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ORIGINAL RESEARCH ARTICLE

The impact of tides and waves on near-surface suspended sediment concentrations in the English Channel

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Summary Numerous ecological problems of continental shelf ecosystems require a refined knowledge of the evolution of suspended sediment concentrations (SSC). The present investigation focuses on the spatial and temporal variabilities of near-surface SSC in coastal waters of the English Channel (western Europe) by exploiting numerical predictions from the Regional Ocean Modeling System ROMS. Extending previous investigations of ROMS performances in the Channel, this analysis refines, with increased spatial and temporal resolutions, the characterization of near-surface SSC patterns revealing areas where concentrations are highly correlated with evolutions of tides and waves. Significant tidal modulations of near-surface concentrations are thus found in the eastern English Channel and the French Dover Strait while a pronounced influence of waves is exhibited in the Channel Islands Gulf. Coastal waters present furthermore strong SSC temporal variations, particularly noticeable during storm events of autumn and winter, with maximum near-surface concentrations exceeding 40 mg l^{-1} and increase by a factor from 10 to 18 in comparison with time-averaged concentrations. This temporal variability strongly depends on the granulometric distribution of suspended sediments characterized by local bi-modal contributions of silts and sands off coastal irregularities of the Isle of Wight, the Cotentin Peninsula and the southern Dover Strait.

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1. Introduction

An accurate knowledge of suspended sediment concentrations (SSC) is required for numerous ecological issues of continental shelf ecosystems. SSC influence thus water clarity, limiting the amount of light available to phytoplankton for photosynthesis and the biological primary production (Hoppe, 1984). Suspended particulates may also absorb and transport polluting substances such as heavy metals or radioactive materials with harmful consequences in terms of water quality (Haarich et al., 1993). A refined estimation of suspended sediment transport rates constitutes finally a prerequisite of coastal engineering applications dealing with maintenance dredging projects of estuaries or harbors.

Recognized as an important coastal ecosystem of north-western European shelf seas, the English Channel (Fig. 1) has been the subject of numerous studies dedicated to suspended sediment transport. Initially based on in situ observations along transects in the Wight-Cotentin area and the Dover Strait (Dupont et al., 1993; Eisma and Kalf, 1979; Van Alphen, 1990; Velegrakis et al., 1997), first investigations exhibited a spatial "zonation" between (1) high turbid coastal waters with mean near-surface SSC of 10—35 mg l^{-1} and (2) central waters with low concentrations of 2—3 mg l^{-1}. Numerical modeling tools were then implemented to extend these local analyses focusing on effects of major hydrodynamic forcings of tides and waves (Gerritsen et al., 2000; Grochowski et al., 1993; Guillou and Chapalain, 2011; Guillou et al., 2009; Velegrakis et al., 1999). Three-dimensional (3D) predictions exhibited, in particular, remote advective and diffusive transport of silts ($d < 30$ μm) during spring tide with noticeable effects on grain-size variability of suspended sediments. Impacts of waves were furthermore quantified with SSC increase by a factor between 10 and 20 in exposed coastal areas during storm events.

Nevertheless, whereas these simulations provided interesting insights about temporal and spatial SSC variabilities in the English Channel complemented further local evaluations (Rahbani, 2015), numerical studies remained primary restricted to the vicinity of measurement sites. Broad-scale assessments of near-surface SSC have however been conducted relying on satellite monitoring of ocean color (Fettweis et al., 2007, 2012; Gohin et al., 2005; Gohin, 2011). Despite the reduced number of high-quality images fully covering the whole area over long time periods and the low accuracy of satellite observations (Wozniak, 2014), the refined analysis of remote-sensing images exhibited close correlations between observed SSC and hydrodynamic forcings of tides and waves (Rivier et al., 2012). Satellite-retrieved observations have thus been considered in numerous assessments of numerical simulations investigating regional variabilities of near-surface SSC at increased spatial and temporal resolutions in the English Channel (Guillou et al., 2015; Menesguen and Gohin, 2006; Souza et al., 2007; Sykes and Barcelia, 2012). Nevertheless, the attention was primary dedicated to approach of major SSC patterns and improvements of numerical predictions neglecting accurate evaluations about the roles of tides and waves on SSC variabilities.

The present study investigates the spatial and temporal variabilities of near-surface SSC under combined influences of tides and waves relying on numerical simulations established by Guillou et al. (2015) in the English Channel (Section 2). Predictions are first exploited to assess the global effects at the scale of the Channel identifying areas where concentrations are highly correlated with the evolutions of tides and waves (Section 3.1). Further investigation is then conducted about the temporal variabilities of nearshore SSC patterns quantifying effects of waves on near-surface concentrations in shallow waters (Section 3.2). The influence of

