Synthesis - new insights in the dynamics of sediment suspensions, associated with the coastal turbidity maximum, Belgian-Dutch coastal zone

A synthesis and discussion are provided on the understanding of suspended particulate matter (SPM) dynamics in the Belgian-Dutch nearshore zone. A coastal turbidity maximum (CTM) characterizes this area; still different processes control its dynamics. A particular phenomenon is the formation of high-concentrated mud suspensions (HCMS), impacting on near-bed processes.

Main questions are:

(1) What is the temporal variability of SPM concentration within the CTM zone?

(2) What is the spatial variability of the extent of the CTM zone?

(3) When and how are HCMSs formed? What is there influence on near-bed processes?

(4) Can acoustic and optical sensors be used to estimate the composition of SPM, especially in case of mixed (sand-mud) sediments?

(5) Can anthropogenically-induced changes in SPM concentration, due to e.g. disposal activities, be distinguished from the natural variability?

These five questions are addressed in four topics. A first topic relates to the natural SPM dynamics in the CTM zone. A second topic is on the formation of HCMS, with a focus on near-bed processes. A third topic is on the mixed-sediment environment in the CTM zone, and the implications on optical and acoustic measurements of turbidity. Finally, in a fourth topic, SPM concentrations and HCMS layers are proposed as indicators of environmental changes.

8.1.   *Natural variability of sediment suspensions*

In the Belgium-Dutch coastal zone high SPM concentrations occur that are highly variable in time. The natural variability is related to overall SPM dynamics (re-suspension, settling), as well as to CTM-associated processes (advection), both acting on different time-scales:

- Intra-tidal (tides)
- Sub-tidal (meteorological, spring-neap, seasonal)
- Long-term climatic influence (NAO)

The knowledge of these processes is critical to understand the CTM system, to reveal natural trends, and to distinguish those from turbidity increases, induced by human-related activities. Long-term observations are available in the vicinity of Zeebrugge harbour allowing investigation of this variability. It is well-known that advection of water masses influences physical parameters such as salinity and SPM concentration in front of the Belgian coast (e.g. Lacroix et al. 2004). Both parameters are proxies for describing the horizontal distribution of different water masses as was shown in Baeye et al. (2011) (Chapter 2), Fettweis et al. (2010), and Chapter 4.
The marine waters from the English Channel that enter the North Sea through the Dover Strait have high salinity (>34) and generally low SPM concentrations. The coastal zone includes the region of freshwater influence from the Scheldt river (and Rhine-Meuse), which is characterized by lower salinity (28-32) and high SPM concentrations. These water masses can be advected under the influence of wind and tides. Therefore our data showed that high SPM concentrations are often more closely related to advection (Velegrakis et al. 1997, Blewett and Huntley 1998), rather than to instantaneous bed shear stress (Stanev et al. 2009). On a longer term, 2 periods, i.e. a high turbidity (late fall until early spring) and a low turbidity period (late spring until early fall) can be distinguished, corresponding to high-energy seasons (more storm activity) and low-energy periods (less storm activity). Other processes (water temperature and biological activity, river runoff and sediment load) are correlated with seasons, but they are of minor importance. Group-averaging procedures and entropy

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analysis (statistical treatment) were used taking into account classification parameters that incorporate variability induced by:

- subtidal flow direction and strength;
- alongshore and cross-shore wind components (local wind field);
- North Atlantic Oscillation Index (NAOwi) (contrasting winters); and
- storminess (linked to winds with north component)

