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Long-term and high-resolution measurements of bed level changes in a temperate, microtidal coastal lagoon

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Abstract

This study presents the results of a long-term monitoring program of bed level changes measured during 8 yr at an intertidal mudflat in a microtidal, temperate coastal lagoon. Additionally, bed level measurements obtained at a 10-min temporal resolution at the same tidal flat and at the bed of a nearby tidal channel are presented. Short-term changes in bed level are one or two orders of magnitude larger than the annual net-deposition rate, which shows that the environment is highly dynamic with respect to erosion, transport and deposition of fine-grained sediment. Some seasonality in the bed level changes was observed and there is a tendency for mudflat deposition in spring, summer and early autumn and erosion during the rest of the year, but interannual variations are large and different parts of the mudflat show different seasonal signals. A close coupling between sub- and intertidal deposition and erosion was observed. The time-series showed that some of the material eroded from the mudflat was not exported to the open sea, but instead temporarily deposited in a nearby shallow tidal channel and later returned to the mudflat during calmer weather conditions. These findings support previously published hypothesis and results of modelling studies. Based on the observed abundance of fine-grained sediment at the study sites and the high accretion rates generally found on fine-grained tidal flats in the Danish Wadden Sea area, it is argued that these fine-grained tidal flats are not seriously threatened by the expected sea level rise in the 21st century.

Keywords: mudflat; sediment transport; erosion; deposition; bed level; sea level rise

1. Introduction

Mudflats are abundant on many coasts worldwide and are often found in estuaries and coastal lagoons but may also be situated at exposed coasts if the supply of fine-grained sediment is large. Intertidal mudflats are generally accretionary and a large part of the fine-grained material found in estuaries and coastal lagoons will eventually end up in the associated mudflats. They are often important habitats for various macrozoobenthic species and provide feeding grounds for both fish and birds. They may also act as natural shoreline protection and this ability is one of the reasons for the increased interest in intertidal mudflats. The location in the intertidal zone and the inherent sensitivity to sea level changes also calls for attention due to the possible future sea level rise caused by global warming. Recent interdisciplinary European research programmes (e.g., LISP UK, Black and Paterson, 1998; INTERMUD, Dyer et al.,

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2000) have shed increased light on the complex sedimentological processes and the generally strong interaction between biota and sediments. The sediment dynamics on an intertidal mudflat was addressed in an early review by Anderson (1981), but quantification of a number of key processes only took place recently, partly due to lack of appropriate measuring equipment. The mediation of the erodibility of fine-grained sediments by both microzoobenthos and macrozoobenthos has for example now been described for several species and field sites (e.g., Nowell et al., 1981; Paterson, 1989; Yallop et al., 1994; Widdows and Brinsley, 2002). In spite of these studies, little is still known about the net-effect of biotic processes with respect to mudflat sedimentation and budgets of fine-grained sediments although a few modelling studies have indicated that this effect may potentially be large (Wood and Widdows, 2002; Widdows et al., 2004; Lumborg et al., in press).

Although mostly situated at sheltered sites, mudflats may show substantial sediment reworking induced by waves and currents (Christie et al., 1999; Kirby, 2000) and some studies of the hydrodynamics and sediment transport on tidal flats have been carried out in the past (e.g., Pejrup, 1986; Christie et al., 1999; Bassoullet et al., 2000; Andersen and Pejrup, 2001). These studies have given valuable insight into the sediment dynamics at mudflats and for example highlighted the importance of waves. However, one of the major challenges for such studies is that the net-deposition which takes place is normally orders of magnitude smaller than the gross-deposition and it has generally not been possible to determine the net-deposition from measurements of the hydrodynamics at the study sites. A possible solution to this problem is to undertake measurements of the actual accumulation/erosion, which takes place by repeated measurements of bed level.

Bed level changes on tidal flats occur on a wide range of timescales spanning from tidal cycles to decades or longer. Recordings of bed level changes in intertidal environments have generally been few and the periods between measurements have mostly been days when tidal cycles were investigated and months when longer periods like years were addressed (e.g., Kirby et al., 1992; Allen and Duffy, 1998; O'Brien et al., 2000; Andersen and Pejrup, 2001). Such measurements give valuable information on the amount of sediment cycling and redistribution and may also record seasonal and yearly changes in sediment deposition. Measurements at high temporal resolution provide detailed information on the sediment dynamics but only few studies have been undertaken and they were generally restricted in time to days or weeks (e.g., Bassoullet et al., 2000; O'Brien et al., 2000; Gouleau et al., 2000; Lund-Hansen et al., 2004).

