Full length article

Weather and climate induced spatial variability of surface suspended particulate matter concentration in the North Sea and the English Channel

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A B S T R A C T

Images from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite have been used to investigate the meteorological and climate induced variability of suspended particulate matter (SPM) concentration in the North Sea. The meteorology has been characterized by the 11 weather types deduced from a refined system of Lamb’s classification of synoptic weather charts. Climatological effects have been related to the North Atlantic Oscillation index. The surface SPM concentration maps from MODIS have been ensemble averaged according to these weather types or climatological conditions. The data show that each type has a distinct distribution of surface SPM concentration in the North Sea. The differences are explained by different hydrodynamic and wave conditions. The occurrence of storms will impact the shallow regions by increasing the resuspension of bottom material. Prevailing winds will, on the other hand, change the residual transport of SPM in the North Sea. The more protected Southern Bight exhibits relatively stronger influences of advection, whereas in the central North Sea and the German Bight resuspension is more pronounced. This patterns result in an alternation of relatively high SPM concentration in the Southern Bight and in the rest of the southern North Sea during certain weather conditions. Limitations in satellite images have been assigned to stratification effects due to the occurrence of highly concentrated mud suspensions during certain

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1. Introduction

Various processes may induce variations of suspended particulate matter (SPM) concentration on temporal and spatial scales. On short time scales, the predominant forcing is related to tides, waves and atmospheric circulation (Baeye et al., 2011), and locally to stratification by fresh water input (Pietrzak et al., 2011). These variations are caused by resuspension, mixing, settling and deposition of fine-grained sediments, as well as by advection due to subtidal flows. On longer time scales neap–spring cycles and meteorological and climatological variations become significant. Meteorological patterns, acting on regional and global scales, are responsible for wave induced resuspension and determine the advection of water masses. Annual variations are caused by seasonal changes in wind pattern and strength and result in high SPM concentration during winter and low concentrations during summer. Climatological effects are linked to the frequency of occurrence of certain weather patterns, e.g. the North Atlantic Oscillation (NAO) is responsible for much of the observed weather and climate variability in the North Sea, especially during winter months (Hurrell, 1995; Schwierz et al., 2006) and this has thus a pronounced effect on SPM concentration. The meteorology of the southern North Sea is characterized by the west to east passage of depressions, and by the development or weakening of high pressure systems. These fluctuations of the wind field occur at time scales of a few days to one week, whereas the climate variability acts on seasonal and longer time scales. The winter NAO exhibits significant multi-decadal variability with positive values indicating anomalously strong westerly winds and wet conditions over north-western Europe, whereas negative values indicate weaker westerly flow, less precipitation and intrusion of colder arctic air (Hurrell, 1995).

The use of atmospheric circulation patterns to describe different situations has proven to be very useful in meteorological and climate change studies (Demuzere et al., 2009; Ullmann and Monbaliu, 2010). For the North Sea region, spatial and temporal changes of weather pattern strongly influence the climatic conditions and the hydrodynamic circulation patterns. The effect of weather and climate on hydrodynamics are well described for the North Sea (Holt et al., 2010), however, their influence on SPM concentration is often limited to the description of seasonal SPM concentration patterns (e.g. Fettweis et al., 2007). The present research focuses therefore on large scale geographical variability of high turbidity zones in the North Sea and the English Channel induced by meteorological and climatological variations using remote sensing data. The southern North Sea, with stronger tidal currents and shallower water, has higher SPM concentrations than the northern North Sea. The most important high turbidity areas are the Belgian Dutch Coastal zone (Flemish Banks); the Thames plume extending eastward into the East Anglian plume; the Humber coast; the Wadden Sea and the coastline along the West Frisian (The Netherlands), East Frisian (Germany) and North Frisian (Germany and Denmark) Islands, see Fig. 1. The main sources of the SPM are coastal erosion (Holderness coast; cliffs of Dover and Calais), local erosion of fine-grained sediments (e.g. Flemish Banks), rivers and the Atlantic (Eisma, 1981). Eroded fine-grained sediments from the Holderness cliffs are transported in the East Anglian plume towards the east and are partly deposited as muddy sediments in the Oyster Ground (Zuo et al., 1989). The Strait of Dover functions as the major source of SPM to the southern North Sea, resulting in high turbidity areas along the continental and UK coasts of the Southern Bight, further enhanced locally by erosion of fine-grained cohesive sediments (Fettweis et al., 2007; Velegrakis et al., 1999; Gerritsen et al., 2001). Sandy mud and mud occurs in the central North Sea, along the Belgian–Dutch coastal area, in the Oyster Grounds, the German Bight, the Wadden Sea, an area off the Thames estuary and the East Anglian coast (Eisma, 1981; OSPAR, Quality Status Report, 2000). The Wadden Sea is characterized by a quasi-equilibrium between local erosion and deposition and transport, with net import of SPM during good weather conditions and net export of sediment out.
of the tidal basins to the North Sea during storm surges (Bartholdy and Anthony, 1998; Chang et al., 2006; Lettmann et al., 2009).