All 4 parameters are related to the wind climate, but correspond to different time-scales. Regarding the first 2 parameters, two cases are considered, based on differences in advection (northeast- against southwest-ward alongshore flow regime). Briefly, one can state that the northeast-ward flow corresponds to sustaining southwest winds, resulting in an overall decreased SPM concentration background. Further, major southwest wind events re-suspend bottom sediments (combined wave and current interaction) showing peaks in SPM concentration. Under these hydrodynamic conditions, in-situ re-suspension of mixed sediments (cohesive sediments and fine sands) can occur, and the CTM is extended more towards the Dutch coastal zone (entropy based analysis of MODIS-Aqua derived SPM maps in Chapter 3). The southwest-ward flow regime, typically under winds blowing from the N to NE sectors, tends to decrease the spatial extent of the CTM, but increases the SPM concentration. Here, it was observed that the advective sediment flux is the major process. The role of the Westerscheldt river on SPM input is considered as minor, since freshwater outflow is low (Fettweis et al. 2007a). Several authors have suggested that the estuary acts as a temporary sink of fine-grained (marine) sediments, rather than being a significant source of fine-grained (fluvial) sediments (Terwindt 1977, Van Alphen 1990, Verlaan and Spanhoff 2000). Arndt et al. (2011) studied the Westerscheldt estuary freshwater plume dynamics; they concluded that during prevailing winds with north component (SW-ward flow regime) the fresher water region extends maximal towards the SW; whereas under sustained SW winds the plume is much reduced, and retreated in the estuary. The synoptic SPM concentration maps regarding the two regimes are thus not linked to the observed freshwater Scheldt river 'plume'. In addition, the CTM zone extent under the SW ward flow regime is not connected with the Scheldt river mouth. Therefore, the CTM is not a typical river plume system, but is rather governed by the local hydrodynamics along the coast.
The storminess affecting the study area is also an important contributor for sediment re-suspension (Fettweis et al. 2010). Storminess is related to the NAO index which explains most of the variability in wind climate during December to March (NAO winter index = NAOwi Hurrell (1995)) providing the following synthesis:

- Sustained negative phases in the winter index are generally associated with dry and calm weather, with observations of weaker and more variable winds; and
- Positive phases: wetter, stormier weather over Europe, with increased abundance of southwesterly winds.

Variation in the NAOwi index (- or +) can be a proxy to explain the variation in the spatial distribution of SPM along the coast. In chapter 3, it was found that the influence of contrasting NAO conditions during two winters has a striking effect on the spatial extension of the CTM zone. Further, the storminess in the North Sea will also result in the development of high waves travelling from the North (large fetch). These waves are energetic, and will easily stir up bottom sediments. These meteorological events are the most extreme conditions for the Belgian-Dutch coastal zone, with a maximal CTM spreading and SPM concentrations (see Chapter 4).
Over the last decades, trend analyses of wind directions show an increase of southwesterly winds (Siegismund and Schrum 2001, Van den Eynde et al. 2011) in the southern North Sea. The geographical extension of the CTM during the last decades was thus more often spreading towards the mouth of the Westerscheldt estuary/Dutch waters as before, with a buffering of SPM into the river system (e.g. Terwindt 1977).

8.2. HCMS appearances in the coastal turbidity maximum

Direct evidence of high-concentrated mud suspensions (HCMS) was found in bottom samples. However, this study allowed identifying HCMS in the coastal turbidity maximum, through a combination of different instrumentation:

- optically (Optical Backscatter Sensor (OBS), Burial Recording Mine (BRM))
- acoustically (Acoustic Doppler Velocimeter (ADV), Acoustic Doppler Profilers (ADP))

The water column is typically characterized by high near-bed SPM concentrations decreasing towards the sea surface. Evidence derived from OBS points to the existence of HCMS. This study showed that the optical-based BRM is also able to measure HCMS. With nowadays acoustic instrumentation bottom detection routines have become available that are able to track bed evolution. Good bottom boundaries, such as hard bottoms (sand, concrete), generate well-defined peaks, in contrast to HCMS or fluid mud providing gradual transitions in their density gradient. Still, it is possible that a layer of higher concentration sediment is developing and triggers the peak-finding routine (pers. communication Velasco). In Chapter 2, it was suggested that a strong vertical sediment-induced density gradient acts as an acoustic reflector associated to the presence of HCMS. The generation of very high SPM concentrations near the bed implies that significant amounts of fine-grained sediments have to be re-suspended and/or eroded (see Chapters 3, 4 and 6). Spatial variability in the extension of the CTM zone, as well as in the SPM concentration, controls the extension, formation and the duration of HCMS occurrence. HCMS are related to different time-scales:

1. random events, such as storms;
2. low-energy conditions (e.g. neap tides; overall weak (land) wind conditions (typically <0.1 N m^{-2}); and
3. slack water phases

Waves may fluidize and erode cohesive mud beds (Maa and Mehta 1987, De Wit and Kranenburg 1997, Li and Mehta 2000, Silva-Jacinto and Le Hir 2001). In the Belgian nearshore area, it was found that during or after a storm, the SPM concentration increases significantly and HCMS are formed (evidence from OBS on benthic tripod).