The purpose of the present study has been to examine the short- to medium-term sediment dynamics at a temperate microtidal mudflat and in a nearby tidal channel by use of manual and automated acoustic bed level measurements for longer periods. The results of these measurements are then discussed in terms of possible seasonal signals and the possible biological contribution to such seasonalities. The implications for the dynamics of fine-grained sediments in the entire coastal lagoon are also addressed.

2. Study site

The main investigation site is the Kongsmark mudflat situated in the microtidal Rømø Bight (Fig. 1), which is part of the Lister Dyb tidal basin. Additional bed level measurements were carried out in a tidal channel situated 3.6 km south of the mudflat station. The tidal range in the basin is about 1.8 m (Pejrup et al., 1997) and the water column is well-mixed due to low freshwater inflow and frequent mixing by wind waves. The sediments in the tidal basin are generally sandy but muddy sediments are found in the sheltered parts of the basin. A causeway connecting the barrier island Rømø with the mainland was finished in 1948 and fine-grained sediments have accumulated in large parts of Rømø Bight since then. The net accumulation at the mudflat (inferred form ^{210}Pb and ^{137}Cs dating) is about 15 mm yr^{-1} (Andersen and Pejrup, unpublished data). The average local sea level rise has been 1.3 mm yr^{-1} during the last century, but has increased recently to about 4 mm yr^{-1} for the last 25 yr (Nielsen and Nielsen, 2002).

Maximum current velocities measured 0.5 m above the bed are only about 30 cm s^{-1} at the mudflat and about 50 cm s^{-1} in the tidal channel. However, wind-generated waves often cause erosion of the bed at the mudflat as shown by numerous time-series records of the suspended sediment transport (Andersen and Pejrup, 2001). The mudflat site is very fine-grained with a sand content mostly below 2% and the bed is hosting a large macrozoobenthic population including the bivalves *Cardium edule*, *Macoma balthica* and *Mytilus edulis*, the polychaete *Nereis diversicolor* and the prosobranch *Hydrobia ulvae*. The channel site is mainly composed of sandy and mixed sediments and the macrozoobenthic community is very sparse with

