

## Chapter 11

# Long-Term Model Simulation of Environmental Conditions to Identify Externally Forced Signals in Biological Time Series

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**Abstract** A case study is presented to demonstrate the added value which can be gained from combining long-term biological observations with model-based hind casts of physical environmental conditions. The study utilizes numerically simulated high-resolution fields of currents and water levels in the North Sea to investigate the relevance of hydrodynamic conditions for the occurrence of phytoplankton blooms, as observed at Helgoland Roads in the inner German Bight. Inter-annual variations as well as a possible regime shift are discussed with regard to the spring mean diatom day. The long-term high-resolution simulations of the North Sea circulation are taken from the data base 'coastDat'.

**Keywords** Hydrodynamics · Long-term time series · Phytoplankton spring bloom

### 11.1 Introduction

Trends and shifts of biological parameters in the North Sea and Wadden Sea are an important topic broadly discussed in the literature. Examples of interest are increased abundances of polychaetes in the western Wadden Sea (Beukema, Cadée, & Dekker, 2002), changes in the timing and abundance of zoo and phytoplankton species in the late 1970s (Edwards, Beaugrand, Reid, Rowden, & Jones, 2002) or the late 1980s (Dickson, Colebrook, & Svendsen, 1992; Edwards et al., 2002), changes in the abundance and

distribution of North Sea fish stocks in the late 1970s (Corten, 1990) or 1980s (Reid, DeFatima-Borges, & Svendsen, 2001). The existence of discernible regime shifts has been proposed for the years around 1979, 1988, and possibly 1998 (Radach & Pätsch, 2007; Weijerman, Lindeboom, & Zuur, 2005).

The temporal evolution of ecosystems, via the growth of primary producers, is largely driven by variations of external physical forcing (e.g. Colebrook, 1986; Gröger & Rumohr, 2006; Wiltshire et al., 2008). The most obvious example is the seasonal cycle brought about mainly by changes in radiation and temperature. However, changes on many other time scales have a bearing on the behaviour of ecosystems and should therefore be taken into account for a meaningful interpretation of biological time series. Changes of the North Sea ecosystem have been assumed to be linked to the Atlantic inflow (Turrel, 1992; Reid, Edwards, Beaugrand, Skogen, & Stevens, 2003) or to local hydro-meteorological forcing parameters (Beaugrand, 2004; Reid et al., 2001). Therefore, long and homogeneous data on the physical environment are a prerequisite for the successful interpretation of time series of long-term ecological monitoring programs.

Ideally data on physical external forcing should be free of variation caused by changes in instrumentation, measurement techniques, or observational practices, which prevent reliable analyses of long-term trends and variability. Unfortunately for the oceans and the coastal zone such data are rare. Often observations have been taken only for a limited period and are spatially patchy or simply not available. Observed data almost never cover the whole domain of interest with a sufficient spatial or temporal resolution.

Numerical model simulations provide the option to at least partially overcome these difficulties. If models

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are run in a hindcast mode, methods of data assimilation may be applied to feed all available information into the numerical model system over a continuous time period (e.g. Salomon, Breton, & Guegueniat, 1993; Weisse & Günther, 2007). Then the model's role is to transfer and spread this information in time and space according to known physical laws. Each time new data become available, these data will be merged with the model state which summarizes all past information up to the present point of time. The resulting best analysis may be stored on an hourly basis, for instance, to guarantee sufficient representation of short-term system variability. In meteorology such model-based weather re-analyses (hind casts) based on frozen state-of-the-art models have now become common tools for atmospheric analyses. The so-called global re-analyses projects (Kistler et al., 2001) provide gridded atmospheric data of best possible homogeneity for several decades, albeit at relatively coarse spatial and temporal resolutions.

For coastal and offshore purposes atmospheric data are the most essential boundary values. The global atmospheric re-analyses may be regionally refined by a nested modelling approach. The higher resolution of atmospheric data may then be employed as upper boundary conditions for numerical models dealing with storm surge and wave simulations. Similar to the global atmospheric model, all subsequent regional scale high-resolution models may be run for many decades to produce a consistent reconstruction of regional scale weather-related variability.

The main objective of this chapter is to illustrate the application of such detailed reconstructions of the North Sea circulation on long-term biological observations. We report a case study dealing with the relationship between diatom abundances observed in the vicinity of the island of Helgoland and reconstructed hydrodynamic circulation patterns in the inner German Bight.

