

Quantification of long-term changes in the German Bight using an ecological development index

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During recent decades, remarkable long-term changes have taken place in many coastal ecosystems of north-west European shelf seas. These changes have been described in many papers, but an overall quantification is lacking. An ecological development index (EDI) is proposed here, consisting of two parts – a statistical description of the state of the ecosystem and a metric in a multi-dimensional space of statistical descriptors of states for quantitatively characterizing the change of any number of state variables by only one characteristic number. The concept of the EDI is generally applicable by yielding a measure of the distance between system states. Indices are comparable between different ecosystems and within different subspaces of the ecosystem's state space, provided the same characterization is used. The concept is applied to the 32-year time series (1962–1993) of measurements of nine physical (sea-surface temperature, salinity), chemical (phosphate, nitrate, nitrite, ammonia, silicate), and biological (biomass of diatoms and flagellates) state variables at Helgoland. The analysis of consecutive 5-year quantiles of monthly mean values, which are used as statistical descriptors, elucidates the long-term perturbations of the coastal marine system in the German Bight. It is shown that the states of the ecosystem in the 1970s and 1980s have abandoned the region of the 1960s, but are possibly returning in the 1990s to the situation of the 1970s.

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Key words: ecological development index, ecosystem change, German Bight, long-term changes, North Sea, nutrients, plankton, time series.

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Introduction

Marine coastal ecosystems change on time scales of decades in many places in the world. On the north-west European shelf long-term changes have been documented in the Irish Sea (Laane *et al.*, 1995), the English Channel (Southward, 1980; Laane *et al.*, 1995), the Skagerrak (Danielssen *et al.*, 1996), Dutch coastal waters (Laane *et al.*, 1993; Cadée, 1986, 1992; Cadée and Hegeman, 1993; Bot and Colijn, 1995; Bot *et al.*, 1996), and the German Bight (Radach *et al.*, 1986, 1990; Radach and Bohle-Carbonell, 1990; Hickel *et al.*, 1992, 1993, 1995). Lindeboom *et al.* (1996) has reviewed many of these long-term changes for the North Sea.

In all these studies of long-term perturbations of coastal ecosystems, the question arises as to how to describe and evaluate the perturbations found. Many of the data sets mentioned were evaluated using regression analysis (Radach and Berg, 1986; Bot *et al.*, 1996), spectral analysis (Radach and Bohle-Carbonell, 1990;

Visser *et al.*, 1996; Sündermann *et al.*, 1996), or multivariate statistical methods such as principal oscillation patterns (Sündermann *et al.*, 1996). These various methods give insight into the variability of the system and possible relations between the state variables. However, when comparing different time intervals for a specific ecosystem, or different ecosystems for the same time span, a single concise quantitative measure of the long-term changes is needed to rate these changes, i.e. in determining how much value should be assigned to them. This is an important problem for water quality management, but also in ecosystem research.

Several attempts have been made to quantify the long-term changes of an ecosystem by one or a few characteristic numbers. Starting from the full mathematical description of ecosystem dynamics, based on network analysis and information theory, Ulanowicz (1986) has developed indices, such as ascendancy, which describe the system by its total through-flow and the single flows between the state variables; his static theory

was extended to time-dependent networks in ecosystems by Pahl-Wostl (1991).

For practical purposes in eutrophication research in fresh water systems, Vollenweider and Kerekes (1980) started from the other extreme, taking only a few state variables into account (total phosphorus, yearly average chlorophyll, peak chlorophyll, Secchi transparency) to characterize the trophic state of the ecosystem by defining five trophic categories (ultra-oligotrophy, oligotrophy, mesotrophy, eutrophy, hypertrophy). Several attempts have been made to develop such a trophic reference system for the marine environment (Giovanardi and Tromelline, 1992; Ignatides *et al.*, 1992; Innamorati and Giovanardi, 1992).

It is important to formulate an ecological development index (EDI) as a characteristic number that is open to additions and subtractions of state variables to enable comparisons between different (long) time intervals for a specific ecosystem or different ecosystems for the same total time span. The applicability of the characteristic number to various circumstances without prescribing the state variables (and/or fluxes) from the start would then be possible. A concise measure of the ecological long-term development is also needed in cases where several state variables exhibit positive, others negative, trends: What, then, can be said about the development of the whole system? This leads to the definition of a sound measure for the overall change of the ecosystem under consideration. However, such a measure must fulfil a number of requirements. In principle, an EDI of (long-term) changes should have several (indispensable) properties:

- It should be universally applicable to every ecosystem.
- The method should be applicable to the data sets usually obtained.
- The characteristic numbers expressing the deviations should be comparable for different descriptions of the same system and between different systems.
- The description of the ecosystem's state and the measure of the perturbations should be consistent for the descriptions of two subsystems when one is an extension of the other.
- Once having chosen the units for the state variables, the descriptions should be independent of the different units of different state variables used to characterize the system, i.e. the index should be based on non-dimensional state variables.

In this paper, a technique for comparing the states of an ecosystem using an EDI is proposed. The measure for long-term changes of an ecosystem is defined and its properties are described. In applying the EDI to a specific situation one first has to choose a statistical description for the states of the system and then measure their distance. An approach with similar elements was also proposed by Kersting (1988) for analysing the effects of toxic substances on a three-compartment re-

cycling micro-ecosystem; he defined a normalized ecosystem strain (NES), which measures the deviation of the state of an ecosystem under stress from the unperturbed state.

As an example, the EDI is applied to the long-term development of the marine coastal ecosystem of the German Bight in the south-eastern North Sea using the data set of monthly means calculated from the time series obtained at Helgoland (Radach *et al.*, 1997), and an interpretation is given of the results. The approach was applied earlier to the Helgoland data from 1962–1983 by Radach and Bohle-Carbonell (1990), the time series has now been extended to 1962–1993.

Methods

The proposed EDI combines a statistical description of the state of the ecosystem (which may be chosen according to the available data) with a commonly used metric for measuring the distance between the statistical descriptions of the different states at different times. The different states are thus set in relation to a reference state of the ecosystem, which is defined by the same statistical characteristics.

Formally, the definition of the ecological development index is based on the definition of the N-dimensional state space $\{X_i(t)\}$ of vectors of the state variables X_i ($i=1, \dots, N$)

$$X(t) = (X_1, X_2, \dots, X_N)$$

at time t , which include all (or parts of) the observed state variables X_i . For describing the long-term development, it is proposed here to describe the system's state by the mean statistical properties over several years, derived from observations.

