3. Climate

Albert Oost
Gerd Becker
Jes Fenger
Jacobus Hofstede
Ralf Weisse

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3.1 Introduction

Since there is little difference within the Wadden Sea area in major climatic conditions (de Jong, 1999), the main focus should be on climate change in Northwest Europe and its effects on the Wadden Sea system. The only exception might be local wind climate, a subject which has - until now - received little attention, but which may be important in understanding future coastal and Wadden Sea development. In this chapter we will apply new insights to consider the present-day situation and look forward into this century to form an idea of the changes that may be expected.

3.2 Climate change

3.2.1 Global changes

A few years ago, the Intergovernmental Panel on Climate Change stated that 'Most of observed warming over the last 50 years is likely due to increases in greenhouse gas concentrations due to human activities' (IPCC, 2001). Since the 19th century, average global atmospheric temperature has risen by some 0.6 ± 0.2 °C. For the future, a global average temperature rise of 1.4-5.8 °C by 2100 is predicted, with, however, large local differences. As a result, changes in the rate of global sea level rise between 9 and 88 cm (mean: 48 cm) are expected for the period 1990-2100. Also, storminess will probably increase outside the tropics and waves may become higher. In the northern hemisphere, precipitation at higher and intermediate latitudes has increased during the 20th century by 0.5-1% per decade, coinciding with a probable increase in the number of extreme rainfall events. In the future it is expected that, at intermediate latitudes, the amount of precipitation will continue to increase and will be accompanied by an increase in extremes (Verbeek, 2003).

3.2.2 Local changes in forcing parameters in the Wadden Sea

Temperature of atmosphere and water

Temperature records over the past 120 years show that during the last two decades the air temperatures at the Bilt (The Netherlands) were on average some 0.7 °C higher than in the first two decades (Wessels *et al.*, 2000). In the short term (*i.e.* from year to year), the temperature in the Wadden Sea region depends mainly on the dominant wind direction, but, in the longer term, mainly on global climate development (Verbeek, 2003). It is therefore expected that up to 2100 the air temperature in the Wadden Sea region will increase by on average 2 °C (range: 1-6 °C) (Wessels *et al.*, 2000; IPCC, 2001; Verbeek, 2003). Sea-water temperature is expected to continue to rise similarly since it is closely correlated with the temperature of the atmosphere (Becker and Pauly, 1996; Wessels *et al.*, 2000). It should, however, be noted that serious cooling in Northwest Europe may occur if the North Atlantic Current starts flowing northward at a slower rate due to its own warming and to an increased freshwater influx from the North Pole (Clark *et al.*, 2002; Dickson *et al.*, 2002). Figure 3.1 shows the long-term development of water temperature in the westernmost part of the Wadden Sea, which is a reflection of the west European climatic variability (van Aken, 2003). An overall increase in water temperature has been apparent since about 1980.

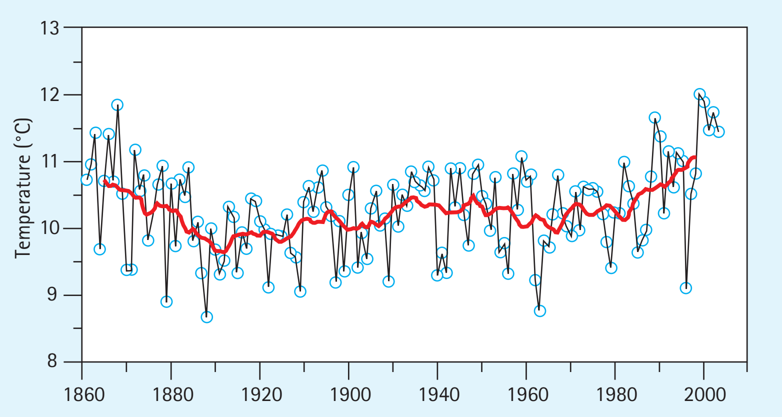

Figure 3.1: Plot of the annual mean sea surface temperature in the Marsdiep tidal inlet from 1861 to 2003. The thick line shows the 10-year running average (Data: Royal Netherlands Institute for Sea Research, Texel, The Netherlands).