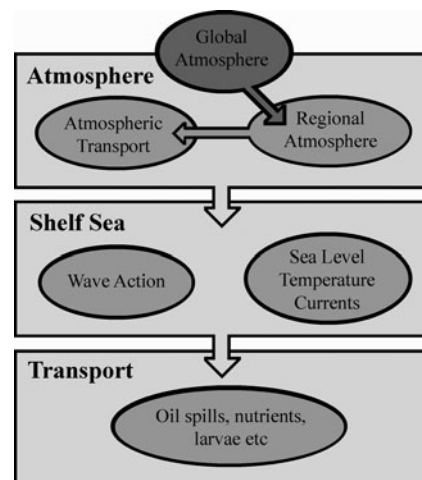
## 11.2 The coastDat Data Set

The portal coastDat ([www.coastdat.de](http://www.coastdat.de)) does not represent a hindcast initiative in itself. The idea of coastDat is to provide a unique platform which hosts, describes, and promotes such data sets (Feser, Weisse, & VonStorch, 2001) and their key applications (Weisse

& Plüß, 2006). A unique combination of consistent atmospheric and oceanic parameters is offered at high spatial and temporal detail, even for locations and variables for which no measurements have been made. Coastal scenarios are provided for the near future to complement the numerical analyses of past conditions. All data sets meet the following minimum quality standards:

- Long and high-resolution reconstructions of recent offshore and coastal conditions
- Performed with state-of-the-art frozen model systems
- Performed with as homogeneous as possible boundary data
- Extensively validated with existing observational data (e.g. Plüß, 2004; Weisse & Plüß, 2006).

For the present study we used currents from the coastDat data set that was produced within the EU-funded project HIPOCAS (Hindcast of Dynamic Processes of the Ocean and the Coastal Areas). The data set consistently combines atmospheric simulations with simulations of currents, sea levels and waves. Figure 11.1 outlines how these partial data sets



**Fig. 11.1** Outline of the generation of consistent data sets stored in coastDat: Numerical models for the atmosphere, currents, or waves are coupled to or nested within each other to provide necessary boundary conditions. Lagrangian trajectory calculations (transports) including estimates of travel times, for instance, may be based on both shelf-sea currents and wind drift effects. Model results are stored with an hourly resolution for several decades; most data sets start in 1958

are related to each other. Current and sea level fields were produced by running the finite element model TELEMAC 2D (Hervouet & van Haren, 1996). For a more detailed simulation of the general model set up the reader is referred to Plüß (2004).

### 11.3 The Helgoland Roads Time Series

In 1962 a long-term pelagic monitoring program, including plankton species composition, was started at the island of Helgoland (54°11.3′N, 7°54.0′E) in the North Sea by the Biologische Anstalt Helgoland, on a work-daily basis (Hickel, Mangelsdorf, & Berg, 1993). This study focuses on the mean diatom day (MDD) – a variable, which represents the mean timing of the diatom bloom. Wiltshire and Manly (2004) computed it from the observed time series for the quarters of each year (January–March, April–June, July–September, and October–December). The MDD was defined as

$$MDD = \frac{\sum f_i d_i}{\sum f_i}$$

where  $f_i$  is the diatom count on day  $d_i$  of the quarter.

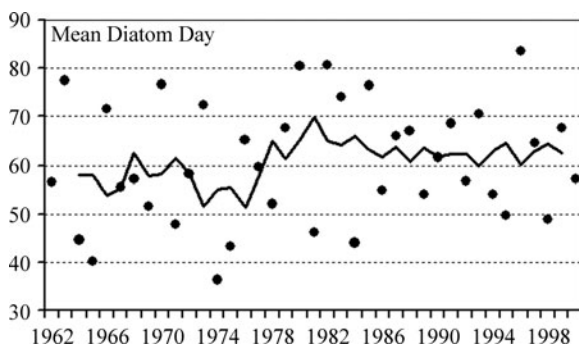
The MDD of the spring bloom is defined for the period from January to March. Observed annual values are shown in Fig. 11.2. Smoothing the MDD using a 5-year running mean Wiltshire and Manly (2004) show a distinct shift around the year 1978. The main motivation for the present study is to investigate whether

this shift can be explained by corresponding changes of circulation patterns in the North Sea.

