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Climate Change

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4.1 Climate

4.1.1 Introduction

There is little difference within the Wadden Sea area in major climatic conditions (de Jong, 1999): for that reason the main focus here is 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 received some attention, but which may be relatively important in understanding future coastal and Wadden Sea development. In this chapter we will discuss new insights to consider the present-day situation and look forward into the coming century to form an idea of the changes that may be expected. The chapter is partially based on Kabat *et al.* (2009a).

4.1.2 Climate change

4.1.2.1 Global changes

In 2007, the Intergovernmental Panel on Climate Change (IPCC) stated in their fourth assessment report (AR4) that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (IPCC, 2007). However, IPCC AR4 (2007) was limited to science published by early 2006. Subsequent research shows increasing rates of: 1) Global greenhouse gas emissions: 3.3%/yr in the 2000s, versus 1.3%/yr in 1990s; 2) Temperature rise, especially in polar regions; 3) Ice melt (Arctic: 40% loss since 1980 and accelerating in 2006-07 (Schubert *et al.*, 2006; Bogataj, 2007; Clark *et al.*, 2008; Csatho *et al.*, 2008, but also see van der Wal *et al.*, 2008 and Nick *et al.*, 2009). Furthermore there is uncertainty concerning the continuity of the Atlantic Meridional Overturning Circulation (AMOC) and the possibility of a massive release to the atmosphere of methane trapped in permafrost and on continental margins (Schubert *et al.*, 2006; Clark *et al.*, 2008). As a result, there is serious doubt whether the IPCC AR4 report did not underestimate some of the effects (a.o.: Schubert *et al.*, 2006; Rahmstorf *et al.*, 2007).

The IPCC AR4 results on global climate change have been converted towards local climate scenarios (for instance KNMI'06; Van den Hurk *et al.*, 2006), These local scenarios involve local circulation patterns for western Europe because the wind direction strongly determines the weather and climatological characteristics (Lenderink *et al.*, 2007; Van Oldenborgh and Van Ulden, 2003). The Royal Netherlands Meteorological Institute (KNMI) applies four scenarios of climate change (Table 1) composed of a moderate (G) and high (W) temperature increase and a changing (+) and non-changing circulation pattern. Next to that, two scenarios have been constructed for sea level rise. On behalf of the Delta Committee maximum scenarios for sea-level rise have been added (Vellinga *et al.*, 2008). To that end, the scenario for wind climate and storm-surge levels have also been re-examined. The scenarios allow for regional differentiation. For the period until 2050, scenarios are relatively accurate as they are governed by the greenhouse gas releases of today (Lowe *et al.*, 2009). However, for the period thereafter, the uncertainties are larger because the climate will depend on the emissions in the years to come (IPCC, 2007), and from poorly understood climate feedback mechanisms such as the relation between global warming and the sudden release of methane from the oceans and permafrost areas on land (Friedlingstein *et al.*, 2006). Uncertainties for temperature changes are much smaller than for precipitation, wind and sea-level rise (Kabat *et al.*, 2009a).

4.1.2.2 Temperature

Since the 19th Century, average global atmospheric temperature has risen by some 0.7+/- 0.2°C The increase in air temperatures in Northwestern Europe is faster than the world average increase (Figure 4.1.1). This is due to the increase in the number of winds from the west in late winter to early spring and the increase in radiation in spring and summer (Van Oldenborgh *et al.*, 2009).

The yearly average air temperature in The Netherlands (De Bilt) has risen by some 1.2°C in the course of the 20th Century. The higher mean temperatures coincided with a decrease in the number of days with a minimum temperature less than 0°C and an increase in days with a maximum temperature higher than 20°C (Sluijter, 2008).

It is to be expected that temperatures will rise. Climate models predict an increase for global mean air temperature of 1°C up to 6°C for the year 2100 relative to 1990 (IPCC, 2007). Dutch predictions indicate an average rise of summer temperatures with some 0.9-2.8°C by 2050 and 1.7-5.6°C by 2100, with, however, large local differences. At the same time the number of days with maximum temperature above 20°C, 25°C and 30°C will rise so that the coast will have as many warm days as at present does the inland (van den Hurk *et al.*, 2006). Extreme temperatures will increase stronger than average temperatures (Sterl *et al.*, 2008b) leading to maximum temperatures well above 40°C at the end of 2100 (Sterl

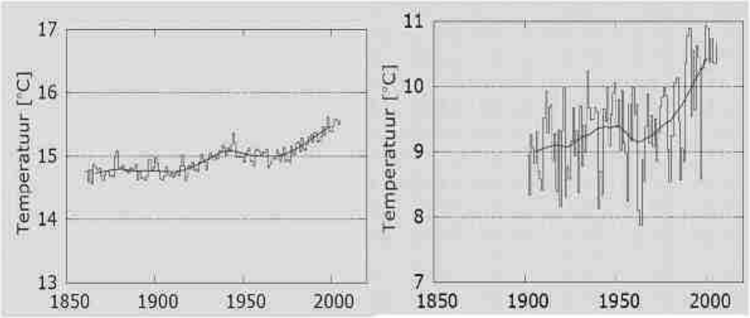

Figure 4.1.1: Difference between global temperature (left) and local temperature (Source: De Bilt, Kabat *et al.*, 2009a).

et al., 2008a). According to the Dutch scenarios, the average winter temperature will also increase by between 0.9-2.3°C by 2050 and 1.8-4.6°C by 2100. The number of days with ice will decrease, especially if the wind will come more from the west. Similarly, the German GKSS Research Station projects increasing temperatures for Northern Germany. Results are presented in the internet (www.norddeutscher-klimaatlas.de). Until the middle of the century, yearly mean temperatures may rise between 1.2-2.2°C with a "best-guess" of 1.8°C. For the end of the century, temperatures are projected to be between 2.0-4.9°C higher (mean 2.9°C). For the same projection period, the number of days with frost might decrease by up to 45 days per year. As already stated before, days with ice cover in the Wadden Sea would become very rare.