HCMS types 2 and 3 differ from each other in terms of the duration of the HCMS occurrence (days vs. hours); HCMS layers formed during neap tides tend to last several days and are called semi-permanent HCMS layers in Chapter 2. In the much smaller time window of slack waters, transient or rapid HCMS may occur if SPM concentration is sufficiently high. The latter is typically associated with settling and re-suspension cycles occurring on a quarter-diurnal time scale. The characteristics of the near-bed current ellipse will determine the time of settling and re-suspension. In the nearshore area (CTM zone), the tidal ellipses are elongated, with more pronounced slack waters. The circular ellipses, typically occurring offshore, have less pronounced slack water phases. The altimetry of the ADV was configured to measure the vertical variations in seabed level, used to detect deposition and re-suspension of fine-grained sediments, and more specifically the presence of HCMS. Often a failure of the bottom boundary detection of the ADV was observed, that was explained by attenuation of the acoustic signal due to too high SPM concentration. Therefore the total attenuation of the signal or the failure of the bottom detection in the ADV indicates HCMS occurrence. In Fig. 8.1, time-series of ADV 5 MHz attenuated signal of bed detection is correlated with wind data, tidal range and current velocities. This particular time-series comprises the different types of HCMS favouring conditions, and corresponds in 52% of the time to the occurrence of HCMS. At about day 308, a HCMS occurred associated with a southwesterly storm. During neap tide, around days 300-306, a long-term HCMS layer (~fluid mud) was perceived under sustained southerly, weak winds (eventually backing to easterly winds and weak northern winds). During this period, the ADV currents measurements failed, as also the measuring volume was situated in the HCMS, which was at least 20 cm thick (20 cm corresponds to the distance of the

measuring volume of the ADV above the bed). Short-term slack water HCMS occurrences are observed throughout the first 6 days.

Table 8.1 lists up the percentage of time that the ADV failed in sensing the bottom for all benthic tripod moorings (at sites nearby the harbour of Zeebrugge - BLA and MOW1). HCMSs were present about 10% of the time at both mooring stations. Further, HCMS layers occurred throughout the year. When seasonality of the SPM concentration time-series is considered, HCMS layers occur in about 12 % of the time during the high-energy season, and in about 5 % during the low-energy season. The latter indicates the highly reduced SPM availability under those conditions, as also the lack of storm periods.

HCMS formation may be responsible for fast and massive siltation of the navigation channels, the access channel to the port of Zeebrugge (Pas van het Zand), and the port of Zeebrugge itself. Massive siltation is often observed during or after storm events. Indeed, soft mud deposits may be re-suspended from the navigation channels during stormy periods (see Chapter 4, Fettweis et al. 2009, 2010). This release of fine-grained sediments contributes to the formation of HCMS layers in the adjacent areas and to massive siltation after the storm in the dredging areas. The measurements carried out in the framework of an alternative disposal of dredged material practice revealed another HCMS formation (Chapter 7). The disposal of mud caused a long-term and significant increase in SPM concentration in the benthic layer. Evidence from ADV boundary detection (at least 32% of the mooring period) strengthens the idea of HCMS layers formed during the disposal of mud.

HCMS processes have an influence on object and mine burial applications (Chapter 6). From the test mine burial experiment, conducted at a site at the offshore edge of the CTM zone, a cyclic burial signal was found that was associated with HCMS formation during slack tide (1-2 hours). The study suggested that longer-term burial of the object by HCMS may occur, depending on the location (or local hydrodynamics). Hydrodynamic modelling has shown that most of the CTM zone is considered as a risk area for periodic mine burial by HCMS layers (Legrand et al. 2011).

8.3. Cohesive and non-cohesive sediment dynamics in the CTM zone

8.3.1. Combined-use of acoustic and optical instruments

A suite of optical and acoustic sensors, mounted on various platforms (tripod, bottom-mounted), was used to study sediment processes in the coastal turbidity maximum zone. By combining all available data sets, it was possible to improve the understanding of the behaviour of cohesive and non-cohesive sediments and their dynamics, and to monitor the occurrence of HCMS layers. It is suggested that cohesive and non-cohesive SPM dynamics may occur simultaneously in the study area under storm and enhanced flood phase conditions. Consequently, particle fraction separation, due to differential settling, may lead to an alternation of sand and mud layers. Indeed, seabed cores showed often that thin sand layers overtop Holocene mud layers, but also that HCMS or fluid mud layers occur on top of sand layers. This has implications towards erosion, as shown by e.g. van Ledden et al. (2004) and Le Hir et al. (2007).

