3. Climate

3.1 Introduction

3.1.1 Climate differences

Within the Wadden Sea area, there is little difference in climatic conditions. Only in the northern regions is the average winter temperature lower. This results in a higher mortality of cockle stocks, which are susceptible to low temperatures, and significantly more days with ice cover. Moving ice can cause great damage to intertidal mussel beds and ice damage is more severe in the Danish part of the Wadden Sea than in other parts. With regard to climatic parameters, it is much more important to address the expected change in the global climate.

3.1.2 Climate changes

In its report 'Climate Change 1995, the science of climate change' (IPCC, 1995) the Intergovernmental Panel on Climate Change made the following very cautious statement: "The balance of evidence suggests that there is a discernible human influence on climate". In any case, there is now clear evidence that human activities have affected concentrations, distributions and life cycles of the so-called greenhouse gases. For instance, carbon dioxide concentrations have increased by almost 30% from about 280 ppmv (parts per million of volume) in the late 18th century to 358 ppmv in 1994 (IPCC, 1995) as a result of human activities. For the future, an anthropogenic temperature rise in the order of 1 to 3.5 °C by 2100 is predicted (Kattenberg *et al*., 1996).

Recent modelling results show, that a global warming might also lead to modifications in the oceanic circulation pattern in the Nort Atlantic (*e.g.* Rahmstorf, 1999).

As a result of this global warming, changes in sea level rise and storminess might occur. These changes as well as their possible morphologic effects in the Wadden Sea ecosystem are addressed in 3.2 by Hofstede and Schmidt.

Possible effects of changes in temperature are discussed in 3.3 by Diel-Christiansen and Christiansen.

3.2 Climate change: water levels and storminess

J.L.A. Hofstede
H. Schmidt

3.2.1 Water levels

From the last century, numerous water level data for the Wadden Sea are available from tide gauges. Töppe (1993) analysed water level data of ten long-term gauges in the German Wadden Sea (Borkum, Emden, Norderney, Wilhelmshaven, Bremerhaven, Cuxhaven, Büsum, Husum, Dagebüll, List) (Figure 3. 1). According to Töppes analysis, the average Mean High Water (MHW) rise for the period 1855-1990 amounted to 2.3 mm/yr. The rise of the Mean Tidal Level (MTL) amounted to 1.5 mm/yr, the rise of the Mean Low Water MLW to 0.9 mm/yr and the rise of the Mean Tidal Range (MTR) to 1.3 mm/yr. Averaged over the period 1972-1990, these figures amounted to 7.5, 6.7, 5.9 and 1.6 mm/yr respectively. Dillingh and Heinen (1994) did the same for long-term gauges in the Dutch Wadden Sea (Figure 3.2). In general, the long-term trends established by Dilling and Heinen correspond well with the trends for the German Wadden Sea (Fig. 3.1). This, despite the fact that the trends for the Dutch Wadden Sea are established only for the period 1940 to 1990. The building of the Enclosure Dike in 1932 caused a major change in the tidal regime.

For the period 1975 to 1990, the Dutch Wadden Sea showed less pronounced accelerations of sea level rise than the German Wadden Sea. The MHW rise varies between 2 and 5 mm/yr, the MTL rise between 1 and 4 mm/yr for the different stations. Only in the Ems-Dollard Estuary, with its channel maintenance dredging works, stronger accelerations of MHW are measured: between 4 and 7 mm/yr. The MTL rise here lies in the same order as in the rest of the Dutch Wadden Sea.