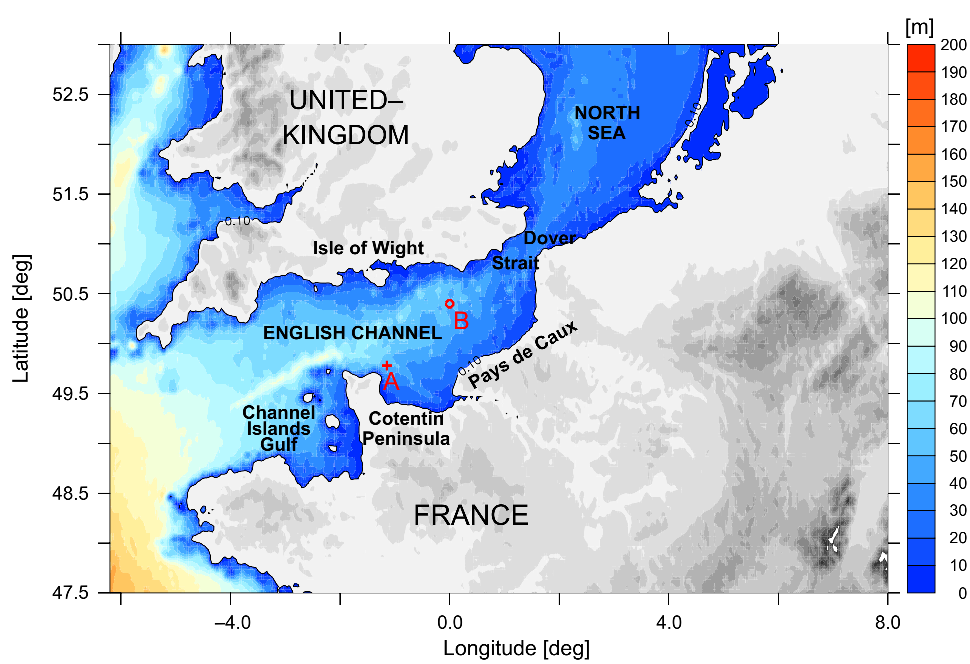

Figure 1 Bathymetry of the English Channel with locations of points A and B.

the granulometric distribution of suspended sediments is finally analyzed with a particular focus off coastal irregularities characterized by a local heterogeneity of grain sizes of suspended particles (Section 3.3).

2. Numerical modeling

Numerical modeling is based on the 3D multicomponent sediment transport model ROMS (Regional Ocean Modeling System) (Haidvogel et al., 2000; Warner et al., 2008) assessed against satellite-retrieved observations from raw remote-sensing images for the year 2008 (Guillou et al., 2015). Major characteristics of numerical model and performances evaluation are briefly described hereafter. Further details are available in Guillou et al. (2015).

The modeling system, implemented with a horizontal resolution of 3 km, takes into account the spatial distribution of seabed sediments by applying the interpolation method proposed by Leprêtre et al. (2006) to a series of available bottom sediment samples in the English Channel. Tidal free-surface elevations at open boundaries derive from harmonic components of TPOEX/Poseidon 6 database (Egbert and Erofeeva, 2002) while wind speeds above free surface are provided by meteorological ALADIN (Bénard, 2004; Météo-France). Waves effects are included following the parameterization adopted by Soulsby et al. (1993) on interactions between wave and current bottom boundary layers, with wave input parameters taken from the IOWAGA (Integrated Ocean WAves for Geophysical and other Applications) database (Ifremer, Ardhuin et al., 2011). Sediment transport is finally computed for the four finest grain size classes of silts (d_1 = 25 μm), very fine sands (d_2 = 75 μm), fine sands (d_3 = 150 μm) and medium sands (d_4 = 350 μm). SSC inputs of fine suspended particles (d_1 = 25 μm) are considered at open boundaries according to the statistical model developed by Rivier et al. (2012). ROMS is finally run during two years, 2007 and 2008, considering the first year as an initialization period.

Predictions are assessed against local and synoptic observations of near-surface SSC derived from raw MODIS/AQUA (MODerate resolution Imaging Spectroradiometer, NASA) and MERIS (MEdium Resolution Imaging Spectrometer, ESA) satellite images (Gohin, 2011). Whereas points predictions show a general tendency to underestimate highest observed concentrations in winter following results from Sykes and Barcelia (2012), the local evaluation confirms model's capability to approach observed spring-neap tidal modulations of near-surface concentrations (Fig. 2). Synoptic evaluations exhibit furthermore model's performances in approaching the large-scale variability of near-surface SSC characterized by (1) strong horizontal gradients in nearshore regions and (2) a prominent turbid area around the Isle of Wight (Fig. 3). These predictions approach also secondary features identified in the vicinity of protruding headlands and isles along the English and French coastlines.

3. Results and discussion

3.1. Global effects of tides and waves

ROMS' implementation by Guillou et al. (2015) in the English Channel primary focused on improvements of predictions neglecting further investigations about the effects of tides and waves on near-surface SSC variability. Numerical results are exploited here to assess spatial and temporal variabilities of near-surface concentrations in relation to major hydrodynamic forcings of tides and waves. Fig. 4 shows the maximum predicted near-surface SSC during the year 2008 and its relative increase with respect to yearly-averaged concentrations. Temporal variations of surface concentrations are particularly pronounced in the most turbid areas of the English Channel. Whereas offshore waters show weak SSC variations in relation to reduced concentrations and near-bed resuspensions, coastal waters exhibit significant evolutions at a distance up to 10 km from French and English coastlines. This spatial "zonation" between high turbid coastal waters and low turbid central waters confirms previous investigations conducted by Fettweis et al. (2012) or Lafite et al. (2000) in the English Channel.