Storm-induced waves, and associated sediment mobilization, lead to deposition of sand-dominated layers (storm deposits). As a result, the sand layer may act as a reservoir for fine-grained material (Chapter 2). On the other hand, HCMS may also protect the sand from being eroded in the CTM zone, due to inverse armouring. The particle size distribution (PSD) of the SPM is discussed in Chapters 2, 4 and 5. Different classification techniques (entropy, group-averaging) revealed a distinct (multi-modal) behaviour in PSD during tide-dominated and major wind (or storm) conditions. Particle size class spectra are dominated by micro-flocs with a rising tail in the lower size classes during maximum flood currents, suggesting partial disruption of micro-flocs into primary particles. Surprisingly, in the case of sustained winds (or storm-induced winds) blowing from the southwest (typically associated with increased wave action, and most abundant wind sector for the study area), it was found that the Laser In-Situ Scatter- and Transmissometer (LISST-100), or in-situ particle sizer, revealed the absence of primary particles. Particle size distributions were log-normal and shifted towards the silt to fine sand range. The OBS-3 systematically showed reduced SPM concentrations under these conditions, whereas increased SPM
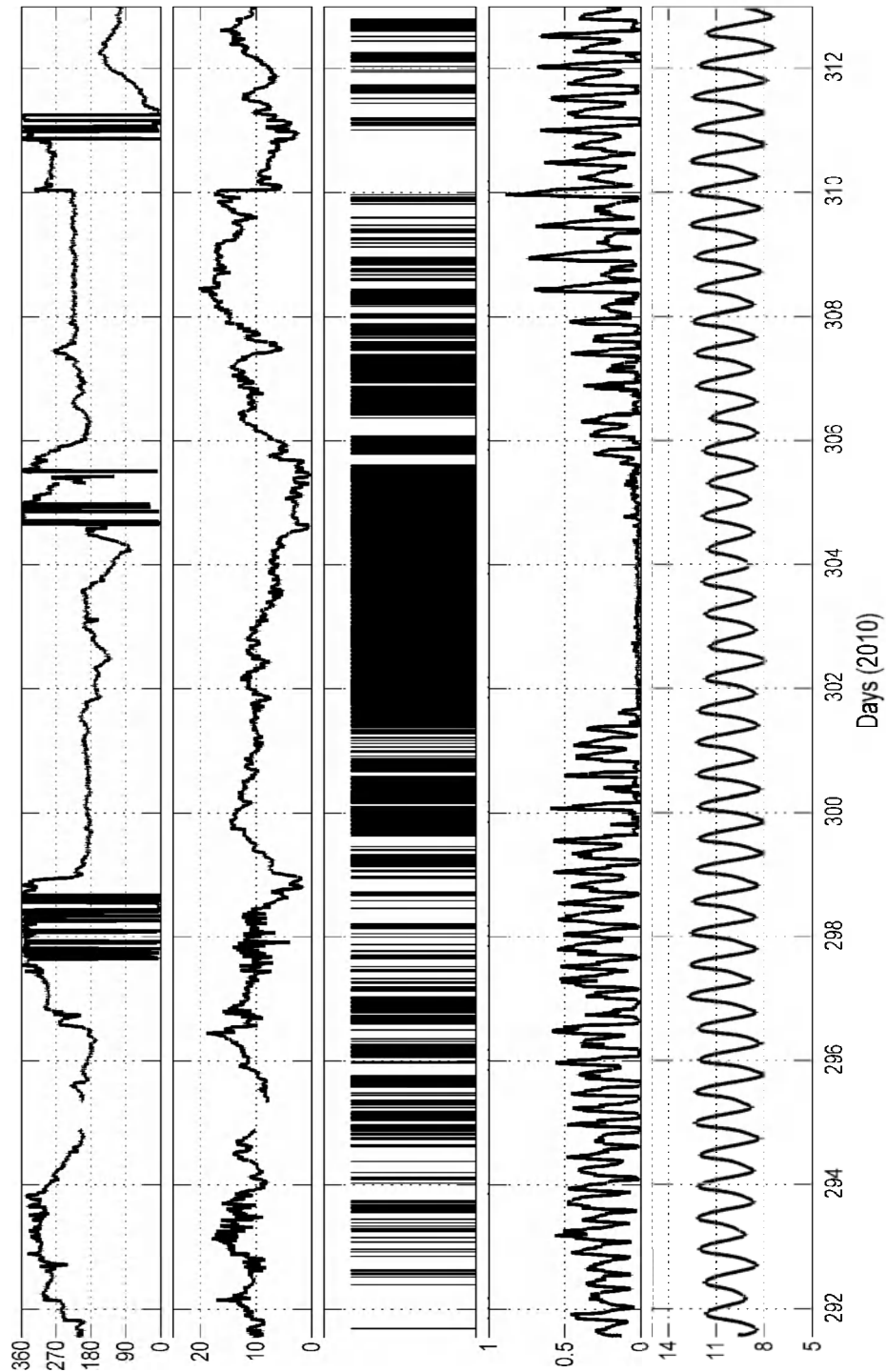
Figure 8.1 Time-series of wind direction (meteorological convention, °), wind strength (m s^{-1}), ADV failures in detecting the seabed (= HCMS appearances), ADV currents (m s^{-1}), water depth (m- MLLWS), from **top** to **bottom** respectively