The description of the system's state depends on the availability of data. With respect to the German Bight, monthly means of several state variables are available for about 30 years, and therefore the following procedure has been followed. First, for each state variable a time series of running medians of monthly means is formed over 5 years, thus creating a new time series of running 5-year medians. Each median value is attributed to the time at the centre of the 5-year interval. Second, the time series is normalized by the median at the starting point t_0 to obtain non-dimensional numbers and to make it comparable to time series of other state variables X_i with originally different units. Thus, all time series have unity as their starting values. If a normalized time series of 5-year medians increases to values $F > 1$, this means that the non-normalized 5-year medians increased by a factor of F . Third, the time series of the 5-year medians of each of the N different state variables for each time instant t , denoted by $M_i(t)$ (where $i=1, \dots, N$), are collected into a vector of dimension N :

$$M(t)=(M_1(t), \dots, M_N(t)).$$

The result is a time series of such N-dimensional vectors, M(t), containing the statistical information about the time series of state variables, X(t).

Expressed in more generality, it is proposed to use the T-year quantile of p percent, referring to the values of the i-th state variable X_i at time t, Q_i(t;T,p), as the statistical measure for each observed state, and to form the vector:

$$Q(t; T,p)=(Q_1(t;T,p), \dots, Q_N(t;T,p))$$

in N-dimensional space of T-year quantiles, {Q(t;T,p)}, which will be called system's (state) space of the p-quantiles, SSS(t;p)={Q(t;T,p)}, which is abbreviated in the following for T=5 years as SSS(p).

The distance D(t;T,p) of such states Q(t;T,p) is defined by a metric for this N-dimensional space. The distance will also be a function of the time interval of averaging, T, and quantile, p, because the system's states are dependent on both. The distance of the evolving states from the initial state (as the starting point) will be calculated here consecutively (which need not necessarily be done). The starting point corresponds to the first of the normalized N-dimensional vectors of 5-year medians Q(t₀;T,p). This allows one to follow the development in time. Subsets of several state variables are followed in a subspace of dimension M<N, and the development of the total system behaviour is followed in SSS(p), the N-dimensional space of vectors of p-quantiles.

The EDI is defined as the Euclidean distance D in N-dimensional space of vectors Q(t;T,p). This definition has a number of advantages. The distances in this space are directly comparable, and when projecting the distance from the full N-dimensional space onto a subspace, the resulting value of D equals the distance in the subspace. The Euclidean distance is defined as mean quadratic distance of two states Q(t₁;T,p), Q(t₂;T,p) in systems' space. This definition corresponds to its analogue in our common three-dimensional physical space, where the distance is the length between two points on a straight line. In the case of the N-dimensional system's space SSS(p), the vector Q(t) at different time instants t₁=0, t₂=t is used to define the distance D(t;T,p), here abbreviated as D(t,p), as T is always 5 years in the application to the German Bight.

$$D^2(t,p) = \sum_{i=1}^N (Q_i(t;T,p)/Q_i(t_0;T,p) - 1)^2. \tag{1}$$

This quantity is named EDI and describes the long-term change relative to a predefined initial state; it depends on time and on the state variables included, and on the statistics (p-quantiles) used:

$$EDI(t,p)=EDI(t, X_1, \dots, X_N,p).$$

Table 1. Distances for different number of state variables (N) included and multiplication factors (F).

F	N=	2	3	4	5	10	20	30
0.5		0.70	0.86	1.00	1.12	1.58	2.24	2.74
1.0		0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.5		0.70	0.86	1.00	1.12	1.58	2.24	2.74
2.0		1.41	1.73	2.00	2.24	3.16	4.47	5.48
3.0		2.83	3.46	4.00	4.47	6.32	8.94	10.95

The above-mentioned special case for Q_i arises when taking the 5-year medians:

$$M_i(t)=Q_i(t;5,50),$$

to describe the average (or long-term) state of the system; then the ecological development index reads:

$$D^2(t,50) = \sum_{i=1}^N \left(\frac{M_i(t)}{M_i(0)} - 1 \right)^2. \tag{2}$$

The numerical measure EDI for long-term perturbations in state space fulfils the following conditions for a given set of state variables included: (1) it is a non-dimensional number, calculated from non-dimensionalized state variables; it measures the distance from the initial state, normalized by the initial state; (2) it is invariant against extension and reduction of state space (or subspace); (3) each state variable included is weighted with its initial state, yielding equal starting points for all state variables; (4) in all cases the measure gives comparable numbers.

The index has further properties, which should be noted. The more this value differs from one (D>1), the more distant is the state from its starting point. For instance, if the median concentrations of all state variables were to increase by a factor F at time t:

$$M_i(t)=F \cdot M_i(0),$$

the distance measure D would become:

$$D(t,50)=\sqrt{N} \cdot |F - 1|,$$

which yields a general dependence on \sqrt{N} for an F-fold increase of all state variables. For instance, if F=1, no change occurs; if F=2, the state variable underwent a doubling, but D= \sqrt{N} ; etc. To get a feel for the meaning of such distances, the distances D due to an increase by a factor of F are listed in Table 1, depending on the number N of state variables included. Thus, a doubling of all 10 state variables in a corresponding 10-dimensional state space results in D=3.16. However, with increasing number of state variables N, the dependence of D on \sqrt{N} becomes less and less important,

which is a positive feature of EDI. This is, by the way, no contradiction to the invariance of the measure D against extension or reduction of state space.

Using this index, the distances of the states of the 5-year medians will be measured in N -dimensional system's space $SSS(50)$. Parallel to the characterization of the system's long-term development by the temporal development of the medians, one may follow the temporal developments of different aspects of the system by utilizing other quantiles in a corresponding N -dimensional space $SSS(p)$ of vectors of other quantiles. They will express long-term changes in variability by showing how far a certain quantile has deviated from the initial state. As for the vectors of medians, the distance is the greater the larger the value of D is. In the following application the 1/6-quantile ($p=16.7\%$) and 5/6-quantile ($p=83.3\%$), respectively, are chosen to represent the lower and the upper 16.7% of the data.

The method will be applied to all observed state variables together, and the distances within subspaces for different groups of state variables will be calculated; these form subsets of all state variables. In this way one can discriminate which sets of state variables cause the long-term changes over the years. This feature, however, is usually aimed at when applying statistical multivariate analyses methods.

When interpreting the figures, one has to recognize that the 5-year quantiles as well as EDI values are always plotted at the centre of the corresponding 5-year interval. Long-term changes have always to be interpreted with reference to this time interval. The points of the curve are in this case not independent of each other. Correctly seen, a value of the curve means: the state of the system, as represented by the vector of quantiles $Q(t,5,p)$ over the 5-year interval, with the distance $D(t,p)$ from the initial state, has the EDI(t,p).