Many studies on SPM concentration in the North Sea use oceanographic (wave, currents, tides, wind, temperature, stratification) and SPM concentration data from in situ, remote sensing measurements and numerical models (e.g. Pietrzak et al., 2011, Fettweis et al., 2007, Gerritsen et al., 2001, Pleskachevsky et al., 2005, Eleveld et al., 2008, Stanev et al., 2009, Dobrynin et al., 2010, Rivier et al., 2012) to explain distribution and variability. The method proposed here is different as it is based on weather types to produce ensemble averages of SPM concentration maps from satellite for typical meteorological and climatological conditions. Polar orbital satellite images alone cannot be used to assess SPM concentration variations on short time scales because sampling frequency is too low and clouds often obscure the ocean surface; on average 60 cloud-free images have been acquired per year for the southern North Sea. However, averaging of the data according to well defined classifications will result in synoptic maps that are representative of the mean SPM concentration during specific conditions (Fettweis and Nechad, 2011).

The recently adopted EU Marine Strategy Framework Directive has as its main objective to maintain a good environmental status using an ecosystem-based approach. Good-quality waters are needed to sustain a fully-functioning healthy ecosystem. The latter implies the understanding and quantification of major processes in order to identify the natural vs. human induced variability of processes. In recent years, many studies considered potential changes in the North Sea due to climate change. Our approach provides a tool to improve understanding of coastal and shelf sea processes, especially with respect to variations of SPM concentration distribution according to weather; how it may change under enhanced greenhouse gas conditions and how this could affect marine ecosystems.

2. Data and methods

2.1. Weather types and classification of satellite images

Meteorological data over the period 2002–2009 were received from the UK Met Office and consist of 6 hourly wind and pressure fields. In order to investigate the weather related influence on surface SPM concentration in a larger area, the weather classification as proposed by Demuzere et al. (2009) has been used to summarize the atmospheric circulation. This classification is based on the method proposed by Lamb (1972), which was further developed into an objective classification scheme (Jenkinson and Collison, 1977) and validated (Jones et al., 1993). The automatic weather type scheme grid is described using the locations of high- and low-pressure centers that determine the geostrophic flow. A set of indices associated with the direction and the vorticity of the geostrophic flow defines the weather type. The grid is centered above Belgium and is representative for the circulation patterns of the larger Western and Central European Regions (Demuzere et al., 2009). We have used 11 weather types (WT), consisting of 2 pure vorticity types (Anticyclonic, Cyclonic), 8 directional types (N, NE, E, SE, S, SW, W, NW) and an unclassified type (U). Furthermore, climatological impact has been investigated using the NAO indices in order to classify the winter SPM concentration maps. The NAO Index data were provided by the Climate Analysis Section, NCAR, Boulder, CO, USA. The NAO-winter (December through March) time series exhibits two consecutive winters with opposite NAO-winter index within the period of MODIS data collection: −1.09 in winter 2005/2006; and 2.79 in winter 2006/2007. MODIS images have been averaged according to these periods.

