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Species response to climate change could affect the fate of fine sediment in the Wadden Sea

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ABSTRACT: Climate change is considered to affect large scale processes on the long term. In the classical view to hierarchy and coupling of spatial and temporal scales, a large scale process can be seen as a forcing function to subsequent smaller scale. In this paper, it is hypothesized that short-cuts exist that directly link the long term climate change to processes on small temporal and spatial scales. Water temperature is a dominant factor in the reproduction success and survival of many species. At present shifts in species composition in the Wadden Sea have been observed due to changing winter water temperature. From researchers investigating the interaction between species and sediment characteristics it is known that many bottom dwelling ecosystem-engineering species can either stabilize or destabilize sediment and therefore influence sediment transport. Ecosystem engineering benthic species have been shown by many authors to interact especially with dynamics of fine sediment transport on sub-mudflat scale causing sandy and silty patches. Recent research results show the influence of ecosystem engineers on estuary scale fine sediment transport. This paper concludes that shifts in occurrence of ecosystem engineering species, caused by large scale climate change affecting benthic species communities, can affect the fine sediment transport on estuary scale, leading toward a system dominated by sandy beds. In combination with species community shifts, this could result in ecosystem state change that is not reversible. Increased storminess is another scale short-cut caused by climate change that possibly could exacerbate this effect, as it affects sediment transport likewise.

1 INTRODUCTION

At continental, regional and ocean basin scales numerous effects of climate change have been observed. Effects include changes in temperature and ice cover, changes in precipitation amounts, salinity, wind patterns en aspects of extreme weather including heavy precipitation, heat waves and droughts (IPCC, 2007). In the Wadden Sea effects of changing water temperature on abundance of many species have been observed (Beukema, 1992). Researchers have linked the occurrence of certain marine intertidal species to local influences on sediment composition (van de Koppel et al., 2001). This paper explores the possibility that top-down, cross-scale, effects of climate change can result in bottom-up, cross-scale, non-linear effects in distribution and transport of fine sediment by affecting abundances of key ecosystem engineering species. This pape first describes observed effects of climate change, knowledge on across scale propagation of these effects and the possibility of non-linear amplification that could lead to ecosystem state changes. Following, observed species changes in the Wadden Sea are related to known effects of ecosystem engineers on transport of fine sediment on the mudflat and whole Wadden Sea system scale. In the last part of the paper consequences of climate change for ecosystem state are elaborated. Finally, considerations on management of changing ecosystems are given and conclusions are drawn.

2 EFFECTS OF CLIMATE CHANGE

The earth climate is being studied in more and more detail on all spatial scales. Recently the fourth assessment report of the IPCC has been published (IPCC, 2007). The report describes numerous effects of climate change. The human influence on the climate has become very likely after six more years of study since

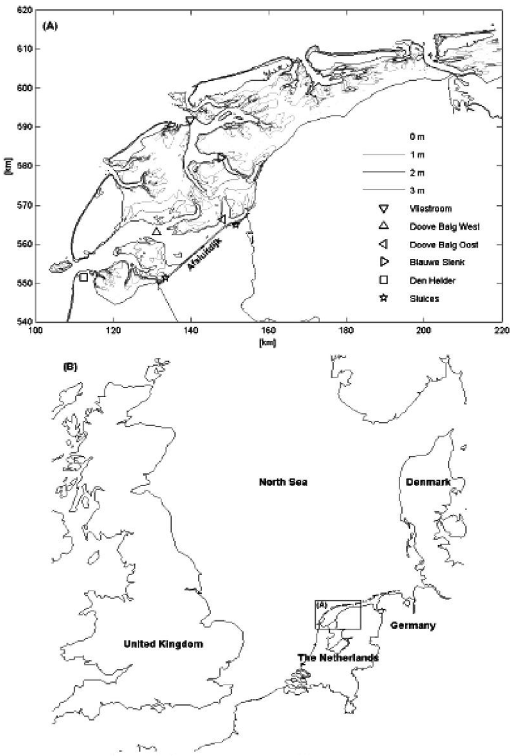

Figure 1. Location of the Western Wadden Sea (A) in the Netherlands (B). Depth with respect to Mean Sea Level (MSL) and co-ordinates are based on the Paris co-ordinate system. Copy from Borsje et al., RCEM 2007.