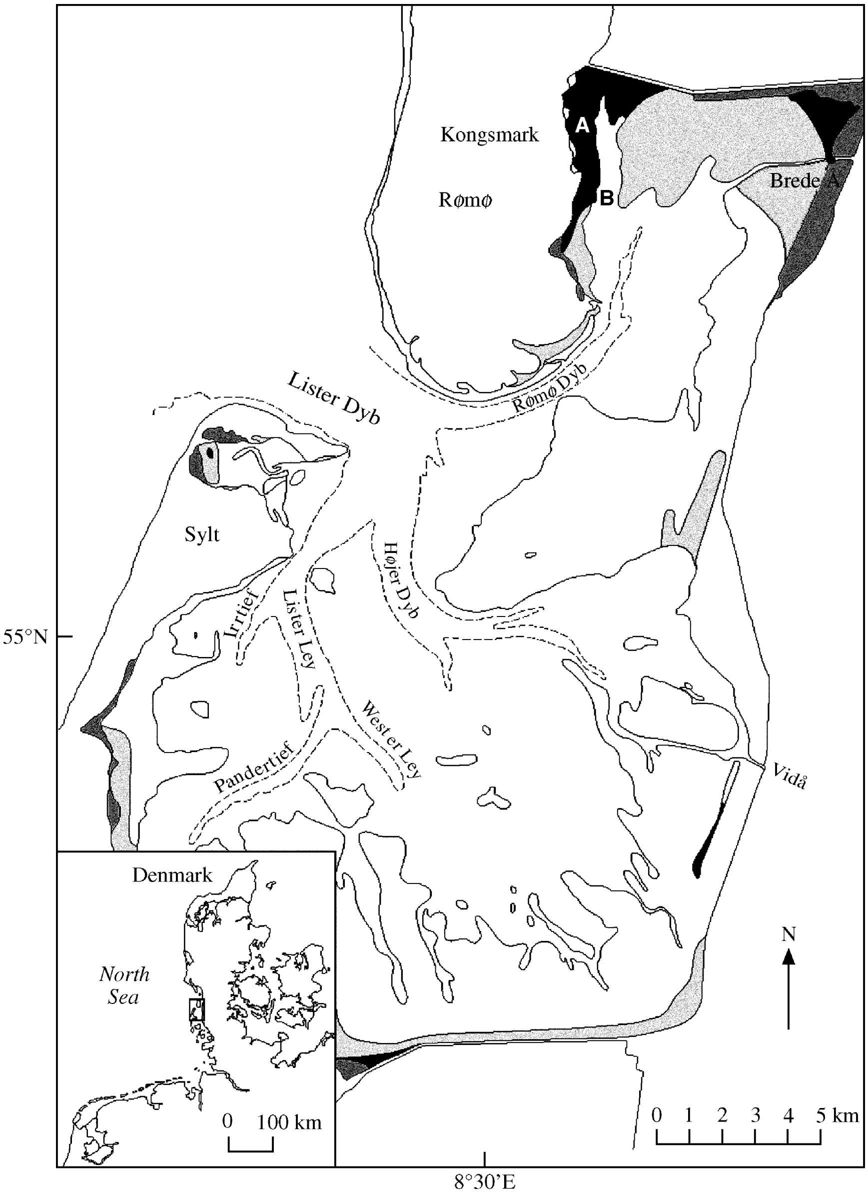

Fig. 1. Sedimentological map of the study area. The mudflat and tidal channel positions are marked “A” and “B”, respectively. Light grey: mixed mudflats; dark grey: salt marsh; black: mudflats.

only few polychaetes and bivalves present (Andersen et al., 2005).

3. Methods

3.1. Long-term monitoring of bed level

Six stations for long-term measurements of bed level were established in 1997 and the bed level has been measured since then at intervals of between 2 and 8 weeks. Stations are situated 20, 150, 225, 400, 500 and 700 m from the salt marsh on a transect perpendicular to the mudflat/salt marsh edge. Each measurement station consists of a 20×20-cm plate of stainless steel buried horizontally in the sediment and a stick, which mark the position. The bed level is measured as the distance between the plate and the sediment surface by use of a ruler (average of five measurements).

3.2. Bed level measurements at high temporal resolution

Measurements at a high temporal resolution have been carried out by use of two 2-MHz acoustic bed level sensors (Mrk. Altimeter, Micrell; described by Jestin et al., 1998). The self-recording instrument measures the distance between the sensor and the bed with an accuracy of ±2 mm and a resolution of 0.6 mm. Measurements were carried out every 10 min in 2003 and 2004 in the periods March to December corresponding to periods with no risk of ice-formation at the mudflat. Additional bed level measurements were obtained from a 10-MHz Acoustic Doppler Velocimeter (ADV), model Hydra, Sontek/YSI, which as part of the measuring program measures the vertical distance from the acoustic transmitter to the sediment bed with an accuracy of ±1 mm and a resolution of 0.1 mm. Measurements with the acoustic instruments were carried out at the mudflat 500 and 600 m from the salt marsh at stations, which initially showed large differences in benthic biology (microphytobenthos and macrozoobenthos) and hence sediment erodibility (e.g., Paterson, 1989; Austen et al., 1999). During part of spring 2004, one bed level sensor was placed at the bed of a tidal channel in order to provide simultaneous measurements in the tidal channel and at the mudflat.

3.3. Statistical analysis

A principal component analysis (PCA) was performed on the data-set from the long-term monitoring of the mudflat using MatLab. The analysis was performed for the period where measurements from all five stations were recorded, i.e., the period 1999 to 2005. The year 2005 was excluded from the analysis as the salt marsh now was only 2 m from the 20-m station, which changed the system from a pure mudflat to a combination of mudflat and pioneer-zone.

4. Results

An 8-yr record of bed level change at five stations (20, 150, 225, 400 and 500 m from the salt marsh) at the Kongsmark mudflat is shown in Fig. 2. The linear regressions shown in the figure give accretion rates of 17 and 12 mm yr^{-1} for the 20-m and 500-m stations, respectively. However, it is obvious that this accretion is not a slow and continuous process. Both periods of intense deposition and erosion are observed. Although interannual variations are large, there is a tendency for a seasonal variation. The seasonality is highlighted in Fig. 3 (modified after Andersen et al., 2005), which shows the difference between the measured bed level at station 500 m and the 8-yr trend line for the period March 1997 to December 2004 plotted as a function of season. The seasonality is apparent in this figure and the best third degree polynomial fit shown in the figure accounts for 40% of the variation in the data.