Earlier, scientists (*e.g.* Führböter, 1989) contributed this strong increase in MHW-, MTL- and MLW-rise over the last decades to the observed climatic changes. Töppe (1993), on the other hand, suggests that these changes are probably the result of long-term cyclic processes rather than climatic changes. Also, civil engineering works, for instance channel dredging, are locally responsi-

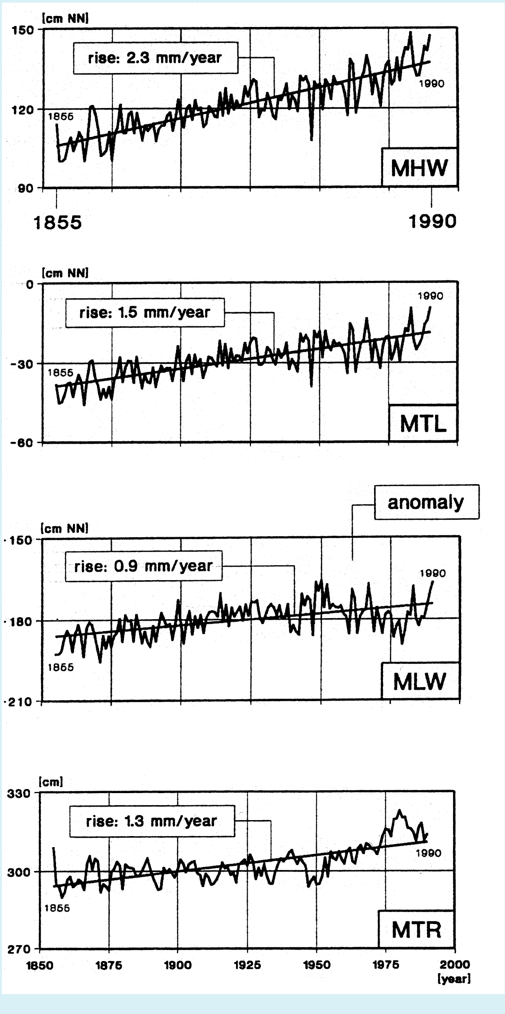

Figure 3.1(left): MHW, MTL, MLW and MTR of tide gauge 'Mean German Bight' 1855-1990. Source: Töppe, 1993.

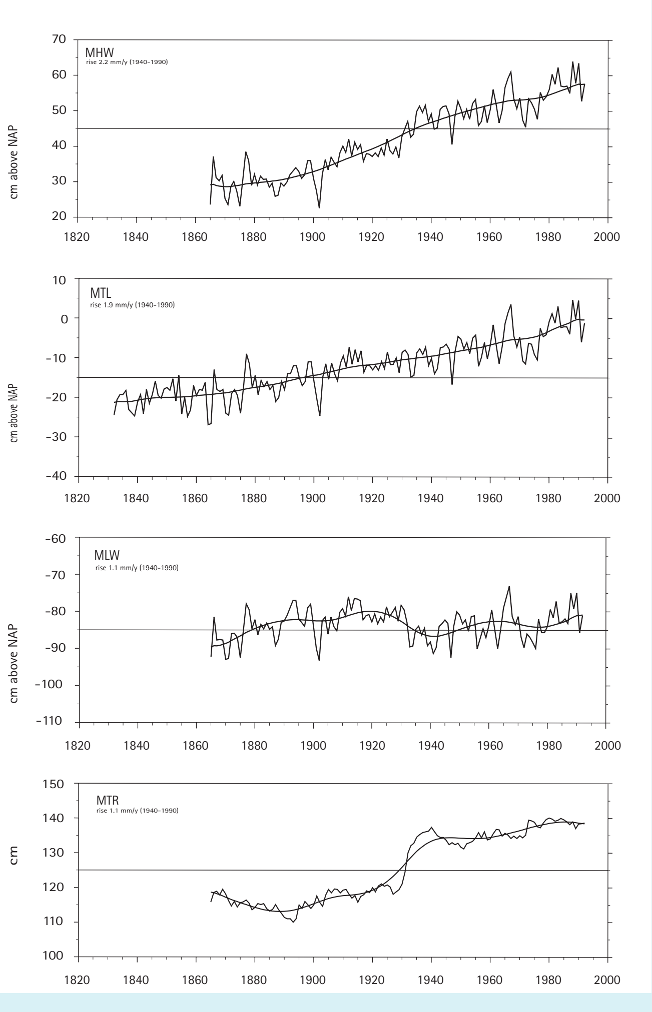

Figure 3.2 (right): MHW, MTL, MLW and MTR of tide gauge Den Helder 1860-1990 Source: Dillingh and Heinen, 1994.

ble for a stronger increase of MHW and weaker increase or even decrease of MLW. Using the IS92a-f emission scenarios, Warrick *et al.* (1996) project sea level to be about 38 to 55 cm higher than today by the year 2100. These global values are lower than the regional MTL-rise values of Töppe (1993) for the period 1972-1990.

