Invited paper

A brief analysis of North Sea physics

doi:10.5697/oc.53-3.663
OCEANOLOGIA, 53 (3), 2011.
pp. 663–689.

KEYWORDS
Shelf seas
Marine physics
Dynamical balances
Tides
Circulation
Surges

Jürgen Sündermann*
Thomas Pohlmann

Institute of Oceanography,
University of Hamburg,
Bundesstr. 53, Hamburg D-20146, Germany;

e-mail: juergen.suendermann@zmaw.de

*corresponding author

Received 30 July 2011, revised 22 August 2011, accepted 29 August 2011.

Abstract

The current state of understanding the North Sea's physical system is presented. First, basic phenomena like astronomical tides and general circulation will be described and analysed with respect to their physical nature and respective interactions. There will be special focus on fundamental dynamic balances. Next, some specific topics relevant to the marine ecosystem, the economy and society will be considered: among them, spreading and transport processes, the fresh water budget, the heat budget and storm surges. A separate section is dedicated to the North Sea of Tomorrow, i.e. the prospective variations of the physical environment resulting from global changes in future decades. The statements are based on the long experience of the authors and their groups and include findings that are

little known if at all. The review finishes with a list of open questions and the corresponding research demands.

1. Introduction

The North Sea region is the living domain of about 50 million people in nine highly developed industrial countries. It is one of the best and most intensely investigated sea areas in the world. For accounts of the present state of knowledge, we refer the reader to Otto et al. (1990), Charnock et al. (eds.) (1994), Sündermann (ed.) (1994), Laane et al. (1996), Proctor (ed.) (1997), Ruddick K. (ed.) (1997), Prandle (ed.) (2000), Sündermann et al. (2001), Lozan et al. (eds.) (2003), Pohlmann (2003) and Pohlmann (2006).

As far as the physical (oceanographic and meteorological), chemical and biological parameters of the North Sea are concerned, comprehensive data sets are available, providing three-dimensional distributions and time series from many decades. These data are constantly being supplemented by in situ observations and remote sensing information. Major data centres for the North Sea are the BODC (British Oceanographic Data Centre), the DOD (German Oceanographic Data Centre) and PANGAEA (Data Publisher for Earth & Environmental Science). Furthermore, in the states surrounding the North Sea there exists a variety of complex computer models simulating the physical state of the water body for research purposes and for operational applications in hydrography, sociology and economics (POLCOMS, NORWECOM, HAMSOM, BSH-mod). They are often coupled with models of the North Atlantic Ocean and the Baltic Sea (providing lateral boundary interactions) and with regional meteorological models of north-western Europe (providing atmospheric forcing). For estimating the quality of the currently available hydrographical and numerical data, see Delhez et al. (2004).

It turns out, however, that remarkable data gaps still exist for spatial distributions of parameters (velocity, radiation, precipitation data) and with respect to long-term records (velocity, salinity data). New models for both research and routine purposes are still being developed. The trends are towards higher resolution, adaptive grids, coupling of physical, geochemical and biological sub-models and – more technically – towards data assimilation and the parallelizing of computer codes. Owing to the stochastic nature of the processes involved, ensemble runs are often carried out with subsequent model output statistics (MOS). In this situation of innovation and experimenting, it does not yet seem advisable to introduce standardized community models for the North Sea (and all the more so for shelf seas in general).

2. Basic features

The North Sea is a shallow shelf sea adjacent to the North Atlantic with a mean depth of 80 m (the maximum water depth in the Norwegian Trench is about 800 m) (see Figure 1).

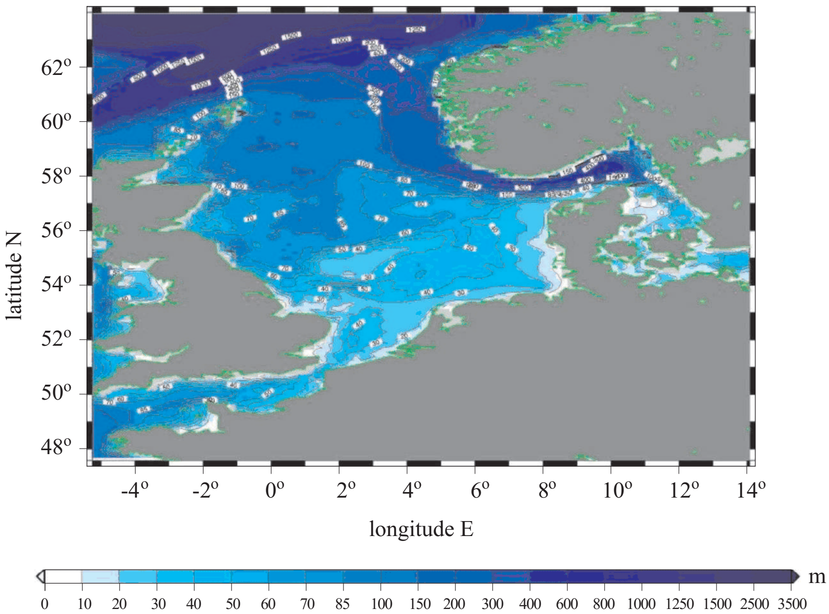

Figure 1. Topography of the North Sea [m]

It is characterized by a broad connection to the ocean and by strong continental impacts from north-western Europe. This results in a substantial interplay of oceanic influences (tides, the North Atlantic Oscillation NAO, North Atlantic low pressure systems) and continental ones (freshwater discharge, heat flow, input of pollutants). This interaction generates a specific physical and biogeochemical regime that requires an appropriate modelling concept. Ocean circulation models cannot be directly applied to the North Sea.

2.1. The role of topography

Schematically, the bottom of the North Sea rises from a depth of 200 m at its northern entrance to 50 m at the cross-section from the Dogger Banks to northern Denmark and to 20 m and less off the Dutch-German coast. This topography influences especially the system of eigen-oscillations (and hence the resonance to tidal forcing) and water level rise during storm surges.

Figure 2 shows the ranges and phases of the semidiurnal tides $M_2 + S_2$. It exhibits in principle the classical oscillation pattern of Taylor's solution for a rectangular basin of constant depth. Owing to the inclined bottom, the position of the central amphidromic point is shifted southwards.

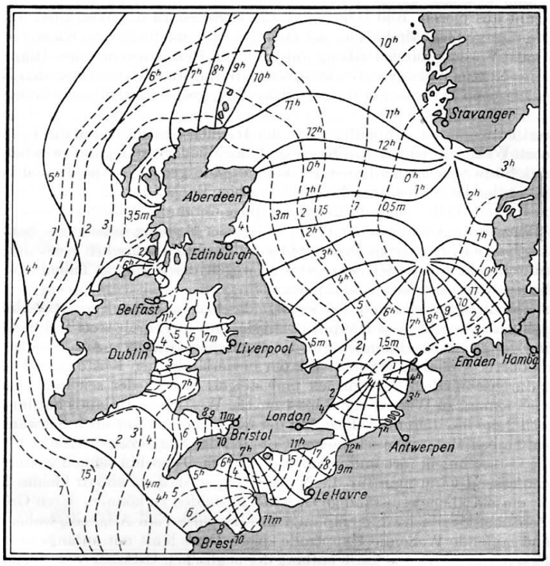

Figure 2. Co-phase lines (solid – hours) and co-range lines (dashed – metres) for the semidiurnal tides $M_2 + S_2$. From Sager (1959)

Two additional amphidromies are generated by eigen-oscillations in marginal sub-basins. The Kelvin wave penetrating from the north (with its increasing amplitudes towards the British coast) is strongly dissipated by bottom friction in the shallow southern coastal waters. Thus, the reflected wave shows significantly smaller amplitudes (off the Danish and Norwegian coasts).