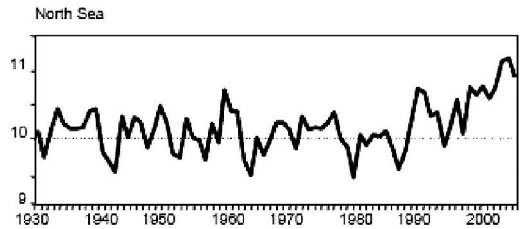

Figure 2. Area averaged annual sea surface temperature North Sea, based on HADSST2 data, compiled by Licandro & Philippart in European Science Foundation (2007).

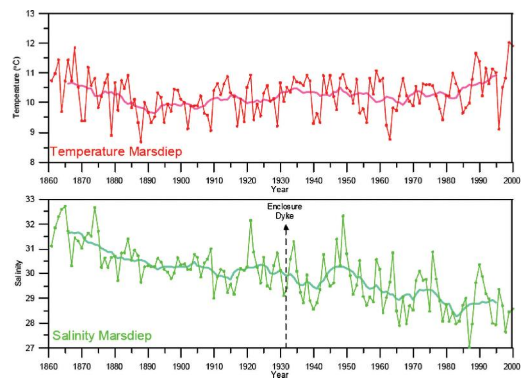

Figure 3. Annual means of sea surface temperatures and salinities measured in the Marsdiep. Copied from van Aken (2001).

the third assessment report. Increased global levels of carbon dioxide in the atmosphere are considered the most important anthropogenic factor of climate change, based on burning of fossil fuels and changes in land use. According to the IPCC report, warming of the climate system is unequivocal. In the region of northern Europe, significant increased precipitation has been observed. Changes in precipitation and evaporation over the oceans are suggested by freshening of mid and high latitude waters together with increased salinity in low latitude waters. Mid-latitude westerly winds have strengthened in both hemispheres since the 1960s.

These winds could cause a redistribution of fresh and cold water from the Arctic by affecting ocean currents such as the North Atlantic Oscillation (NAO). The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapour. This will cause a changed temporal distribution and volume of discharge of river waters into estuaries and seas. Heavy precipitation could also have direct effects on survival of species in the coastal zones by causing more extreme salinity swings in shallow intertidal areas. Widespread changes in extreme temperatures have been observed over the last 50 years. Cold days, cold nights and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent (IPCC, 2007). Reproduction success of many benthic species is linked to water temperature (Beukema, 1992). Daily survival of exposed species on the intertidal is dependent on drying and heating during ebb-periods.

Licandro & Phillipart (ESF, 2007) show the increase of sea surface temperature for the North Sea. A clear upward trend is observed after 1990 (Figure 2). Van Aken (2001) gives an overview of 150 years of daily measurements of water temperature and salinity by the Royal Netherlands Institute of Sea Research (KNIOZ) in the Marsdiep, the southernmost inlet into the Wadden Sea (Figure 3). Van Aken concludes that 1999 and 2001 are the two warmest years since 1861, while 1996 is one of the five coldest years. Furthermore it is concluded that the data reflect the west European climatic variability and correlate very well with annual mean air temperatures measured in nearby Den Helder. Winter temperatures are also linked to the status of the NAO. Beukema (1992) reports that water temperature during the 1980's in the Wadden Sea is

0.7°C above the long term averages. In 1989 and 1990 these temperatures are 1.5°C higher, mainly caused by winter temperatures being elevated by 3°C. Beukema & Dekker (2005), conclude that a significant shift toward higher winter water temperatures has taken place after 1988. The measured trend of decreasing in salinities is caused by increasing river discharge, according to van Aken. The salinity variations between years are a result of a combination of river discharge and impacts of the NAO.