3.2.2 Storminess

Another very important climatic phenomenon for the future of the Wadden Sea is storminess. An increase in storminess in the Wadden Sea area would result in higher wave energy input into the ecosystem, which could influence its sediment balance.

For the German Bight, a long time series of almost 120 years of daily geostrophic winds could be derived from surface air pressure measurements. The geostrophic wind is proportional to the horizontal pressure gradient and is a measure for the driving force of the real surface wind.

In Figure 3.3 (Schmidt and von Storch, 1993), the speed limits are plotted, which are the minima of the 1, 10 or 50% highest geostrophic wind speeds of each year, respectively. For a windy year, the speed limits are high, for a calm year they are lower. There are some variations but no long-time trend can be detected over the whole period of the past 120 years. The impact of the wind upon the surges in the German Bight strongly depends on wind direction. Figure 3.4 (Schmidt, 1995, unpublished) shows the annual percentage of geostrophic wind speeds greater than 15 m/s for the surge enhancing directional sector NW and for the opposite sector SE. Strong variations are visible, but again, no long-time trend can be detected. The storminess did not increase. On a shorter time scale, from both figures 3.3 and 3.4 it can be seen, that the last decade was rather windy with relatively frequent northwesterly winds. An exception was the last winter (1995/1996), which is not contained in both figures. It was strongly dominated by very steady southeasterly winds.

Among the climatological estimates for the next 100 years, there are some (*e.g.* von Storch *et al.*, 1993) which indicate the possibility of a slight increase in extreme wind speeds and in the frequency of northwesterly winds, both in the order of a few percent for the North Sea. In general, however, in the few analyses available, there is little agreement between models on changes in storminess that might occur in a warmer world (Kattenberg *et al.*, 1996).

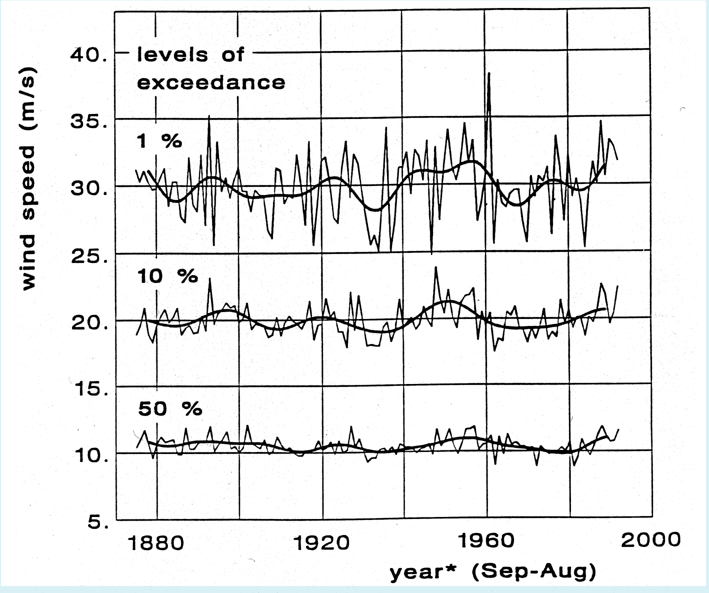

Figure 3.3: Percentiles 1%, 10% and 50% of the annual geostrophic wind speed distributions for the German Bight 1876-1992. Source: Schmidt and van Storch, 1993.

The morphologic response to the observed and expected changes in sea level rise and storminess within the Wadden Sea varies regionally (Hofstede, 1994). Model investigations on low gradient sandy coasts indicate that sea level rise constitutes the dominant factor when the rate of sea level change exceeds 10 mm/yr (Roy and Cowell, 1995). Below this rate, local factors in sediment supply might become more important. For instance, the west coast of the Island of Sylt is retreating as a response to sea level rise. The eroded sediments drift to the north and to the south and accumulate on the beaches of Rømø and Amrum. As a result, these coastlines are stable, or even accreting, despite the observed sea level rise.