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Table 8.1 (**left**) MOW1 moorings with percentage of time with expected HCMS occurrence, and (**right**) BLA moorings

| deployment | | % of Time Failed |
start	end	Bottom Detection
07/02/05	08/02/05	6%
04/04/05	15/04/05	23%
22/06/05	12/07/05	14%
22/11/05	05/12/05	28%
13/02/06	27/02/06	7%
15/05/06	15/06/06	29%
10/07/07	19/07/07	2%
17/11/08	12/12/08	29%
09/02/09	19/03/09	24%
26/03/09	29/04/09	4%
06/11/09	08/12/09	9%
11/12/09	25/01/10	22%
25/01/10	25/03/10	16%
25/03/10	20/05/10	9%
20/05/10	23/07/10	6%
18/10/10	17/11/10	52%
17/11/10	15/12/10	27%
15/12/10	11/01/11	27%
31/01/11	21/03/11	23%

| deployment | | % of Time Failed |
start	end	Bottom Detection
08/11/07	15/12/07	20%
28/01/08	24/02/08	8%
06/03/08	08/04/08	20%
15/04/08	05/06/08	7%
04/05/09	15/06/09	32%

concentrations were derived from the ADP. These results are compared to independent observations from the LISST-100, revealing a shift in the particle size spectrum towards the sand fraction. Optical and acoustic sensors are indeed sensitive to changes in the particle size distribution (Thorne et al. 1991, Lynch 1997, Hamilton et al. 1998, Creed et al. 2001, Fugate and Friedrichs 2002, Voulgaris and Meyers 2004, Downing 2006). Generally, acoustic back-scatterance is more sensitive for larger solid particles than the OBS. The sensitivity of the instruments (OBS-3, ADCP) for different particle sizes was investigated. First results are presented in Chapter 4 where, the corrected backscatter, derived from the bottom-mounted ADCP, was correlated with the LISST. It was found that particle sizes, ranging between 40 and 100 µm, are most accurately measured by the ADCP. This is in agreement with the theory indicating that acoustic signals are most sensitive for $ka \sim 1$, k being the frequency of the acoustic signal and a the particle diameter (e.g. Lynch et al. 1997). A similar analysis was performed by comparing the OBS-3 output voltage to the different particle sizes measured by the LISST-100 (Fig. 8.2). A maximum ($R^2 > 0.90$) is obtained for the particle sizes 25 to 80 µm, but decreases significantly for sizes larger than 80 µm. Subsequently, three individual size classes of the LISST are plotted against OBS-3 voltage and remarkably, the higher size classes correspond readily to 2-phase response curves (i.e. two different volume concentration population curve) (Fig. 8.3). This also explains the decrease in correlation degree, and pleads for cohesive sediment dynamics. Flocculation will lead to increasing volume concentration of the flocs. On the other hand, the lower curve (less steep slope) agrees with the presence of fine-grained material (fine sands) that is in suspension at 2 mab. Acoustics better estimate mass concentration since it is insensitive to density and size of flocs (Gibbs and Wolanski 1992, Bunt et al. 1999, Fugate and Friedrichs 2002, Hatcher et al. 2011). The acoustic backscatter-concentration is based on the mass concentration of the smaller constituent primary particles.
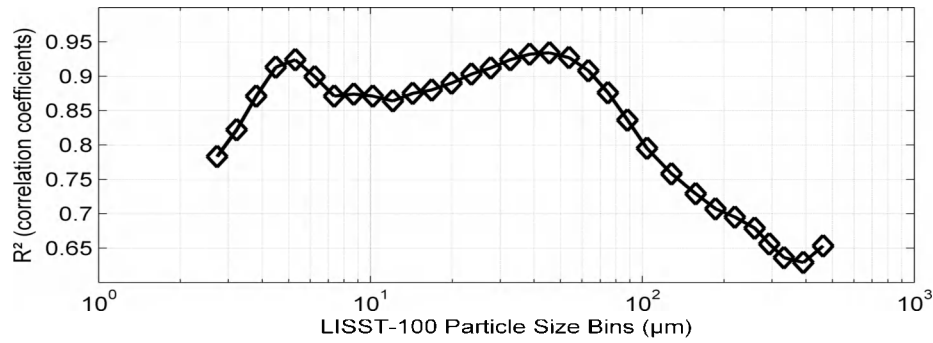
Figure 8.2 *Correlation between OBS output voltage and LISST volume concentration for each particle size class (total of 32 classes, ranging between 2.5 and 500 μm)*