3 COUPLING OF SCALES

The structure and behavior of ecosystems is the product of many processes acting at many spatial and temporal scales. Cross-scale processes will link different scales. The direction of the influence, either upscale or downscale will define the characteristics of each influence. De Vriend et al. (1993) elaborated this linkage of scales in conceptual terms for morphodynamics, describing that influences from higher scales are more or less constant 'boundary conditions', where influences from lower scales are considered to be 'noise'. Only processes on the same scale can have dynamic interactions. De Vriend et al. (1993) argued that increasingly detailed process knowledge and modeling capabilities on a small scale will not inevitably lead to the correct prediction of processes on a larger scale, due to emerging non-linearity's, unpredictable events and neglect of processes that were not relevant at the smaller scale. The existence and importance of emergent properties were for the first time identified by Odum (1971). By definition, emergent processes and patterns 'emerge' at a certain temporal and spatial scale and cannot be easily seen on smaller scales. Odum (1971) proposed and studied the concept of ecosystem self-design. The change of properties of an ecosystem by local species is part of this self-design process and is termed *ecosystem-engineering* by many authors. In a more recent publication, Odum (1996) stressed the importance of linkage of scales, stating that information is fed forward from lower scales and fed back from higher scale to the scale of interest. According to Peters et al. (2004), the propagation of fine-scale changes to broader spatial scales can either be rapid (responses are amplified) or slow (responses are buffered). Rates depend on the spatial configuration, connectivity, and flows within and among fine-scale units, the interaction of these patterns with broad-scale forcing functions, and feedbacks among these elements across scales. Research on Wadden Sea scale is relevant for society because emergent ecological processes – such as ecosystem self design and human induced ecosystem engineering – act on this scale (Odum, 1996), and therefore, by definition, both must be interacting dynamically. Such a long term large scale knock-on effect is clearly observed after closure of tidal basins connected to the Wadden Sea (Kragtwijk et al., 2004). Also, de Jonge (2000) argued that, for the Wadden Sea ecosystem, relevant temporal and spatial scales for management are annual and estuary wide, further emphasizing the need for research and monitoring on that scale.

4 NON LINEAR INTERACTIONS AND STATE CHANGE

The existence of multi-modal state switching in ecosystem behavior is well documented for both fresh and marine systems (Scheffer et al., 1993; van de Koppel et al., 2001). In 2001, Scheffer et al. argue that human activities have reduced resilience of large scale ecosystems to cope with further change and that dramatic self sustaining ecosystem state shifts are to be expected. One major cause could be gradual shifts in species abundance due to changes in physical forcing or anthropogenic impacts. These can lead to self sustaining state change due to an external shock to the ecosystem, such as unusual high temperatures or salinity changes. Harley et al. (2006), report possibility of impact of climate change to change ocean circulation, which drives larval transport, with important consequences for population dynamics. Climatic impacts as observed in the Wadden Sea by Beukema et al., on one or a few key species may result in sweeping community-level changes. Finally, Harley et al. conclude that synergistic effects between climate and other anthropogenic variables, particularly fishing pressure, will likely exacerbate climate-induced changes. Peters et al. (2004) find that propagation of fine-scale changes can lead to non-linear, catastrophic changes of ecosystem state. Identification of governing conditions and thresholds is needed to better understand (the risk of occurrence of) these changes and to eventually predict the effect of measures to counteract such changes.