Temperature of the seawater

There is a strong correlation between the temperature of the North Sea and air temperatures in western Europe, which influence each other depending on the wind direction. Therefore, on a yearly basis, the temperature in the Wadden Sea region depends mainly on the dominant wind direction, but, in the long-run, mainly on global climate development (Verbeek, 2003). Because North Sea water is mainly derived from the warm North Atlantic current it increases the air temperature above land by some 1.5°C; an effect which is stronger in winter than in summer (Wessels *et al.*, 1999). Observations of the Sea Surface Temperature (SST) from the western Wadden Sea (Marsdiep Inlet) show a cooling trend in the late 19th Century, followed by a steady warming since ~1980 of 1.5°C (van Aken, 2008a), consistent with the trends in the North Sea area. Ongoing research and analyses shows that the year-to-year variations in SST as well as the long-term trends correlate well with changing atmospheric circulation and with changes in cloudiness (H. van Aken, pers. comm.).

Sea-water temperature is expected to continue to rise since it is closely correlated with the tem-

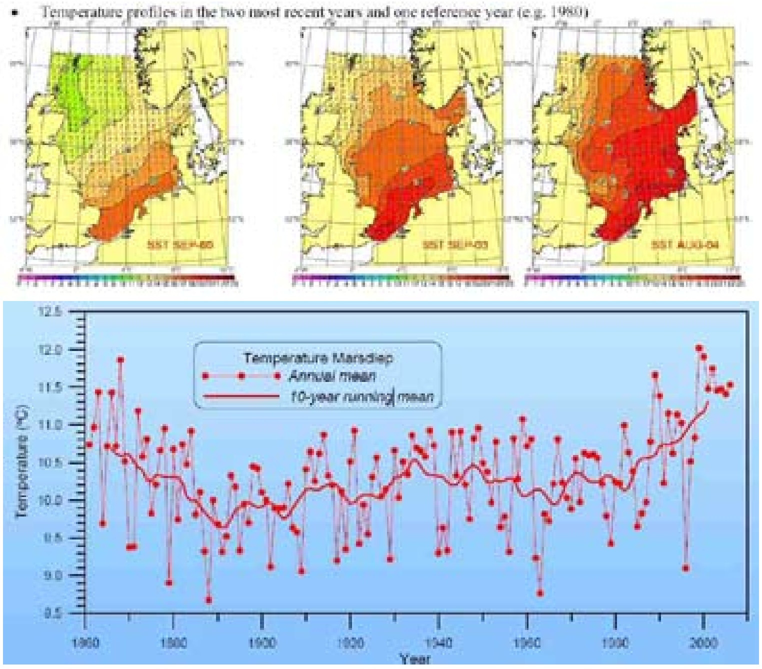

Figure 4.1.2: Trends in the sea-surface temperature of the North Sea waters in September 2003 and August 2004 as compared to reference of September 1980 (source: Hadley Centre, 2009) and the water temperature of Marsdiep Inlet (van Aken, 2008a) The development of the water temperature is a reflection of the west European climatic variability (van Aken, 2003). An overall increase in water temperature has been apparent since ca. 1980. (Courtesy Kabat *et al.*, 2009a).

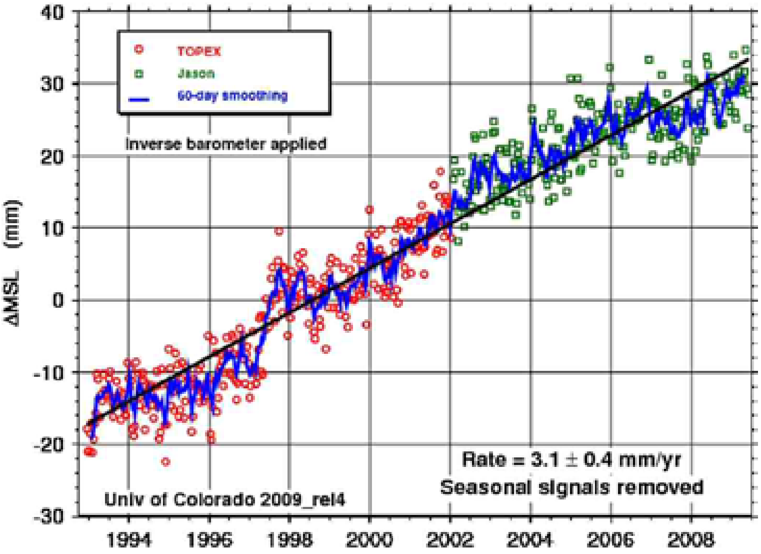

Figure 4.3: Global mean sea level based on the TOPEX-Jason satellite data after correction for seasonal effects and inverted barometer effects (source: http://sealevel.colorado.edu/).

perature of the atmosphere (Figure 4.1.2; Becker and Pauly, 1996; Wessels *et al.*, 1999). This would result in an increase in the longer run of 2-5°C in yearly average temperatures (Kabat *et al.*, 2009a). It should, however, be noted that a weakening of the North Atlantic Current due to its own warming and an increased freshwater influx from the North Pole could have a cooling effect on northwest Europe (Dickson *et al.*, 2002; Clark *et al.*, 2002, 2008). Nevertheless, most climate models simulating a decrease in North Atlantic Current strength with increasing atmospheric greenhouse gas concentrations still show a warming over Europe, implying that greenhouse warming is overwhelming the cooling effect of weakened warm ocean currents (Gregory *et al.*, 2005).