These variations of near-surface coastal SSC appear primary associated with waves effects on seabed sediments. As exhibited by Grochowski and Collins (1994), sand-sized particles may be disturbed by wave activity during more than 20 % of a year over most of nearshore waters of the English

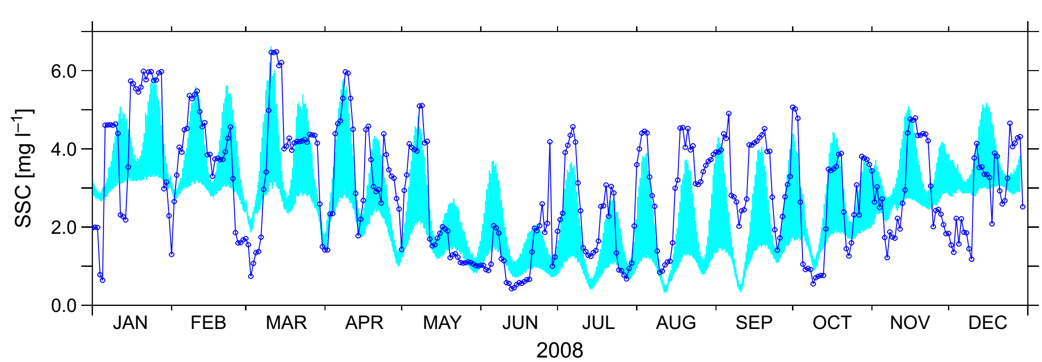

Figure 2 Time series of suspended sediment concentrations (SSC) (light blue) observed and (dark blue) predicted off the Cotentin Peninsula (point A). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Adapted from Guillou et al. (2015).

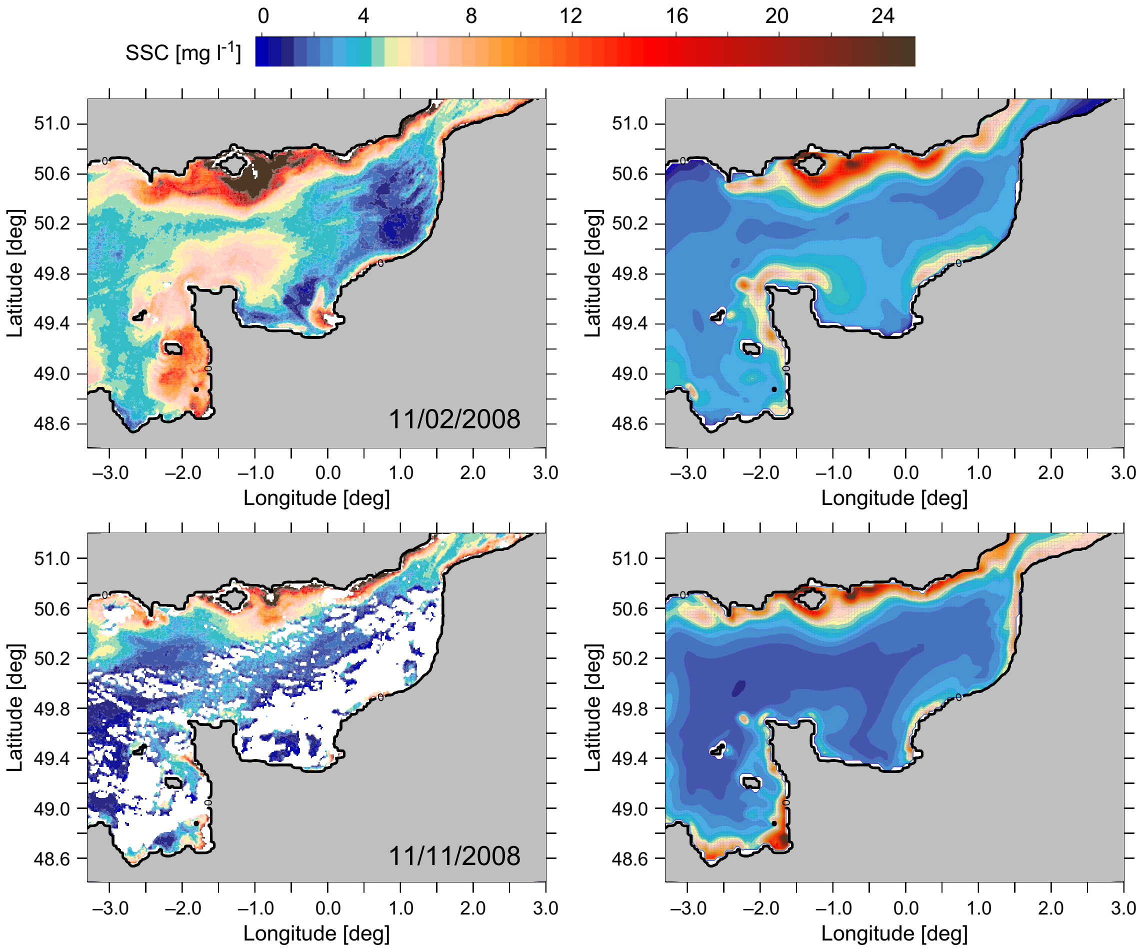

Figure 3 Near-surface suspended sediment concentrations (SSC) observed (right) and computed (left) for stormy for stormy wave conditions and spring (11 February 2008) and mean (11 November 2008) tides.
Adapted from Guillou et al. (2015).

Channel. This period corresponds globally to storm waves conditions of autumn and winter. In the present investigation, the associated near-surface concentrations present thus strong temporal variations with mean values over 8 mg l^{-1} against less than 4 mg l^{-1} in summer and spring (Fig. 5). Maximum near-surface SSC are furthermore reaching values over 40 mg l^{-1} with increase by a factor from 10 to 18 in comparison with time-averaged concentrations (Fig. 4b). Whereas seldom in situ SSC measurements are available in the English Channel to confirm these values, comparable increase have been reported from field studies near the Isle of Wight by Velegrakis et al. (1997). These predictions are also consistent with broader observations conducted in the southern North Sea off Maplin Sand (UK) by Owen and Thorn (1978). Predicted increase factors fall finally in the range of numerical values obtained by Gerritsen et al. (2000) in the eastern English Channel.

