure 7). Two clusters show up with a separation in 1987. This year marks a tipping point around which the system shifts into a new state.

The year 1996 is confirmed to be anomalous in that the changes occurred did not force the system to shift into a contrasting permanent regime.

We performed Canonical Correlation Analysis (CCA) studying the relationship between biogeochemical and hydrophysical data. This statistical technique identifies the maximized correlation between two data sets. For both data sets the canonical correlation was r = 0.93.

Underlying mechanisms for the shift can be inferred by analysing the SST data in more detail. Figure 8 shows the SST averaged over winter (Jan-Mar) and the SST averaged over summer (Jul-Sep). There were two exceptionally cold winter years (1979 and 1996) and an event of persistent cold winters from 1985 to 1987. The extreme cold anomaly of North Sea SSTs in 1996 is correlated with a persistent negative phase of the North Atlantic Oscillation Loewe (1996). The regime shift of 1987 is also preceded by persistent cold summers (from 1984). We suggest that the repeated cold events both in summer and winter SST might have been responsible for the shift shown in variables of higher trophic levels (including some fish, sum of five small calanoid copepods, *Noctiluca scintillans* and *Pleurobrachia pileus*) through the impact of persistent lower temperatures on physiological processes.

The increasing warming trend (see temperature anomaly in Appendix B), which has been attributed to global warming (Edwards et al., 2004), might have been responsible for the persistency of the second regime shown by our analysis.

4 Conclusions

We compiled a diverse set of long-term time-series for the German Bight. The resulting data set contained variables representing atmospheric, hydrophysical, biological and chemical observations. We used Principal Component Analysis (PCA) to identify the most important modes of variability in the data and determined the variables with highest correlation to these modes.

This approach allowed us to tackle novel (for the German Bight) and important scientific questions listed in the Introduction.

1. Our analysis indicates that the major mode of variability in the data is characterised by two regimes separated by an abrupt shift in 1987/88 (first PC).
2. The two regimes persist for more than a decade (although we cannot provide evidence for the state of the system before 1975 and after 2004). The regime shift takes place in within a year and it is statistically significant.
3. We found that SST, Air temperature and SST winter showed the highest positive correlation to the major mode of variability (first PC), while phosphate, ammonium and some fish (*Cod, Haddock* and *Saithe*) showed the highest negative correlation with the first PC. High positive correlation was also found with the Gulf Stream Index, Secchi depth and salinity (although less pronounced with the former). Consistently with an increasing warming trend, frost days showed high negative correlation with the first PC.
4. High positive loadings in SST, Gulf Stream Index and Secchi depth (and to some extent also in salinity) suggest that the regime shift of 1987/88 in the German Bight is likely caused by changes in hydro-meteorological forcing. This conclusion is also supported by a previous study (Wiltshire and Manly, 2004) maintaining that the German Bight has been

characterised in the last decade by clearer more marine waters. Changes in ecosystem variables (plankton and fish) can be taken as effects of changes in the hydro-meteorological forcing. However, not all biological/ecosystem variables showed pronounced shifts. Diatoms and *Calanus spp.*, for instance, did not show high correlation with the major mode of variability (first PC).

Our study documented for the first time that the German Bight is characterised by patterns of variability similar to the ones of the all North Sea (Beaugrand, 2004; Weijerman et al., 2005). This result is not so obvious given that the German Bight is more directly exposed to anthropogenic perturbation than the overall North Sea. We included in our analysis various nutrients and we showed that phosphate and ammonium are characterised by stronger negative trends with respect to the weaker positive trends of silicate and nitrate. Given the complexity inherent to the studies of coastal ecosystem variability, it is crucial that long-term monitoring programmes are maintained in the future and that combined statistical analysis and ecosystem modelling approaches are undertaken.