4.1.2.3 Sea levels, wind and storm surges

Average global tide-gauge records show a relative sea-level rise of ca. 1.8 mm/yr over the past century. This is more than could be expected on the basis of a 1 mm/yr contribution from the melting of global land ice reservoirs (Mitrovica *et al.*, 2006), and a 0.4 mm/yr contribution from thermal expansion of the world ocean to absolute sea-level rise (Antonov *et al.*, 2005). Correcting the tide-gauge records for the vertical land motion with GPS techniques reduced the estimated global average sea-level rise to 1.3 mm/yr (Wöppelmann *et al.*, 2007). Berge-Nguyen *et al.* (2008) concluded, on the basis of a combination of thermosteric sea-level data based on temperatures in the top 700 meters of the ocean, tide gauge, satellite altimetry, and ocean reanalysis data, that sea level rose over the period 1950-2003 by some 1.5 mm/yr. It thus seems likely that absolute sea-level rise over the past century has mainly been a function of climate change. Over the period 1992-2009, satellite data are available covering the global oceanic sea-level rise. After correction for seasons and inverted barometer effects, an average global sea-level rise is observed of 3.1 ±0.4 mm/yr over the period 1992-2009 (http://sealevel.colorado.edu/current/sl_ib_ns_global.jpg). This deviation from the long-term average has been explained by increases in thermosteric effects (contribution 1.2, vs. 0.4 mm/yr) and a faster melting of Greenland (0.4 vs. 0.2 mm/yr), Antartica (0.5 vs. 0.3 mm/yr) and glaciers (0.9 vs. 0.4 mm/yr) for the period 1993-2005 (Nerem, 2005).

Combining data from reliable stations over the past 50-100 years from the Dutch and German Wadden Sea indicates a mean average sea-level rise varying from station to station between values of 1-2 mm/yr and average high-water rise between 2-2.5 mm/yr (Hofstede, 2005; 2007; Dillingh, 2008; Von Storch *et al.*, 2008; Kabat *et al.*, 2009a). Local sea-level rise in the Wadden area is attributed to global trends, and partly to local and regional effects such as atmospheric circulation, oceanic currents, subsidence due to isostasy (0.3 mm/yr) and gas mining and water-management works (the latter especially after 1950 [Kooi *et al.*, 1998; CPSL, 2005; Katsman *et al.*, 2008a]). The increased global rate of sea-level rise of 4.1 mm/yr, as observed from the satellite data, has not yet been observed along the tidal gauges of the Wadden Sea coast (Figure 4.1.4; Hofstede, 2007; Dillingh, 2008). It should be noted, however, that the tide gauges represent a rather restricted part of the oceans (Nerem *et al.*, 2006). Furthermore on a decadal timescale, the length scales of sea level change are quite

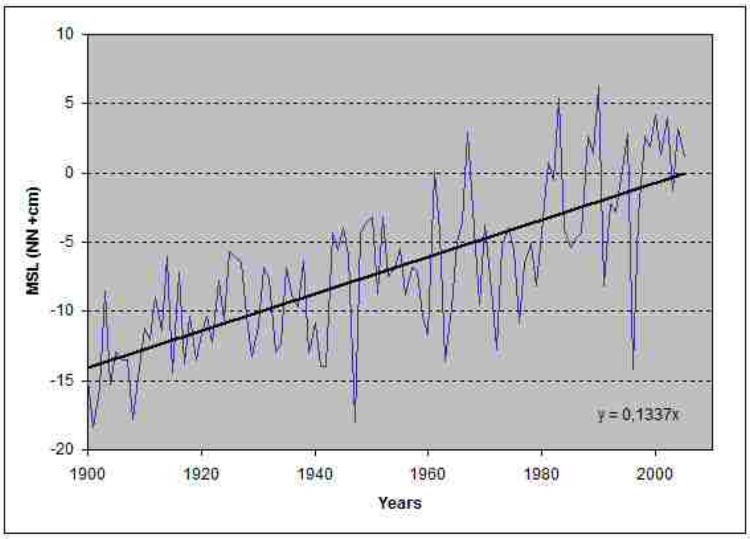

Figure 4.1.4: Mean sea-level rise in the Wadden Sea from 1900-2005, averaged over 10 long-term tidal gauge stations (Den Helder, Harlingen, Terschelling-West, Delfzijl, Norderney, Cuxhaven, Büsum, Husum, Wittdün, List; adapted from Hofstede (2007) and corrected for varying base levels).

large (up to 1,000 km), and as a result many tide gauges in a region are highly correlated with each other (Holgate, 2007). From observations of selected stations, it seems that local sea-level rise may vary on a decadal scale and in such a period reach annual velocities of +/-15 mm/yr (Holgate, 2007). Thus, if it is assumed that the satellite data are correct, an acceleration of sea-level rise in the Wadden Sea might yet occur.

IPCC AR4 estimates of global sea-level rise by 2100 are 18-59 cm (Meehl *et al.*, 2007). However, these estimates have been challenged on the basis that large ice sheets appear to be changing much more rapidly (Nerem, 2005; Ekström *et al.*, 2006; Velicogna and Wahr, 2006) than models predict (Overpeck *et al.*, 2006); a reality recognized by the IPCC summary report (IPCC, 2007). Locally large differences in sea-level height can occur under the influence of currents in the atmosphere and oceans (IPCC, 2007; Von Storch and Woth, 2008), and by changes in the gravity field and redistribution of mass (a.o. land ice) (Mitrovica *et al.*, 2001; Katsman *et al.*, 2008b).

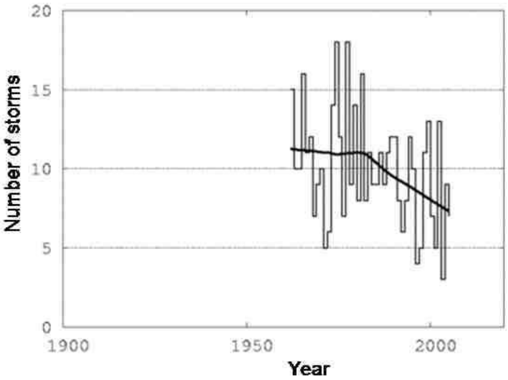

Figure 4.1.5: Annual number of storms in The Netherlands (>6 Bft inland and >7 Bft at the coast; Source: KNMI, Kabat *et al.*, 2009a).