Relative sea level

Tide-gauge data indicates a relative sea level rise of a few mm/year during the last century, about half of which is attributed to large-scale subsidence (Töppe, 1993; Dillingh and Heinen, 1994). Also, most stations show a faster rise in Mean High Water (MHW) level than of Mean Low Water (MLW). In The Netherlands, there are no indications of an accelerated rise of MHW, MLW or Mean Sea Level (MSL). In Germany, however, clear accelerations have been observed (Hofstede, 1999a). Töppe (1993) suggests that these changes are the result of long-term cyclic processes rather than of climatic change. The marked differences between the various Danish, German and Dutch measuring stations in the Wadden Sea, however, strongly suggest a dominant role for civil engineering works, such as the dredging of channels (Rakhorst, unpubl.). The rate of relative sea level rise is expected to increase by 10-100 cm/century between 2000 and 2100.

Storminess

Storm activity and the related storm surge and wave conditions in the Wadden Sea show pronounced inter-annual and inter-decadal variability (Figure 3.2). Since *ca.*1960 storm activity in the Northeast Atlantic has increased, but storm activity in the 1990s is comparable to that at the beginning of the last century (WASA, 1998). Alexandersson *et al.* (2000) made an update of the WASA-analysis and showed that in the past few years the storm activity over the Northeast Atlantic and North Sea had decreased. This is in agreement with the decadal fluctuations in storm activity with maxima around 1920, 1950 and 1990 described by Schmidt (2001) and Weisse *et al.*, (2005) for the North Sea. Storm surges and severe wave conditions also show pronounced annual and decadal variations (*e.g.*, Flather *et al.*, 1998; Langenberg *et al.*, 1999; Weisse *et al.*, 2002).

Projections of the expected increase in atmospheric greenhouse gas concentrations indicate a moderate increase in storm activity over the North Sea towards the end of this century. Using different (A2, B2) IPCC SRES emission scenarios (see Houghton *et al.*, 2001), Woth *et al.* (2005) forced a storm surge model for the North Sea with meteorological data sets from various atmosphere models. The results indicate that the largest increase in storm surges is to be expected along the Wadden Sea coast, while changes along the En-

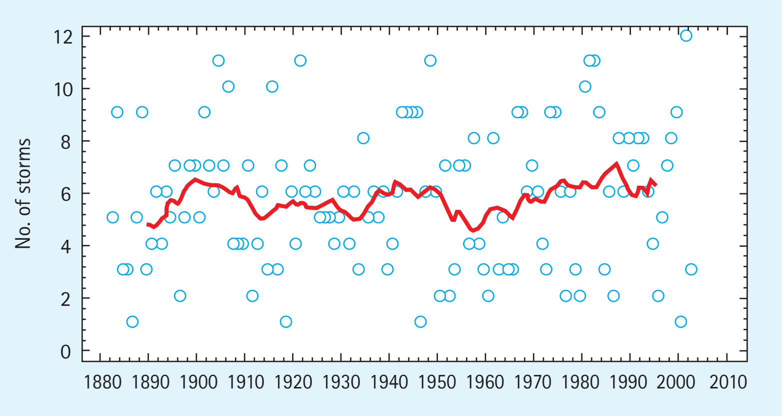

Figure 3.2: Number of times per winter (1 Oct. – 15 March; 1882-2003) that a storm over the North Sea resulted in a water level enhancement >90 cm during high water in Delfzijl, The Netherlands. Red line: 15-year running average (Data: Doekes, RIKZ; Können, 1999).

glish east coast and the Jutland (Denmark) west coast are smaller. This large-scale pattern is consistent with results from earlier studies (*e.g.*, Langenberg *et al.*, 1999; Kaas, 2001).

Precipitation

After the little Ice Age, roughly since 1825, the Wadden Sea climate has become more maritime in character and precipitation has increased, in The Netherlands with 12% between 1900 and 2000 (Können, 1999). For the period 2000-2100 a further increase in precipitation in the winter half year of approx. 12% (range 6-25%) is expected in The Netherlands (Table 3.1). Also for the summer half year the average precipitation is expected to increase by (central estimate) some 2% (range 1-4%). These figures are comparable to those estimated for Germany and Denmark. Extreme precipitation events have gradually increased since the 1970s (Klok, 1998). It is expected that this trend will continue with a 10% increase per degree Celcius (Verbeek, 2003).

Increased precipitation may also lead to increased run-off through rivers to the Wadden Sea. This may result in a further decrease of salinity of the Wadden Sea water (*cf.* Marsdiep tidal inlet; van Aken, 2003).