5 OBSERVED SPECIES CHANGES IN THE WADDEN SEA

Within the context of functioning of the Wadden Sea ecosystem, regional climate (change) forces system wide effects on ambient water temperatures and salinities. The reproduction success of key high biomass bivalve species, living in and on the intertidal zones, is affected, such as *Macoma balthica*, *Mya arenaria*, *Mytilus edulis* and *Cerastoderma edule* (Beukema et al., 2001). Knock-on effects were observed on phytoplankton concentration and survival of birds. Polychaete species (worms) are less affected. The brown shrimp *Crangon crangon* appears earlier in spring in large numbers on the intertidal areas and shore crabs occur in much larger numbers (Beukema, 1992). A shift toward polychaete domination of biomass and productivity, combined with introduction of new species that are adapted to warmer water, is expected. Beukema (1992) estimates that a 20–30% increase in benthos species numbers is possible if annual water temperature rises with 2–3°C. Ieno et al. (2006) report that increases in biodiversity and abundance in benthic infauna will result in increased exchange of nutrients between the bed and the pelagic, mainly governed by the intensity of bioturbation.

6 ECOSYSTEM ENGINEERS INFLUENCE ON WADDEN SEA SCALE

The amount of fine sediment in the water phase and in the estuary bed is an important factor influencing the functioning of the estuarine ecosystem. For instance, turbidity and sediment composition are important factors related to species composition of intertidal areas (van Katwijk et al., 2000; Beukema et al., 2001). Therefore, man-made and natural changes in the amount and distribution of fine sediment will affect the functioning of the ecosystem. Many authors reported that a large variety of bottom dwelling organisms engineer the temporal and spatial distribution of fine sediment in the bed in their habitats by actively changing settling and erosion processes (for reviews see Paterson et al., 1997; de Deckere et al., 2002; Widdows et al., 2002). These influences have been described consequently on sub-mudflat scale. However, both Postma (1981) and Dronkers (1984) already considered biological influences on settling and erosion to be possible important factors for the residual sediment transport between the North Sea and the Wadden Sea. Key species that engineer sediment stability and therefore influence sediment composition in the Wadden Sea are benthic diatoms (stabilizing effect) and high biomass bivalve (*Macoma*, *Mya*, *and Cerastoderma*), mollusc (*Hydrobia*) and polychaete (*Arenicola*) species (dominantly destabilizing effects). The highest biomasses of these key species in the Wadden Sea are found on the intertidal and shallow subtidal areas. Below the 3 meter depth contour (relative to MSL) the biomass of benthic organisms is much lower (Dekker & de Bruin, 1999). The modeling study of Paarlberg et al. (2005) has shown that the effect of (de)stabilizing species on sediment composition and bed level on mudflat scale can be significant within realistic biomass ranges. This result reproduced the existence of bimodal states on a mudflat as suggested by van de Koppel (2001), sandy bed with dominance of lugworm (*Arenicola*) or muddy bed with dominance of benthic diatoms. The analysis of de Vries (ECSS, submitted), based on existing datasets, reveals that mudflat scale influences of biota

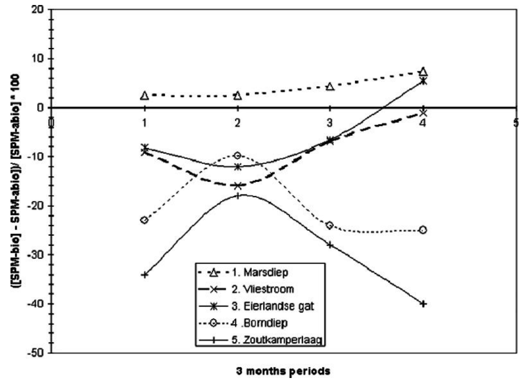

Figure 4. Change of SPM concentration in 5 basin inlets due to influence of ecosystem-engineers (see Figure 4 for location). Values shown are 3-monthly averaged ratios of a model run with (SPM-bio) and a model run without (SPM-abio) for 1998; Derived from results presented by Borsje et al. (RCEM 2007).