Wind direction and force, air pressures, sea-level height and tidal amplitude determine the height of the water levels and thus of storm surges. In addition, waves amplify the effect of storm surges, especially on the North Sea coasts where long waves can reach the dunes if the beach plain is not too broad. In the back-barrier area, mainly locally generated wind waves are important, possibly with the exception of the inlet channels. Storm activity and the related storm surge and wave conditions in the Wadden Sea show pronounced inter-annual and inter-decadal variability, with maxima around 1920, 1950 and 1990 (Flather *et al.*, 1998; Langenberg *et al.*, 1999; Schmidt, 2001; Weisse *et al.*, 2002, 2004; Matulla *et al.*, 2007). In the past decennia the atmospheric flow above the northern part of the Altantic Ocean which determines European storms was on average stronger than in the period before and followed a more northerly path. It is not clear if this should be attributed to the enhanced greenhouse effect (KNMI, 2006). In The Netherlands the average wind force has decreased slightly (Sluijter, 2008; WSH, 2009). An analysis of the Dutch storm climate over the period 1962-2002 showed a marked decrease of strong wind (7 Bft along the coast), with 5-10%/10 yrs (Smits *et al.*, 2005). Trends in stronger storms (10 Bft) cannot be determined significantly (Sluijter, 2008; Smits *et al.*, 2005).

For the Dutch coastal area the wind coming from the NNW is quite important for set-up of the water levels due to the long fetch over the North Sea. Although the number of western winds increases in the late winter and early spring, the number of N to NW winds is not changing (Figure 4.1.5; Van Oldenborgh *et al.*, 2009). An analysis of the number of storms with a set-up of more than

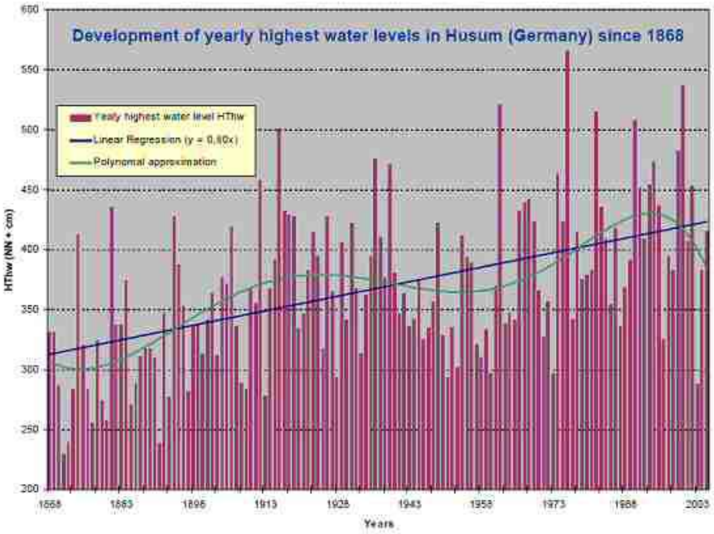

Figure 4.1.6: Development of the highest annual water levels at Husum, Germany since 1868 (adapted from Hofstede, 2007).

0.9 m does thus not show a trend. In contrast to this are observations in the Schleswig-Holstein sector of the Wadden Sea that show a strong trend of up to 8 mm per year since 1868 in the yearly highest water levels (Figure 4.6). Apart from artificial causes (building of a dam that closed the Husumer Bight to the north in the 1920s), this may be the result of a shift in storm wind directions. The polynomial approximation in Figure 4.1.6 shows a significant decrease since the mid 1990s.

Regional scenarios project an absolute mean sea-level rise of 20-35 cm in 2050, and 40-80 cm in 2100 (Van den Hurk *et al.*, 2006; Katsman *et al.*, 2008b). In order to guarantee the safety of The Netherlands in the long run, the Dutch Delta Committee has been asked to predict plausible upper limit scenarios. Based on the findings of the IPCC AR4 report (IPCC, 2007), the scenarios of KNMI (Van den Hurk *et al.*, 2006) and new insights in ice sheet dynamics (Katsman *et al.*, 2008b) the scenarios show good agreement with the KNMI scenarios until 2050, but an increase in absolute sea-level rise along the Wadden coast of 120 cm by 2100 (Figure 4.1.7; Vellinga *et al.*, 2008) with large uncertainties (Katsman *et al.*, 2008b, Kabat *et al.*, 2009a&b).

Climate scenarios suggest that the average wind force will hardly increase until 2100 (KNMI, 2006; Van den Hurk *et al.*, 2006; Sterl *et al.*, 2008c). Wind direction also determines the number of days with high water levels (Von Storch and Woth, 2008). Some climate models show a continuing increase in the number of western winds, but not of northern winds. However changes are small compared to the natural variability (Sterl *et al.*, 2008c). It should, however, be noted that the uncertainties in the future storm climate predictions remain large, especially due to the uncertainties in the emission scenarios which influence atmospheric pressure patterns and wind climate (Von Storch and Woth, 2008; Kabat *et al.*, 2009a).