8.3.2. Conceptual nearshore sediment transport

An extract from a spring-neap cycle time-series has been selected to show the different situations that are representative for the processes occurring in the CTM zone (Fig. 8.4). Most of the findings described above and in previous chapters are briefly schematized regarding SPM behaviour (concentration and nature) and HCMS occurrences:

Event I (day 28-30) & **V** (day 37-42): coastal waters; low energetic conditions (wind speeds < 10 ms^{-1}); spring tidal excursion (see large salinity and transmission oscillations); cycles of ebb floc formation and flood floc breakup; wide multi-modal particle size spectrum (or multiple particle size populations); slack water HCMS; long ebb phase allowing cohesive particles to floc together up to sizes of 500 μm.

Event II (day 30-31): more oceanic water input (increase in salinity); strong south-westerly winds; fine sands and decrease in (total) volume concentration (sand has higher density); decrease in the OBS-3 response; increase in acoustic backscatter; increased uni-modal particle size distribution (note that the particle size distribution is measured 2 mab); vertical segregation in the sand fraction; the higher in the water column the smaller the sand particles; absence of cohesive sediments; flocs are broken, and transported away from the measuring locations by wind-induced flows (SW winds).

Event III (day 32-33): storm event (winds with north component); increased SPM concentration; fine sands in suspension (since cohesive sediments were broken up and largely transported towards the northeast during event II); the cohesive sediment layer becomes exposed and fluidized as HCMS.

Event IV (day 33-36): medium energetic conditions (wind speeds ~10ms^{-1}); neap tidal signal in the cohesive SPM dynamics is less pronounced; post-storm HCMS formation during neap tide (day 34).

8.4. SPM concentration and HCMSs as indicators to detect environmental changes

Environmental changes are often inferred from changes in benthic communities (Dauer et al. 2000, Dauvin et al. 2007). SPM may be a driver of such change since it carries a major part of the food resources, though high concentrations may interfere with species filtering and respiratory systems (Rodriguez-Palma 2011). However, SPM concentration is known for its high spatial and temporal variability. Hence, it remains utmost challenging to distinguish naturally- from anthropogenically-induced disturbances. From long-term change analysis of the spatial distribution and relative abundance of macrobenthic species within the Belgian part of the North Sea, SPM was
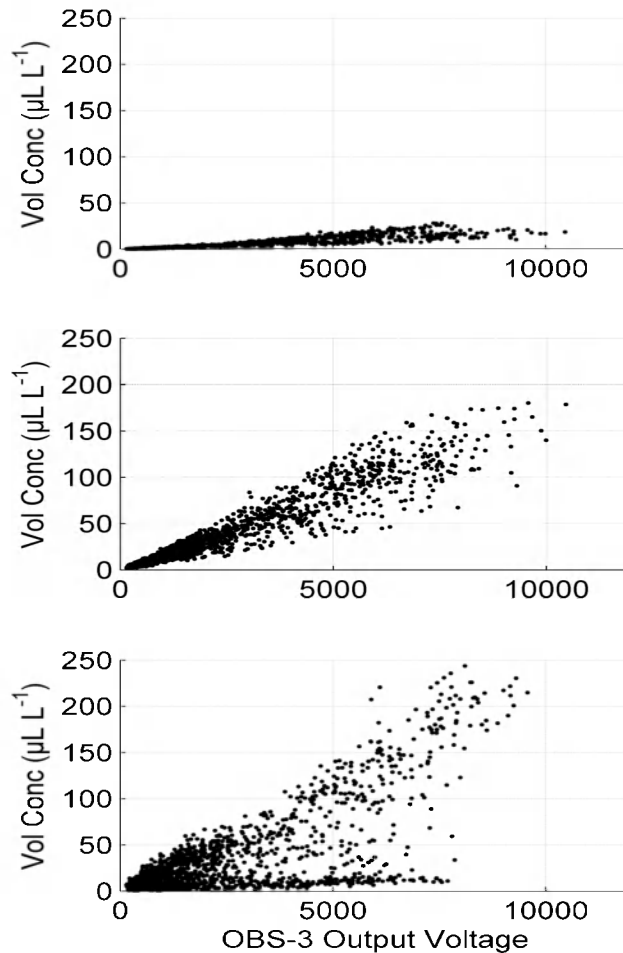
Figure 8.3 *Scatter plots for three different LISST-100 bins and OBS output signal; from **top** to **bottom** ~5 μm, ~45 μm, ~150 μm, respectively*