Some elements of this method may remind the reader of multivariate statistics. However, calculation of the EDI is no multivariate statistical method, and it is not meant to replace such methods, which aim at finding relations between state variables. The EDI is rather a concept adding some special information, which is not supplied by multivariate statistics.

Data

The Helgoland Reede data originate from the Biologische Anstalt Helgoland and were obtained from surface samples between the main island and the "Düne" ($54^{\circ}11.3'N$ $7^{\circ}54.0'E$, see Fig. 1). Samples have been collected since 1962, first on 3 days, later on 5 days, a week. After temperature measurement, samples were analysed for salinity and the nutrients phosphate, nitrate, nitrite, ammonium, and silicate. Phytoplankton cells were counted, and biomass was estimated after

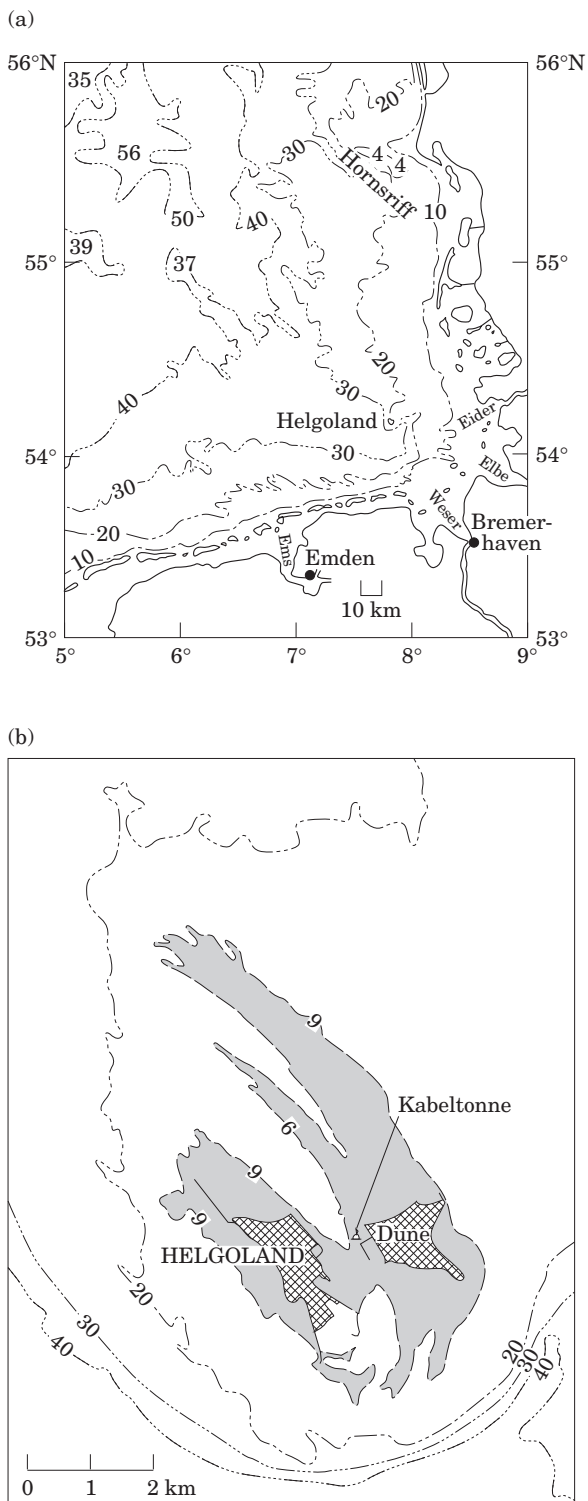


Figure 1. Position of Helgoland in the German Bight: (a) depth distribution in the German Bight, North Sea, and (b) Helgoland islands, German Bight.

conversion to carbon. Phytoplankton is subdivided into diatoms and the rest, consisting mainly of flagellates including *Phaeocystis*. The methods were described in detail by Radach and Bohle-Carbonell (1990). The data of the single years were taken from the annual reports of the Biologische Anstalt Helgoland (1962–1984). All nine observed state variables at Helgoland Roads mentioned above are used here. In addition, Elbe River discharge is considered as a state variable.

The period of 5 years for averaging was chosen, because this yields averages on a medium scale between the annual cycle and the long-term time scales, allowing averaging out of the strong year-to-year variations, but enabling the long-term development to be followed. The frequency distributions of the observed state variables are mostly non-normal (Radach and Bohle-Carbonell, 1990), and therefore the quantiles were chosen for the statistical description.

Results

Long-term changes of average low, mean and high levels of state variables

Before presenting the ecological development indices determined, the time series of 5-year quantiles for the single state variables are discussed to give an impression of the long-term changes in each of them. The time series of the medians describe the long-term development of the mean concentration levels taking into account the observations from all the year. The time series of the 1/6-quantile (5/6-quantile) is an indicator of what is called “low (high) values” in the period under consideration. When these quantiles change with time, the range of all observed values changes. These two quantiles include 66.7% of all observed values, and their changes indicate changes in the variability of the state variable. For nutrients, the 5/6-quantile is an indicator of the concentrations during the winter half year; for phytoplankton it is an indicator of the concentrations during the summer half year. The 1/6-quantile indicates summer values for nutrients and winter values for phytoplankton. For illustrating the results that can be obtained using the different quantiles, the state variables measured at Helgoland are presented as absolute, non-normalized 5-year quantiles (Fig. 2). Numerical values are given in Table 2.

The discharge from River Elbe oscillates with two extended positive anomalies around 1967 and 1980 and a negative one at about 1973 around the mean state (Fig. 2a). Temperature and salinity (Fig. 2b, c) exhibit positive long-term changes of their medians around 1975 and 1990. Also the 1/6-quantiles of temperature and salinity exhibit an increase in the mid-1970s and around 1990, whereas the 5/6-quantile of salinity has a maximum around 1978 (Fig. 2b, c).

Phosphate (Fig. 2d) and nitrate medians (Fig. 2e) increase 1.6-fold and 2.5-fold, respectively, until the early 1980s (Radach and Bohle-Carbonell, 1990). Phosphate decreased thereafter to levels around 1965, whereas nitrate increased further. Nitrate concentrations started to decrease in the late 1980s, reaching about 1985 levels in the end. The low phosphate concentrations (1/6-quantile) decreased after 1973, faster than the medians, and the range of variability, which was at its maximum around 1983, decreased after that. The three quantiles did not develop in parallel. For nitrate, the 1/6-quantile increased after 1976 faster than the median until 1986; its maximum was reached during the late 1980s, and it decreased after that to around 1985 levels. The 5/6-quantile of nitrate and thus the large values of about $18 \mu\text{mol l}^{-1}$ did not increase before 1979, but then much faster than the median and the 1/6-quantile in two pulses to levels of about $40 \mu\text{mol l}^{-1}$. In the end also the “high values” and thus the range of variability decreased.