The effect of topography on a schematic storm surge with a constant northerly wind is shown in Figure 3 (model result by Sündermann (1966)).

On the left-hand side (a) the natural depth distribution of the North Sea is chosen, on the right-hand side (b) a constant depth of 80 m (corresponding to the mean depth) is assumed. The southward water level rise up to the 80 m isobath is nearly the same in both cases. Thereafter, the piling up is much higher for the shallower real depth situation. One reason for the

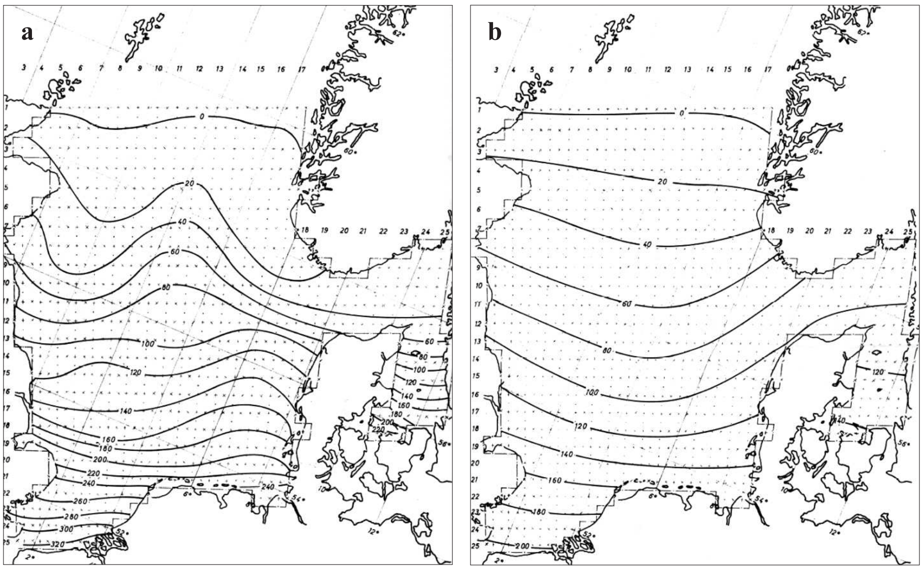

Figure 3. Stationary sea level [cm] for a constant northerly wind of 23.2 m s^{-1}; (a) real depth (see Figure 1), (b) constant depth 80 m. From Sündermann (1966)

increased storm surge danger in the southern North Sea is therefore the specific topography of the basin.

We may add that the analytical formula for the maximum water elevation in a one-ended, open, wind-driven basin

$$\xi_L = \frac{\lambda W^2 L}{g\,h}\,,$$

where W – wind speed, L – length of the basin, h – water depth, g – the acceleration due to gravity, and $\lambda = 3.2 \times 10^{-6}$, yields for North Sea conditions with a 23.2 m s^{-1} wind speed the value $\xi_L = 159.3$ cm, which is in very good agreement with the 160 cm of the numerical solution.

2.2. Role of the atmosphere

Through the vertical flux of momentum the atmosphere significantly controls the general circulation of the North Sea. Figure 4 shows the basic patterns of the wind-driven currents depending on the wind direction. As a result of the prevailing westerly winds on the north-west European shelf an intense cyclonic circulation (lower left picture) is dominant, which occasionally (in the case of easterly winds) reverses. For north-westerly and south-easterly winds states of stagnation appear. In the process of

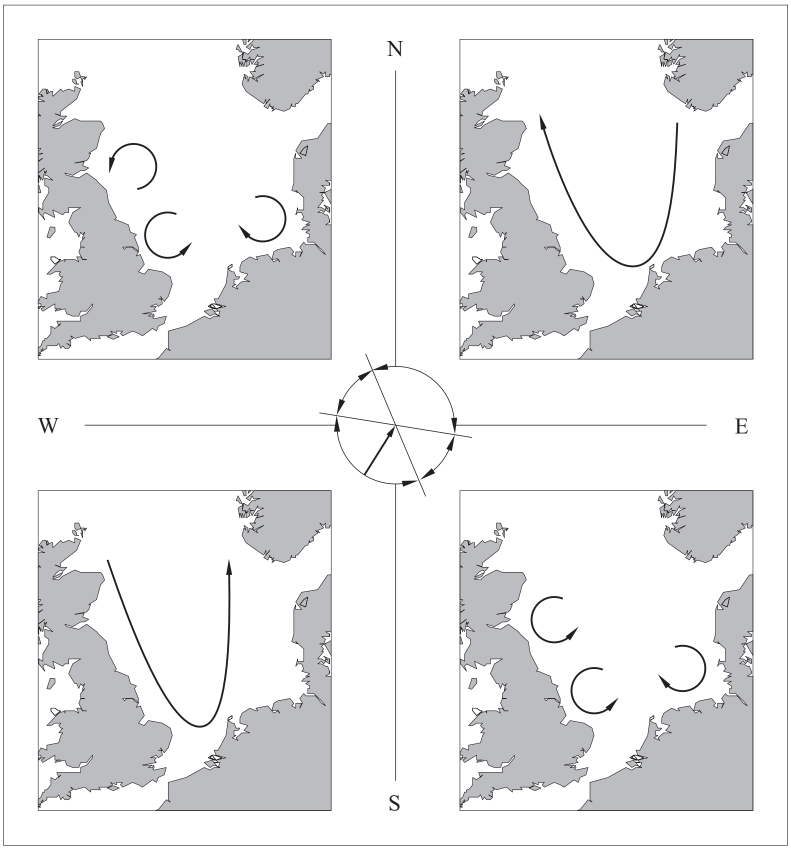

Figure 4. Wind-driven circulation in the North Sea. There are four basic states, corresponding to the sectors of the prevailing winds. (Reproduced from Sündermann 2003b, Fig. 3)

evolution the ecosystem of the North Sea has become adapted to these current regimes. Climate change could, in turn, disturb the marine ecosystem.

The wind further controls the spectrum of sea waves in the North Sea, and storms can lead to heavy and dangerous storm surges.

The atmosphere influences the heat budget of the North Sea via the heat fluxes and their variability. A thermal stratification is generated in the northern and central parts during early summer (see Figure 5) and remains up to early autumn, when stronger winds mix the water again. There is no thermocline in southern coastal waters throughout the year as a result of strong tidal mixing.

Precipitation on the north-west European shelf influences the salinity of the North Sea and its seasonal variability directly or via continental

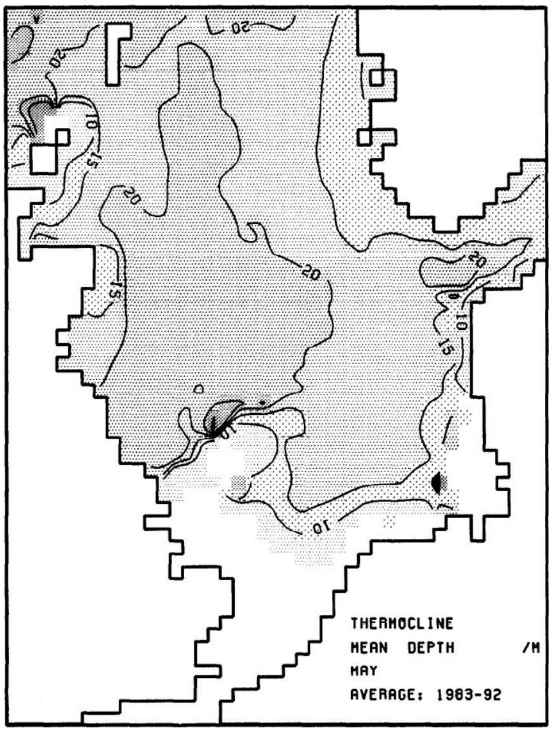

Figure 5. Climatological monthly mean extension and depth [m] of the thermocline in May. From Pohlmann (1996)

discharge. Temperature and salinity determine the density of the sea water and the structure of the water masses. The corresponding thermohaline circulation exhibits a cyclonal current pattern as well.