indeed hypothesized as being a main driver of environmental change (Van Lancker et al. 2011). Comparing the periods 1899-1908 and 1994-2008, it was shown that bivalves, tolerant to higher mud contents, expanded, whilst bivalves typically thriving in clean sands, reduced significantly in their distribution and relative abundance. These findings agreed well with the suggestion of a human-induced increase of turbidity, which has likely resulted in transient deposition of higher amounts of surficial mud (Fettweis et al. 2009, Houziaux et al. 2011). Macrobenthos analyses pointed also to a higher amount of species contributing more evenly to bivalve species richness, as compared to the historical situation. A probable effect of eutrophication of the area, during the second half of the 20th century was hypothesized, as also the influence of NAO cyclicity. The latter was investigated in relation to the Westerscheldt river discharge, but no significant correlation could be found (Van Lancker et al. 2011).

The human-induced increase in turbidity was attributed mainly to increasing port and dredging works altering the fine-grained sediment dynamics (Fettweis et al., 2009). However, data, presented in chapter 3, suggest also that the CTM zone has become more significant (i.e. increased spatial extension and SPM concentration), due to an increasing frequency of occurrence of SW winds (Van den Eynde et al. 2011). As such, human-induced changes in SPM concentration are further influenced by changes in natural conditions.
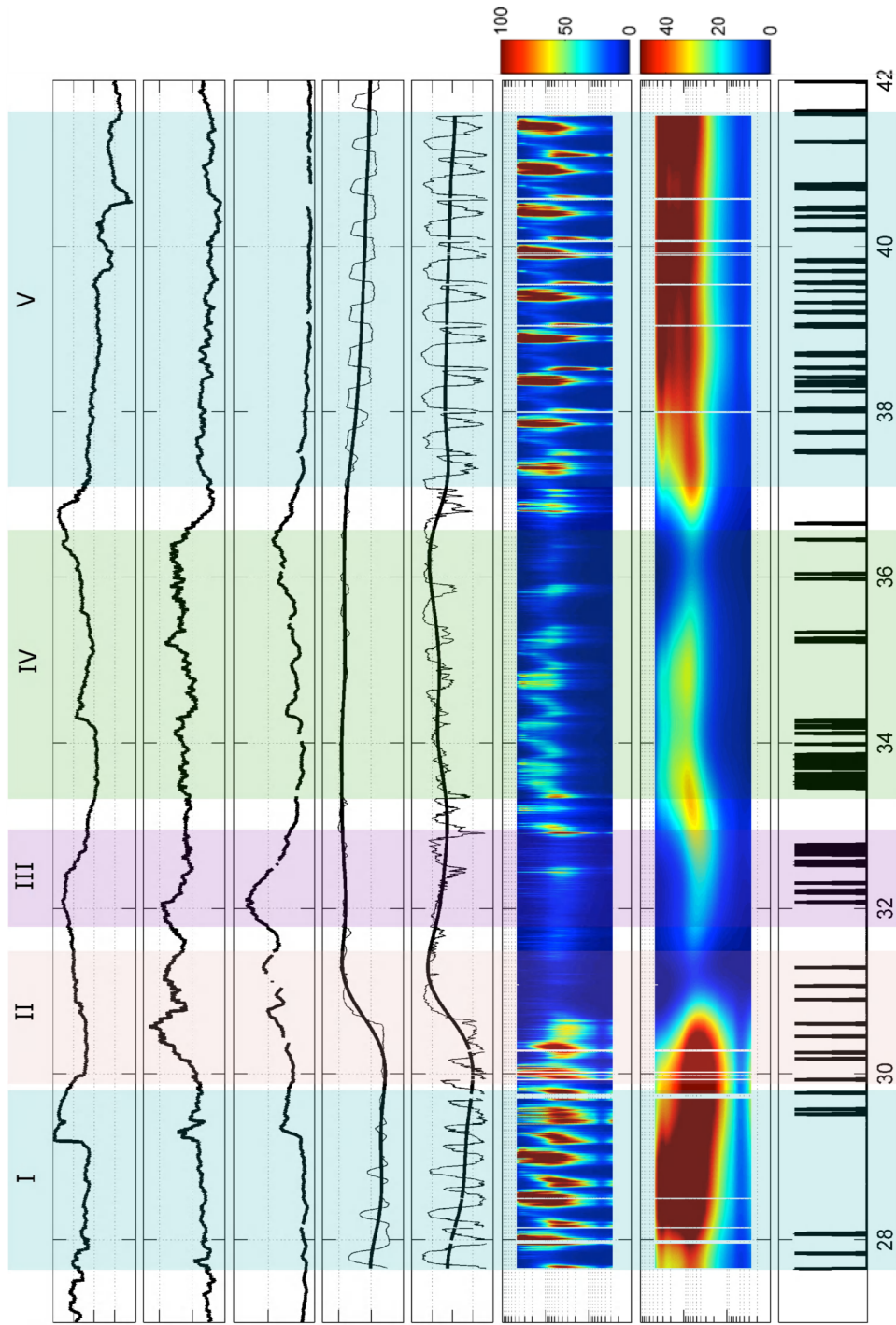
Figure 8.4 *Time-series: wind direction (°, meteorological convention), wind speed (m s⁻¹), wave height (m), salinity (PSU), LISST-100 turbidity (in %), LISST-100 particle size distribution (PSD) (in µL L⁻¹), low-pass filtered LISST-100 PSD (in µL L⁻¹), ADV-derived HCMS occurrences (spikes)*