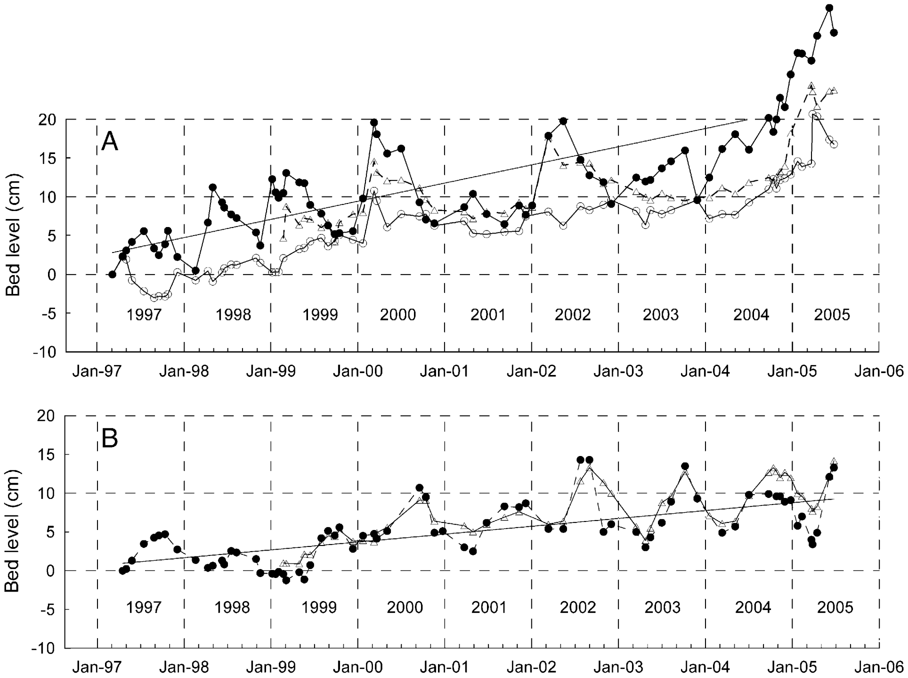

Fig. 2. (A) Long-term bed level change at the mudflat 20 m (solid circles), 150 m (open triangles) and 225 m from the salt marsh edge (open circles). Linear fit for the 20-m data is shown. (B) Long-term bed level change at the mudflat 400 m (open triangles) and 500 m from the salt marsh edge (solid circles). Linear fit for the 500 m data is shown. Based on manual measurements to buried steel plates.

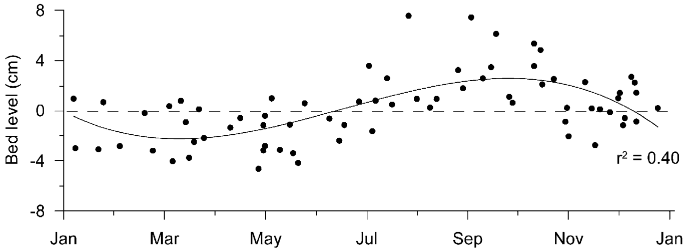

Fig. 3. Seasonal variation of bed level at the mudflat at the 500 m station. All data from the period March 1997 to December 2004 are included. The single data points reflect the bed level subtracted the long-term trend plotted as a function of date. Based on manual measurements to buried steel plates. Adapted after Andersen et al. (2005).

The seasonality is also apparent in the results from the PCA. More than 93% of the variance in the dataset can be described by the first two components. The first component, which accounts for 71% of the variance (Figs. 4 and 5), is related to the accretion-trend in the dataset and all five stations have positive weights (Fig. 5). The second component accounts for 22% of the variance and a very clear seasonal behaviour is observed (Fig. 4). This confirms the seasonality shown in Fig. 3. The change in sign of the weights (Fig. 5) shows that the 20-m station is behaving out of phase with the 400- and 500-m stations—when the innermost station is eroded, there is a tendency for deposition at the two outermost stations and vice versa.

The seasonality is discussed in detail in Andersen et al. (2005) and is related to both seasonality of hydrodynamics (low water temperature and generally more windy weather/higher waves in the winter compared to summer) and benthic biology (less biostabilization by benthic diatoms and less bioaggregation by *H. ulvae* in winter compared to summer). The effect with respect to sedimentation at the 500-m station is a tendency for net-deposition from late spring, over the summer season until early autumn. During this period, microphytobenthos will tend to stabilize the mudflat and the pelletization induced by the snail *H. ulvae* increases the aggregation and hence settling velocity of the bed material (Andersen, 2001a; Andersen and Pejrup, 2002). The biological impact on the sediment transport decreases during the winter period both due to the reduced solar radiation which reduces microphytobenthic growth and due to the colder temperatures which limits the activity of *H. ulvae* (Hylleberg, 1975). The hydrodynamic forcing is also higher during the winter period due to stronger winds and the result is a tendency for erosion of the mudflat during the winter season and early spring. However, this erosion mainly takes place early in the winter period, probably because the mudflat is quickly eroded down to a level of higher shear strength.