2.3. Interaction with the Atlantic Ocean

The open connection with the Atlantic (mainly through the northern entrance, less so through the English Channel) allows the free exchange of momentum, energy and matter between the two seas. Planetary waves generated by astronomical and atmospheric forces in the ocean penetrate over the shelf break into the North Sea, where they produce tides and water mass transports. In contrast, continental fresh water discharges (specifically the Baltic outflow) influence the current system of the North Atlantic.

Figure 6 depicts a 40-year time series of net outflows from the North Sea with an average of about 2 Sverdrups.

The decadal variability of the Atlantic, mainly the North Atlantic Oscillation (NAO), is transferred to the North Sea. Figure 7 illustrates

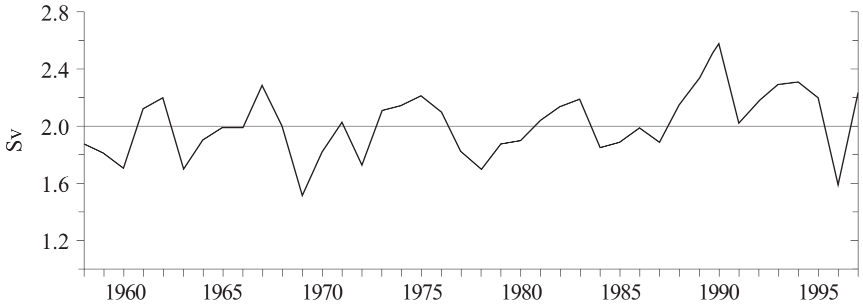

Figure 6. Net transports [Sv] out of the North Sea into the Atlantic for the period 1958–1997. From Schrum & Sigismund (2001)

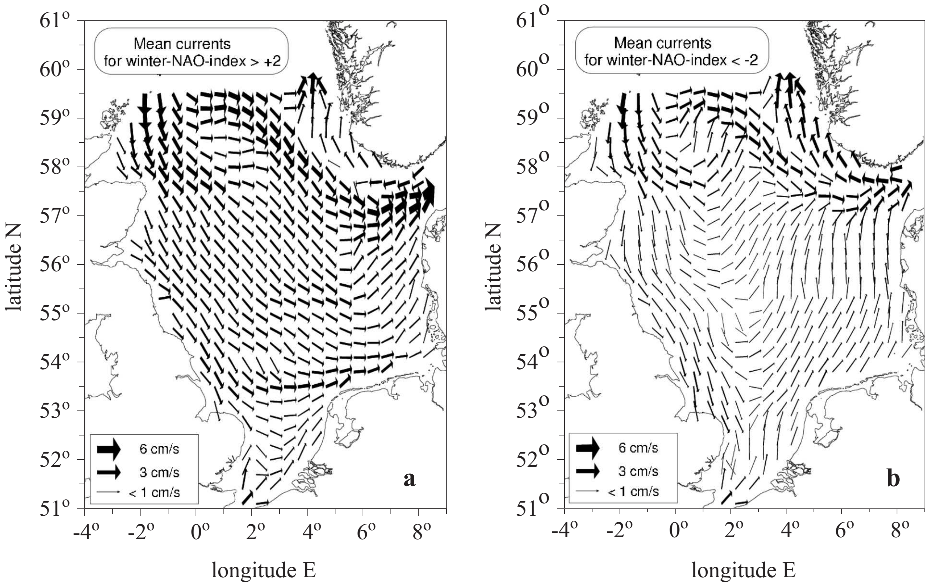

Figure 7. Circulation of the North Sea for different values of the winter NAOI; (a) index > 2, (b) index < −2. Model calculation by Schrum & Sigismund (2001)

the wind- and thermohaline driven circulation in the North Sea for two different NAO indices (NAOI) as a result of a model simulation. It is obvious that a positive winter NAOI causes a significantly stronger flow than a negative one.

The transfer of NAO variability to the North Sea happens mainly through the atmosphere, less through the direct exchange of water masses. This can be inferred from the correlation pattern of the NAOI and SST anomalies in the North Sea (see Figure 8). The high values in the central North Sea indicate this interrelation.

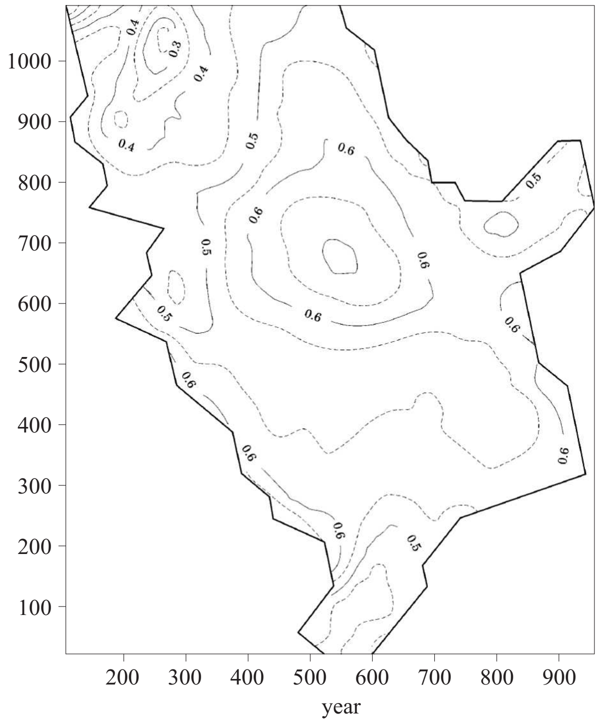

Figure 8. Correlation between NAOI and standardized annual SST anomalies for the period 1969–1993. From Löwe & Koslowski (1993)

2.4. The role of astronomical tides

The dynamics of the North Sea is significantly influenced by astronomical tides. These are co-oscillations with the autonomous tidal waves of the Atlantic (the North Sea is too small for a direct effect of the tidal potential). The specific geometry of the North Sea basin implies eigen-periods and hence resonance in the semidiurnal spectral range (see Figure 2). The superposition of the semidiurnal principal lunar and solar tides $M_2 + S_2$ causes a significant spring-neap rhythm. The tidal currents may reach a speed of a few dm s^{-1} and dominate any other flow, the more so as they move the whole water column. They give rise to strong mixing of water masses, preventing thermohaline stratification in the shallow southern North Sea. In the Wadden Sea tides cause the periodic exposure of large areas of the sea bed.

2.5. Nonlinear dynamics

The shallow topography of the North Sea supports nonlinear effects caused by energy dissipation at the bottom and changing depths due to tidal waves. These processes are stronger than the nonlinearity due to advection. As a result tidal curves and figures are severely non-harmonic. Averaging the tidal flow results in significant residual currents, which means a permanent displacement of water masses that is independent of any wind or density forcing (see Figure 9). This permanent flow system supports the cyclonic circulation of the North Sea. It may be mentioned in passing that model calculations with a random forcing at the North Sea's open boundaries yielded a similar system of residual currents (Günther Radach, personnal communication). Obviously, the specific topography of the North Sea together with nonlinear effects leads to a rectification of chaotic movements.