Fig. 2(a) shows that weather types A, SW, W and NW have higher frequencies of occurrence than the other, which occur less than 8% of the time. Furthermore, some weather types are more equally distributed over the year (C, A, NE), whereas others are more frequent during autumn–winter (S, SW, W) or spring–summer (U). The average duration of each weather type is between 1.5 to 2 days. The averaged frequency of occurrence of all weather types during the winters of 2002–2009 is compared in Fig. 3(a) with their frequency during the winter of 2005–2006 (negative NAO index) and the winter of 2006–2007 (positive NAO index). Significant differences occur in the frequency of weather types N, NE, SW and W. Weather types N and NE are more (less) frequently occurring during a winter with negative (positive) NAO index as compared to the mean winter frequency. The opposite holds for the other three weather types: they occur more (less) often during a winter with positive (negative) NAO
Fig. 1. (a) Mean SPM concentration (mg/l) for all data (2002–2009). Triangles indicate wave rider buoys at Bol van Heist (51.38°N, 3.21°E), Eierlandse Gat (53.28°N, 4.66°E) and Helgoland (54.10°N, 7.87°E); the crosses show the in situ SPM concentration measurement stations Warp Anchorage (51.53°N, 1.03°E), West Gabbard (51.98°N, 2.08°E) and MOW1 (51.36°N, 3.11°E). 1 = Flemish Bank area, 2 = Thames, 3 = East Anglian plume; 4 = Humber coast; 5(a–c) = West, East and North Frisian coast. (b) Bathymetry of the North Sea and the English Channel (from Smith and Sandwell, 1997) and the major river basins, the discharge is the yearly averaged value: 1 = Elbe (870 m³/s), 2 = Weser (327 m³/s), 3 = Ems (80 m³/s), 4 = Rhine (2200 m³/s), 5 = Meuse (250 m³/s), 6 = Schelde (120 m³/s), 7 = Seine (500 m³/s), and 8 = Thames (66 m³/s).
Fig. 2. (a) Frequency of weather types over seasons. (b) Frequency of cloud-free data in the Southern Bight (51.50°N, 3.10°E), along the Dutch coast (53.30°N, 4.40°E), in the German Bight (54.15°N, 7.50°E) and in the central North Sea (55.00°N, 4.00°E). (c) Mean significant wave height at three stations.

index. These results confirm the general climate conditions during positive (strong westerly winds) and negative NAO index (weaker westerly flow and intrusion of colder arctic air) (Hurrell, 1995).

The meteorological effects have been addressed by classifying and ensemble averaging the satellite maps according to the weather type at the moment of MODIS Aqua overpass. Satellite images record SPM concentration only during cloud-free conditions and this depends on weather type and latitude (Fig. 2(b)). More cloud-free data exist for the southern North Sea; north of 58°N the number of good data is low (<10 good pixels per WT). There are also differences between the weather types; on average the number of good pixels is higher in weather types NE, E, SE and S. In order to take into account these differences the satellite images classified per weather type have first been averaged per month and then over the year. The ensemble averaged SPM concentration maps according to weather types are further analyzed using in situ data of significant wave height and SPM concentration and water transport data from numerical model simulation in order to assess the importance of resuspension and advection of SPM.

2.2. Remote sensing data

The Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua satellite, part of the NASA Earth Observation System, provides 1 to 2 daily images over the North Sea area. These data are used to build up daily maps of SPM concentration. In total 3097 MODIS images, covering the period between July 2002 and December 2009, have been processed from Level 1A (NASA/Ocean Biology Processing Group website, http://oceancolor.gsfc.nasa.gov/cgi/browse.pl?sen=am) to Level 2, using the SeaDAS software (available at http://oceancolor.gsfc.nasa.gov/seadas/). This consists of 2
steps: producing the Level 1B data by geo-referencing Level 1A data, and subtracting the atmospheric contributions by air molecules and aerosols from the radiances measured by the sensor at the top of the atmosphere; these yield Level 2 data, where the marine reflectance at MODIS bands may be obtained. Surface SPM concentration is then retrieved from remote sensing reflectance at the MODIS band centered at wavelength 667 nm, using the algorithm of Nechad et al. (2010). Finally, Level 2 processing flags (Patt et al., 2003) are used to mask out the land and cloud pixels and any bad quality pixels (e.g. due to atmospheric correction failure, negative reflectance, neighboring clouds, adjacency effects).