3.3 Geomorphological and ecological changes

3.3.1 Introduction

The geomorphologic response of the Wadden Sea to the observed and expected changes in forcing factors varies regionally. The same holds for the ecological response, which depends on both the hydraulic and the geomorphological change. Most important are the changes in wave climate and the rate of sea level rise. Locally, changed wind directions, freshwater run-off and precipitation may be important. Below, the combined effects will be presented for the salt marshes, the Wadden Sea proper and the North Sea coast.

3.3.2 Salt marshes

Geomorphology

Higher rates of relative sea level rise (locally enhanced by human-induced subsidence due to extraction of minerals) and higher storm surge frequencies will result in a higher flooding frequency of the salt marshes. This may cause regression of the plant-cover if the vegetation does not trap enough sediment to compensate for, or even outpace, mean high-water rise. Furthermore, erosion will occur when, in the pioneer zone (the border between marshes and tidal flats), sedimentation is insufficient to compensate for sea level rise, causing formation of cliffs.

	Low estimate	Central estimate	High estimate
Mean precipitation in summer	+ 1 %	+ 2 %	+ 4 %
Mean evaporation in summer	+ 4 %	+ 8 %	+ 16 %
Mean precipitation in winter	+ 6 %	+ 12 %	+ 25 %
Annual maximum for 10-day sum of winter precipitation	+ 10 %	+ 20 %	+ 40 %

Table 3.1: Estimated change in precipitation and evaporation in The Netherlands in 2100 based on three scenarios. From: IPCC (2001) and Verbeek (2003).

An accelerated rate of relative sea level rise of up to 60 cm/century will until 2050 not lead to large problems for the mainland salt marshes if these are bordered by brushwood groynes resulting in sedimentation rates which are higher than sea level rise rates (Oost *et al.*, 1998). Problems will occur for the pioneer zone where sedimentation cannot keep up with sea level rise. At 85 cm/century of sea level rise, it is expected that some mainland salt marshes will start to decay locally. On the barrier islands (at least in the Dutch Wadden Sea) salt-marsh sedimentation rates are lower than on the mainland. Here, it is expected that at a sea level rise of 85 cm/century, regression of the salt marsh vegetation will occur after 2025 (*e.g.*, Dijkema, 1997).

Cliff erosion is already occurring on the salt marshes on the islands and locally on the mainland (*e.g.*, Janssen-Stelder, 2000). Wave heights exceeding 20 cm (during storm surges) result in strong erosion of the marshes and of the mudflats in front (Janssen-Stelder in Brinkman *et al.*, 2001). It is therefore expected that cliff erosion in particular will increase when the rate of sea level rise or of storm frequencies increases (Janssen-Stelder, 2000; Brinkman *et al.*, 2001). Local ef-

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fects will be strongly dependent on local measures taken to protect the marshes.

Observations in England showed that a considerable lowering of the intertidal mudflats was caused by an increase in extreme precipitation (K. Dyer, pers. com.). If this applies to the Wadden Sea, this would be another factor causing cliff formation.

Ecology

Increased cliff erosion due to changed storm conditions and accelerated sea level rise will decrease the area of salt marshes, and therefore cause loss of habitat for birds such as Brent geese (Ens in Brinkman *et al.*, 2001). On the other hand, rapid relative sea level rise will slow down the rapid vertical accretion of tidal marshes with respect to sea level, thus resulting in a slower loss of rare salt marsh species (Oost *et al.*, 1998).

3.3.3 The Tidal Area

Geomorphology

The various geomorphological features of the Wadden Sea, such as outer deltas, barrier islands, tidal flats and channels, are in most cases in a dynamic equilibrium with the prevailing current and wave conditions. This is caused by the continuous transport and redistribution of sediment. At a constant rate of sea level rise, a tidal inlet system will import sediment.

The tidal inlet system is expected to compensate for changes in the rate of sea level rise up to a critical limit (see Table 3.2). A possible exception is the Lister Tief inlet which is either eroding or not yet in equilibrium (Wang and van der Weck, 2002). The precise critical limit for the rate of sea level rise that can still be compensated for by sedimentation depends in part. on the size of the tidal basin. The larger the basin the lower the critical limit (Oost *et al.*, 1998; Stive *et al.,* 1998; van Goor *et al.*, 2001; Kragtwijk, 2001). In the Dutch Wadden Sea, assuming the present wave conditions, this critical limit is thought to be 30 cm/century for large tidal basins and 60 cm/century for small tidal basins. Above this limit the tidal flats will 'drown'.