The 5-year medians of nitrite (Fig. 2f) increased until about 1972 by a factor of 1.8; they stayed essentially at this level until 1987 and then decayed. However, the low values (1/6-quantile) increased steadily until 1986, but then decreased until the end. The high values had a maximum between 1971 and 1983, decreased and remained after 1983 on the same level as around 1965.

Ammonium medians (Fig. 2g) decreased in three steps, from around 1965 to 1971, from 1971 to 1983, and from 1983 to 1993. The levels of all three quantiles were lowest in the end. The variability range of ammonium remained fairly constant over the years. Silicate medians (Fig. 2h) decreased during the first years until 1970, stayed on nearly the same level until 1982, decayed a little further and then went steeply up in 1985. The 1/6- and 5/6-quantiles followed the median. During the last years silicate median concentrations decreased.

The 5-year medians of diatoms (Fig. 2i) increased during 1965–1980 up by a factor of 3, then decreased until 1985, but increased again until the end to three times the initial levels. The 5/6-quantile showed two relative maxima around 1968 and 1983. The 5/6-quantile was always $>40 \mu\text{gC l}^{-1}$. The 5-year medians of flagellates (Fig. 2j) increased by a factor 4.4 until 1983, and remained on a high level until 1990. Since the late 1970s their biomass level has been much higher than during the period 1965–1975. The 1/6-quantile increased by a factor of 12 until 1983 and changed only little until the 1990s, which means that the low level of flagellates biomass has increased dramatically since the 1960s.

The 5-year quantiles of the N/P ratio (Fig. 2h) summarize the different developments of phosphate and nitrogen nutrients. The 5-year median started on a level of about 35 in 1965, decreased until 1971, and increased thereafter steadily to values of about 45–50. The 1/6-quantile followed the 5-year median on a lower level. The 5/6-quantile, however, ran in parallel only until

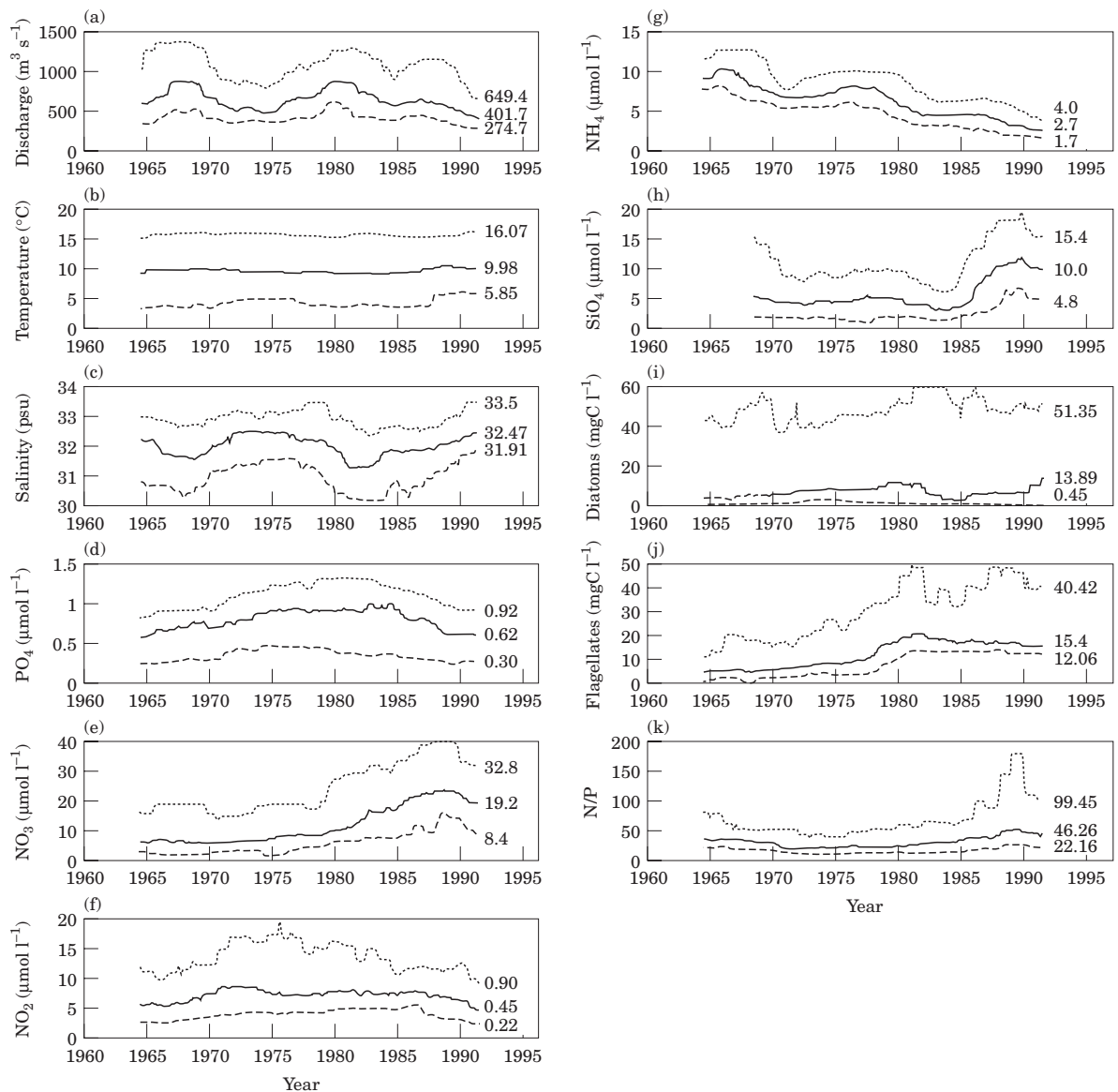


Figure 2. Running 5-year 1/6-quantiles (dotted line), medians (full time), and 5/6-quantiles (broken line) of the monthly means of various state variables (b/k: based on monitoring programme at Helgoland): (a) Elbe River discharge, (b) temperature, (c) salinity, (d) phosphate, (e) nitrate, (f) nitrite, (g) ammonium, (h) silicate, (i) diatoms, (j) flagellates, (k) N/P ratio.

about 1985, with higher levels between 40 and 80; but thereafter it increased to a maximum of 180 in 1989, before decaying to levels of 100.