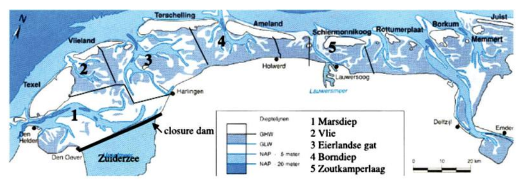

Figure 5. Wadden Sea with approximate boundaries of tidal basins (copy from Kragtwijk et al., 2004).

on fine sediment transport emerge as dynamic interactions on Wadden Sea scale, linking mudflat scale processes to the Wadden Sea scale. The modeling study of Borsje et al. (see the relevant RCEM 2007 paper), has shown quantitatively that on the scale of the Wadden Sea significant effects of bio(de)stabilizers occur, with suspended sediment transport connecting spatial scales. This modeling approach is based on the quantification of the spatial and temporal effect of species on critical shear stress, erosion rate and bed mixing rate. The modeled fine sediment fraction is assumed to behave in a cohesive fashion. The dynamics of accumulation of fine sediment in the channels and on various depth zones of the intertidal areas is influenced strongly by activity of organisms, according to the model results. Modeled effects are non-linear, seasonal, caused by basin shape, vertical zoning and biomass variations of species and thresholds affecting sediment erosion.

In Figure 4 the influence of (de)stabilizers on the concentration of suspended matter is shown for each sub basin within the Dutch Wadden Sea per 3 months period in 1998. (see Figure 5 for location of basins). The results show clearly that the suspended matter concentration in each inlet is influenced by biological activity that is situated on the intertidal areas within each basin (it is assumed that no relevant biological activity takes place in the areas below 3 meter depth contour). The seasonal biomass variations of the various (de)stabilizing ecosystem-engineering species change the nett effect throughout the yearly cycle, caused by shifts between the relative influences of specific species biomass. The shape of the basin defines the spatial distribution and area of habitats of destabilizing and stabilizing species. From this figure two groups of basins can be distinguished. Firstly the deeper Marsdiep, Vliestroom and Eierlandse gat. These basins have relatively small areas suitable for benthic diatoms and therefore are dominated by biomass of destabilizers. The SPM concentrations therefore don't respond to seasonal benthic algae biomass change and are sensitive to biomass variation of destabilizers. This will result in an inability of SPM to get fixed to the bed and therefore little accumulation of fine sediment occurs during the year. SPM concentrations are close to or higher than 'abiotic processes only' model simulations. The shallower Borndiep and Zoutkamperlaag react in an opposite fashion, fine sediments are fixed to the bed, due to large areas with suitable benthic diatoms habitat. SPM concentrations are always much lower than during the 'abiotic processes only' model simulations. The peak concentrations in Q2 are related to fine sediment being resuspended in the steep channels, before being deposited on the shallow areas. Stormy weather events in the autumn do not result in higher SPM concentrations in Q4. These basins act as 'magnets' for fine sediment.

Within the whole Wadden Sea, the gross sedimentation/erosion fluxes influenced by the biota are two orders of magnitude larger than the multi-year averaged nett import flux of fine sediment into the Wadden Sea and one order of magnitude larger than the gross daily exchange through the inlets as reported by Postma and Dronkers (de Vries, submitted). In combination with results shown in Figure 4, it is therefore expected that changing influence of ecosystem-engineers can seasonally, between years or on the longer term affect the (sign of) the exchange of fine sediment between North Sea and Wadden Sea basins.