The effects of sea level rise up to 2050 are rather limited. Models predict a relative lowering of the intertidal flats of maximally 20 cm. Locally, subsidence due to extraction of minerals may result in an additional lowering of 15 cm.

Table 3.2: Loss of relative height of tidal flats (in cm) according to various sea level rise (SLR) scenarios (Oost, in prep.).

	Expected loss of relative height (cm) of tidal flats in 2050	
SLR scenario	**Minimum**	**Maximum**
18 cm/century	0	0
60 cm/century	0	11
85 cm/century	5	18

There has been little study of the effects of changes in storminess and wave-action in the back barrier area (Hofstede, 1999b). An increase in storm frequency might result in a lowering of the tidal flats (cf. Jansen-Stelder, 2001), possibly enhanced by the concomitant destruction of seagrass areas and mussel banks. Surprisingly, however, model studies by van Goor (2001) show that the probability of tidal flats drowning will decrease with increasing storminess. This is due to increased sand imports from the North Sea coasts of the barrier islands. If correct, and combined with the above observation by Jansen-Stelder (in Brinkman *et al.*, 2001), this may lead to the development of more pronounced inner deltas, while the more landward parts of tidal flats may become deeper. Another effect of stronger wave-action will probably be increased channel dynamics, especially in the outer deltas and near the inlets.

Ecology

Climate change may change the ecosystems in the Wadden Sea, the adjacent North Sea zone and on the mainland. These changes are expected to be minor until 2050. An increase in temperature may lead to changes in species composition, due to species adapted to a cooler environment retreating northward, whereas new species from southern areas will appear.

Climate change may lead to a range of ecological effects, such as an increase in viral infection (*cf.* Brussaard *et al.*, 1999; Harvell *et al.*, 1999; Mulder and Peperzak, 2003), and a faster growth of bacteria causing faster mineralization of organic matter (Mulder and Peperzak, 2003). The phytoplankton species composition may change as a result of increasing temperatures and changes in the nutrient supply (L. Peperzak, pers. com.; Peeters *et al.*, 1999). Increased occurrence of algal blooms may cause problems because of their toxicity (*e.g.* dinoflagellates) and accompanying oxygen deficiency (*e.g.*, Peperzak, 2003). It is not known whether the growth rate of zooplankton species will increase or decrease due to climate change (Peperzak, 2003). Climatic changes in the north Atlantic area and changes in position of the North Atlantic Current are thought to have already caused shifts in zooplanktic copepod assemblages in European coastal waters (Beaugrand *et al.*, 2002; Frid and Huliselan, 1996).

Lowering of the tidal flats in the Wadden Sea is expected to lead to a decrease in zoobenthic biomass (Beukema, 2002). An increased storminess may lead to a decrease of epibenthic species such as oysters, blue mussels and seagrass. Changes in the discharge of fresh water will probably only have local effects. Milder winters will affect the reproductive success of bivalves and probably lead to reduced stocks (see chapter 8.2 Macrozoobenthos).

The Wadden Sea area is important as a nursery and a migration route for many fish species. Temperature changes may have a significant impact, for example, on growth (Wanink, 1999), also changing the species composition of fish (*cf.* Atrill and Power, 2002).

Bird numbers, and species composition, may change 10% or more until 2050, due, for example, to changes in food availability (decrease in tidal flat benthos) and loss of roosting sites (due to erosion), this being dependent on the rate of loss of intertidal area by drowning. Milder winters, on the other hand, may be beneficial for birds since their energy uptake requirement will be smaller (Moss, 1998; Mulder and Peperzak, 2003).

For the common seal, suitable haul-out places may decrease in number, possibly affecting its reproduction success in the Wadden Sea, and causing the population to decrease. Higher temperatures may cause enhanced occurrence of viral infections (Harvell *et al.,* 1999).

3.3.4 Beaches and dunes

Geomorphology

Under conditions of sea level rise and changing wave climate, the reinforced coasts (dikes, tetrapods) will not change much. Sandy coasts, however, will change.