Acknowledgments

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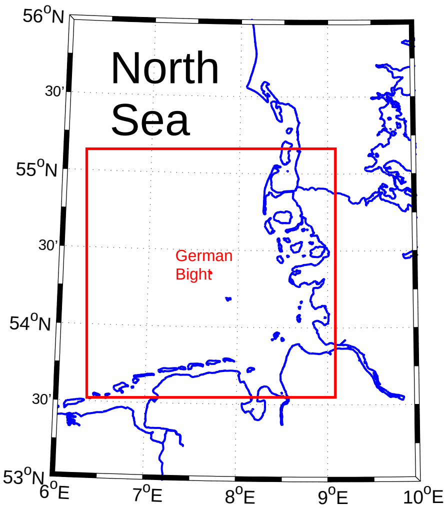

Fig. 1: Map of the North Sea and the area of the German Bight for analysis enclosed in the red box.

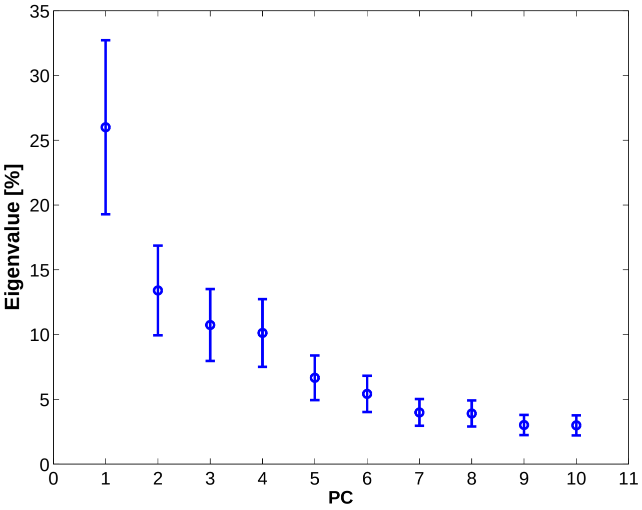

Fig. 2: Scree plot of the first 10 eigenvalues for the principal component analysis of the full set of variables and their standard errors.

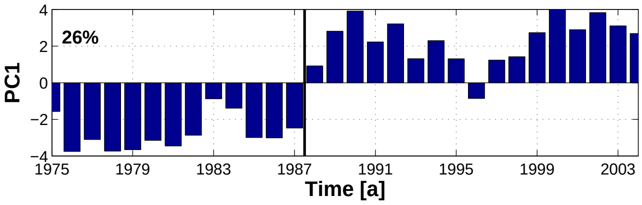

Fig. 3: The first principal component (PC1) of the principal component analysis of the full set of variables for the time period from 1975 to 2004. The black vertical bar is shown before the data point 1988.

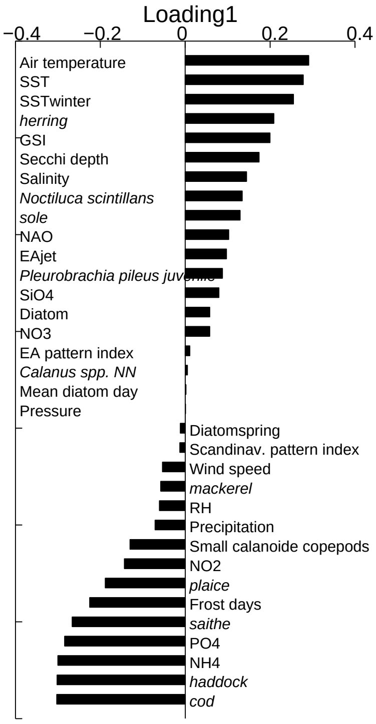

Fig. 4: Spectrum of loadings for the first principal component from a principal component analysis of the full set of variables. The corresponding variable to each loading is written next to each bar.