Influences of tides and waves on near-surface SSC are finally investigated displaying Pearson's correlation coefficients between (1) predicted concentrations and (2) integrated parameters characterizing the local evolution of hydrodynamic forcings. These site-specific explanatory parameters are (1) the tidal free-surface elevation and (2) the significant wave height at point B in the eastern English Channel (Fig. 1). Point B corresponds to the offshore lightship 62305 of the UK Meteorological Office. Resulting spatial distributions of correlation coefficients (Fig. 6) refine the cartography previously established by Rivier et al. (2012) on the basis of remote-sensing images over the period 2003—2009. Indeed, applying statistical treatments on satellite images, an initial cartography was obtained identifying, at a coarse spatial resolution of 36 km, areas of the English Channel where near-surface SSC are highly correlated with spring-neap tidal variations. Strong tidal modulations of near-surface concentrations were exhibited in the eastern English Channel with null to low influence in the western Channel in relation to dominant waves conditions. Whereas the present investigation is restricted to the year 2008, the resulting spatial distributions of correlation coefficients (Fig. 6) confirm the large-scale influence of tides on near-surface SSC modulations. Spring-neap tidal correlations appear however moderated in the Channel Islands Gulf where waves are predominantly influencing the evolution of near-surface SSC. The refined spatial resolution obtained by the exploitation of numerical predictions reveals finally a strong influence of tidal cycles along the French southern Dover Strait corroborating previous estimations performed by Guillou et al. (2009) and Guillou and Chapalain (2011) in these areas.

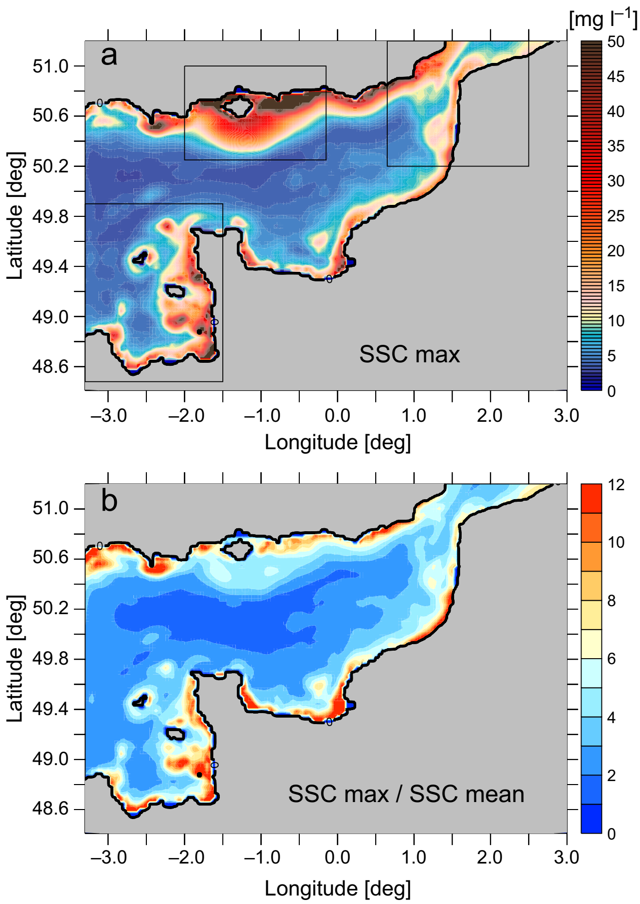

Figure 4 (a) Maximum predicted near-surface suspended sediment concentrations (SSC) in 2008 with the areas of interest delineated in black rectangles. (b) Relative increase of predicted near-surface suspended sediment concentrations with respect to averaged concentrations for the year 2008.

3.2. Variability of nearshore near-surface SSC patterns

Further investigation is conducted focusing on the temporal variability of (1) nearshore concentrations patterns separating French and English coastal waters and (2) areas with the highest contributions around the Isle of Wight, in the Channel Island Gulf and in the Dover Strait (Fig. 4a). Mean near-surface SSC of French and English waters show nearly similar temporal evolutions in spring and summer whereas more significant differences are exhibited in winter (Fig. 7a). In January, maximum concentrations are thus reaching peak values over 16 mg l^{-1} in English coastal waters while maximum concentrations remain below 10 mg l^{-1} in French waters. These differences are mainly associated with the contribution of the area of high concentrations identified around the Isle of Wight (Fig. 7b). The evolution of near-surface SSC of English coastal waters is directly correlated with the temporal variability of concentrations around the Isle of Wight. As identified in Fig. 6, this latter region experiences significant influences of tide and wave forcings corroborating previous investigations performed by Velegrakis et al. (1997, 1999). Tidal currents influence thus advection of finest suspended particles along the west-eastern direction modulating the longshore extension of the turbid area around the Isle of Wight at semi-diurnal frequencies. This evolution is modulated by waves which impact the northern offshore extension of this area with noticeable effects during storm events when near-surface concentrations are reaching values of 20 mg l^{-1} at a distance of 20 km from the Isle of Wight (Figs. 3 and 4).