7 INFLUENCE OF CLIMATE CHANGE ON FINE SEDIMENT TRANSPORT

It has been made clear by various authors (De Vriend, Harley, Odum, Peters and Scheffer) that small scale changes can have amplifying, non-linear effects on larger spatial and temporal scales. Climate change has been observed in the Wadden Sea to cause shifts in benthic species biomass, causing a loss of bivalves and an increase in polychaetes and crustacea, through increasing water temperatures. Increase in biomass and biodiversity of in-sediment species will increase bioturbation rates according to Ieno. Authors researching the influence of ecosystem engineers on fine sediment transport find clear relations between system-scale parameters and the activity of biota on the intertidal areas. Basin wide dynamic interaction on seasonal timescale is emerging from the results. Large scale climate change could across-scale influence short-term morphodynamics through impacting on zoobenthos populations. Figure 6 illustrates the findings. Changes in species community composition toward domination of (burrowing) polychaetes that favor sandy beds can impact within seasons on fine sediment transport on the estuary scale, leading to increased erosion rates by reduction of sediment stability. Given the high gross erosion/sedimentation fluxes of fine sediment in the Wadden Sea, this could cause a spatial redistribution of sandy and muddy areas on relatively short time scales (within decades). Another climate change effect, increased storminess, could help exacerbate the impact, by enhancing the intensity of (fine) sediment fluxes. If species shifts are irreversible due to higher temperatures, this could lead to an irreversibly increased occurrence of sandy areas and higher turbidity in the pelagic, affecting habitats of many species. Could this be an example of sustainable drastic ecosystem state change in the making?

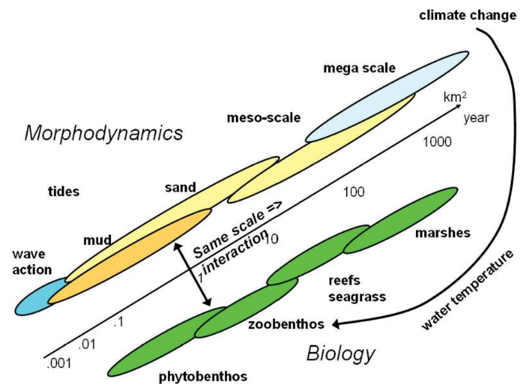

Figure 6. Interaction between morphodynamics and biology within a coastal ecosystem, based on concepts of Odum and de Vriend. Large scale climate change is affecting zoobenthos species composition on small spatial and temporal scales. Mud timescales (especially in the bed toplayer) are relatively short.

8 CONSIDERATIONS FOR MANAGEMENT

Ecosystem change in the Wadden Sea has been observed. At present, there is no practical method for predicting the effects that climate change might have on the Wadden Sea or any other ecosystem. In order to better understand the mechanisms, to establish a baseline situation, and to confirm observed trends or ecosystem state changes, it is very important that monitoring of key physical, chemical and biological variables is coordinated and intensified on relevant spatial and temporal scales. At present coherent data sets are lacking or incomplete. In the ESF 2007 report, a proposal of possible indicators has been given. The monitoring should be designed to make it possible to detect trends above the noise due to the natural (short-term) variability of the ecosystem. This will lead to better information for managers on the options to how to manage human activities in a changing ecosystem and how to mediate possible ecosystem state changes.

9 CONCLUSIONS

The impact of climate change on the Wadden Sea ecosystem is observed. Especially benthic species abundancies have shifted, causing reduced biomass of key bivalve species. In this way the large scale global changes affect small-scale short-term population dynamics due to increasing water temperature. Benthic species such as diatoms, bivalves and polychaetes are known as ecosystem engineers the influence on a sub mudflat scale fine sediment composition and transport. It has been shown with on the basis of data-analysis and mathematical modeling that local scale ecosystem engineering will affect basin scale fine sediment transport in the Wadden Sea. Basin shape is important in defining the effect of this large scale ecosystem engineering by benthic species. Model results have shown, in agreement with findings of other authors, strong non-linear bottom-up effects of ecosystem engineers biomass on sediment transport. Amplifying impacts from small scales to ever larger scales is creating a risk of irreversible ecosystem state change. The observed switch toward polychaete biomass domination in the Wadden Sea could force a system state where sandy beds are dominant, with higher rates of fine sediment resuspension, causing higher turbidity levels, higher nutrient fluxes, less import from the North Sea and temporary increased accumulation of fines on the bordering saltmarshes. Increased storminess could exacerbate this effect.

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