The accuracy of satellite derived SPM concentration has been assessed for errors that may arise from the optical model used to convert marine reflectances to SPM concentrations. The model parameterizes the inherent optical properties of particles in suspension as site-averaged coefficients. This induces errors in SPM estimation when a significant change in particle size and composition occurs under tidal and wind effects (Nechad et al., 2010), changing significantly their mass specific inherent optical properties. The uncertainty in SPM concentration propagating from errors in the water-leaving reflectance retrieval has been evaluated on the basis of 29 match ups taken in clear to moderately turbid waters (3–80 mg/l). A bulk mean relative error of about 37% has been found in SPM concentration retrieval from MODIS imagery. For waters with SPM concentration > 10 mg/l, the relative errors in MODIS-derived SPM concentrations are significantly lower than in clearer waters. This comes from the fact that there are higher relative errors in water-leaving reflectance retrieved in clearer waters and also because the SPM concentration algorithm is adapted to turbid waters. On the other hand, satellite-visible bands usually saturate in very turbid waters (Doxaran et al., 2002). The band centered at wavelength 667 nm used here in the retrieval of SPM concentration reaches its maximum limit of detection around 80 mg/l. Acceptable accuracy is given for values between 3 and 80 mg/l; in the data treatment only pixels with SPM concentration in this range have been selected for further analysis.

2.3. In situ data

In situ measurements of SPM concentration from Warp Anchorage (WA), West Gabbard (WG) and Zeebrugge (MOW1) have been used to validate the remote sensing results. WA is located in the mouth of the Thames, WG along the Humber coast and MOW1 in the Belgian coastal turbidity maximum zone (Fig. 1). At WA (15 m depth) and WG (25 m depth) optical backscatter measurements have been collected during 2002–2009 by SeaPoint turbidity meters on surface SmartBuoys with a time step of 30 min (Mill et al., 2003). Near-bed SPM concentration from acoustic and optical backscatter sensors (ADP, OBS) in the first 2 m above bed (mab) have been collected during about 340 days with a time step of 1 s to 10 min in the period 2005–2009 at MOW1 (water depth 10 m) (Fettweis and Nechad, 2011; Fettweis et al., 2012).

In situ wave data (significant wave height) have been used from Bol van Heist (Flemish Bank area), Eierlandse Gat (Dutch Coast) and Helgoland (German Bight). The averaged significant wave height is shown for the 11 weather types in Fig. 2(c). The results exhibit generally similar behavior in all stations, i.e. highest waves during N, NW and W and lowest during S, SE, E and C weather types. Differences in wave height between the three stations are related to fetch length, resulting for instance in relatively low wave heights at Bol van Heist (Helgoland) during SW (NE, E, SE) winds and relatively high wave heights during NE, E and SE (SW) weather types. Differences in wave height for different weather types exist depending on NAO index (Fig. 3(b)–(d)). Winters with positive NAO index have generally higher wave heights than winter with negative NAO index.

2.4. Numerical model data

The current velocities due to tide and wind forcings for the period 2002–2009 have been obtained using the 3D hydrodynamic model COHERENS (Luyten et al., 1999) for the North Sea and part of the English Channel (4°W–9°E, 48°N–57°N), termed hereafter OPTOS-NOS. The 3D model solves the continuity and momentum equations on a staggered sigma coordinate grid with an explicit mode-splitting treatment of the barotropic and baroclinic modes. The horizontal resolution is 5’ (longitude)
Fig. 3. (a) Frequency (%) of weather types during winters of 2002–2009, winter of 2005–2006 (NAOWI− 2006) and winter 2006–2007 (NAOWI+ 2007). Mean significant wave height at (b) Bol van Heist, (c) Eierlandse Gat and (d) Helgoland for the same periods.

and 2.5° (latitude). Boundary conditions are water elevation and depth-averaged currents; these are provided by OPTOS-CSM, which comprises the Northwest European continental shelf. The OPTOS-CSM model runs in 2D and is driven by the elevation at the open boundaries, governed by four semi-diurnal (M2, S2, N2, K2) and four diurnal (O1, K1, P1, Q1) harmonic constituents. The 6 hourly wind and pressure field from the UK Met Office have been used as meteorological forcing of both models. The current data have been ensemble averaged according to the above described 11 weather types using:

$$\vec{u}_{res−wt} = \frac{1}{nwt} \sum_{i=1}^{nwt} \vec{u}_i$$

where $\vec{u}_{res−wt}$ is the residual surface current, $\vec{u}_i$ the $i$th surface current vector and $nwt$ the number of surface current vectors for a certain weather type.