In summary, the state variables do not exhibit a clear and unambiguous picture of the ecosystem monitored at Helgoland. Within different periods different processes were probably dominant. When looking into state space for two selected state variables one may arrive at results explaining parts of the history observed. One important condition for algal growth is the availability of nutrients. Flagellates seem to be strongly dependent on inorganic

nitrogen nutrients; when plotting the 5-year medians of monthly means of flagellates against those of nitrate, two domains show up where the states remain for about 10 years each, from 1965–1975 and from 1985–1993 (Fig. 3a), with a jump from one domain to the other from 1976 to 1983, passing a maximum of flagellate biomass around 1981/82, when the level of phosphate concentrations was highest (Fig. 2d). The long-term behaviour of phosphate versus nitrate (Fig. 3b) proves this; it shows in addition that the molar N/P ratio of the 5-year medians was less than 16 until about 1980 and

Table 2. Qualitative and quantitative characterization of the state variables as described by the 5-year quantiles of 10 state variables during four phases of eutrophication (C: constant; I: increase; D: decrease; different trends within each phase separated by a comma).

Variable unit	Phase 1 Starting Eutr. 1962–1970	Phase 2 Increasing Eutr. 1970–1977	Phase 3 Maximum Eutr. 1977–1985	Phase 4 Decreasing Eutr. 1985–1993
Temperature (°C)	C (9.3–10.0)	C (9.3–9.9)	C (9.1–9.5)	Slight I (9.3–10.3)
Salinity (psu)	Min. (31.5–32.2)	Max. (32.0–32.5)	Min. (31.3–32.2)	I (31.8–32.5)
Elbe discharge (m ³ s ⁻¹)	Strong I, max., D (589–869)	Fairly C (470–659)	Strong I, max., D (555–860)	D (402–644)
Phosphate (µmol l ⁻¹)	I (0.59–0.78)	I (0.72–0.95)	max., D (0.87–1.0)	D (0.83–0.62)
Nitrate (µmol l ⁻¹)	C (5.8–6.8)	Slight I (5.8–8.5)	Strong I (8.2–19.9)	max., D (19.2–39.9)
Nitrite (µmol l ⁻¹)	I (0.53–0.72)	D (0.6–0.84)	C (0.69–0.78)	D (0.45–0.76)
Ammonium (µmol l ⁻¹)	max., D (7.0–10.3)	Local max., D (6.8–8.2)	D (4.4–8.0)	D (2.7–4.6)
Silicate (µmol l ⁻¹)	D (4.3–5.4)	C (3.8–5.5)	Slight D (3.0–5.2)	Strong I, max., D (4.4–11.9)
Diatoms µg C l ⁻¹	C (3.9–6.3)	Weak I (5.6–9.1)	Max. D (2.7–11.7)	I (5.1–13.9)
Flagellates µg C l ⁻¹	C (4.7–6.1)	I (6.1–10.3)	I (10.5–20.6)	C (15.4–18.3)
N/P ratio (–)	Slight D (35.4–25.4)	C (19.0–24.2)	Slight I (22.1–37.4)	Strong I, max., D (37.4–51.8)
N/Si (–)	C (3.5–4.1)	I (4.0–6.0)	I (4.4–8.2)	D (2.4–5.5)

that it reached the Redfield ratio of 16 around 1980, but changed thereafter to values >16. This probably caused the decay from the maximum level of flagellate concentrations in the early 1980s. There are thus two domains in phosphate-nitrate state space of 5-year medians, separated by N:P=16, where flagellates can maintain a fairly constant basic biomass level.

The single state variables exhibit very different trends (Fig. 2), which confirms the earlier analyses by Radach and Berg (1986), Radach and Bohle-Carbonell (1990), and Hickel *et al.* (1993, 1995). But it is not clear from the partly opposing, non-parallel trends how to determine which of the single developments is the leading one and where the overall development can be localized in state space.

Ecological development index (EDI)

The EDI is calculated for the physical, chemical, and biological subspaces and the full set of state variables, defined by (1) the oceanographic state variables temperature and salinity as well as Elbe discharge (N=3); (2) the chemical state variables phosphate, nitrate, nitrite, ammonia, and silicate (N=5); (3) the biological state variables diatoms and flagellates (N=2); and (4) all state variables together (N=10).

Case (1) describes long-term changes of the physical state, which provides the forcing of the system by weather, water discharge, and by currents. Case (2) describes the chemical part of the system, which is strongly influenced in the southern North Sea by nutrient river loads. Case (3) describes the biological state of the system as a consequence of the long-term changes in physical and chemical subsystems; and case (4) comprises the total system state, as represented by the available observations. Table 3 summarizes the values obtained. The long-term changes can be assessed using Table 1.

The physical median state (case 1: Fig. 4a) oscillated around the initial state, deviating up to 0.5 from the outset, starting with an oscillation during 1965–1970, performing a second one during 1976–1983, and beginning a third one around 1988. The states defined by the vector of 5/6-quantiles (high values) deviated from the initial state by less than 0.4. The 1/6-quantiles (low values) of temperature, salinity, and discharge of the River Elbe (Fig. 2a) developed in a way that the EDI is 0.8 at its maximum. All three quantiles started their oscillations in phase, but progressively developed a sequence that first the low values, then the medians, and lastly the high values started their oscillations. In the last decade the low values are 3–5 years ahead of the high