### 11.4 Methods

For the present study we chose water flow (product of velocity and total water depth) as our basic physical variable to be related to the biological observations. Using water flow instead of velocity puts less emphasis on near shore shallow water currents and is in line with a concept of mass balances. Since we were interested in anomalies, all externally forced periodic signals were removed from the current data as follows: A Fourier analysis was applied to extract all variations that are related to astronomically prescribed frequencies with time scales up to one year. The resulting filtered residual data contained neither tidal nor long-term seasonal cycles. The filtering has been applied to currents and water levels individually, prior to the calculation of water flows.

Next we subjected the time series of hourly residual water flow fields to empirical orthogonal function (EOF) analysis. This mathematical technique corresponds to principal component analysis (PCA), and a detailed description can be found in von Storch and Zwiers (1999). Spatial patterns of water transport anomalies in the inner German Bight are identified, the amplitudes of which (principal components, PCs) can be related to anomalies (i.e. inter-annual variations) of the MDD observed at Helgoland Roads.

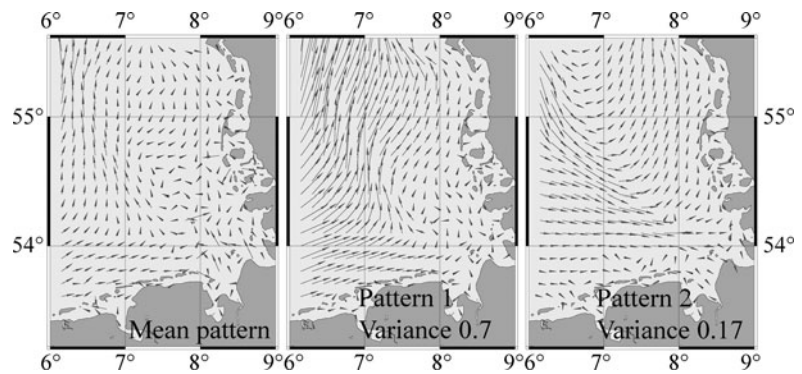


**Fig. 11.2** Annual values of the spring bloom mean diatom day observed at station Helgoland Roads. The black line represents corresponding 5-years running means (after Wiltshire & Manly, 2004)

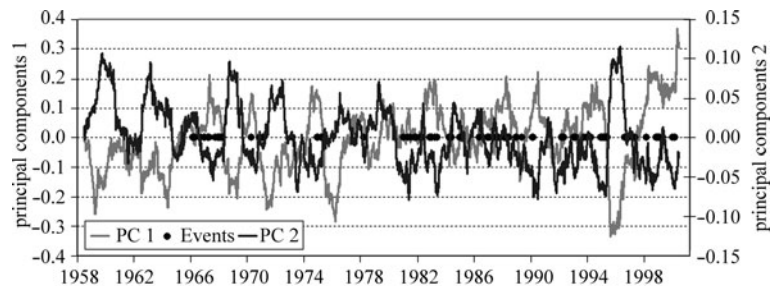
### 11.5 Results

Figure 11.3 shows the mean residual flow pattern (left panel) together with the two most important anomaly patterns which explain 70 and 17%, respectively, of total residual variability. Time series of the annually averaged amplitudes of the residual transport patterns (i.e. the corresponding principal components, PCs) are shown in Fig. 11.4 (PC 1 for pattern 1, PC 2 for pattern 2). The mean residual transport not including tidal effects turns out to be very weak (close to zero). For this reason superimpositions of the two anomaly patterns shown in Fig. 11.3 multiplied with

**Fig. 11.3** Anomaly patterns of residual water flows as obtained from EOF analysis (see text). Amplitudes of the two anomaly patterns are shown in Fig. 11.4



**Fig. 11.4** Annually averaged time series of amplitudes (principal components, PCs) of the two anomaly patterns shown in Fig. 11.3. *Black dots* indicate observations of freshwater signals (low salinity in combination with high nutrient concentrations)



their corresponding amplitudes closely approximate actual residual flow patterns.