3. Results and discussion

3.1. General patterns

The difference between the mean surface SPM concentration per weather type and the yearly average data is shown in Figs. 4 (pure weather types) and 5 (directional weather types) together with the residual surface currents during the corresponding weather type. The SPM concentration is not spatially homogeneous and some pixels show anomalously high values. These pixels can be traced back to the occurrence of erroneously high SPM concentration around clouds. Differences in
SPM concentration between the 11 weather types and the yearly average data occur on regional and local scales. They can be related to changes in advection and resuspension. Weather type U has generally a lower and weather type S a globally (slightly) higher SPM concentration in the North Sea compared with the average situation. This is mainly caused by seasonal effects, with U more frequent during the low SPM concentration spring–summer season and S more frequent during the high SPM concentration autumn–winter season. The low significant wave heights during both weather types indicate that the patterns are caused by mainly tidal forcing. Weather type A is the most frequently occurring; it is almost equally distributed throughout the year and thus reflects nearly the average situation. The slight increase in SPM concentration as compared with the average situation from the Southern Bight towards the German Bight can be linked with a similar trend in wave heights. The other weather types all exhibit regional and local changes with no global trends that can be attributed to resuspension and advection processes.

The SPM concentration maps confirm that changes in weather type affect the distribution of surface SPM concentration in the North Sea as they have an influence on hydrodynamics, and consequently on the transport and resuspension of cohesive sediments. Furthermore significant differences in behavior exist between the high turbidity areas, which can be linked to advection and/or resuspension events. Resuspension depends on the water depth and the wave height. As the waves are higher along the
Fig. 5. Difference between mean SPM concentration according to directional weather types (N, NE, E, SE, S, SW, W, NW) and yearly average data (negative values: lower than, and positive values: higher than, yearly average values; the arrows are the residual current vectors).
Dutch coast and the German Bight than in the Southern Bight (Fig. 2(c)) and as water depth is similar (10–20 m) (Fig. 1(b)), resuspension will in these areas be more important than in the Southern Bight.

The residual currents per weather type are an indication of the advection of SPM in the surface layer. We see that significant differences occur in magnitude and direction depending on weather type. The advection is generally southwest to westward during weather types N, NE and E. The opposite was found for weather types C, E, S, SW, W and NW. Towards the coastline current ellipses are more elongated and residual flow is dominated by alongshore flow and the direction of the flow can locally be different from the general residual circulation.

The higher than average SPM concentrations observed in the East Anglian plume, Thames and/or the German Bight during weather types NE, N, NW, W and SW correlate well with the higher significant wave heights during these weather types and are thus the result of mainly local resuspension, as confirmed by Pietrzak et al. (2011) and Pleskachevsky et al. (2005). Locally differences can be seen during these weather types that are linked to a stronger influence of advection especially around Dover, and along the Belgian–Dutch and North Frisian coast. The high turbidity around Dover and along the Belgian–Dutch coast for example, has shifted towards the northeast during weather types SW and W whereas during weather types NE and E the opposite occurs with generally higher concentrations towards the southwest. This has been correlated with the occurrence of an increased subtidal alongshore flow towards the northeast induced by the wind patterns (Baeye et al., 2011).

The shear stresses due to waves during the other directional weather types (E, SE, S) are low and the changes in SPM concentration relative to the yearly average situation are thus not caused by significant resuspension events. Wave height is relatively high in the Southern Bight as compared to the German Bight for weather type NE (Fig. 2(c)); this together with the southwestward directed subtidal alongshore currents explains the enhanced SPM concentration in the Strait of Dover. We observe a general decrease in SPM concentration in the North Sea during weather types E and SE, except in the Strait of Dover. These two weather types have no typical seasonal signal, and as a consequence the pattern is explained by a low resuspension of fine-grained sediments in the North Sea, whereas the increase in the Strait of Dover area is caused by advection of SPM towards the English Channel.