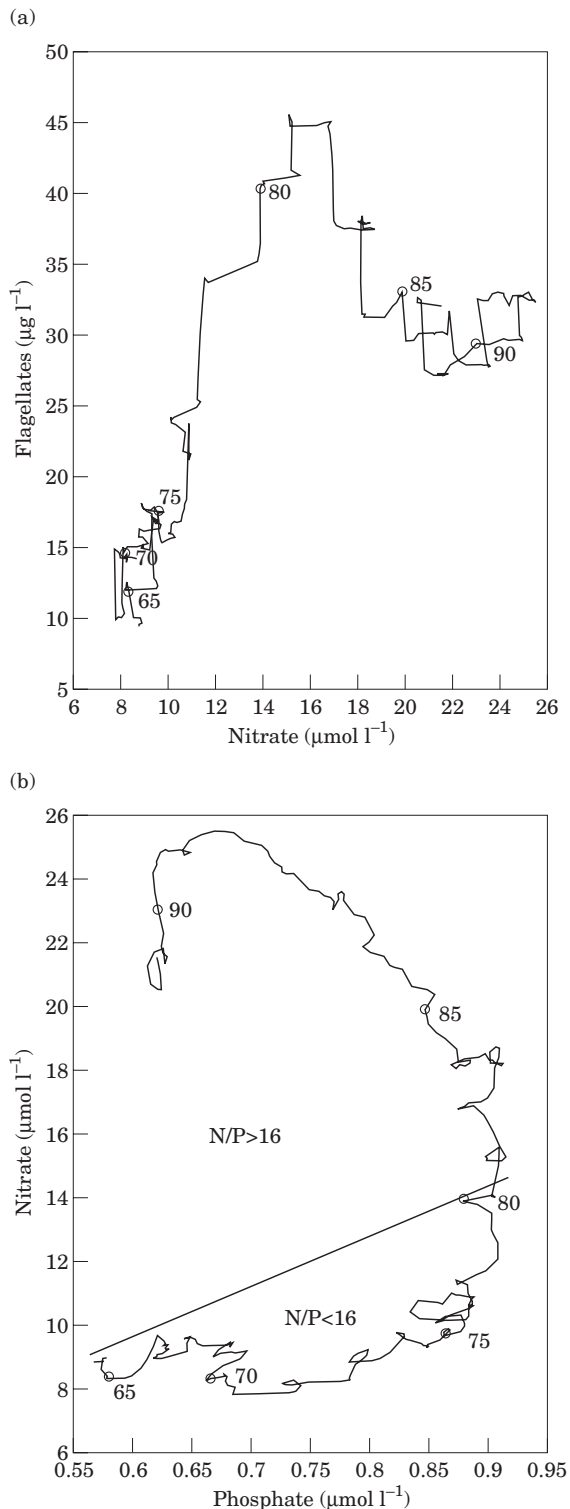


Figure 3. Running 5-year medians of monthly means of: (a) flagellates vs. nitrate, (b) phosphate vs. nitrate (straight line indicates N/P ratio of 16). The numbers at the circles on the curves indicate the years.

values. The development in physical subspace is dominated by river discharge and not by the oceanographic state variables temperature or salinity (Fig. 2b, c).

The chemical state, as described by the developments of the main nutrients (case 2; Fig. 4b) developed nearly in parallel in all three subspaces. The (relative) deviation of the median state from its initial state (1962–1966) occurred in three pushes, until finally around 1990 the distance of 2.2 was reached: The first push arrived at the system between 1969 and 1972, the second around 1978–1982, and the third between 1985 and 1988.

It is noticeable that the low values of nutrients deviate more strongly from their initial levels than the medians. This means for the original time series that the low values (relative to 5-year periods) have changed most in absolute terms during the 32 years ($\text{EDI}=2.4$). The high values have not changed as much as the medians in absolute terms ($\text{EDI}=1.3$).

In characterizing the biological state, one is restricted to the two state variables diatoms and flagellates (case 3; Fig. 4c). Their joint EDI increases until 1973 to 1, stagnates at 1.3 until about 1976, and increases again dramatically, i.e. from the 5-year interval around 1977 until 1980, to a value of 3.1. The low values deviated from the initial state up to 12.5 in 1980. The EDI for high values developed in a similar way to that of the medians.

In the comprehensive SSS, including all 10 observed state variables (case 4; Fig. 4d), drastic long-term changes of EDI are recognized. There are four phases: during the first phase (1962–1970) the EDI increased, followed by a short decay after 1968 and a stagnation (for the medians); an increase during the second phase (1970–1977); then a jump to about 4 in 1981, followed by a decay until 1985; in the last phase (1985–1993) the EDI stayed on the same level until the end ($\text{EDI}=3.7$). The EDI for the high values developed similarly, with a smaller change from the start, and remained at about 3 from 1980 onwards. The EDI for the low values finally reached about 13.5! The increase in the EDI occurs in three ever-increasing pushes, one at the start, a second one around 1971, and a third and strongest one around 1978, shifting the ecosystem towards a totally different state, from where it started to return only slightly until the end ($\text{EDI}=11.2$). The strong change of the index shows clearly how the increasing levels of the measured biological state variables determine the ecosystem state. The ecosystem operated during the 1990s still on a much higher level of nutrient availability, resulting in strongly increased biomasses, placing the present ecosystem state at a distinctly more remote position in system space than ever before until around 1989; after that the ecosystem may have tended to return to former states, but this is still speculative, because the decay of the EDI during the last 5 years is still within its variability between around 1980 and 1991.