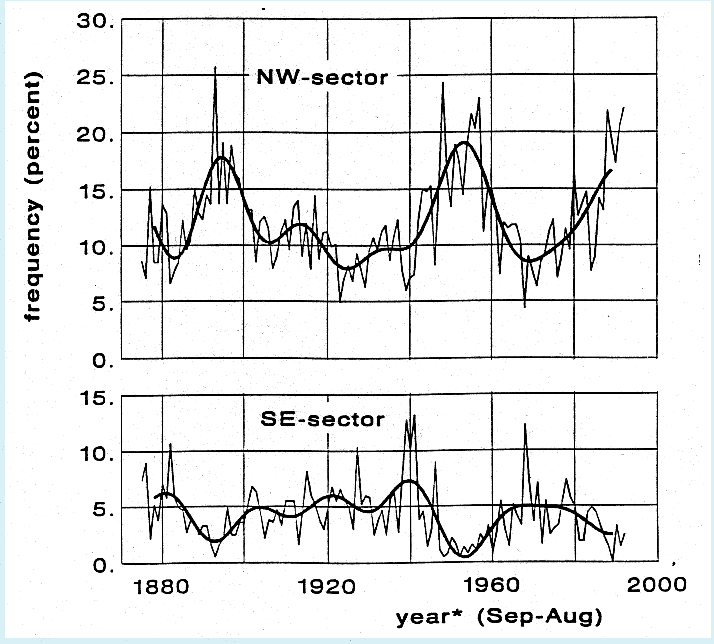

Figure 3.4: Annual frequencies of geostrophic wind speeds greater than 15 m/s for the directional sectors NW (on shore, surge enhancing) and SE (off shore), German Bight1876-1992. Source: Schmidt, 1995, unpublished.

3.3 Climate patterns and ambient temperatures

S. Diel-Christiansen
B. Christiansen

3.3.1 The North Atlantic oscillation

Based on continuously improving data sources, a large-scale, long-term oscillation of the climate in the North Atlantic domain with a periodicity of eight years was detected (Lamb and Peppler, 1987; Hurrell, 1995). The North Atlantic Oscillation Index (NAOI) is defined as the difference between the normalized pressure anomalies in winter (December - March) at Punta Delgada (Azores) and Akureyri (Iceland), or Lisbon (Portugal) and Stykkisholmur (Iceland), respectively. The long-term mean reference period is 1961-1990, and 1864-1994, respectively. A high index (>+1) is associated with strong westerlies, and a low index (<-1) represents weak westerlies. A 'normal' index covers the mid-range from -1 to +1 and stands for a zonal circulation of average strength. Ecologically, however, not only the direct implications of the wind direction, but mainly the associated effects play a role (Table 3.1):

Hurrell (1995) demonstrated the strong correlation of European regional winter temperatures with the NAO Index, and Kröncke *et al.* (1998) showed the same for the sea surface temperatures of the North Sea. An example for years with a high NAO Index are the winters of 1989-1994 (Becker and Pauly, 1996): This period seems to represent the mildest years in the last 50 years, which means that not only the average winter water temperatures, but also the summer heat content was significantly elevated (Pohlmann 1995 in Becker and Pauly, 1996). In 1989, the NAO Index reached its centennial maximum of >+3, the water temperatures being about 3 °C higher than average in the western Wadden Sea (Beukema, 1992b), and coinciding with an exceptional salt water intrusion (Becker and Dooley, 1995). On the other hand, the very cold winter of 1979/80 had an NAO Index of -2, coinciding with the so-called Great Salinity Anomaly, a water body of exceptionally low salinity admixing to the North Sea (Dickson *et al.*, 1988). Comparable to 1979, the winters of 1995/96 and 1996/97 were extraordinarily dry and sunny with temperatures 4.5 °C below average (Becker, 1997), setting an exceptional physical frame to biological production.