In the long term, the position of the North Sea sandy coast is determined by the balance between sand supply from the North Sea and transport of sand from the coast into the Wadden Sea. Sand supply from the North Sea is limited (van der Molen and Swart, 2001; van der Molen, 2002). The transport of sand to the Wadden Sea via the inlets and wash-overs may thus result in coastal erosion. Accelerated sea level rise, increasing the sand demand in the back barrier areas, will result in a retreat of the North Sea coasts through faster erosion and faster flooding of the coasts (Mulder, 2002). Locally, however, exceptions occur. At present, the west coast of the island of Sylt is retreating as a result of sea level rise. The eroded sediments drift to the north and to the south and probably partly accumulate on the beaches of Rømø and Amrum. As a result, the coastlines of the latter two islands are stable, or even accreting, despite the observed sea level rise.

It can be calculated that the rate of coastal retreat can increase up to a long-term average of about 8 m/yr, *i.e.* until the critical upper boundary of the rate of sea level rise above which tidal flats start to drown. It is estimated that for a sea level rise scenario of 60 cm/century, the total sand demand and sea level rise may result in a coastal retreat up to 3 times faster than at present, and up to 3.5 times more rapid in the case of a sea level rise of 95 cm/century. Such retreats, however, can and probably will largely be counteracted by sand nourishment of beaches or foreshores, thus preserving the characteristic sandy coast dynamics of the Wadden Sea coasts.

More frequently occurring storm surges tend to make the coast more dissipative, resulting in flat beaches. Calculations indicate that the already quite dissipative character of the Dutch Wadden Sea coast is not very likely to change much.

A higher storm surge frequency and higher water levels will also influence the unprotected parts of barrier islands, either via wash-overs or via flooding of the backbarrier side. For several areas above MHW-level it has been observed that wash-over and spit-formation may help to keep up with sea level rise while retreating in a landward direction (Hofstede, 1999a). An increase in sea level will also result in stronger erosion of the dunes. The exact rates of such erosion are not yet known. If dunes are to protect inhabited areas, more work will be needed to maintain them at higher rates of sea level rise.

Changes in wind- and thus wave climate may result in increased dynamics for the coasts and ebb-tidal deltas. An increase in storm activity has resulted in a retreat and decrease in sand volume of the ebb-tidal delta of the Hörnum inlet (German Wadden Sea) since 1960 (Hofstede, 1999a). This is in contrast with a possible increase in tidal volume in the backbarrier area if sea level rise cannot be fully compensated by sedimentation, resulting in a larger sand volume of the ebb-tidal delta. It is unclear which effect will dominate in the future.

Ecology

On the barrier islands an increase in sea level may lead to higher groundwater tables, resulting in vegetation changes in the lower dune valleys and a possible enhancement of peat growth. Also, salinity gradients may change, resulting locally in a shift in distribution of plant and animal (mainly invertebrates) species. More frequent flooding may also lead to eutrophication and calcification of the soil, leading to a decrease of species having a preference for poor soil conditions such as orchids and lichens (Ketner-Oostra and van der Loo, 1998).

3.4 Conclusions

Climate changes in the Wadden Sea area are mainly related to large-scale (*e.g.* Northwest European) changes in climate. The precise response of the Wadden Sea system, however, depends to a large extent on local conditions and configuration of the tidal basins.

Changing rates of sea level rise, a changing river discharge and changes in the storminess and wave-action may change the geomorphology of the Wadden Sea area. In the Dutch basins and probably also in most of the others too tidal flats are expected to be able to keep up with sea level rise due to faster sedimentation up to a critical limit of sea level rise of 3 mm/yr (for large tidal basins) to 6 mm/yr (for small basins). For salt marshes, this critical limit is at least 8.5 mm/yr, and for the pioneer zone 3-6 mm/yr. Above the critical limit flats and marshes will 'drown'. The increasing sediment demand in the tidal basins will trigger a faster erosion of the sandy North Sea coasts. Combined with the direct effect of a rising water level, it is estimated that the total coastal erosion will increase to 250% of the present level of 6 mm/yr and to 330% at 8.5 mm/yr. This can be compensated for by nourishments.

Effects of changes in temperature, in hydrodynamic regime and in geomorphology on the ecology of the coastal zone are expected to be minor up to 2050, with the exception of the possibility of more frequently occurring toxic algae blooms. Possible effects are a shift in species composition, changed growth rates, a decrease in benthos biomass and of benthos consuming birds (in case of lowering of the tidal flats), and the risk of increased viral infections.

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