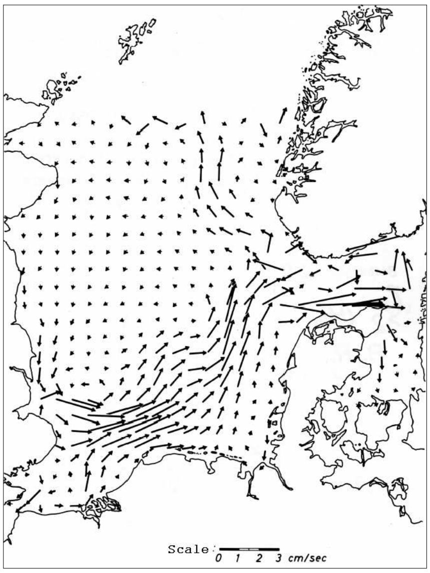

Figure 9. Residual currents of the M_2-tide. From Brettschneider (1967)

Another example of nonlinearity is the superposition of the wind- and density-driven circulation on the tidal flow. Figure 10 shows the propagation of a wind surge in the North Sea with and without considering tidal interaction. The generation of secondary waves around the basin is strongly reduced by tidal dissipation.

Backhaus et al. (1986) have shown that whenever a constant flow component is combined with a time-dependent periodic tide, there is a considerable reduction in the resulting residual flow. They explained this process by the presence of a much higher energy dissipation due to bottom friction when the actual tide is included, compared to the linear superposition of constant residual flow fields.

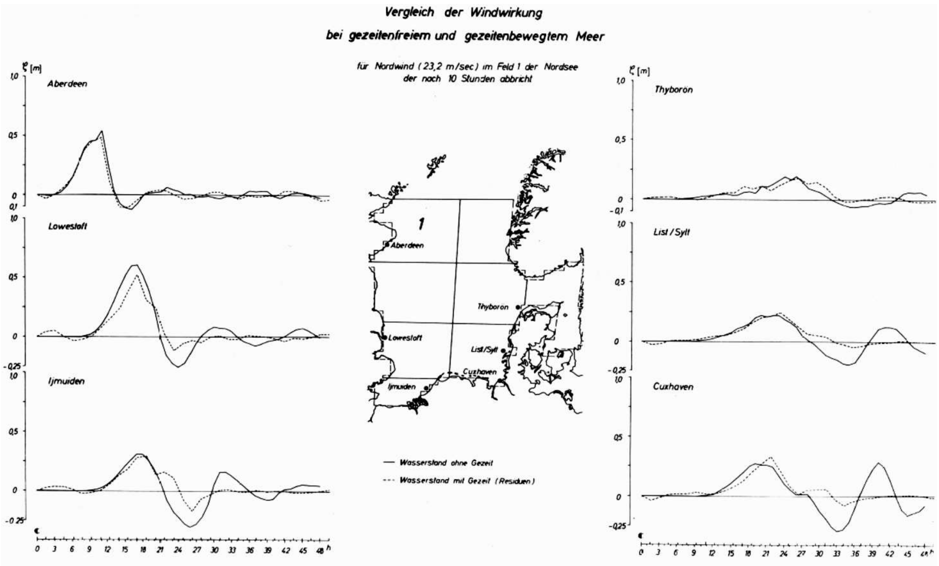

Figure 10. Propagation of a wind surge generated by a northerly wind of 23.2 m s^{-1} speed and 10 h duration in field 1. Solid line – water level without tidal interaction, dashed line – water level with tidal interaction. From Sündermann (1966)

3. Fundamental balances

In the following, the relevance of the fundamental oceanic forcing mechanisms (geostrophy, Ekman flow, Joint Effect of Baroclinicity and Relief JEBAR) for the North Sea will be examined. The numerical simulations are based on the Hamburg Shelf-Ocean Model HAMSOM, a three-dimensional, baroclinic circulation model with a free surface (Backhaus 1985). For details, see Sarkisyan & Sündermann (2009).

3.1. Relevance of geostrophy

Pohlmann (2003) extracted the baroclinic part $\underline{v}_g = (v_g, u_g)$ of the geostrophic flow from the results of the complete circulation model HAMSOM. First, the temperature and salinity fields $T, S(x, y, z, t)$ were computed on the three-dimensional model grid, next the density $\rho(x, y, z, t)$ was determined by the equation of state, and finally $\underline{v}_g$ was calculated:

$$v_g(x, y, z, t) = \frac{g}{\rho\ f} \frac{\partial}{\partial x} \left(\int_z^0 g\ \rho(x, y, z', t) dz' \right),$$

$$u_g(x,y,z,t) = -\frac{g}{\rho_0\, f}\,\frac{\partial}{\partial x}\left(\int_z^0 g\,\rho(x,y,z',t)dz'\right),$$

where g is the acceleration due to gravity, f is the Coriolis parameter and ρ_0 is a reference density.

For comparison with the total mean current field the temporally (over one month T) and vertically (over the water depth H) averaged horizontal currents were chosen:

$$\underline{\hat{v}}_g(x,y) = \frac{1}{T}\int_0^T\int_H^0 \underline{v}_g(x,y,z',t')dz'dt'\,.$$

As an example, Figure 11 shows the baroclinic current $\underline{\hat{v}}_g$ and the difference $\underline{\hat{v}}-\underline{\hat{v}}_g$ of the total flow $\underline{\hat{v}}$ and the baroclinic flow part (both monthly means) for August 1991.

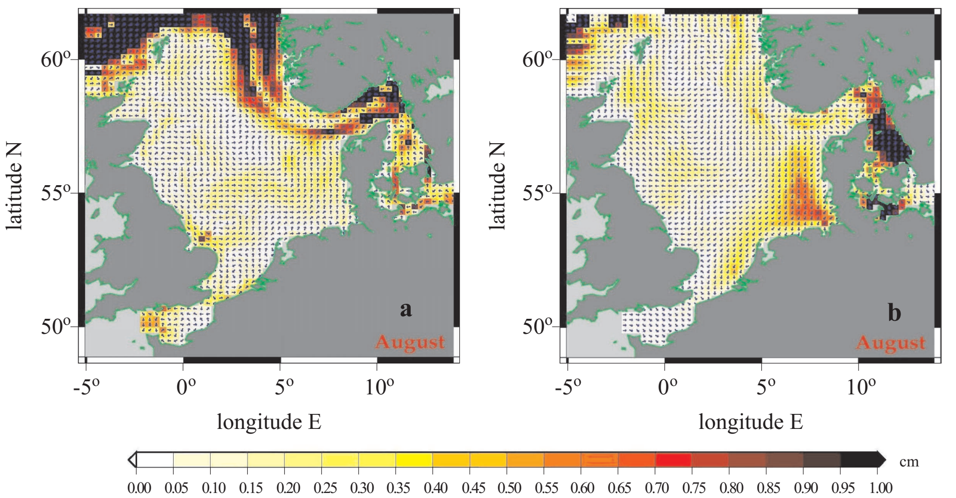

Figure 11. (a) Monthly mean of the baroclinic-geostrophic part of the flow in the surface layer for August 1991 [cm s^{-1}], (b) difference between the monthly means of the total flow and the baroclinic-geostrophic part in the surface layer for August 1991 [cm s^{-1}]

It is seen that the baroclinic part generally forms a basin-wide anticyclonic circulation, which is opposite to the known cyclonic gyre. The speed increases towards the continental coast (Figure 11a). The difference plot (Figure 11b) shows that the baroclinic component amounts to 10% of the total flow weakening the cyclonic circulation.

3.2. Relevance of the Ekman equilibrium

The Ekman regime is characterized by the balance of the Coriolis force and the vertical exchange of momentum:

$$-f\ v_e(x,y,z,t) = \frac{\partial}{\partial z}\left(A_v(z)\ \frac{\partial u_e(x,y,z,t)}{\partial_z}\right),$$

$$f\ v_e(x,y,z,t) = \frac{\partial}{\partial z}\left(A_v(z)\ \frac{\partial u_e(x,y,z,t)}{\partial_z}\right).$$

In the work of Pohlmann (2003) the terms on the right-hand side are again calculated by means of the complete circulation model HAMSOM. From this forcing the Ekman flow (u_e, v_e) is deduced. $A_v(z)$ is the vertical eddy coefficient and depends on depth. Stronger currents (not Ekman balanced) are now appearing along the Norwegian coast.