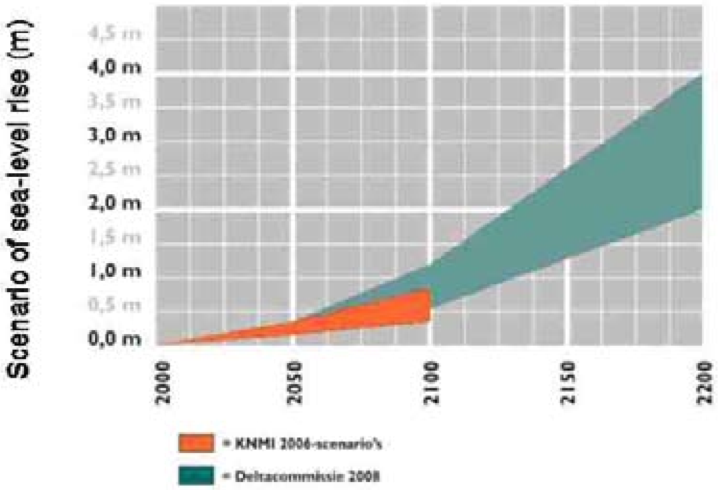

Figure 4.1.7: Scenarios for absolute sea-level rise of KNMI (2006) and Vellinga (2008) (Sources: Delta Committee, 2008; Kabat *et al.*, 2009a).

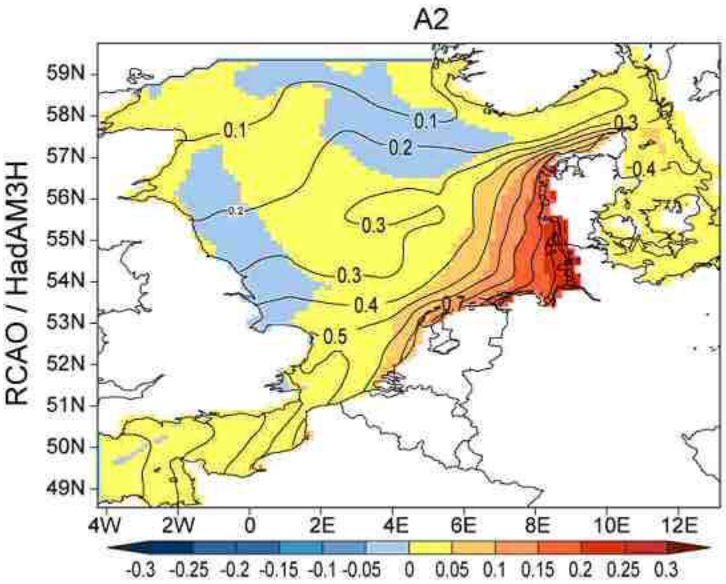

Figure 4.1.8: Simulated difference in the annual 99.5 percentile values of water level increase (in m), between 2071-2100 and 1961-1990, at IPCC scenario A2 (Weisse *et al.*, 2009). Contours show the values for the period 1961-1990.

Important details of changes in wind climate in the Wadden Sea area and its influence on wave climate and surge levels are as yet unclear (Kabat *et al.*, 2009a). As an example, model studies indicate that in the German Bight storm surge, water levels may increase strongly along the coast and up to about 0.3 m in the German sector of the Wadden Sea (Weisse *et al.*, 2009; Figure 4.8). Another example is that the 99 percentile of the significant wave height in models is underestimated (Sterl *et al.*, 2008c).

To estimate the possible extreme changes in water levels at the coast, a first order approach is to add the mean sea-level rise and the storm surge levels and to discard non-linear effects (Vellinga *et al.*, 2008). Applying this method, Woth *et al.* (2006) projected storm surge water levels (including mean sea-level rise) in the inner German Bight to be about 0.6 to 0.7 m higher at the end of this century compared to the end of the last century.

Precipitation and evaporation

After the little Ice Age, roughly since 1825, the Wadden Sea climate has become more maritime in character. Thus, in The Netherlands the annual precipitation increased since 1906 by 18% with marked seasonal differences (autumn and winter by 26%, spring 21%, summer 3% – KNMI, 2006) These figures are comparable to those estimated for Germany and Denmark. Extreme precipitation events have gradually increased since the 1970s (Klok, 1998; Sluijter, 2008). In general, coastal precipitation increases faster than further inland and is enhanced by higher sea-water temperatures. In The Netherlands the intensity of precipitation in the coastal zone increases by some 15% for every degree of water-temperature increase, against 5% for inland locations (Lenderink and Beersma, 2008; Lenderink *et al.* (2009). Especially in autumn, precipitation in the Wadden Sea area is higher than inland, whereas in spring inland precipitation is higher (Heijboer and Nellestijn, 2002).

In scenarios without changes in wind circulation patterns, the precipitation in The Netherlands is thought to increase by 3%/1°C global temperature increase, both in the summer and winter half year. Scenarios with a change in circulation pattern expect an extra increase in precipitation during winter (7%/1°C) and a decrease in summer (-10%/1°C), especially due to a reduction in the number of rainy days (KNMI, 2006). As noticed above, coastal precipitation patterns might differ somewhat from the inland averages. Increased precipitation may also lead to increased run-off through rivers to the Wadden Sea, leading to a further decrease of salinity of the Wadden Sea water (cf. Marsdiep tidal inlet; van Aken, 2003). On the other hand, a precipitation deficit along the Rhine might influence the water discharges in the summer season strongly. For Northern Germany, the GKSS Research Station (www.norddeutscher-klimaatlas.de) projects a mean increase in precipitation between 1 and 13% (8-102 mm). The increase mainly occurs in the winter season (16 to 58%), whereas the summer will probable become dryer.

Part of the precipitation is evaporated (Kruijt *et al.*, 2008). Based on a model, the evaporation for a well-watered meadow has been calculated for two stations along the Wadden Sea (Eelde and De Kooy; Heijboer and Nellestijn, 2002). A clear increase in the evaporation can be observed since the 1980s (Figure 4.1.9).