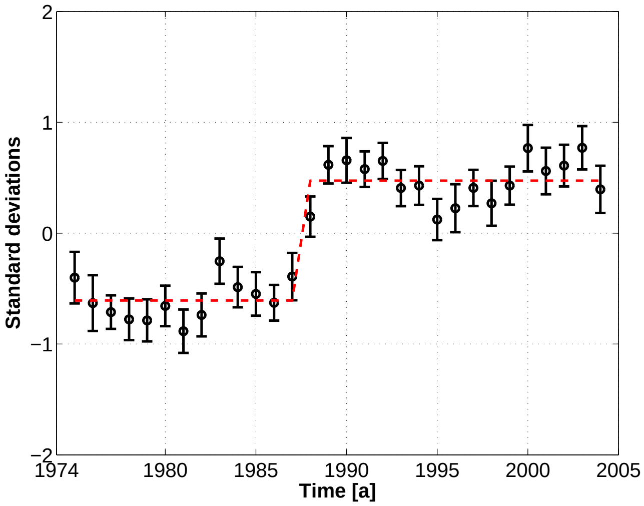

Fig. 5: Results from the regime shift analysis of the full set of variables. The step passes through the mean standard deviate within each regime. The standard error of full set of variables is presented for each year and the circles show the annual means of the standardised time series.