Plots of the high-resolution acoustic bed level measurements are shown for 2003 (Fig. 6) and 2004 (Fig. 7). Both years showed temporal variations, which were consistent with the general pattern shown in Fig. 3. Generally, deposition is seen to be a slow but continuous process with small increments in bed level from tide to tide during longer periods, whereas erosion mostly is confined to shorter periods with onshore winds at the site. Several millimetres of sediment often deposit at high water slack and then erode during the following ebb-period. An example showing data

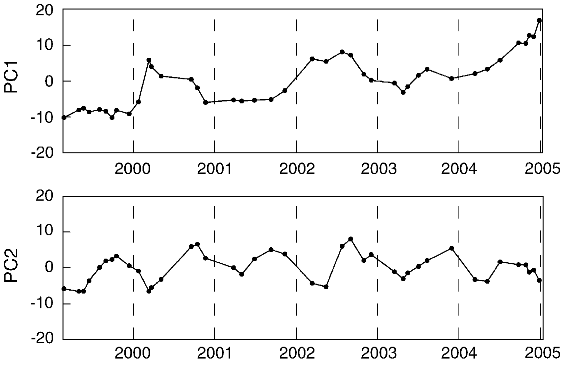

Fig. 4. The first two components of the principal component analysis. The first component accounts for 71% of the variance in the dataset; the second component for 22% of the variance.

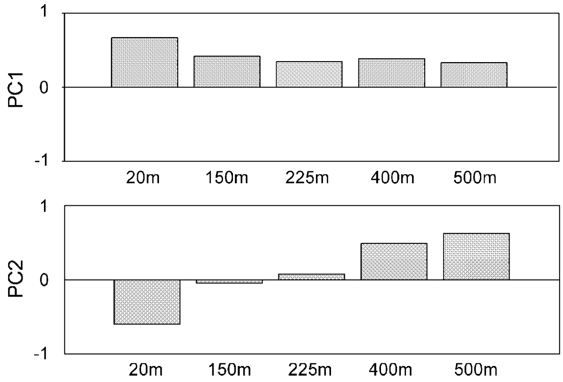

Fig. 5. The loadings of the first two principal components.

Fig. 6. Bed level change measured with a temporal resolution of 10 min at the Kongsmark mudflat, 2003. Data from the 500 m and 600 m stations are shown. Data from 2-MHz Altimeters.

from six tidal cycles in autumn 2004 is shown in Fig. 8. During this short and by no means exceptional period, the amplitude in bed level is 25–30 mm, which is of the same order as the yearly net-deposition. This shows that the gross-deposition is two to three orders of magnitude larger than the net-deposition rate.

The local spatial variation in bed level changes is highlighted in Fig. 6, which shows data from two stations situated 100 m from each other (500- and 600-m station). These two stations initially differed with respect to benthic biology as the 500-m station was dominated by *H. ulvae* whereas the 600-m station initially was dominated by biofilms. One of the results of these biological differences is a higher erodibility at the 500-m station compared to the 600-m station (Andersen, 2001a) and differences in bed level changes between the two stations were consequently anticipated. A difference was also observed during the first month of measurements when higher accumulation was observed at the 600-m station (the less erodible site). However, *H. ulvae* densities increased at this station during the summer to the same level as the 500-m station and little variation in erodibility were consequently observed for the rest of the year. Despite of the similarity with respect to bed sediment properties, rather large differences in sedimentation were observed with about 5 cm of accumulation at the 600-m station compared to less than 2 cm at the 500-m station in the period July 7 to October 1. The general trends at the two stations were similar, but the data shows that large spatial differences may be present.

The small-scale spatial variability can be seen in Fig. 9A, which shows 7 weeks of data obtained with an Altimeter and the ADV placed with a distance of 10 m. Although some differences are apparent, the main features of the two curves are similar. This shows that the bed level changes measured at one particular station generally may be considered representative for not only that single point but also for larger parts of the mudflat. The long-term monitoring presented in Figs. 2 and 6

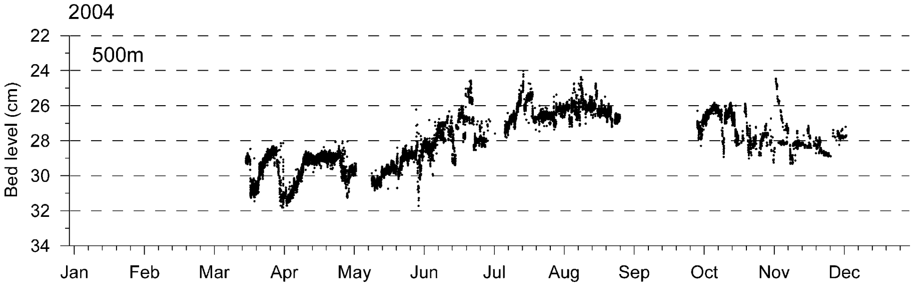

Fig. 7. Bed level change measured with a temporal resolution of 10 min at the Kongsmark mudflat, 2003. Data from the 500 m station is shown. Data from 2-MHz Altimeter.