In addition to this prominent area, two major nearshore resuspensions regions are identified in (1) the Channel Islands Gulf and (2) the Dover Strait (Fig. 4a). Confirming previous investigations performed in Section 3.1 (Fig. 6), averaged concentrations in these areas are strongly influenced by tides with spring-neap modulations of predicted SSC (Fig. 7b). Waves are however found to impact the variability of concentrations in coastal waters with noticeable effects between the months of October and February. This influence is exhibited in the central part of the Dover Strait where waves modify very clearly the “zonation” between central and coastal waters. Confirming previous estimates performed by Eisma and Kalf (1979), Lafite et al. (2000), Mc Cave (1973) and Van Alphen (1990), three main areas of resuspensions are thus revealed: (1) the English coastline with weakest coastal SSC, (2) the transitional zone of gravel and pebbles deposits where no resuspension occurs and (3) the French coastal zone showing the highest concentrations.

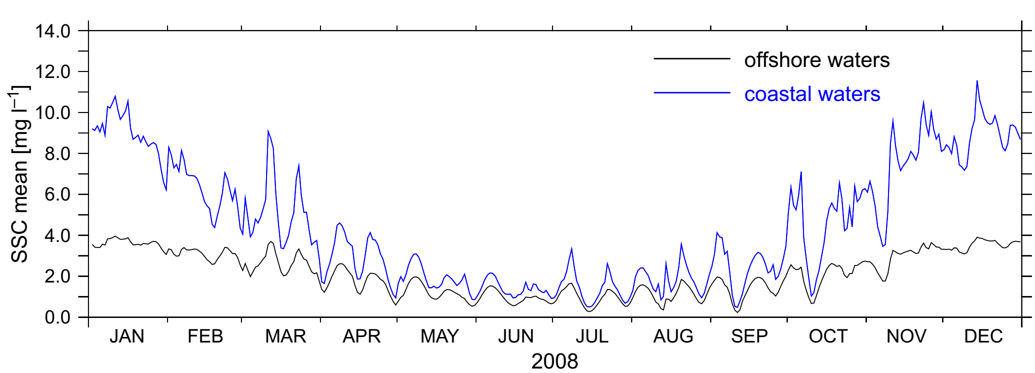

Figure 5 Time series of predicted averaged near-surface suspended sediment concentrations (SSC) in coastal and offshore waters of computational domain.

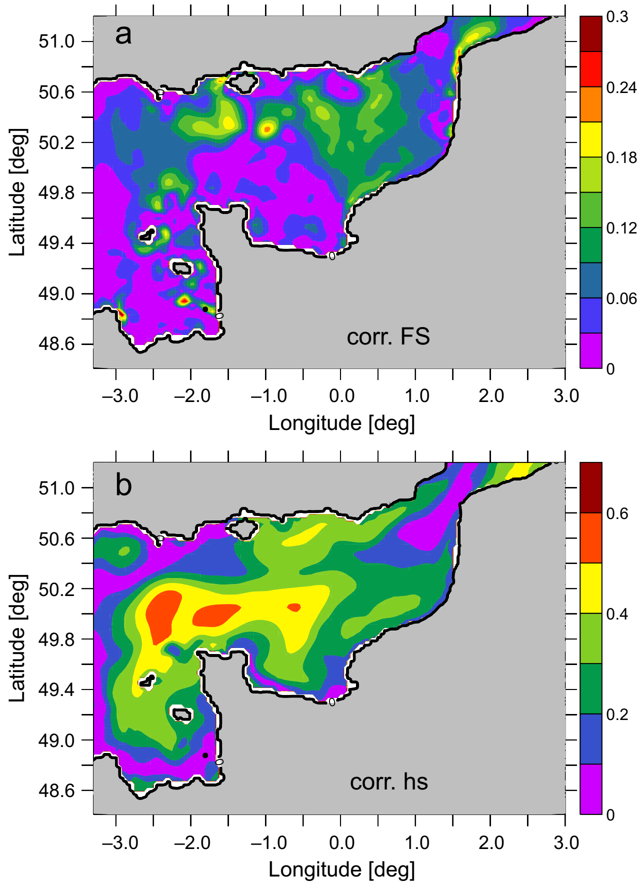

Figure 6 Correlation coefficients between predicted near-surface suspended sediment concentrations (SSC) and (a) predicted tidal free-surface elevation and (b) observed significant wave height at point B in 2008.

3.3. Influence of the granulometric distribution of suspended sediments

As exhibited by Sykes and Barcelia (2012), the granulometric distribution of near-surface suspended sediments influences the temporal variability of the total SSC. Strong temporal variabilities may thus appear as a result of a bi-modal distribution of silts and sands. Indeed, sands contribution to mean concentrations is generally characterized by quarter-diurnal variations in relation to local resuspensions whereas silts evolution may be semi-diurnal as a consequence of remote advection (Jago et al., 1993; Van der Molen et al., 2009). In the English Channel, these processes have been identified on the basis of a comparison between numerical predictions and in situ measurements by (1) Guillou et al. (2009) and Guillou and Chapalain (2011) in the southern Dover Strait and (2) Velegrakis et al. (1997) in the south-eastern edge of the Isle of Wight. These effects are particularly noticeable in nearshore waters in relation to increased influences of waves on the sea floor (Grochowski and Collins, 1994). In the present investigation, bi-modal distributions are thus exhibited off coastal irregularities of the Channel Islands Gulf, the Isle of Wight, the Cotentin Peninsula and the southern Dover Strait (Fig. 8). These nearshore grain-size variabilities contrast with the nearly uniform grain-size distribution of offshore near-surface SSC characterized by an average silt contribution over 90%.