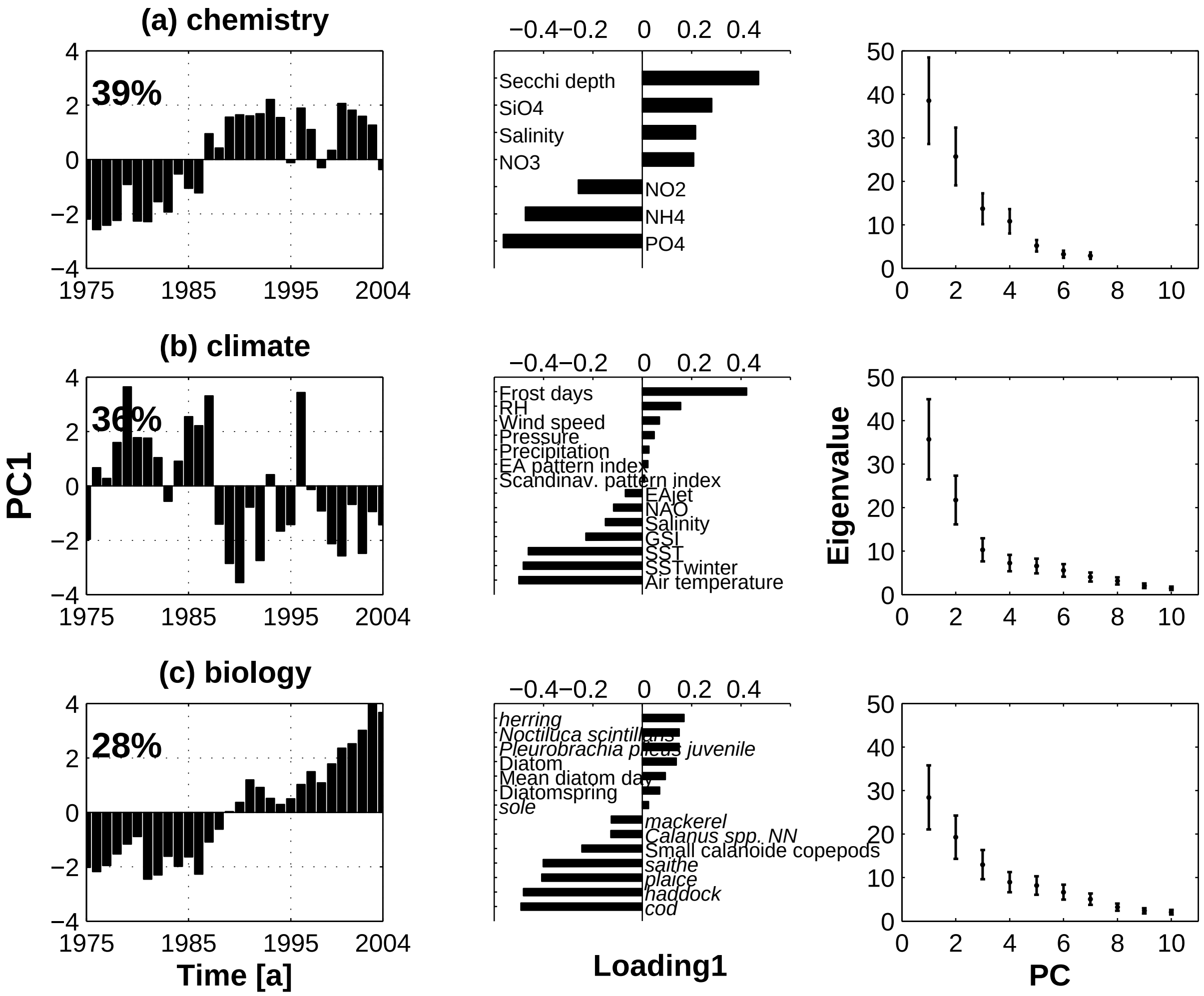

Fig. 6: The first principal component (PC1) from the principal component analysis of the separated data for a) chemistry, b) climate and c) biology for the period 1975 to 2004 is shown in combination with each spectrum of loading and eigenvalue scree plot.

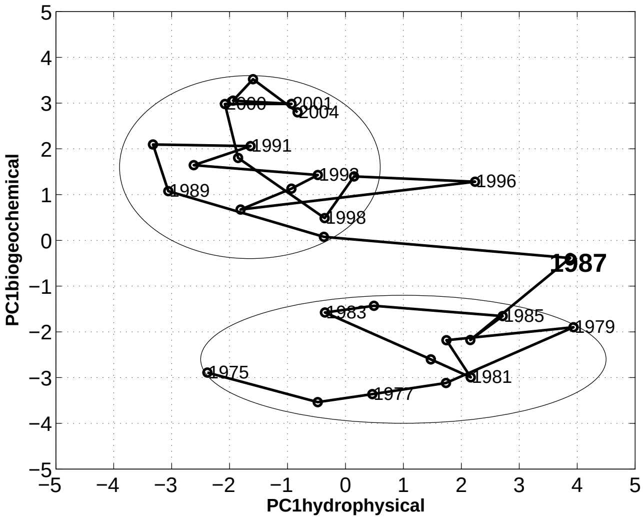

Fig. 7: Scatter plot of the first principal component of all biogeochemical variables against the first principal component of all hydrophysical data. Circles indicate data from 1975 to 2004. The two indetified regimes are surrounded with a black circle and the tipping point (1987) around the shift is highlighted. Lines between the circles indicate the variability.

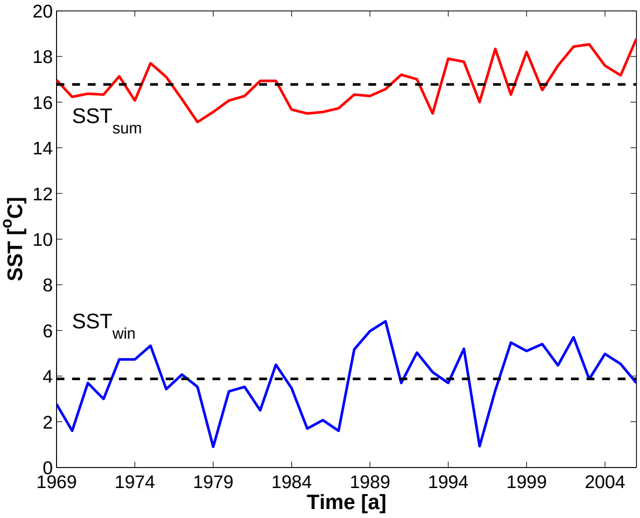

Fig. 8: Time-series of seasonal winter (blue line) and summer (red line) SST for the period 1969 to 2006. The black dashed line is the mean of each seasonal SST.