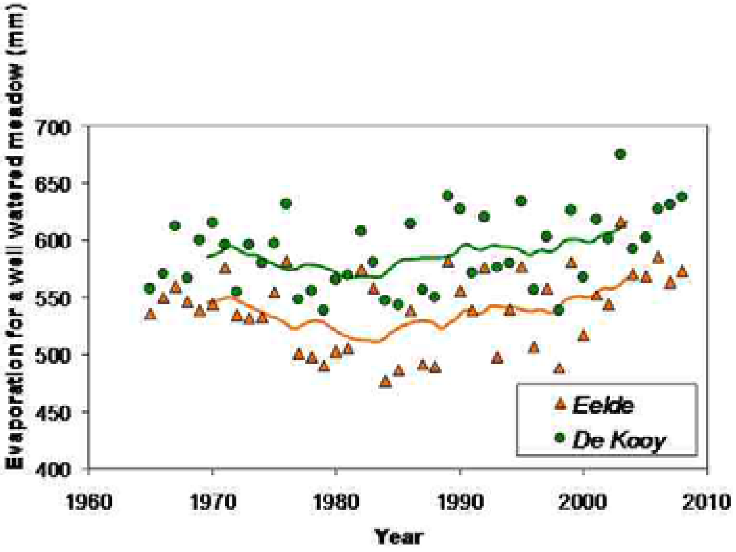

Figure 4.1.9: Evaporation for a well-watered meadow for the Wadden Sea region (Data: KNMI; Kabat *et al.*, 2009a). The line is the 10-year average.

The difference between precipitation and modelled evaporation for a well-watered meadow is the potential precipitation deficit (Beersma *et al.*, 2004). It can be used as a drought indicator but is not the absolute measure for droughts. The available data indicate no trend for long-term maximum precipitation deficit (Figure 4.1.10). The precipitation deficit along the coast is larger than the inland average (Kabat *et al.*, 2009a).

For nature management and agriculture, the precipitation deficit in the summer half year (starting 1 April) is most important. The KNMI 2006 scenarios indicate that the precipitation deficits during the summer half year will increase and that extreme years will occur more frequently than nowadays (Table 4.1.1: KNMI)

4.1.3 Possible consequences

4.1.3.1 Water and sediments

With increasing water temperature, the kinematic viscosity of water decreases. As a result, the mobility potential of non-cohesive sediments decreases, whereas the particle settling velocities increase (Krogel and Flemming 1998). The effect of an increase in water temperatures on settling and resuspension rates of sediment may lead to a shift in the timing of sediment redistribution and of stabilization, which may have consequences for the pelagic (via effects on turbidity) and benthic (via effects on habitats) biomass and production (4.3.1 of Philippart and Epping, 2009).

The runoff of fresh water has increased considerably, leading locally (for instance Marsdiep

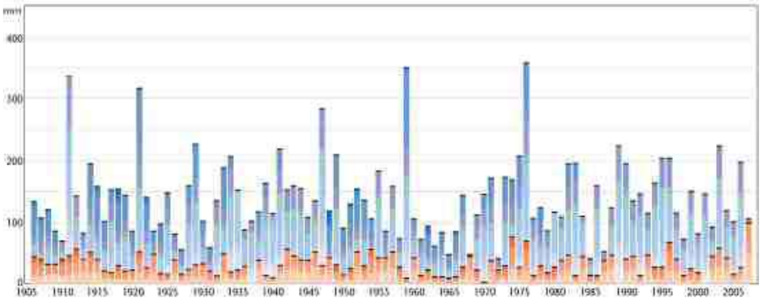

Figure 4.1.10: Maximum potential precipitation deficit in April-September (blue) and March-April (red) from 1906 to 2007 (Source: Lenderink and Beersma, 2008).

	1906-2000	G	G+	W	W+
Average maximum precipitation deficit (mm)	144	151	179	158	220
Repetition time for a maximum precipitation deficit as in 2003 (yrs)	9.7	7.9	4.1	6.5	2.0

Table 4.1.11: Average maximum precipitation deficit in the summer half year (starting 1 April) in 2050 for four different climate scenarios (source KNMI).

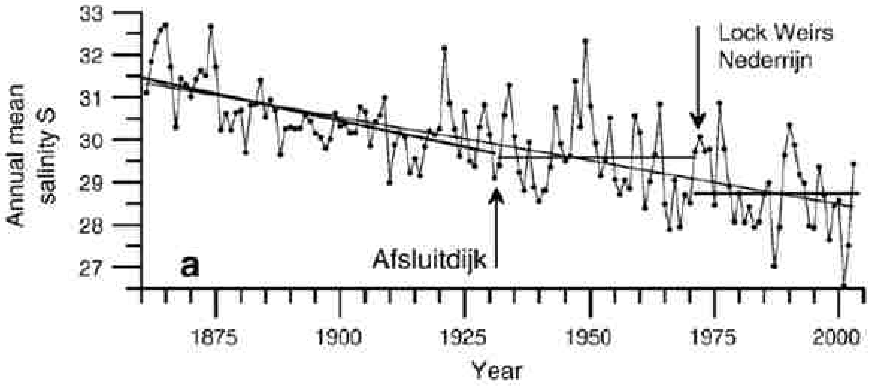

Figure 4.1.11: Salinity in Marsdiep Inlet (van Aken, 2008b).

Inlet, Figure 4.1.11) to lower salinities. In itself such lower salinities are not the major problem, since many organisms can cope well with slightly brackish conditions. However, problems are caused by pulses of almost completely fresh water during several days during extreme run-off from the rivers. If such pulses are not avoided it can, at least locally, lead to a decrease in the number of species (Kabat *et al.*, 2009a).

In the study on behalf of the Delta Committee it was found that higher sea-water levels will cause considerable problems to the fresh water management along low lying areas and rivers. The salt water intrusion hinders the discharge of surplus fresh waters, but will also hinder fresh water intake from rivers (for drinking water or agriculture) where saline waters enter the river mouths further. Also, it was realized that the higher sea levels also resulted in higher river levels, making extensive dyke re-enforcements necessary (Deltacommissie, 2008).