This local heterogeneity of suspended concentrations has to be considered when processing satellite reflectance data. In this study, the backscattering coefficient by unit mass has been considered constant for a given area neglecting inherent optical properties of suspended particles in relation to size and composition (Gohin, 2011; Rivier et al., 2012). This assumption may thus result in differences in the estimation of near-surface SSC from remote-sensing data particularly noticeable in the highly localized energetic regions of the

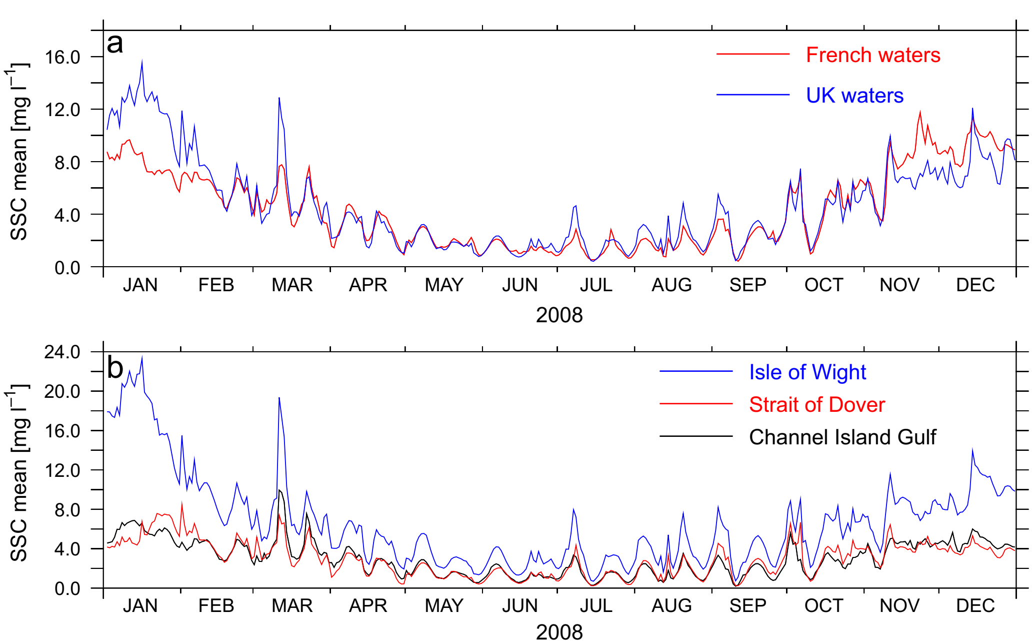

Figure 7 Time series of predicted averaged near-surface suspended sediment concentrations (SSC) over different areas of computational domain.

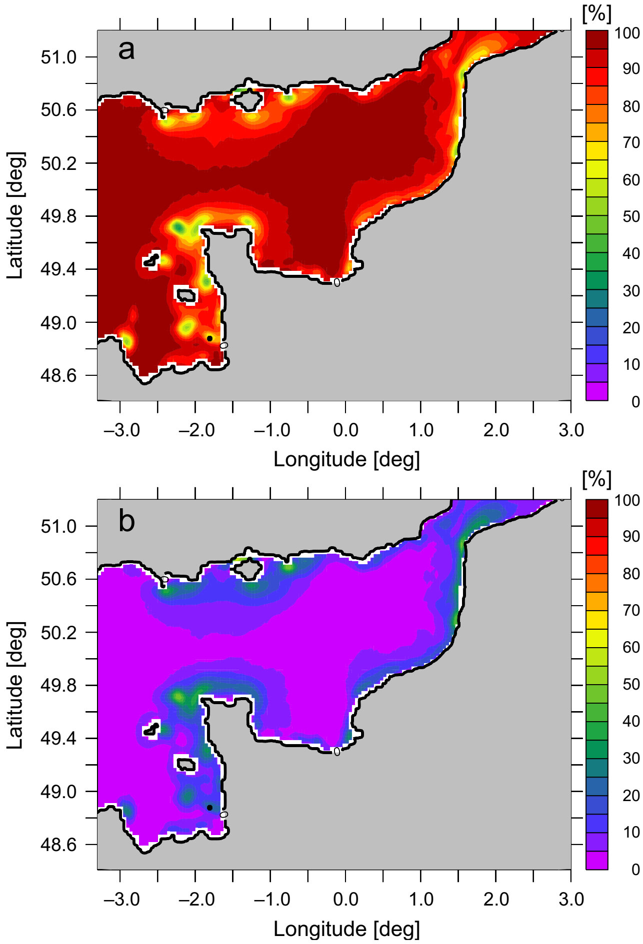

Figure 8 Percentages of (a) silts and (b) sands in the mean predicted near-surface suspended sediment concentrations (SSC) in 2008.

English Channel (Bowers and Binding, 2006; Bowers and Braithwaite, 2012; Lubac and Loisel, 2007). Integrating the grain-size variability of near-surface concentrations may improve estimations derived from remote-sensing data in the nearshore areas.

4. Conclusions

Numerical predictions from the Regional Ocean Modeling System ROMS assessed against satellite-retrieved images have been exploited to investigate the spatial and temporal variabilities of near-surface SSC in coastal waters of the English Channel. The main outcomes of the present study are the following:

1. Predictions exhibit significant temporal variations of near-surface concentrations in coastal waters with increase from 10 to 18 in comparison with time-averaged values. Considering the refined spatial resolution of the computational mesh, two cartographies are produced exhibiting correlations of near-surface SSC with tidal free-surface elevation and significant wave height. Waves influence is exhibited in the Channel Islands Gulf while strong tidal correlations are revealed in the southern Dover Strait.
2. The granulometric distribution of near-surface suspended sediments has been identified exhibiting local bi-modal distributions of silts and sands with a strong influence on SSC variabilities. Whereas near-surface SSC appears predominantly composed of silts, sands may contribute locally to suspended concentrations in the most energetic areas of the English Channel. This may furthermore result in local grain-size heterogeneity of suspended sediments with possible biases in the estimation of associated concentrations from remote-sensing images.