suggests that the appropriate maximum extrapolation distance is in the order of 100 m at the middle part of the mudflat (generally high similarity between 400- and 500-m station) but somewhat shorter at the upper part where larger temporal and spatial variations are observed. The extrapolation of single point measurements to larger areas of the mudflat is only possible due to very flat and generally smooth sediment surface at the site. Larger bedforms are never present and if present ripples are only about 5 mm high. Similar extrapolations are more problematic at mudflats with larger bedforms, e.g., the ridge and runnel structures described for the meso-tidal Humber Estuary and Baie de Marennes-Oleron (Dyer et al., 2000; Bassoullet et al., 2000). Under such circumstances, a denser net of long-term measurement plates may help to determine if one particular station records changes, which are representative for larger parts of the mudflat in question.

Very rapid deposition of about 4-cm fluid mud was observed 3–4 November 2004 (Fig. 9B) in a situation with easterly (onshore) winds and maximum wave-induced orbital velocities of around 30 cm s^{-1} measured about 3 cm above the bed. The Altimeter measured reflections from both the top of the fluid mud and the underlying consolidated bed. The level of the consolidated bed did not change during the following six days, whereas the height of the fluid mud decreased. This decrease may both be due to erosion of the very mobile material and to autocompaction of the fluid mud. However, due to the continuous and smooth decrease in thickness, autocompaction is the most likely explanation. The observation of this deposition event clearly demonstrates that large amounts of mobile, fine-grained sediments are present in the tidal basin. Deposition of a similar fluid mud layer (although only 1 cm thick) was also observed by Bassoullet et al. (2000) in the Baie Marennes-Oleron (France).

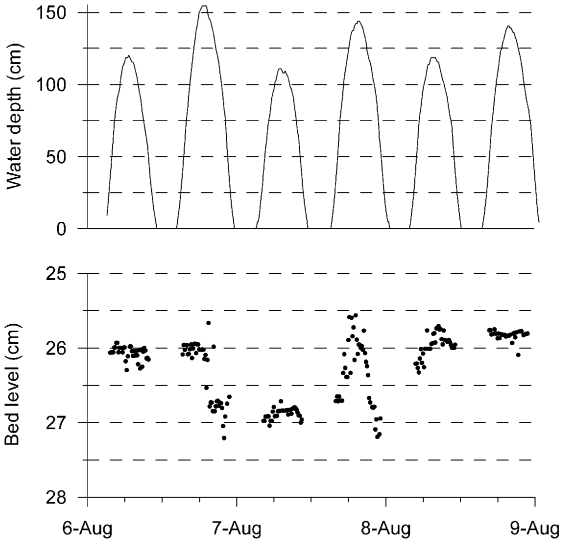

Fig. 8. Bed level change during six tidal cycles. 500 m station, summer 2004. Data from 2-MHz Altimeter.

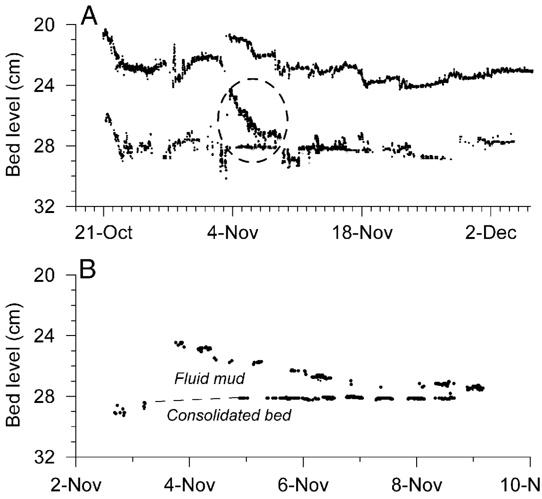

Fig. 9. (A) Comparison of bed level changes measured with a Sontek 10-MHz ADV (upper line) and a 2-MHz Altimeter (lower line) placed 10 m from each other. Measurements from the 500-m station. (B) A close-up of the time-series presented in (A). The rapid deposition of about 4 cm of fluid mud and subsequent consolidation/erosion of the mud in the following week is seen. Data from 2-MHz Altimeter.

The bed level data from simultaneous measurements at the mudflat and in the tidal channel are presented in Fig. 10. A very strong tendency for co-variation but in opposite directions is observed: when the mudflat is experiencing erosion, the tidal channel bed shows deposition and vice versa. This demonstrates that there is a close coupling between the sediment dynamics in these two morphological units of the sedimentary system. The erosion of the mudflat in the beginning of the period was caused by waves induced by strong westerly winds and it is readily seen that a substantial part of the eroded material immediately was deposited in the adjacent tidal channel. This event was followed by a calm period in which sediment slowly was eroded from the channel bed and deposited at the mudflat. Finally, wave-induced erosion of the mudflat took place due to easterly winds (onshore at the mudflat) and the material again seemed to be deposited at the channel bed.