Due to the relatively small water volume in the shallow Wadden Sea, water temperatures here are influenced in particular by air temperature. Therefore, winter temperatures are lower, and summer temperatures are significantly higher compared to the adjacent North Sea water (Postma, 1983). However, comparisons of the long-term variability of water and air temperatures offshore and at the Dutch coast led to the conclusion that the underlying patterns are also determined partly by the global climate pattern (de Vooys, 1990). The implication of this is that the presently debated trend of globally rising air temperatures (Houghton *et al.*, 1996; Watson *et al.*, 1996) will superimpose its effects on the 'normal' oscillation inherent in our climate. Sterr (1995) defined the following scenario to address the possible consequences of an anthropogenic climate change for the southern North Sea coast:

1. an estimated increase of average air temperatures by 1.5-3°C in the next hundred years, possibly increasing more in winter than in summer.
2. Coinciding, a substantial rise in average sea level and tidal range.
3. More frequent and more extreme strong wind events, in particular westerly winds, with a coinciding increase in wave height and wave impact.
4. German Bight salinity modified as a factor of precipitation.

Temperature is, thus, only one among other climate-induced factors acting on the ecosystem of the Wadden Sea.

Table 3.1. Phenomena associated with extremely high (Index >1) and low (Index < 1) NAO Indices.

NAO Index >1	**NAO Index <1**
low pressure field over the North Sea	high pressure field over the North Sea
strong westerlies	weak westerlies, but more northerlies
high cloud cover - less light	less cloud cover - more light
warm SSTemperature	cool SSTemperature
strong mixing	stagnation periods in winter
more advection of heat, nutrients, plankton?	high turbulence in spring due to northerly winds
high precipitation	low precipitation
high run-off-volume rivers	low river run-off
high nutrient input coastal area	lower nutrient input coastal area

3.3.2 The ecological expression of various temperature regimes

Temperature is one of the key factors structuring marine communities. The temperature tolerance range may limit the geographical distribution of a species. Lusitanian immigrants, as observed in the plankton after the 1989 saltwater intrusion (Lindley *et al.*, 1990; CPR Survey Team, 1992; Greve, 1994) have or have not the chance to conquer a niche in the food web, depending particularly on the winter temperatures. An increased abundance of southerly fish species in the southern North Sea and Wadden Sea in recent years correlates with overall warmer temperatures (Lozán *et al.*, 1994; Heessen, 1996). In the benthos, some, up-to-now, non-resident species established in recent years (Reise, 1994a), without causing noticeable disturbances of the resident species (Michaelis and Reise, 1994).

On an individual basis, temperature determines physiological rates like growth, reproduction, metabolism. The seasonal variation of temperature may synchronize life cycles within populations. Due to its variable effects on the individual physiological rates and the population dynamics of auto- and heterotrophs, temperature is one of the crucial factors determining the biological expression of interactions between the trophic levels in an ecosystem (*e.g.* Beusekom and Diel-Christiansen, 1996).

The Wadden Sea is a highly dynamic system which is subject to large temperature fluctuations at various temporal and spatial scales. Therefore, only eurytherm organisms (organisms which can live under different temperature regimes) thrive in the Wadden Sea and are supposed to be only little affected by changing temperatures, particularly during the growing season in summer. However, for organisms living at the limit of their distribution, small changes in temperature may have severe effects on their growth, reproduction and mortality.

3.3.3 Effects of winter temperatures

Overwintering is a particularly critical period during the life cycle of many planktic and benthic as well as bird species. During this time, relatively small differences in mean temperature and in temperature extremes can have a strong influence on survival as well as on biomass and recruitment success in the following spring (Beukema, 1982). In particular, the sessile macrobenthos of the regularly exposed tidal flats is subject to the various winter conditions such as the extreme subzero temperatures, wind chill and ice shear, or, on the other hand, warm temperatures, high predator densities and sediment displacement due to storm surges.