The present study provides interesting insights about the spatial and temporal variabilities of near-surface SSC in the English Channel complemented previous studies based on remote-sensing data. This research will naturally benefit from extended comparisons of numerical predictions with in situ observations based on acoustic and/or optical devices in conjunction with direct sampling of surface water for evaluation of measurements accuracy. Taking into account errors usually associated with remote-sensing images during rougher sea states, these in situ measurements will confirm model's performances in the most turbid areas during storm events. This objective will be achieved with longer simulations covering major measurements campaigns in the English Channel. This long-term evaluation of near-surface SSC will also assess the variability of suspended sediment transport in relation to the inter-annual variability of wave climate in the English Channel. The present modeling focuses furthermore on disturbances induced by tides and waves on near-surface SSC neglecting a refined evaluation of predicted concentrations distributions in the entire water column, exhibiting, in particular, near-bed concentrations. Further investigations are thus required about effects of tides and waves on near-bed sediments. Whereas further studies can be conducted about the role of wind on near-surface concentrations, another prospective of this research will also consist in incorporating fluxes of fresh waters and sediments through river boundaries. These developments will finally aim at improved estimations of sediment fluxes through the English Channel.

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References

Ardhuin, F., Hanafin, J., Quilfen, Y., Chapron, B., Queffeulou, P., Obrebski, M., 2011. Calibration of the IOWAGA global wave hindcast (1991—2011) using ECMWF and CFSR winds. In: 12th Int. Workshop on Wave Hindcasting and Forecasting, Kohala Coast, Hawaii.

Bénard, P., 2004. ALADIN-NH/AROME dynamical core; status and possible extension to IFS. In: Proc. ECMWF Seminar on Recent Developments in Numerical Methods for Atmosphere and Ocean Modelling, Reading, UK, 27—40.

Bowers, D.G., Binding, C.E., 2006. The optical properties of mineral suspended particles: a review and synthesis. Estuar. Coast. Shelf Sci. 67 (1—2), 219—230, http://dx.doi.org/10.1016/j.ecss.2005.11.010.

Bowers, D.G., Braithwaite, K.M., 2012. Evidence that satellite sense the cross-sectional area of suspended particles in shelf seas and estuaries better than their mass. Geo-Mar. Lett. 32 (2), 165—171, http://dx.doi.org/10.1007/s00367-011-0259-6.

Dupont, J.P., Collins, M.B., Lafite, R., Nash, L., Huault, M.F., Shimwell, S.J., Chaddock, S., Brunet, C., Wartel, M., Lamboy, M., 1993. Annual variations in suspended particulate matter within the Dover Strait. Oceanol. Acta 16 (5—6), 507—516.

Egbert, G., Erofeeva, S., 2002. Efficient inverse modeling of barotropic ocean tides. J. Atmos. Ocean. Technol. 19 (2), 183—204, http://dx.doi.org/10.1175/1520-0426(2002)019%3C0183:EIMOBO%3E2.0.CO;2.

Eisma, D., Kalf, J., 1979. Distribution and particle size of suspended matter in the Southern North Sea. Neth. J. Sea Res. 13 (2), 298—324, http://dx.doi.org/10.1016/0077-7579(79)90008-5.

Fettweis, M., Monbaliu, J., Baeye, M., Nechad, B., Van den Eynde, D., 2012. Weather and climate induced variability of surface suspended particulate matter concentration in the North Sea and the English Channel. Methods Oceanogr. 3—4, 25—39, http://dx.doi.org/10.1016/j.mio.2012.11.001.

Fettweis, M., Nechad, B., Van den Eynde, D., 2007. An estimate of the suspended particulate matter (SPM) transport in the southern North Sea using Sea WiFS images, in situ measurements and numerical model results. Cont. Shelf Res. 27 (10—11), 1568—1583, http://dx.doi.org/10.1016/j.csr.2007.01.017.

Gerritsen, H., Vos, R., der Kaaij, T.V., Lane, A., Boon, J., 2000. Suspended sediment modelling in a shelf sea (North Sea). Coast. Eng. 41 (1—3), 317—352, http://dx.doi.org/10.1016/S0378-3839(00)00042-9.

Gohin, F., 2011. Annual cycles of chlorophyll-*a*, non-algal suspended particulate matter and turbidity observed from space and in-situ in coastal waters. Ocean Sci. 7 (5), 705—732, http://dx.doi.org/10.5194/os-7-705-2011.

Gohin, F., Loyer, S., Lunven, M., Labry, C., Froidefond, J.M., Delmas, D., Huret, M., Herbland, A., 2005. Satellite-derived parameters for biological modelling in coastal waters: illustration over the eastern continental shelf of the Bay of Biscay. Remote Sens. Environ. 95 (1), 29—46, http://dx.doi.org/10.1016/j.rse.2004.11.007.

Grochowski, N.T.L., Collins, M.B., 1994. Wave activity on the sea-bed of the English Channel. J. Mar. Biol. Assoc. U. K. 74 (3), 739—742, http://dx.doi.org/10.1017/S0025315400047792.