Figure 12a shows by way of example for August 1991 the monthly mean of the Ekman currents at 5 m depth. It has maximum values along the British coast with an onshore direction. Owing to stronger winds it is higher in winter. The difference plot (total current minus Ekman current) in Figure 12b exhibits a residual flow of equal magnitude, but directed offshore (which means a compensation of the Ekman current).

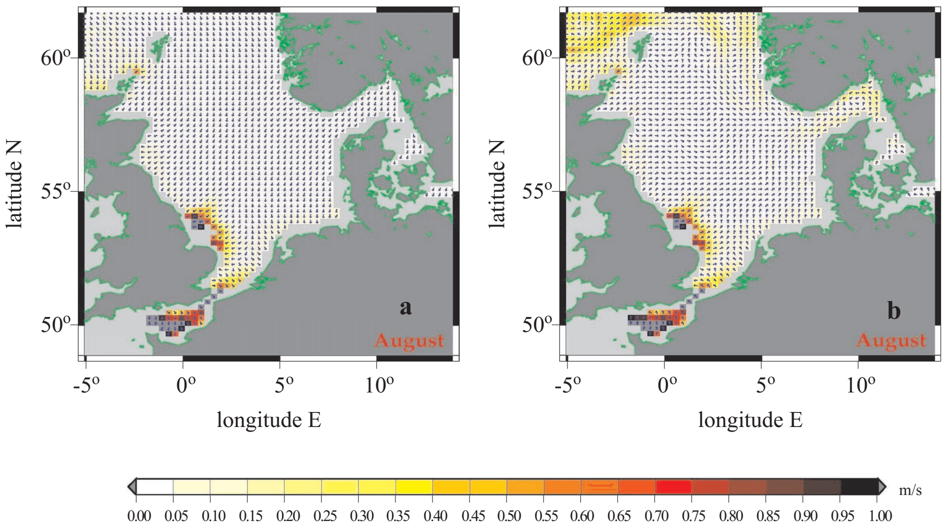

Figure 12. (a) Monthly mean of the Ekman flow at 5 m depth for August 1991 [m s^{-1}], (b) difference of the monthly mean of the total flow and the Ekman part at 5 m depth for August 1991 [cm s^{-1}]

3.3. Relevance of JEBAR

The JEBAR term is a component of the oceanic vorticity balance; it describes how baroclinic pressure gradients force the flow in the case of a non-uniform bottom topography. Pohlmann (2003) analysed the vorticity balance of the North Sea for a certain time period, calculating separately the β-term, the vortex stretching and the JEBAR term. From this study, Figure 13 shows the spatial structure of JEBAR for August 1991:

$$J\left(\chi, \frac{1}{H}\right) = -\frac{f}{H}\,(\underline{v}_g\ \underline{\nabla} H), \quad \text{with} \quad \chi \equiv \frac{g}{\rho_0} \int\limits_{-H}^{0} z\ \rho\ dz\,.$$

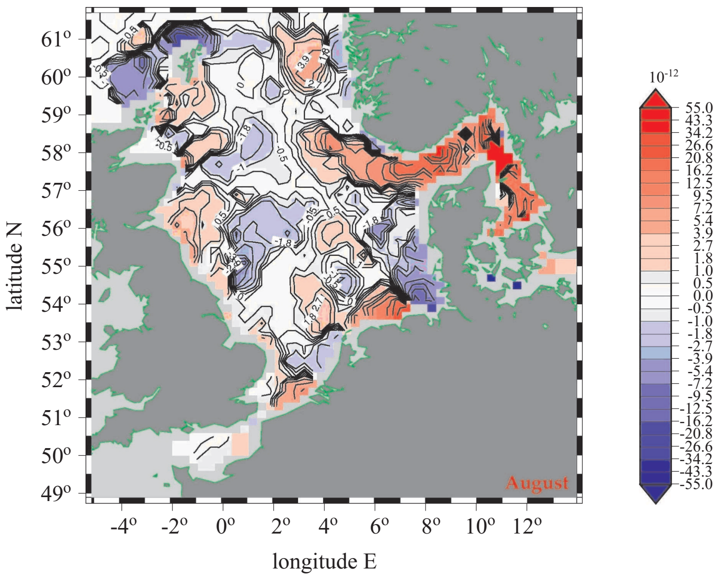

Figure 13. Monthly mean of the JEBAR term for August 1991 [10^{-12} s^{-1}]

Maximum values are seen in the regions where density and topography gradients intersect. Examples are the outer estuaries of the Rivers Rhine and Elbe, the Norwegian Trench and the Fair Isle Passage. During summer the JEBAR gradients, which are directed towards the centre of the North Sea, are enlarged as a result of the joint action of temperature and salinity gradients. Of the remaining terms of the vorticity balance, the temporal derivative and the β-term are smaller than JEBAR by one to two orders of magnitude, whereas the vortex stretching is equally important.

4. Specific phenomena

Here we present some results of research work done at the Institute of Oceanography, University of Hamburg, within the last two decades. They concern storm surges and the budgets of heat and fresh water in the North Sea.

4.1. Storm surges

Storm surges constitute the most serious hazard as far as natural disasters in the North Sea region are concerned, having formed and changed the coastal shape for centuries. In Hamburg more than 300 people died as a result of a storm surge as recently as February 1962, even though the city is 100 km from the sea. Since then, all the dikes along the German North Sea coast have been raised; thanks to this action, the highest storm surge ever recorded (January 1976) caused only minor damage.

An analysis of all historical surges (Hewer 1980) showed that these extreme events fall into two classes:

- 'Static' type: low pressure track Iceland – northern North Sea – Scandinavia; extended, cold low; a long-lasting but not necessarily extreme wind pushes water into the German Bight. The most prominent example: 17 February 1962.
- 'Dynamic' type: low pressure track Subtropical Atlantic – Great Britain – Denmark; small-scale, warm low; a short-lived, rotating extreme wind moves the North Sea water like a centrifuge, raising the sea level along all coasts. The best example: 3 January 1976.

In a numerical investigation both these historical surges were modified (by changing wind amplitudes and phases somewhat, but within what is physically possible) with the aim of achieving more dramatic effects (Hewer 1980). The results are shown in Figures 14 and 15. According to these studies, the maximum sea levels recorded in the inner German Bight up till now could be exceeded by 2.54 m for the static type and 1.70 m for the dynamic type.

4.2. Heat budget

The long-term heat budget of the North Sea has been analysed using decadal simulations of HAMSOM (Pohlmann 2003). First, the influence of wind and atmospheric heat fluxes was studied. Surprisingly, it turned out that the correlation of maximum wind stress and maximum monthly total

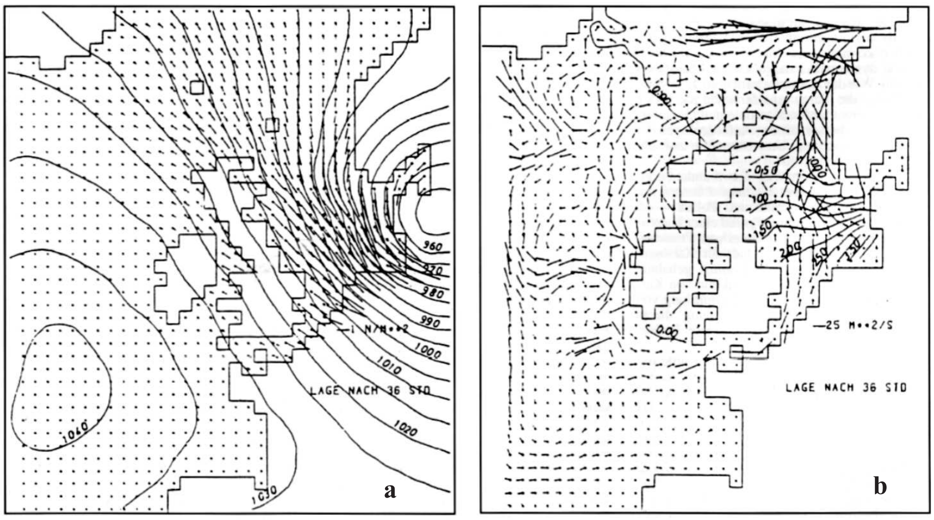

Figure 14. Extreme surge of the static type. Meteorological and oceanographic situation after a 36 h simulation; (a) pressure [HPa] and wind stress [N m^{-2}], (b) water level [m] and transport [m^2 s^{-1}]. From an unpublished thesis in the library of the University of Hamburg