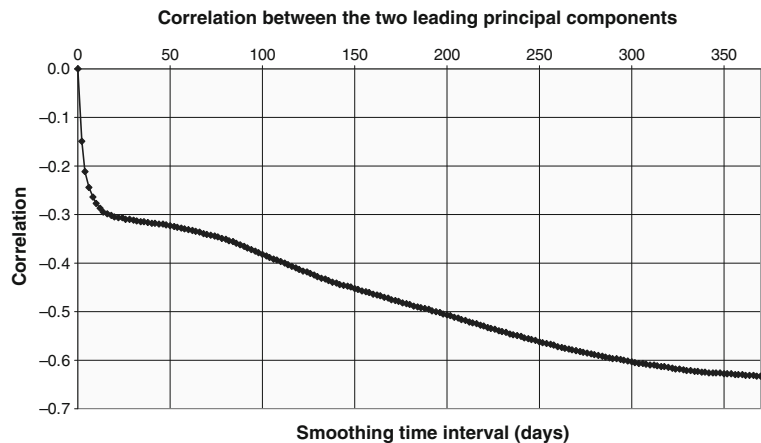
Due to the lack of sufficiently dense observations, validation of modelled water flow fields is a difficult task. It is even more difficult to validate water mass exchanges between different regions, as such calculations amount to an integration of changing flow fields over a certain span of time. Tracer experiments are the only way to check in detail whether modelled water mass transports are realistic (e.g. Maier-Reimer, 1977). For the present study we chose a related approach to check whether the model simulations can be regarded meaningful. From the time series of salinity and nutrient concentrations observed at Helgoland Roads, special freshwater inflow events were identified. Within six to eight hours salinity decreased by approximately ‰ and simultaneously an increase of nitrate and silicate concentration was measured, which was mirroring the salinity curve. An automated procedure extracted about 150 of such events from the time series according to two pre-specified objective criteria. In Fig. 11.4 these events are marked as black dots.

The first observation from Fig. 11.4 is that the symbols which indicate freshwater signals are not evenly distributed but tend to be clustered during certain periods. The second very interesting observation is that

there seems to be a relation between the occurrence of freshwater events and the annual running mean amplitudes of the water flow anomaly patterns. Freshwater inflow events never occur with high positive values of PC 2. According to the right panel of Fig. 11.3, a positive amplitude implies that the island of Helgoland will be hit by water from the northwest. It is consistent to assume that if this situation is dominant, freshwater inflow from the coastal area of the inner German Bight (or from the river Elbe) will be suppressed.

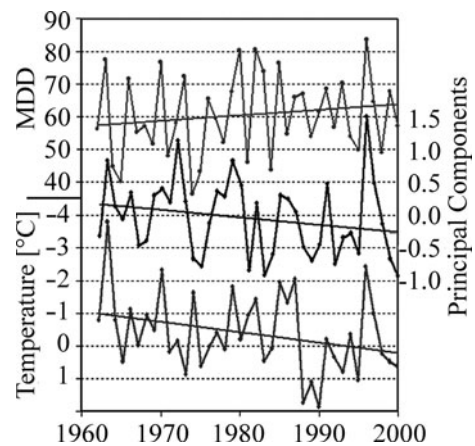
With regard to Fig. 11.4 the question of a possible conflict of time scales may be raised. The freshwater events are defined on a time scale of the order of two days. In the figure these events are combined with annual averages of the PCs representing instantaneous patterns of water transport. We suggest reading Fig. 11.4 in the sense that observed events are conditioned by means of hydrodynamic conditions. It should not be read in the sense that actual residual currents can be used as efficient predictors for the occurrence of freshwater events. Typically, freshwater from the river Elbe that arrives at Helgoland has been transported by changing currents for about two weeks, which by far exceeds the time span during which the resulting freshwater signal can be observed at Helgoland.

**Fig. 11.5** Correlation between the two PCs, corresponding with the two anomaly residual flow patterns in Fig. 11.3. The correlation is shown as a function of the time interval used for moving averaging



By definition, the time coefficients (PCs) that belong to different EOFs (i.e. anomaly flow patterns) must be uncorrelated. This holds for time series of instantaneous values. According to Fig. 11.4, however, annual averaging produces a significant amount of negative correlation between the two PCs. Figure 11.5 shows correlation between the two PCs as a function of the smoothing interval. A negative correlation between the two time series originates rapidly when the smoothing interval is extended up to about two weeks. For longer time intervals the correlation increases at a lower rate. A spectral analysis of the data (not shown) reveals that the second PC has much more variability on short-term scales than the first PC. This short-term variability being present in only one PC seems to be the major reason for the lack of correlation of instantaneous values. It will be a topic of further research to investigate how the different behaviour of the two PCs can be linked to different modes of atmospheric forcing. Here, just two examples will be given to indicate which kind of links can be expected to exist.