3.2. Limitation of satellite imagery

The main drawback of satellite images is related to the low sampling frequency and the occurrence of clouds. The frequency of cloud-free data is highest in the Southern Bight and the English Channel and decreases towards the North and East (Fig. 2(b)). It is not necessarily correlated with WT frequency, as can be seen from weather types SW, W and NW, which are relatively abundant (> 10%) but have only relatively few good data. In contrast weather types NE, E and SE are less abundant (± 5%), but have higher frequency of cloud-free data. Further shortcomings exist as SPM processes are governed by near-bed dynamics (resuspension, deposition) and are not necessarily coupled with surface processes (Fettweis and Nechad, 2011). A nice example is the Rhine region of freshwater influence and the seasonal thermal stratification of central North Sea waters, as these stratified waters reduce vertical mixing and surface SPM concentration underestimates significantly the depth-integrated SPM concentration (Pietrzak et al., 2011; McCandliss et al., 2002). Salinity stratification associated with the inflow of fresh water occurs also in the inner German Bight (Elbe plume) and the Skagerrak (Huthnance, 1991) (Fig. 1(b)). The East Anglian plume extends eastward to areas with thermal stratification in early summer.

The average SPM concentration per weather types and the difference with the yearly average SPM concentration are shown in Fig. 6 for the three measuring locations (WA, WG, MOW1). The in situ data at WA and WG confirm that the SPM concentration in the southern Bight is generally lower during weather types U, C, A, S and SE, and higher during weather types N, NE, SW, W and NW.

The comparison is less good between the near-bed in situ data and the MODIS derived surface data at MOW1 for the weather types C, SE and NE, where the SPM concentration relative to the yearly averages increases near the bed but decreases at the surface. A decrease in surface SPM concentration can also be seen in the satellite maps along the German coast between the Elbe and Denmark during weather types W and SW, along the German and Danish Wadden Sea during weather types E and SE,
and along the Belgian–Dutch coast in weather types C, SE and NE. In the Belgian–Dutch coastal area the decrease in surface SPM concentration is explained by the reversal of the sub-tidal alongshore flow towards the southwest, which enhances the outflow of the Scheldt estuary, reduces the vertical mixing and results in the formation of highly concentrated mud suspensions (HCMS) (Baeye et al., 2011). It is not sure if similar processes are responsible for the lower SPM concentration along the German–Danish coast or if, during weather types SW and W, the stronger import of water and thus SPM into the back-barrier basin resulted in a decrease of the SPM concentration off the islands. The lower SPM concentration could also be caused, in addition to the low wave activity, by thermohaline stratification associated with westerly winds in the Elbe region and with easterly winds along the German and Danish Wadden Sea (Schrum, 1997).

HCMS or fluid mud layers are formed when the carrying capacity of cohesive sediments is exceeded, leading to a two-layer fluid with significant damping of the turbulence flow field and the vertical mixing (Winterwerp, 2006). The low surface SPM concentration in the satellite images along the Belgian–Dutch coastal zone during weather types C, SE, NE and also NW is due to HCMS formation and reflects thus the reduced vertical mixing rather than a decrease of the depth-integrated SPM concentration. It highlights the fact that near-bed SPM concentration dynamics are partially

![Figure 6](image_url)
Fig. 7. Mean SPM concentration according to NAO index. (a) Winter 2006 with strong positive NAO index. (b) Winter 2007 with strong negative NAO index. (c) Difference between NAOWI− and NAOWI+ SPM concentration maps (negative values: higher in NAOWI+; positive values: higher during NAOWI−).

uncoupled from processes higher up in the water column (Pietrzak et al., 2011; Fettweis and Nechad, 2011). Consequently, surface SPM concentrations measured by satellites can only be used as a proxy for SPM transport when the water column is well mixed or when near-bed or fluid mud layers are absent. Fluid mud or HCMS are often found in estuaries, bays and coastal zones; their occurrence in the North Sea has been confirmed for the Belgian–Dutch coastal zone (Baeye et al., 2011). Possibly they occur in other high turbidity areas, such as the English coast or the inner German Bight.

3.3. Weather and climate influence on SPM concentrations

The NAO exerts a dominant influence on the distribution of wintertime SPM concentration as shown in Fig. 7. The difference between both situations shows that during winters with negative NAO index the SPM concentration is on average higher in the Strait of Dover and the Belgian–French and
English coastal areas. During a winter with positive NAO index, higher SPM concentrations are found in the German Bight, the central North Sea and along the Dutch coast (except the West Frisian coast). Positive NAO winters are associated with higher frequency of SW winds, generally higher waves and an enhanced northeastward directed residual water transport. The observed differences between both winter situations are thus explained by a combination of transport of SPM out of the Southern Bight and local resuspension due to higher waves in the rest of the North Sea.