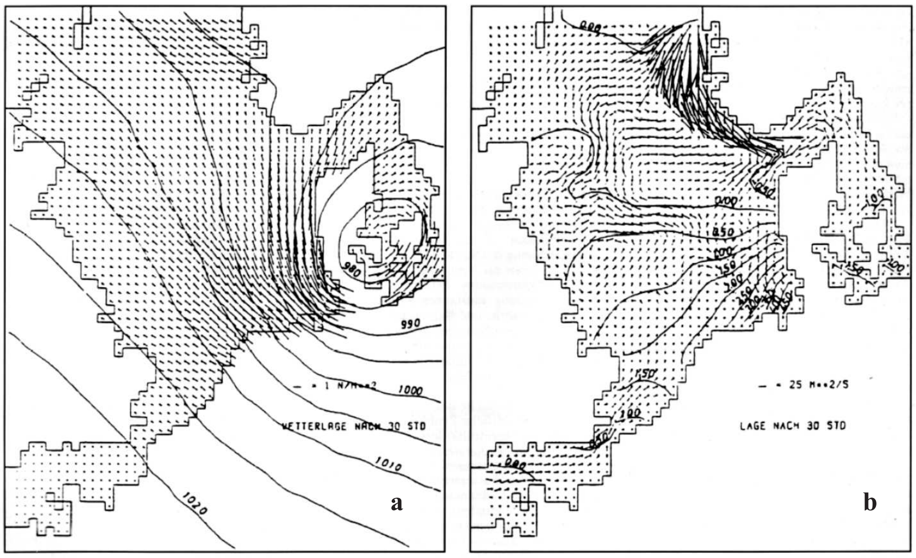

Figure 15. Extreme surge of the dynamic type. Meteorological and oceanographic situation after a 36 h simulation; (a) pressure [HPa] and wind stress [N m^{-2}], (b) water level [m] and transport [m^2 s^{-1}]. From an unpublished thesis in the library of the University of Hamburg

heat content is nearly zero. The logical expectation would be that a stronger wind deepens the upper thermal layer, thereby enlarging the heat content of the water body. This is explained by the negative correlation of the wind stress and the maximum sea surface temperature SST. As a matter of fact, in the North Atlantic system a warm summer is connected with weak winds (and vice versa), which means a damping of interannual fluctuations in the heat content.

Nevertheless, a clear correlation (0.75) exists between the maximum heat content in summer and the minimum SST of the preceding winter. This can be explained as follows. In winter the water column is vertically mixed resulting in an almost homogeneous temperature distribution (equal to SST). During the formation of a thermal upper layer in spring/summer the bottom water is decoupled from ongoing surface processes in broad regions of the North Sea. A real interaction happens again only in the following winter. In this way the winter SST can influence the heat content in the following summer. The conservation of the winter bottom water temperature in the central and northern North Sea is one of the rare hydrographical phenomena with a 'memory' scale of one year. Normally, typical spin-up periods (within these the preceding dynamic state is lost) amount to only a few days in the shallow North Sea.

In the cited paper (Pohlmann 2003) the interannual variability of the North Sea's heat content was also simulated for the years 1982–1998 (Figure 16).

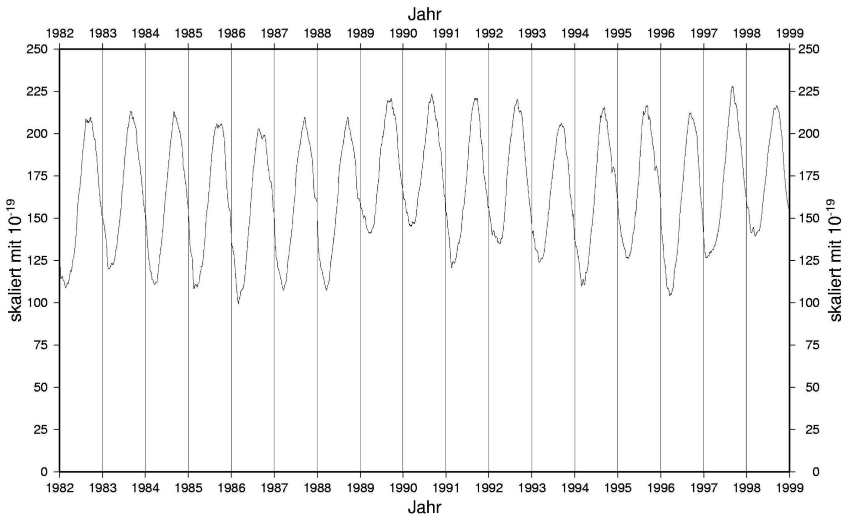

Figure 16. Time series of the total heat content [10^{-19} J] of the North Sea for the period 1 May 1982–31 December 1998. From Pohlmann (2003)

The most striking signal is the system shift between 1988 and 1989. Up till this event, the minimum heat content in winter had been rather constant at 12×10^{20} J; subsequently it was 14×10^{20} J (with a higher inter-annual variability). There are clear indications that this shift initiated a large-scale change within the biological species spectrum of the North Sea (Edwards & Reid 2001). A Fourier analysis of the time series in Figure 16 exhibits periods of 7 to 9 years correlating with modes of the North Atlantic Oscillation NAO (Sündermann et al. 1996). As already mentioned, the high correlations (0.75) between SST and NAO in the central North Sea (Figure 8) suggest that atmospheric heat fluxes play a dominant role in the heat budget of the North Sea.

4.3. Fresh water budget

The mass of water and salt in the North Sea is controlled by the following variable in- and outflows: exchange with the Atlantic Ocean, exchange with the Baltic Sea, and exchange with the atmosphere by precipitation and evaporation. Damm (1997) has calculated a balance of these values based on long-term field records (admittedly with gaps). The result is summarized in Figure 17, which shows the water budget of the North Sea for a climatological year.

The upper diagram (a) depicts the different in- and outflows, the lower one (b) the seasonal run of the fresh water mass accumulated in the North Sea. This reaches its maximum in July/August and is – with a phase lag of 2–3 months – clearly related to the Baltic outflow. The water supply from the Atlantic exceeds the sum of all freshwater sources by two orders of magnitude. This explains the relatively high salinity of North Sea water.