5. Discussion

The present study has clearly demonstrated that large amounts of fine-grained sediments are eroded, transported and deposited each year in the coastal lagoon

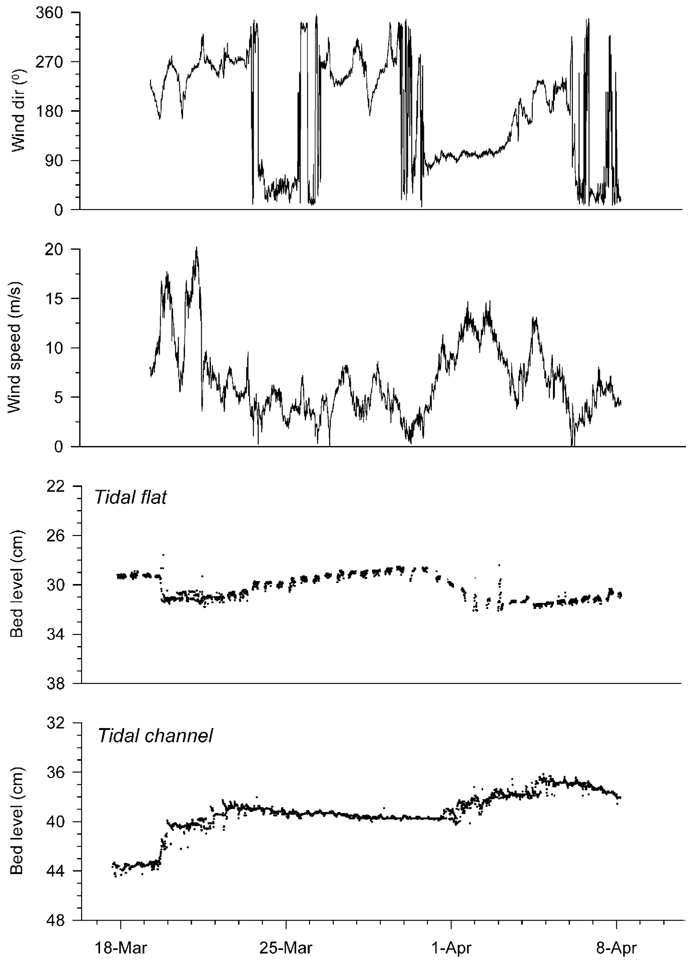

Fig. 10. Simultaneous measurements of bed level changes at the mudflat and in the nearby tidal channel. Data from 2-MHz Altimeters.

and that the net-deposition only constitutes a very small fraction of the gross-deposition. The general long-term trend of the net-transport direction of fine-grained suspended material in the tidal basin is inwards from the North Sea to the accumulating intertidal mudflats. This has earlier been shown by Pejrup et al. (1997) who calculated a sediment budget, which showed that about 65% of the fine-grained material accumulating in the basin was imported from the North Sea. This import is largely the result of tidal asymmetry (Dronkers, 1986) and settling and scour lags (Van Straaten and Kuenen, 1958; quantified for a Danish tidal basin by Bartholdy, 2000). Additionally, microphytobenthos and macrozoobenthos at the tidal flats modify the erodibility and aggregation of the sediment and mostly increase both the settling and the scour-lag and thus tend to increase the intertidal sedimentation (Andersen et al., 2005). This general inward transport of fine-grained sediment switches to an outward transport when the tidal flats are eroded due to local wind-induced waves. In the present temperate study area, erosion may also be imparted by drifting ice-floes during cold winters (Pejrup and Andersen, 2000).

The data-set from the present long-term bed level monitoring program revealed that there is a clear seasonality in the bed level changes at the mudflat and the changes at the inner and outer stations are in opposition to each other. Deposition at the inner station mainly takes place in late winter/early spring when most of the mudflat experiences erosion whereas deposition at the outer stations takes place during summer an autumn. The reason for this difference is not fully understood but is at least partly related to the difference in benthic microphytobenthos and macrozoobenthos at the different parts of the mudflat. Sediment deposited from drifting ice-floes may also contribute significantly to the deposition observed in late winter/early spring at the innermost station. The difference in seasonal behaviour along the mudflat transect highlights the importance of monitoring not just at one or two points at a tidal flat—quite different conclusions may be drawn depending on which part of a given mudflat is investigated. The study by O'Brien et al. (2000) from the macro-tidal Severn Estuary (UK) also revealed a seasonal signal in the erosion/deposition events at the studied mudflat with general erosion in winter and deposition the rest of the year. This behaviour is similar to most of the Kongsmark mudflat and this similarity is in spite of the much higher turbidity, milder winter climate and presence of a relict layer at their study site. This indicates that the seasonality in mudflat deposition in temperate areas mainly is caused by seasonal variations in biological activity, wind climate and water temperature rather than for example tidal range or river run-off, which are very different at the two sites.