The higher precipitation deficits may pose problems for the water availability, especially on the barrier islands. In the long run this cannot be compensated for by pumping larger amounts of ground waters, which will also lead to deficits for nature (Witte *et al.*, 2008). Locally this may lead to dryer dune valleys with more drought resistant plant species. In The Netherlands, the barrier islands have decided to become autonomous for their drinking water demands without relying on extra pumping. A number of measures have been proposed for each island, such as water storage basins, desalination, etc. (Kok, pers. inf.).

Sediment is needed in the back barrier inter- and supra-tidal area to compensate sea-level rise. The major part of the sediment is sand derived from the North Sea coast and through internal sediment redistribution from the deeper channels towards the wadden and salt marshes (Hofstede, 2002). A minor part is finer material which is derived from the Flemish banks and, to a lesser extent, rivers. Historical and model studies suggest that there is an upper limit to the volume of sand which becomes available to the back barrier areas (van Goor, 2001; Van Goor *et al.*,2001, 2004; Hoeksema *et al.*, 2004; Min. EZ, 2006). Above this limit the system cannot keep up with sea-level rise and tidal shoals will drown gradually (CPSL, 2001). The limit for the rate of sea-level rise which still can be compensated by sedimentation is in debate, but thought to be lower for large tidal basins than for small tidal basins (Hofstede, 2002; Hoeksema *et al.*, 2004; Min. EZ, 2006). Long-term beach erosion may increase due to accelerated sea-level rise (SLR) and may lead to landward retreat or even deterioration of barrier chains such as the Wadden Sea islands (Fitzgerald *et al.*, 2008). Sediment transport from the coastal zone increases with increasing wind driven transport (van Goor, 2001). Changes in wind direction or force might therefore lead to changes in sediment availability. It should be realized that, given the height distribution of the tidal flats and the projected acceleration for 2050 and 2100 the loss of intertidal shoals will most likely be relatively small. Extensive tidal flats will most likely still be present in 2100.

On the barrier islands, at many places natural sedimentation on the island is hindered by dykes, artificial dune rows or other human intervention like placing sand fences on the beach. In general this leads to lower sedimentation rates in dunes, wash-overs and tidal marshes, making the back-barrier parts of the islands more vulnerable to accelerated sea-level rise. It is thought that the sand eroded from the North Sea coast is in general transported into the back-barrier area. However, in recent research it was found that a fair part of the sand is deposited in the first dune rows (Arens, 2008), showing the potential for island-ward sediment transport. Furthermore the lack of natural dynamics enhances succession strongly and rare species characteristic of pioneer conditions become rarer or disappear and habitats become smaller (Petersen and Lammerts, 2005; De Leeuw *et al.*, 2008; Ten Haaf and Buijs, 2008; Löffler *et al.*, 2008). Especially open and nutrient-poor habitats have given way to grassy vegetation poor in species, both on the dunes and in the tidal marshes. Currently studies are carried out to investigate how such effects might be mitigated.

4.1.3.2 Regime shifts

There are clear indications that rather abrupt shifts occur between different but persistent conditions in ecosystems and that such "regime shifts" can be caused by abiotic factors (Scheffer *et al.*, 2001a,b). During the past 50 years, two big changes have occurred in the North Sea which likely led to shifts in ecosystem conditions. The first change was during the 1970s when water temperature, salinity and the Atlantic inflow were lower than average. The second change is from the 1980s up to present, with higher than average temperature, salinity and Arctic inflow (Reid *et al.*, 2003; Beaugrand, 2004). Fast and wide spread shifts in plankton (Cadee and Hegeman, 2002), benthic life and fish populations characterize both periods with marked regional differences (Figure 4.12; Beaugrand *et al.*, 2003; Weijerman *et al.*, 2005). Currently, the spring blooms of phytoplankton in the Wadden Sea occur ever later in the Wadden Sea but earlier in the North Sea. As a result, fish larvae and young shrimp occur earlier in the Wadden Sea. Such shifts in seasonal dynamics lead to a mismatch between phytoplankton and zoöplankton peaks, between shrimp and shellfish larvae, between zooplankton and fish, and between fish and sea birds (Beaugrand *et al.*, 2003; Edwards and Richardson, 2004). These observations indicate that shifts in population sizes of many species may be expected.

4.1.3.3 Fish

Changing water temperatures can have strong effects on the species of the North and Wadden Sea. The reproductive potential of fish is for instance influenced by temperature. Some species show a positive correlation between development of larvae and water temperature, but in other species the correlation is inverse (Tulp *et al.*, 2006). In addition, indirect influences such as oxygen uptake may lead to population effects (Pörtner and Knust, 2007). Currently, several studies report trends suggesting migration due to climate change, such as a northward migration of warm water species (anchovy) and disappearance of cold water species (Beaugrand *et al.*, 2002, 2009; Brander *et al.*, 2003; Beare *et al.*, 2004; Perry *et al.*, 2005; Tulp *et al.*, 2006).

4.1.3.4 Bird life

Migration patterns of birds are also influenced by changes in temperature and food availability in the various locations they use. In the period 1987-2004, a decrease was observed in the population of 12 out of 34 species of migrating birds which are important for the Wadden Sea area (Blew *et al.*, 2007). The decrease is caused by a decrease in the quality of the habitat and in the quantity and quality of the food available in the intertidal zone. Indications that climate change is directly and indirectly involved are becoming stronger (Bairlein and Exo, 2007). However, the influence of climate change is hard to quantify, since other human induced disturbances also play a significant role (Reineking and Südbeck, 2007).

In the Wadden Sea, marked differences occur in the numbers of wintering birds in cold and warm winters (Meltofte *et al.*, 1994; Figure 4.1.13). For some species it is known that the spring population is smaller with a higher spring temperature, because species migrate sooner towards Nordic areas. Migration patterns might also change; a fact which should be taken into account when studying population size development (Reineking and Südbeck, 2007).