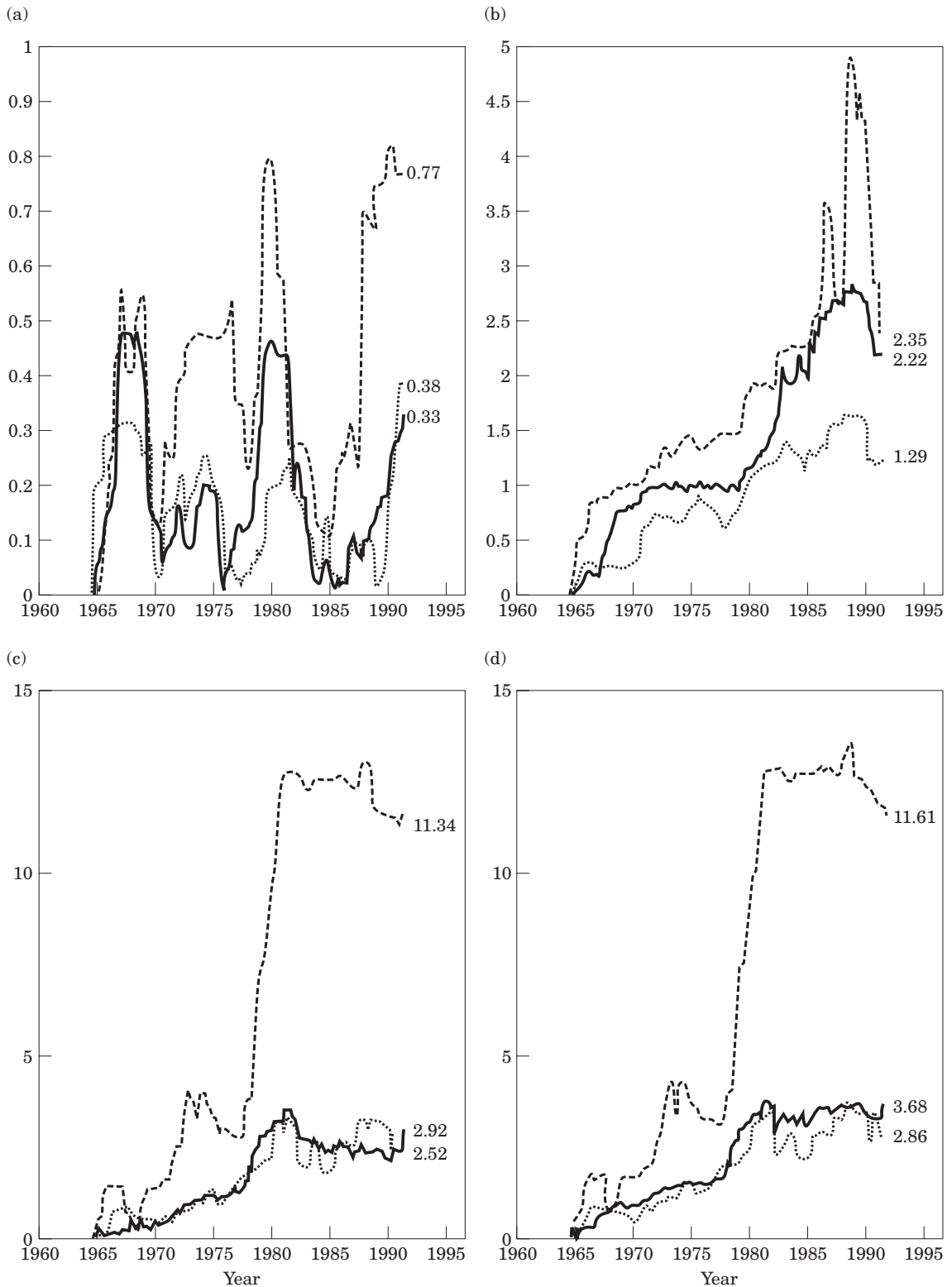


Figure 4. Temporal development of the ecological development index for low values (broken line), medians (full line) and high values (dotted line), for subsets of the state variables observed at Helgoland in the German Bight: (a) physical state variables (temperature, salinity, Elbe River discharge; N=3), (b) chemical state variables (phosphate, nitrate, nitrite, ammonium, silicate; N=5), (c) biological state variables (diatoms, flagellates; N=2), (d) all state variables (N=10).

Discussion and conclusions

Usefulness of the Ecosystem Development Index

The definition of the EDI has the advantage of being clear and obvious. The application should not give any technical problems. However, there are several issues concerning its interpretation which have to be further clarified, and it will be necessary to test and further develop the index. The EDI is a non-dimensional number, which is also independent of units of the state variables, as long as the different units for a specific state variable can be transformed into each other by a multiplicative factor (but not independent of units which must be transformed into each other by a mathematical translation, like °C and °K!). These two properties are considered to be advantages, because they enable the treatment of many different state variables in equation [1] defining the EDI. The non-dimensionalization is based intentionally on the mean starting level of the statistical quantities used and not on the explicit variability during the 5 years of averaging. A weighting of the state variables by their standard deviation during the time of averaging does not seem sensible, because the quantiles are then reduced to the same magnitudes and their differences in variability are mixed into mean levels. This is not intended; it is preferred that the problem of changing variability can be covered by applying the EDI to each of the different statistical quantities separately.

The EDI, as a Euclidean measure, is invariant against extension and reduction of the system's state space (or subspace). However, going from N- to (N+M)-dimensional space (or backwards) by adding (or omitting) M state variables needs further consideration. Although the distances, i.e. EDIs in different subspaces, are fully comparable, the dimension N is inherently woven into the index and also determines the EDI in subspaces of different dimensions, as was shown before when discussing the effect of overall multiplication factors. On the other hand, if one were to introduce a normalization of the EDI by the dimension of the subspace to exclude the dependence on N, then one would obtain obvious coincidences of the distances for the same multiplication factors (see Table 1), but the EDI would no longer be a Euclidean distance, which is comparable in the different subspaces. Therefore, such a normalization by the square root of the dimension is not helpful.

For different ecosystems, the observed sets of state variables probably differ from each other. One should define a minimum set that must be available, and calculate the EDI for this set. When additional state variables are available at certain sites or within certain monitoring programs, the addition of new state variables is possible and should be done, and the corre-

sponding EDI should be calculated. One might select so-called target state variables, which are believed to characterize the ecosystem best. It is clear from equation [1] that new state variables can only be added if their earlier values are not equal to zero.

In the definition, each variable has the same importance in the sense that the starting point is always equal to one, and the relative change compared to the initial state is followed in time. If the same sets of state variables from different sites are compared, this will not give any problems; EDIs have to be defined accordingly. If different sets of state variables are used, comparability is no longer guaranteed. In this case, a standard subset of target variables should be used.

The main problem is still the assessment of the resulting values. It is a matter of individual judgement whether a particular distance means a tolerable or a non-tolerable development of the ecosystem. When using this method, the acceptable distances have to be defined a priori, but rating of the calculated distance remains a case-related subjective task. A correspondence of states of eutrophication and the index has still to be established.

Compared with other existing indices the EDI seems to have a number of advantages. Colijn *et al.* (1996) reported on the Dutch policy-strategy for the development of ecological quality objectives and recommended the AMOEBA approach (Ten Brink *et al.*, 1991), which relates two states of the ecosystem to each other, one representing the (undisturbed) reference state and one characterizing the present conditions. This approach is effectively comparable to a multi-yardstick, by which the change of each state variable is measured separately by direct comparison of the reference values with the actually observed values. There is no link being constructed between the variables. Therefore, the order of the chosen target variables on the circle (of reference), which determines the visual shape of the AMOEBA, is arbitrary: different ordering of the variables results in different appearances. The further procedure of assessing the AMOEBA is subjective, as for EDIs.

The approach by Ulanowicz (1986) and Pahl-Wostl (1991) has a sound theoretical basis. But an obstacle is often that the expressions to be calculated demand the observed fluxes between the state variables averaged over appropriate space and time scales. Concerning existing monitoring data sets, these fluxes are usually not measured, in which case the theory cannot be applied. The definition of the EDI is independent of such demands.

The EDI may be extended to other quantities than proposed so far, or defined by other statistical measures. It would for instance be useful to include observed primary production as a further state variable. Theoretically, there is no limit to the addition of quantities that help to characterize the state of the ecosystem; flux

observations, too, can be included. For certain applications it may be sensible to use winter medians or bloom maxima instead. There are no limitations as long as only EDIs based on the same state variables are being compared. Kersting (1988) defined normal operating ranges (NOR) by the 95% tolerance hyperellipsoids of the unperturbed states of the ecosystem. Such a procedure could be added to identify the domains of unperturbed states in the system's state space. However, the unperturbed states have to be identified in advance, e.g. by defining suitable periods.