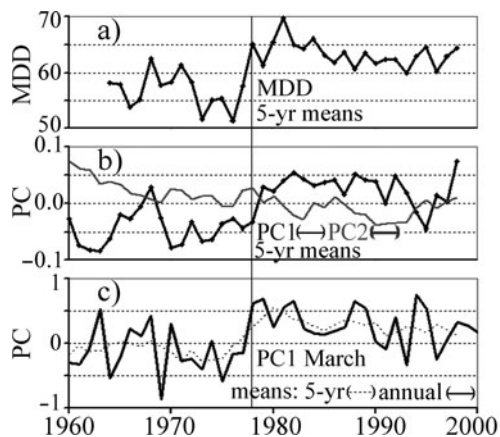
It is reasonable to expect that inter-annual variations of the mean hydrodynamic conditions before spring algae blooms have a major impact on the variability of the MDD. Figure 11.6 compares the de-trended time series of observed MDDs with de-trended time series of the PCs of the second anomaly pattern and temperature, averaged over the 80 days prior to the MDD. We chose a time span of 80 days, because it produces the highest correlations. The MDD seems to be connected to the means of PC 2 (correlation coefficient 0.52) and temperature (correlation coefficient  $-0.40$ ). It was possible for these correlations to reject the null hypothesis on a 1% significance level.



**Fig. 11.6** Mean diatom days (MDD, spring diatom bloom), and temperature and time coefficients (PCs) of the second residual flow pattern, averaged over the last 80 days before the observed MDD. Correlation between de-trended data is 0.52

In agreement with the above correlations, the time series of the MDD, mean PC 2 and temperature show a similar inter-annual variability (Fig. 11.6). This implies that a higher PC 2 in autumn is followed by a delayed MDD and vice versa.

Notwithstanding its short-term correlation with the MDD, the second residual anomaly pattern, however, was found to be unable to explain the shift near year 1978 in the 5-year mean of spring bloom MDD (Fig. 11.2). It has already been mentioned that variability of the first PC is more concentrated in the long wave spectrum. Therefore the first PC may be anticipated to be a better predictor for long-term variations. Figure 11.7 compares the 5-year means of the time coefficient of the first PC with the MDD. Both



**Fig. 11.7** 5-yr means of (a) MDD, (b) PC 1, and PC 2 and (c) PC 1 in March

parameters show a simultaneous increase near the year 1978. Approximately at the same time (in 1977) the Great Salinity Anomaly reached its minimum in the western approaches to the English Channel (Dickson, Meincke, Malmberg, & Lee, 1988) and it is shown that changes in salinity in the northern North Sea during the 1970s were correlated with changes in fish stocks and plankton composition (Corten, 1990; Aebischer et al., 1990). Presumably the changes of the flow pattern in the German Bight with a stronger inflow from west, which change the composition of the water body (salinity, nutrients, temperature), also caused a delayed MDD.

The main changes of PC 1 occur in the month of March. This may also be the reason, why the step-like shift of the MDD can only be found for the spring bloom.

## 11.6 Discussion

A major difficulty with the interpretation of marine biological observations is the fact that local conditions are permanently affected by mostly insufficiently known advection. The objective of the present study was to demonstrate how this problem may be tackled by combining long-term observational evidence with detailed reconstructions of the physical environment.