5. The North Sea of tomorrow

The global climate change has, of course, effects on the North Sea region. In this review only some probable changes of the physical system will be discussed. These have serious influences on the marine ecosystem, which exhibits the most visible reactions: shift of species, biodiversity, algal blooms etc. According to the IPCC scenarios and the respective runs of climate models for the north-west European shelf, a rise of the mean temperature by 1–4°K and of the mean sea level by 25–40 cm can be expected. The production and paths of Atlantic low pressure systems will be modified in such a way that, although extreme wind speeds will not necessarily increase, storms will be more frequent. The prevailing wind direction could veer from south-westerly to north-westerly. These changes will affect the general

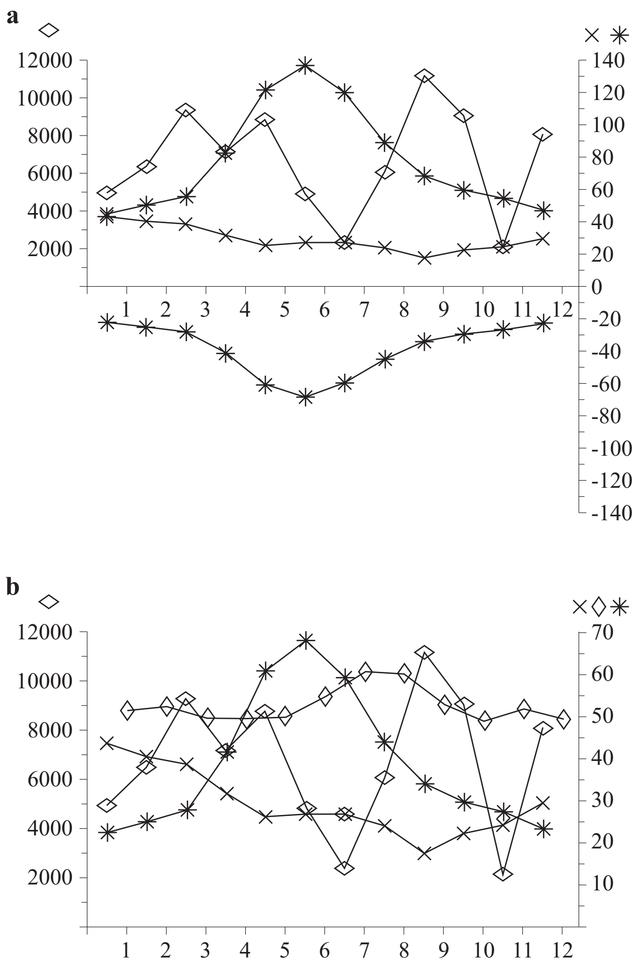

Figure 17. Water budget of the North Sea [10^{12} kg month^{-1}] within one climatological year (month). Crosses – inflow of fresh water from continental discharge, precipitation and evaporation (right-hand scale); rhombuses – inflow of Atlantic water with climatological salinity (left-hand scale); asterisks – a) positive: inflow from the Baltic (salinity 8.7 PSU), negative: outflow into the Baltic (salinity 17.4 PSU), b) net inflow from the Baltic (salinity 0 PSU) (right-hand scale); diamonds – mass of accumulated fresh water (reference salinity 35.1 PSU), (right-hand scale, 10^{13} kg)

circulation and the mean level of the North Sea, as well as storm surges and tides.

5.1. General circulation and mean sea level

From Figure 4 it can be concluded that more frequent winds from the north-west mean less cyclonic circulation, less water exchange with the Atlantic and more stagnation. This change would have negative consequences for the North Sea's ecosystem, which has become adapted to a major cyclonic drift of water masses.

Kauker (1998) investigated the regional effects of global climate change for the '$2 \times CO_2$' scenario. He applied the coupled ECHAM/OPYC model of the Max-Planck-Institute for Meteorology in Hamburg to the North Sea, implementing dynamical downscaling. One important result is depicted in Figure 18.

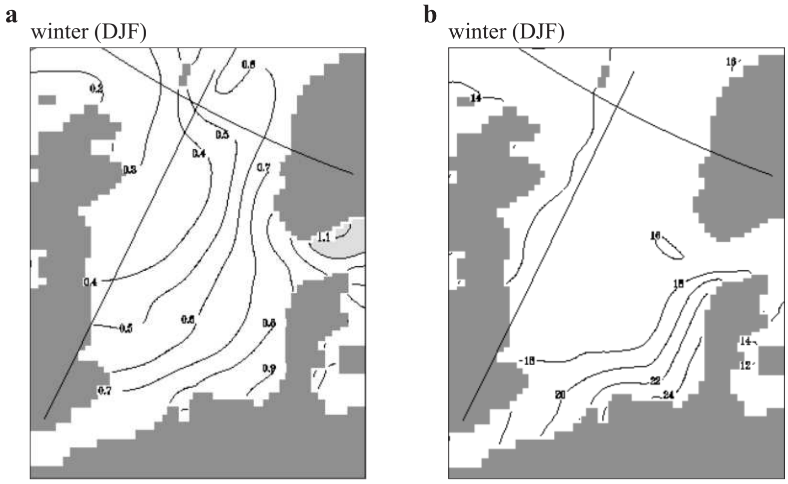

Figure 18. Difference of mean states in winter ('$2 \times CO_2$' scenario – today); (a) sea surface temperature [°K], (b) sea level [cm]

The higher temperature gradient of '$2 \times CO_2$' causes a stronger cyclonic circulation and, as a consequence of the geostrophic balance, a higher mean water level up to 24 cm in the southern North Sea. On top of this, the global isostatic water level rise must be added.

5.2. Storm surges

The regional wind forcing from the '$2 \times CO_2$' scenario has been used by Langenberg et al. (1999) to study storm-related sea level variations along the North Sea coast. The result is summarized for eight locations on the Dutch–German–Danish coast (Figure 19).

The mean storm surge levels (50% percentile) rise significantly along the whole coastal section, but the extremes (90% percentile) do not exceed the statistical noise. The conclusion is that higher surges will be faced but no new extremes.

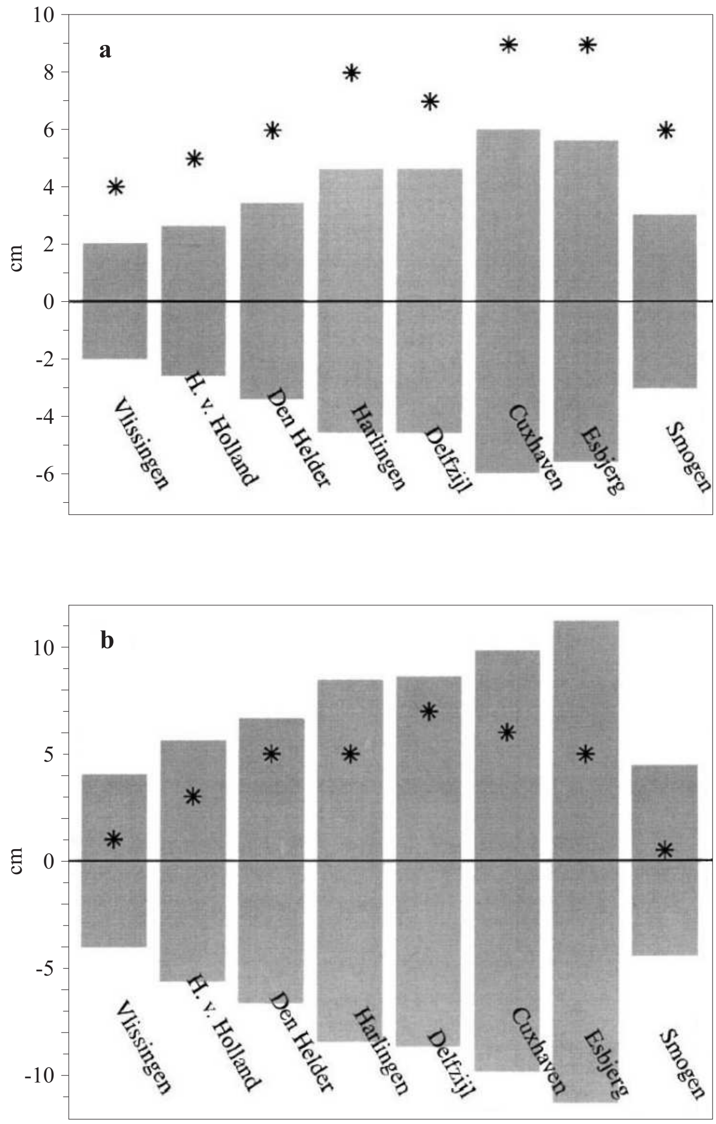

Figure 19. Differences in high water level for the period 1900–1996 ('$2 \times CO_2$' scenario – today, 5-winter-mean; asterisks). The estimated variability (± 2 standard deviations) of all 5-winter-means is added in grey; (a) 50% percentile, (b) 90% percentile. From Langenberg et al. (1999)