In conclusion, the Euclidean distance in state space of normalized quantiles formed over long time ranges represents a suitable measure to serve as EDI in assessing the status of ecosystems. The long-term changes in the system may be characterized by long-term statistical measures, e.g. 5-year medians or other quantiles (or different statistical measures), but can also be characterized in different ways.

Development of the German Bight ecosystem

The continental coastal areas of the southern North Sea have suffered severe long-term changes during the last four decades, mostly due to discharges of nutrients from the rivers (Brockmann *et al.*, 1990, Radach, 1992, Lenhart *et al.*, 1996). The variability exhibited in the Helgoland time series on time scales of short-term (days to months) and long-term events (years to decades) was analysed for 1962–1983 by Radach and Bohle-Carbonell (1990) and Radach *et al.* (1990) with respect to the influences of various external forces determining the internal dynamics of the plankton ecosystem in the German Bight. They found that the high variability of the plankton system in space and time is caused by the actual combination of weather events, riverine input, and physical meso-scale and fine-scale structures, such as coastal currents, fronts and haline stratification caused by freshwater inflow. This is also the reason why different sites in the continental coastal areas of the North Sea show so little interconnectedness (Visser *et al.*, 1996).

Since 1983, important long-term changes have taken place at Helgoland in terms of 5-year medians. Generally speaking, most of the nutrients have started to decrease. Mean salinity has increased by 1.13. Mean phosphate level has decreased from 1.00 to 0.62 $\mu\text{mol l}^{-1}$, but mean nitrate level has increased from 16 to 23 $\mu\text{mol l}^{-1}$ until recently. The mean flagellate biomass has changed only slightly from 18.6 to 15.4 $\mu\text{g C l}^{-1}$ during the last 10 years. Thus, the long-term changes of the various state variables are of very different intensity. While the hydrographic states have not changed markedly over 32 years, the chemical and biological states exhibit large shifts, which can be traced back to anthropogenic influences, mainly via river discharge of nutri-

ents (Radach *et al.*, 1990). An important finding is that parallel with the increase in mean phosphate and nitrate and mean phytoplankton levels the variability of these state variables has also increased.

For the longer time series 1962–1993, the long-term developments of the nutrients seem to be decoupled from those of temperature and salinity, while development of the plankton system is enforced by river discharge of nutrients. Climatic effects on variability, if present at all, are hidden by the much greater effects of river-induced eutrophication, expressed in phosphate and nitrate concentrations. Thus, climatological causes can be excluded as the dominant agent for the variability, as seen at Helgoland. The analysis of productivity and of the phytoplankton standing stocks by simulation models suggests that phytoplankton production under the given nutrient and light conditions was not limited by the availability of phosphate and inorganic nitrogen, but by light and silicate availability during many years in the 1980s and 1990s (Lenhart *et al.*, 1997; Pätsch and Radach, 1997). In accordance with this, simulations of the ecosystem dynamics show that the decrease of nutrient inputs into the German Bight has only a very restricted effect on the productivity of the phytoplankton (Lenhart *et al.*, 1997).

Oceanographic, chemical, and biological subspaces of state variables were investigated here separately as well as the combined 10-dimensional system state space to elucidate the sources of the perturbations from the initial state, which is by definition at the position (1, . . . , 1) in system state space of the 5-year quantiles. The EDI value for the final state of the total system has deviated by 3.7 from this position. As the oceanographical states deviate only marginally from the starting position, the change is exclusively due to chemical and biological long-term changes. The final distance reached is relatively large, as can be seen in Table 1 for $N=10$: a doubling of all state variable values would result in a distance of merely 3.16, a tripling in a distance 6.32.

For assessing the values obtained, a relation between the trophic state of the ecosystem and EDI has still to be established. It is not sufficient to relate the index to phosphorus, as could be done in freshwater systems (Vollenweider and Kerekes, 1980). More variables will have to be included. Tables 2 and 3 summarize the qualitative and quantitative characteristics of the states of the ecosystem as well as the EDIs for the subspaces and the full system space. Eutrophication of the German Bight is divided into four periods during which it was: slightly increasing (1962–1970), more strongly increasing (1970–1977), at its maximum (1977–1985), and declining (1985–1993). The respective values of the state variables are given together with the values of the EDIs in Tables 2 and 3. Maximum coastal eutrophication causes EDI values of about 4 for the mean state and of about 13 (3.5) for the state characterized by low (high) observed

Table 3. Qualitative description of trends (A) in and actual values of ecological development indices for different statistical characteristics (B: medians; C: 1/6-quantiles; D: 5/6-quantiles) and for different system state (sub)spaces during four phases of eutrophication (cf. Table 2; PHC=positive half cycle).

(Sub)space	Phase 1 1962–1970	Phase 2 1970–1977	Phase 3 1977–1985	Phase 4 1985–1993
A: General trends				
Physical	PHC	Fairly C	PHC	I
Chemical	I	C	I	PHC
Biological	Slight I	I	PHC	C
Total	I	I	PHC	C
B: 5-year medians				
Physical	0.1–0.5	0.1–0.2	0.1–0.5	0.1–0.3
Chemical	0.2–0.8	0.9–1.0	0.1–0.5	2.5–2.8
Biological	0.1–0.5	0.4–1.4	1.4–3.8	2.2–3.0
Total	0.6–1.0	1.0–1.7	1.7–4.0	3.1–3.7
C: 5-year-1/6 quantiles				
Physical	0.2–0.6	0.2–0.5	0.2–0.8	0.2–0.8
Chemical	0.5–1.0	1.0–1.5	1.4–2.5	2.5–4.9
Biological	0.7–1.5	1.4–3.9	3.0–12.7	11.0–13.0
Total	0.6–1.2	1.7–4.2	3.4–12.7	11.2–12.8
C: 5-year-5/6 quantiles				
Physical	0.1–0.3	0.1–0.3	0.1–0.2	0.1–0.4
Chemical	0.2–0.4	0.5–0.9	0.6–1.3	1.2–1.5
Biological	0.1–0.8	0.3–1.7	1.7–3.2	2.4–3.2
Total	0.2–0.9	0.7–1.8	1.8–3.5	2.7–3.5

values. Future study will prove whether (or not) similar values of EDI are obtained for similar states of other coastal ecosystems.

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