Siegismund and Schrum (2001) have found, based on a trend analysis of wind directions, that southwesterly winds in the Southern Bight have increased during the period 1988–1997 as compared to the period 1958–1967. Similar results were reported by Van den Eynde et al. (2012). This would imply higher frequency of weather types S, SW and W and thus a general increase of SPM concentration in the North Sea and a decrease in the Strait of Dover. The geographical extension of the high turbidity zone along the Belgian–Dutch coastal zone was thus more often advected towards the northeast as before. Houziaux et al. (2011) reported similar results, based on a comparison of historical (100 year) and recent bed samples. These authors have related the changes mainly to port and dredging works that have severely altered the fine-grained sediment dynamics. Our data suggest that changes in weather type frequency explain partially the observed changes in SPM concentration distribution.

The changes in the mean circulation pattern over the North Atlantic are accompanied by pronounced shifts in the storm tracks. Benniston et al. (2007) predict, e.g. in forthcoming decades, an increase of winter storms with more extreme wind speeds over the North Sea that become more north-westerly than at present, resulting in higher waves and higher resuspension potential. Other results are presented by Demuzere et al. (2009), who calculated the climate change following the IPCC 2001 report scenario A1B. They found an increase in frequency of the W weather type, balanced by a smaller decrease of C and all eastern (SE, E, NE) weather types. Increase of weather type W and decrease of N and NE types are associated with a positive winter NAO index. The high uncertainties of general circulation models for simulating climate scenarios could explain the different predictions. Other studies describe a correlation between decreasing summer ice in the Arctic and cold weather in Europe (Petoukhov and Semenov, 2010; Jaiser et al., 2012). Given the fact that sea ice cover in the Arctic is steadily decreasing in summer during the last decade, these authors expect a threefold increase in the probability of cold winters in Europe in the future. These cold periods, e.g. as in February 2012, are characterized by a negative NAO index, corresponding with a low difference in air pressure between the Azores high and the Icelandic low. Further decrease of sea ice extent in the Arctic is thus projected to increase the frequency of weather types N and NE and decrease the frequency of weather types SW and W during the winter season. For the North Sea this will mean that surface SPM concentration will on average be higher in the German Bight and the Strait of Dover and lower along the Belgian–Dutch coastal zone. Based on the above literature we could thus conclude that future autumns and winters will have more extreme weather resulting in an increase of southwesterly winds when the NAO index is positive and an increase in frequency of winters with a more negative NAO index. These will change the distribution of SPM concentration as they will influence the frequency of weather types.

4. Conclusions

The surface SPM concentration maps from MODIS have been ensemble averaged according to 11 weather types and climatological conditions. Each weather type has a distinct distribution of surface SPM concentrations, which is explained by differences in hydrodynamic and wave conditions. The occurrence of storms especially has an impact in shallow coastal regions through an increased resuspension of bottom material. Prevailing winds will, on the other hand, change the residual transport of SPM in North Sea. The more protected Southern Bight exhibits relatively stronger influences of advection, whereas in the central North Sea and the German Bight resuspension is more pronounced. This results in higher (lower) SPM concentration in the Southern Bight and the English Channel (German Bight) during E–SE weather types. The opposite occurs during weather types W–SW, when SPM concentration is higher in the central North Sea and lower in the English Channel and the Strait of Dover.
Shortcomings in satellite images have been assigned to fresh water stratification effects (Pietrzak et al., 2011). Our data suggest further that stratification due to highly concentrated mud suspensions also limits vertical mixing in the high turbidity area along the Belgian–Dutch coastal zone. Consequently, surface SPM concentrations as a proxy for the depth-integrated SPM concentration should be used with care in regions with thermohaline stratification or with near-bed or fluid mud layers.

The approach provides a tool to improve our understanding of coastal and shelf sea processes, especially with respect to variations of SPM concentration distribution forced by weather, climate and climate change. Furthermore, the method could be useful for synoptic estimation of SPM concentration distribution when no satellite data are available.

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Appendix. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.mio.2012.11.001.

References