There are several direct and indirect mechanisms how winter temperature affects the composition and standing stocks of flora and fauna in the Wadden Sea. A variety of species is directly sensitive to low winter temperatures, *e.g.* the polychaetes *Lanice conchilega*, *Harmothoe lunulata*, *Nephtys hombergii*, the bivalves *Abra tenuis*, *Mysella bidentata*, *Antinoella sarsi*, *Angulus tenuis*, *Cerastoderma edule*, and the decapods *Crangon crangon* and *Carcinus maenas* (Beukema, 1990). During severe winters, these species suffer high mortality, becoming either absent or scarce in the Wadden Sea, or they retreat from the intertidal areas to the subtidal zone (Beukema, 1990; Reise, 1993). Their stocks are usually re-established after 1-2 years. Other species, in particular those of the supra- and eulittoral zone, like the snails *Littorina* spp., the barnacle *Balanus* spp., the bivalves *Macoma baltica* and *Mytilus edulis* are very resistant, even to freezing (*e.g.* Theede, 1981).

Contrary to the reduced species diversity after extremely severe winters, series of mild winters may lead to a higher diversity and stable total biomass in the benthos due to reduced mortality and the advection of immigrants (Beukema, 1992b). However, the population development in the following year depends more on the indirect effects of the winter temperatures on the body condition of the individuals than on the overwintering stock.

The reproduction of a number of macrozoobenthic species, *i.e.* the release of meroplanktic larvae, is triggered by a water temperature of 5 °C (Bayne, 1965). After warm winters, a long spawning period from February onwards can be observed. After cold winters, the temperature increase in spring is more rapid and leads to a distinct spawning peak as late as May (Martens, 1992; Pulfrich, 1997). Whereas after cold winters, the recruitment of macrobenthic species was often found to be exceptionally high (Beukema, 1982; Dörjes *et al.*, 1986; Beukema, 1992b), a series of mild winters resulted in repeated recruitment failure of several bivalve species (Beukema, 1992b) (see also 5.7). In essence, temperature controls the recruitment success of macrobenthos in the Wadden Sea in two ways:

1.Temperature directly determines the metabolic loss during times of low food availability. In cold winters, the metabolic loss is relatively low resulting in higher individual biomas compared to mild winters. In experiments with two of the stock-forming bivalve species of the Wadden Sea, *Macoma balthica* and *Cerastoderma edule*, significantly more eggs were produced after exposure to lower temperatures (Honkoop and van der Meer, 1998). In the case of *Macoma*, this could directly be related to the body condition because this species uses stored energy for gametogenesis.

2. Temperature controls the abundance and start of development of *Crangon crangon* (Beukema, 1992a), the most important predator on *Macoma balthica* larvae in early spring. After cold winters, a low overwintering stock and a delayed-settlement of new generation *Crangon* by several weeks decreases the predation pressure on the spat of early reproducing bivalves like *Macoma balthica* (Beukema *et al*., 1998). In a similar way, winter temperature strongly acts on the abundance of the shore crab *Carcinus maenas* during spring and summer (Beukema, 1991), thus affecting the predation pressure on young bivalves during summer.

Beukema *et al.* (1998) concluded that the most important effect of temperature on the reproductive success of *Macoma balthica* was via the control of predators in spring. However, in late-spawning bivalves like *Cerastoderma* this might be less crucial, which may explain why Dörjes *et al.* (1986) found a high recruitment success in this species after moderate or mild winters.

The timing of settlement is another important factor for the recruitment success of benthic species ('settlement-timing hypothesis', Todd and Doyle, 1981). Because temperature controls the development time of meroplanktic larvae to a large extent, thus determining their distribution and settlement, this is a further way temperature influences the recruitment of macrobenthos stocks (Moloney *et al*., 1994).

Since winter temperature is one of the most important factors controlling the standing stocks of macrofauna, it is also indirectly substantial for predators on macrofauna, like birds. The low survival of macrofauna after cold winters or the low recruitment success after mild winters may lead to food shortage for several species of waders (Beukema *et al*., 1993). The observed synchronized fluctuation pattern of macrofauna over wide parts of the Wadden Sea area (Beukema *et al*., 1996) limits the possibility of birds to switch to other areas (Beukema *et al*., 1993). Prey switching is a possibility for less prey-specific birds to cope with a low abundance of their preferred food and may have a significant impact on the benthic communities, reducing bivalve stocks to a very low level (Beukema, 1993).