5.3. Astronomical tides

Jungclaus & Wagner (1988) have investigated the gradual alteration of the M_2-tide in the North Sea as a consequence of the global rise in mean sea level. They applied a two-dimensional barotropic model to the cases

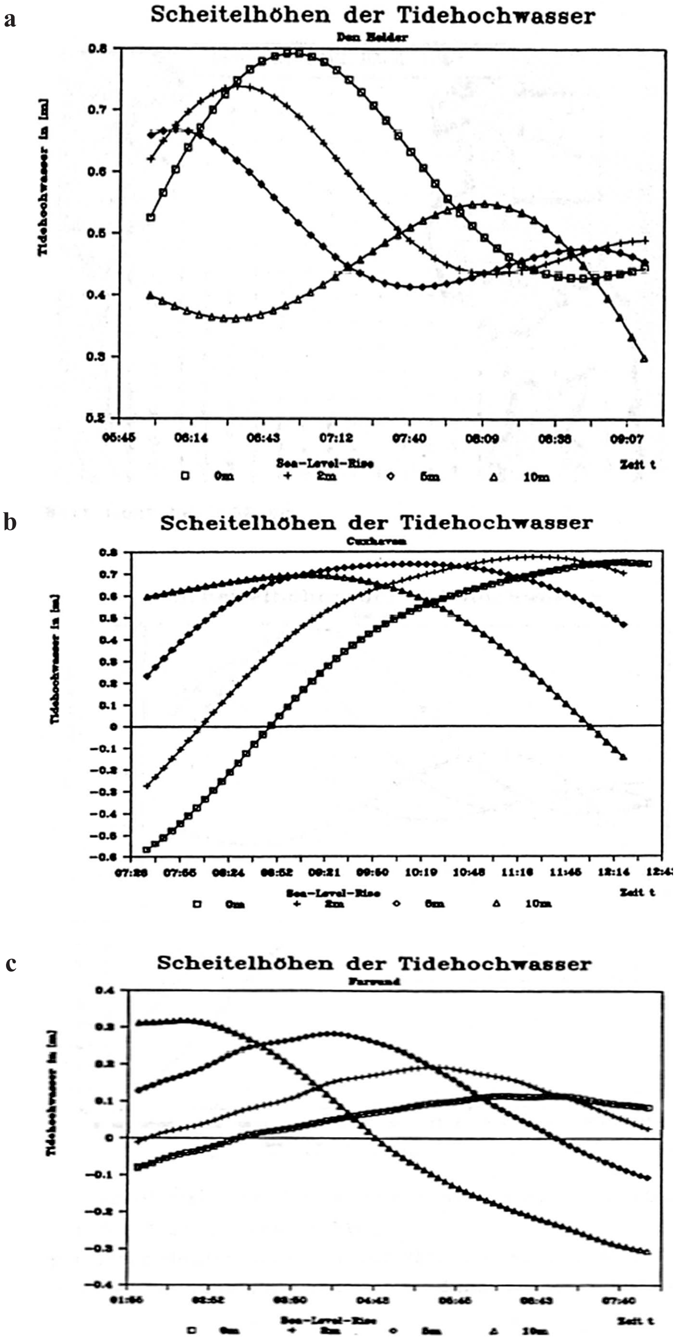

Figure 20. Tidal high waters in the North Sea for different mean sea levels [m]; squares – 0 m (today), diamonds – + 5 m, crosses – + 2 m, triangles – + 10 m; (a) Den Helder (The Netherlands), (b) Cuxhaven (Germany), (c) Farsund (Norway). From an unpublished thesis in the library of the University of Hamburg

of 2, 5 and 10 m rises. The variations are not dramatic, but nevertheless clear in tendency. The central amphidromic point in the southern North Sea (see Figure 2) is gradually shifting (as theoretically expected) towards the north-west. Within the next 100 years this will cause a slight growth of tidal ranges on the German, Danish and Norwegian coasts and a slight decrease in Dutch and British waters (Figure 20).

6. Future research needs

At the International North Sea conferences in Hamburg (1996) and in Wilhelmshaven (2000) 'Grand Challenges' for North Sea research were formulated (Sündermann et al. 2001):

- The interactions between the north-west European shelf and its adjacent oceanic and terrestrial regimes, i.e. with the North Atlantic and the European landmass. This topic has particular relevance to questions on climate change and its effects on the North Sea ecosystem.
- Interactions between the physical and biological subsystems of the north-west European shelf. This topic particularly concerns biodiversity, fisheries and protection of marine habitats, in short, the 'health of the North Sea'.
- Integration of routine field measurements, remote sensing data and model calculations to an operational system for marine now- and forecasting.

These challenges lead, of course, beyond physics and concern all the marine sciences, as well as coastal engineering, socio-economics and politics. For marine physics the following research areas can be highlighted (Sündermann 2003a):

The North Sea as part of the North Atlantic/North European system

- The transfer mechanisms of Atlantic variability to the North Sea have to be analysed and quantified. This concerns both the physical and the biological subsystems, and encompasses time scales from seasons to decades. Of specific interest is the causal chain of global climate change – the reaction of the marine ecosystem to bentho-pelagic coupling and changes in biodiversity.
- A coupled four-dimensional model of the North Atlantic–North Sea–Baltic system has to be developed, which covers the ocean and the shelf scales and resolves sufficiently the transition zone at the

shelf break. The model should realistically simulate the variable transports of saline and fresh water, heat, dissolved and suspended matter between the north-east Atlantic Current and the circulation system of the north-west European shelf. It should form the basis for the interpretation of physical, chemical and biological field data and provide future scenarios of the North Sea state.

Key process complexes

- Key processes include upper layer dynamics, eutrophication, algal blooms, dynamics of pollutants, trophic relations, recruitment, morphodynamics, pelago-benthic coupling, nutrient regeneration and biodiversity. Targeted process-oriented field experiments should be combined with laboratory work (incl. mesocosms) and model investigations.

Coupled models

- The just-started model coupling of atmosphere and ocean for the North Sea/Baltic Sea shelf system should be advanced, verified and made available as a standard tool. This development should not simply combine existing model components but rely on an innovative integrated model for both media.
- A coupled hydrodynamic-morphodynamic model including biological feedback mechanisms has to be developed stretching from the seasonal to the decadal scale.
- The combination of physical, chemical and biological components aiming at a complex ecosystem model of the North Sea has to be continued. The model should simulate scenarios for the reaction potential of the North Sea with respect to natural and anthropogenic disturbances.
- A specific demand exists for the simulation of the oxygen and carbon cycles, biological-ecological key processes and water quality.

Climate change

- Existing approaches for regionalizing climate change in the North Sea/Baltic Sea area must be improved and extended. Of special interest are the effects of long-period variations of the NAO, the wind and wave statistics, the mean sea level and the general circulation. Are storm surges becoming more dangerous? What changes can be expected with respect to the ecosystem and biodiversity?

- A further rising sea level will require new strategies for coastal management. The existing man-made coastal architecture is not adapted to secular morphological changes. Sustainability requires new, flexible solutions in coastal engineering providing living space and safety for future generations as well.
- The water quality of the Baltic Sea depends significantly on the episodic intrusion of oxygen-rich North Sea water through the Danish Straits. Will the frequency and intensity of those events change?

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