The data presented in Fig. 10 demonstrates that a substantial part of the material eroded at the tidal flats during wind events is temporarily deposited at the bed of shallow channels and not lost from the sedimentary system. This finding also supports the results of the modelling study presented by Lumborg and Pejrup (2005) who found that fine-grained sediment was generally not exported from the tidal basin to the North Sea, even during gales. According to their modelling, most of the material eroded during such high-energy events settles within the tidal basin and is rapidly brought back to the tidal flats. Only during severe storms did their modelling suggest substantial export of fine-grained sediment from the lagoon.

The coupling between sub-tidal and intertidal sedimentation which the present study demonstrates is probably also present in other shallow estuaries and coastal lagoons and not just a local phenomenon. Seasonal variations of the bed level somewhat similar to the Kongsmark mudflat were found in the Deben estuary (UK) by Frostick and McCave (1979) who argued that the sediment accumulated on the mudflats during spring and summer due to algae binding and later was eroded and transported to channel banks in autumn and winter when algae were dead or absent. They did not have any bed level measurements in tidal channels to support their conclusions but the present study clearly corroborate their ideas by showing the coupling between sub- and intertidal areas. Christie et al. (1999) also argued that a similar coupling was present in the Humber Estuary (UK) where material eroded at the mudflat probably formed fluid muds at the channel bed. The two examples from the UK were both from meso- to macrotidal estuaries whereas the present study took place in a microtidal environment. Consequently, there is reason to believe that the close coupling between intertidal and subtidal sub-environments with respect to sediment dynamics is a general phenomenon, which is not seriously affected by tidal range. One of the implications of this is that assessment of the depositional state of an estuarine system should include the full system.

The long-term deposition rates, which were found in this study, are substantially higher than the local sea level rise, which shows that the mudflat/salt marsh system is prograding. This is generally also the case for other fine-grained tidal flats in the Danish Wadden Sea area (e.g., Madsen et al., 2005; Andersen and Pejrup, unpublished data). This indicates that, once a large-scale morphology that provides accommodation space for deposition of fine-grained sediment is established, sediment supply in this area is ample and easily counterbalances sea level rise. This is also supported by the observations of large amounts of mobile sediments during the present study. One important implication of this finding is that the anticipated sea level rise in the 21st century will not threaten these fine-grained tidal flats per se. Provided that the sediment supply is not decreased, sedimentation is anticipated to proceed at rates comparable to the present situation until the local morphology possibly restricts the sedimentation due to increased bed level. In this situation, sedimentation may get accommodation space limited as the water depth decreases and the tidal flats grow higher into the tidal frame where erosion due to wind-induced waves is stronger (e.g., Le Hir et al., 2000). There is no indication that the sediment supply will decrease. In fact, an increase is perhaps more likely as a result of a possible increase in the intensity of storms which may be anticipated (Lozano et al., 2004). Stronger storms will induce stronger erosion of coasts and the sea bed in the shallow parts of the North Sea and are consequently likely to supply more fine-grained sediments to estuaries and coastal lagoons in the region. Similarly, an increase in run-off due to increased precipitation (Labat et al., 2004; Thodsen, submitted for publication) is also likely to increase the fine-grained sediment supply from rivers due to the linkage between river discharge and sediment transport (e.g., Horowitz, 2003).

6. Conclusions

– Short-term changes in bed level are one to two orders of magnitude larger than the average yearly net-deposition rate, which shows that even the low-energy

microtidal basin presented in this paper is a highly dynamic environment with respect to transport of fine-grained sediment.
- A clear seasonality in the bed level changes was apparent with a tendency for mudflat deposition in spring, summer and early autumn and erosion during the rest of the year but interannual variations are large. Additionally, spatial differences occurred and the bed level change at the inner and outer part of the mudflat was generally in opposition to each other.
- A close coupling between intertidal and subtidal erosion and sedimentation was apparent due to the novel measurements of bed level change in a tidal channel, which were carried out as part of the present study. This finding supports earlier hypothesis of such a link and indicates that the sediment is generally not lost to the open sea when the mudflat is eroded.
- The data presented here and all measured accretion rates from fine-grained tidal flats in the Danish Wadden Sea area suggest that the mudflats are generally not threatened by the expected sea level rise in the 21st century.

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