For assessing natural from human-induced variability in SPM concentration (e.g. dredging-disposal activities for harbour accessibility or marine aggregate extraction) sufficiently long (monthly basis) time-series of SPM concentration in the CTM zone are needed that cover the highly spatial and temporal variability of the natural SPM concentration. A technique was introduced (Chapter 7) that analysed SPM concentration, at a specific station, as a statistical population. Therefore, the observational time-series (or subsamples) could be considered as subsamples of the total population. Fettweis and Nechad (2011) showed that SPM concentrations are log-normally distributed, and by considering such sub-populations as a log-normal distribution function, conclusions could be drawn concerning the representativeness of the sub-population. Using long-term tripod data, we were able to quantify the effect of disposal activities during a dedicated experiment (Chapter 7) within the CTM zone.

From the previous section, it was observed that salinity (low-pass filtered signal in figure 8.4) and turbidity (low-pass filtered transmission LISST-100) correlated significantly ($R^2=0.90$). It is therefore suggested that long-term salinity observations may act as a reference of the natural variability. Human-induced episodic influences in the SPM concentration time-series are expected to diverge from the salinity time-series trend line. To evaluate this oceanographic parameter as potential proxy for natural changes, hence linked to water mass distribution only, further research is needed.

In addition to the SPM concentration in the water column, near-bed processes associated with HCMS layers, whether or not related to disposal of dredged material, may also affect the habitat and benthos population. Physical properties of the seabed (such as grain size, porosity ...) characterize the substrate which is known to be a driver of patterns in diversity, function and integrity of benthic communities (Cardoso et al. 2010).

Therefore, it is expected that (massive) siltation (with HCMS layers) of the seabed may result in the presence of more opportunistic species in an area.

In summary, it is recommended to further evaluate SPM concentration and HCMS layers as drivers of habitat and benthos changes. If their importance is confirmed, these aspects should be considered also when optimizing disposal operations of fine-grained material from maintenance dredging and deepening works. If relationships can be established with changes in ecosystem structure and functioning, they have a high potential to become indicators of good environmental status for seafloor integrity within Europe's Marine Strategy Framework Directive (Van Lancker et al. 2011 b, Rice et al. 2012).

8.5.   References

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