The effect of winter temperature on the macrobenthos is most pronounced in the intertidal area but long-term changes in the subtidal zone can also be attributed to climatic influences (Dörjes *et al*., 1986). Kröncke *et al.* (1998) related fluctuations in macrofaunal biomass, abundance and species number in the subtidal zone off Norderney to the climatic variability and suggested that sea surface temperature in late winter and spring was the mediator between the NAO and the benthos (see also 5.17). Single cold winters appear to have only little long-term effects on the subtidal benthic communities but series of mild winters may lead to distinct long-term changes.

3.3.4 Effects of fluctuating summer temperatures

The effects of annual fluctuations of temperatures in the warm seasons on the Wadden Sea ecosystem are less pronounced than in winter. Of course, physiological rates and the population development of plankton and benthos depend on temperature to a certain extent; however, the ecological consequences of temperature fluctuations are rarely distinguishable from other sources of variability in a highly complex ecosystem like that of the Wadden Sea.

Some indications exist for the influence of higher temperatures on specific compartments of the Wadden Sea ecosystem. For example, higher than average summer temperatures may cause low survival in the eelgrass *Zostera marina* (Reise *et al*., 1994 and references therein). The collapse of *Phaeocystis globosa* blooms may be related to high temperatures in summer (Elbrächter, 1994). The distribution of *Spartina anglica* on salt marshes may be favoured by increased temperatures (Reise, 1994b).

3.3.5 Temperature and pollution

Organisms living at the limit of their temperature range show an increased sensitivity to environmental stress. For example, Hummel *et al.* (1996) compared populations of *Macoma balthica* in French and Dutch estuaries and found that the populations living at their southern geographical limit were more sensitive to the exposure to copper than the northern populations. Furthermore, fish embryos are known to show a predisposition to the influence of organochlorines at low winter temperatures (Dethlefsen *et al*., 1996).

3.3.6 Hypotheses on possible effects of prolonged temperature increase

The macrozoobenthos of the various tidal zones has a key position in the marine food web of the Wadden Sea (*e.g.* Michaelis and Reise, 1994)), being the primary consumer of phytoplankton, microphytobenthos and detritus, and on the other hand, the indispensable food source for many species of mobile invertebrates, such as crustaceans, as well as fish and birds (Figure 3.5). Contrary to its mobile predators, the more or less immobile benthic species are subject to physical impacts other than water temperatures such as air temperatures, breaking waves, varying current velocities, sediment displacement, *etc*.. Additionally, the macrobenthos would be particularly vulnerable to sea level rise through changes in the low tide period. Therefore, the macrobenthos integrates the combined effects of the various climate scenarios and mediates them to the food web. However, this is not a one way road: the physical (and chemical) environmental conditions only set the framework to the growth conditions of all ecosystem compartments - the food web interactions, however, determine the realized population development.

As concerns the projected warmer winters, coinciding with more and possibly stronger westerly winds, cloudiness, and rainfall, Beukema (1990) expects a higher macrobenthic species diversity with a more stable moderate biomass, limited by moderate recruitment success and a relatively high predatory impact by temperature-limited shrimps and shore crabs. The warmer the winter temperature, the higher the population densities of zooplankton, near-shore fish and seals. Overwintering birds easily find accessible food since bivalves do not borrow as deep as in cold winters and no ice floats cover the tidal flats. However, all poikilotherms have to cope with an increased metabolic energy need in warm winters and depend strongly on a concurrent match in production of their food. Autotrophs, however, as the base of all biomass production in the ecosystem, are even more light-limited in warm winters than during cold winters. As a consequence, a long-term increase in winter temperatures may favor detritivores and their predators in an ecosystem which is in balance with changed environmental conditions.

Figure 3.5. Schematic pathways of energy in the Wadden Sea ecosystem during winter/early spring. + denotes enhanced and – denotes decreased flows of energy after exceptionally mild winters, as compared to average winters.