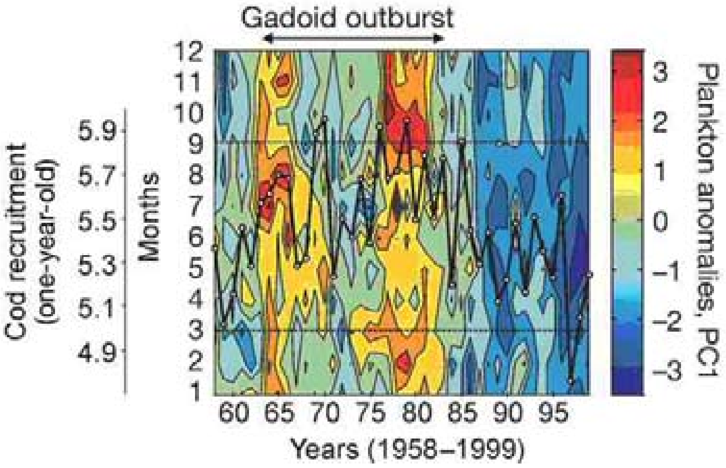

Figure 4.1.12: Illustration of a fast change in the plankton population in the North Sea and its consequences (Beaugrand *et al.*, 2003). Between 1958 and 1983 the anomaly is mainly positive and after that it is mainly negative. In the first period the recruitment of cod (black line) is on average high ("Gadoid outburst"), in the second period it is low.

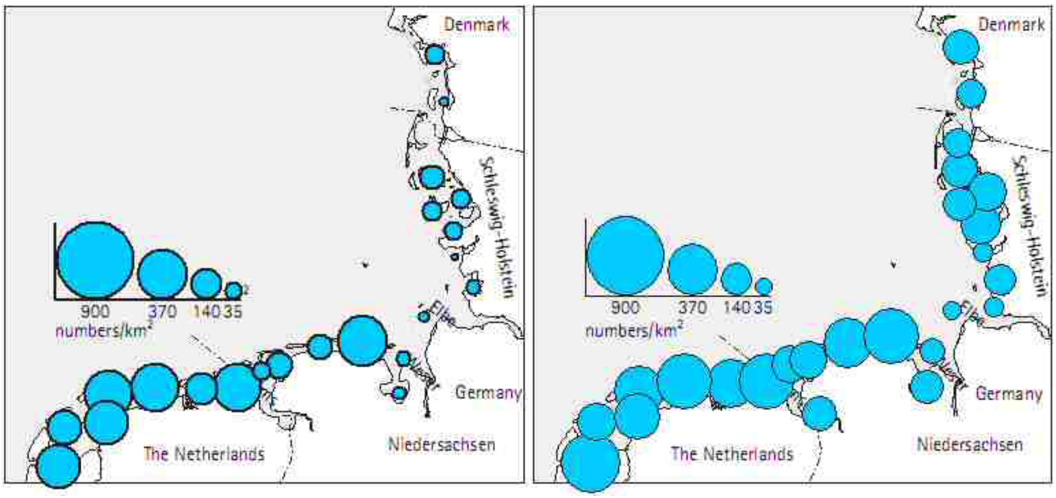

Figure 4.1.13: Waders in the Wadden Sea in cold (left) and mild winters between 1980-1991 (Meltofte *et al.*, 1994).

Climate change is expected to have strong effects on the terrestrial and semi-terrestrial ecosystems of the Wadden Sea area, such as dunes and tidal marshes. Temperature, precipitation and evaporation will have their influence on the growth and living conditions of species and on ecosystem processes. Species may become less abundant or even disappear, while others may invade the area.

Further consequences for the ecosystem are discussed in the following chapter 4.2 by Philippart and Epping.

4.1.4 Next steps

Coastal waters have been changing and will change due to past and current activities and changes in climate settings. The potential climate scenarios provided here are likely? based on the current state of knowledge of climate change. The effect on the ecosystem is still based on limited knowledge of isolated processes. As stated by Philippart and Epping (2009): "Understanding the functioning of the Wadden Sea [morpho-hydro-] eco-system as a composite, including positive and negative feedback mechanisms, is urgently needed to develop prognostic models and to construct reliable future scenarios." To this end, monitoring has to be extended to improve both temporal and spatial resolution to improve both the abiotic and biotic modeling of the Wadden Sea system.

Since not everything can be monitored, scientists and policy makers are advised to identify abiotic key-processes and key factors which dominate the hydro-morphological development of the area and to study this both in the field and under laboratory conditions. In this way adaptation strategies can be developed which make optimal use of the abiotic factors which form the area, for instance by increasing the natural resilience of it. For the abiotic conditions these are, amongst others (Speelman *et al.*, 2009):

- the influence of subsidence;
- the influence of the geo(morpho)logical build up of the area on current processes;
- the natural dynamics of the barrier islands (overwash, erosion and eolian sand transport);
- the dynamics and long-term development of tidal marshes, shoals, estuaries and outer deltas;
- the sediment balance of the Wadden area;
- the differences in dynamics of the various inlet systems (with special attention to shoal-channel interactions);
- quantification of processes (water movements, sand- and mud-transport, vertical sedimentation rates and their interactions on several temporal and spatial scales).

Effort should focus on ensuring that the level of detail (complexity) of the models matches what can and will be measured. For biota see following chapter 4.2 of Philippart and Epping (2009).

As a summary of strategic research topics: in order to adequately understand and project the consequences of climate change for hydromorphodynamics, biodiversity and ecosystem functioning of the sea, we need to (1) extend our coastal monitoring efforts; (2) extend our knowledge on sensitivities and adaptation capabilities of (abiotic) key processes and (biotic) species in the marine environment; and (3) develop fit-for-purpose models to manage our marine environment.

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