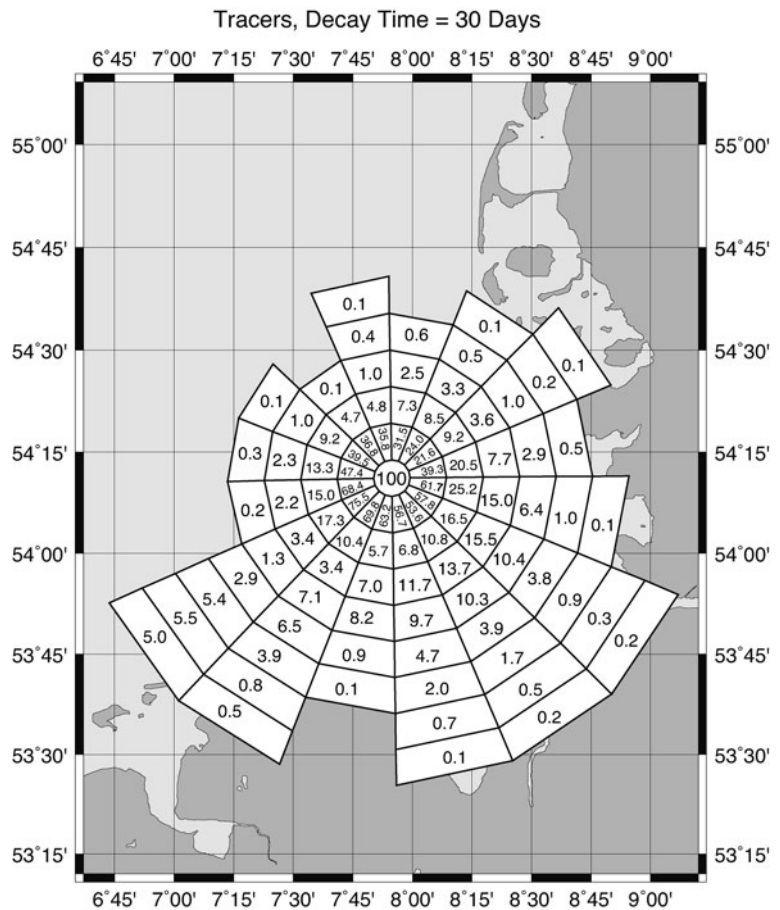
The importance of long-term simulations for a proper interpretation of observed variability is illustrated by Fig. 11.4. In a previous paper, Kauker and von

Storch (2000) investigated the short-term variability of a 15-yr general circulation simulation of the North Sea. Similar to our study the exposure of shelf-sea currents to re-analysed atmospheric forcing was taken into account. However, according to Fig. 11.4 the period 1979–1993 considered by Kauker and von Storch happens to seem qualitatively different from the times before and after, being characterized by the absence of negative mean amplitudes of the first anomaly pattern. At the same time positive mean amplitudes of the second pattern are less pronounced. This means (cf. Fig. 11.3) that during the 15-year period the mean inflow has turned counter clockwise from north-westerly to more westerly directions. If no simulations were available before 1978, the extension of the time series up to 1999 would probably suggest a recent change of in the system in terms of long-term variability. In the light of data before 1978, however, this interpretation becomes much less convincing.

It has been shown that a decomposition of simulated current fields in terms of different modes of circulation can be helpful for the proper interpretation of observational evidence on different time scales. For a more in depth analysis of long-term trends, however, the present study of the circulation in the inner German Bight should be extended by a similar analysis for the whole North Sea. Nevertheless, already the present analysis has allowed us to distinguish between the two time scales. A long-term shift and inter-annual variability, respectively, of the MDD were found to be related to different residual circulation patterns.

The type of data analysis we have described does not cover all the options possible based on a comprehensive data set like coastDat. To provide another example, Fig. 11.8 shows some result obtained from Lagrangian trajectory calculations based on the stored hourly current fields. For many applications in biology it is crucial to know transport rates between different areas of interest. This information may possibly be required in an aggregated version to properly represent the mean conditions during certain periods of time. For this purpose a large number of detailed transport simulations may be superimposed to get a composite picture. In many applications (the drift of larvae, for instance) it is reasonable to assume that the tracer material will not be passive but decreases according to certain pre-specified decay times. In Fig. 11.8 a decay time of 30 days has been assumed. Large numbers in

**Fig. 11.8** Estimated Lagrangian particle transport rates from a given grid cell to Helgoland given the decay time of particle equals 30 days. The estimate is based on a composite of 200 daily simulations that are started within a period of 200 days (July 1982–January 1983). Each individual simulation considers 500-particle trajectories being started at Helgoland and integrated backward in time for 50 days. Numbers give the percentage of all  $200 \times 500$  particles that reach Helgoland given the specified decay time



the figure represent regions from where large amounts of material were advected to Helgoland in relatively short times. Large values in the immediate surrounding of the island are due to tidal movements, while large values in more distant regions are due to the action of efficient residual currents.

In summary, we conclude that the strength of a database like coastDat lies in its provision of information on long-term trends and variability with sufficient detail in time and space. This type of model simulations efficiently complements long-term observations with short sampling intervals.

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