Grochowski, N.T.L., Collins, M.B., Boxall, S.R., Salomon, J.C., 1993. Sediment transport predictions for the English Channel, using numerical models. J. Geol. Soc. (London, U.K.) 150 (3), 683—695, http://dx.doi.org/10.1144/gsjgs.150.4.0683.

Guillou, N., Chapalain, G., 2011. Modelling impact of northerly wind generated waves on sediments resuspensions in the Dover Strait and adjacent waters. Cont. Shelf Res. 31 (18), 1894—1903, http://dx.doi.org/10.1016/j.csr.2011.08.011.

Guillou, N., Chapalain, G., Thais, L., 2009. Three-dimensional modeling of tide-induced suspended transport of seabed multi-component sediments in the eastern English Channel. J. Geophys. Res. 114, C07025, http://dx.doi.org/10.1029/2008JC004791.

Guillou, N., Rivier, A., Gohin, F., Chapalain, G., 2015. Modeling near-surface suspended sediment concentration in the English Channel. J. Mar. Sci. Eng. 3 (2), 193—215, http://dx.doi.org/10.3390/jmse3020193.

Haarich, M., Kienz, W., Krause, M., Schmidt, G.P.Z.D., 1993. Heavy metal distribution in different compartments of the northern North Sea and adjacent areas. Ocean Dyn. 45 (5), 313—336, http://dx.doi.org/10.1007/BF02225884.

Haidvogel, D.B., Arango, H.G., Hedstrom, K., Beckman, A., Malanotte-Rizzoli, P., Shchepetkin, A.F., 2000. Model evaluation experiments in the North Atlantic Basin: simulations in nonlinear terrain-following coordinates. Dyn. Atmos. Oceans 32 (3—4), 239—281, http://dx.doi.org/10.1016/S0377-0265(00)00049-X.

Hoppe, H.G., 1984. Attachment of bacteria: advantage or disadvantage for survival in the aquatic environment. In: Marshall, K.C. (Ed.), Microbial Adhesion and Aggregation, Life Sci. Res. Rep. 131. Springer-Verlag, New York, 283—303, http://dx.doi.org/10.1007/978-3-642-70137-5_19.

Jago, C.F., Bale, A.J., Green, M.O., Howarth, M.J., Jones, S.E., McCave, I.N., Millward, G.E., Morris, A.W., Rowden, A.A., Williams, J.J., Hydes, D., Turner, A., Huntley, D., Van Leussen, W., 1993. Resuspension processes and Seston dynamics, southern North Sea. Philos. Trans. R. Soc. Lond. A 343 (1669), 475—491, http://dx.doi.org/10.1098/rsta.1993.0060.

Lafite, R., Shimwell, S., Grochowski, N., Dupont, J.P., Nash, L., Salomon, J.C., Cabioch, L., Collins, M., Gao, S., 2000. Suspended particulate matter fluxes through the Straits of Dover, English Channel: observations and modelling. Oceanol. Acta 23 (6), 687—699, http://dx.doi.org/10.1016/S0399-1784(00)00144-4.

Leprêtre, A., Chapalain, G., Carpentier, P., 2006. A spatial interpolation method of granulometric properties of superficial sediments. Bull. Soc. Geol. Fr. 177 (2), 89—95, http://dx.doi.org/10.2113/gssgfbull.177.2.89.

Lubac, B., Loisel, H., 2007. Variability and classification of remote sensing reflectance spectra in the eastern English Channel and southern North Sea. Remote Sens. Environ. 110 (1), 45—58, http://dx.doi.org/10.1016/j.rse.2007.02.012.

Mc Cave, I.N., 1973. Mud in the North Sea science. In: Goldberg, E.D. (Ed.), North Sea Science. M.I.T. Press, 75—100.

Menesguen, A., Gohin, F., 2006. Observation and modelling of natural retention structures in the English Channel. J. Mar. Syst. 63 (3—4), 244—256, http://dx.doi.org/10.1016/j.jmarsys.2006.05.004.

Owen, M., Thorn, M., 1978. Effect of waves on sand transport by currents. In: Proc. 16th Conf. Coastal Eng. Hamburg, 1675—1687, doi:10.9753/icce.v16.%25p.

Rahbani, M., 2015. A comparison between the suspended sediment concentrations derived from DELFT3D model and collected using transmissometer — a case study in tidally dominated area of Dithmarschen Bight. Oceanologia 57 (1), 44—49, http://dx.doi.org/10.1016/j.oceano.2014.06.002.

Rivier, A., Gohin, F., Bryère, P., Petus, C., Guillou, N., Chapalain, G., 2012. Observed vs. predicted variability in non-algal suspended particulate matter concentration in the English Channel in relation to tides and waves. Geo-Mar. Lett. 32 (2), 139—151, http://dx.doi.org/10.1007/s00367-011-0271-x.

Soulsby, R.L., Hamm, L., Klopman, G., Myrhaug, D., Simons, R.R., Thomas, G.P., 1993. Wave—current interaction within and outside the bottom boundary layer. Coast. Eng. 21 (1—3), 41—69, http://dx.doi.org/10.1016/0378-3839(93)90045-A.

Souza, A.J., Holt, J.T., Proctor, R., 2007. Modelling SPM on the NW European shelf seas. In: Balson, P, Collins, M. (Eds.), Coastal and Shelf Sediment Transport. Geol. Soc., London, 147—158, http://dx.doi.org/10.1144/GSL.SP.2007.274.01.14.

Sykes, P.A., Barcelia, R.M., 2012. Assessment and development of a sediment model within an operational system. J. Geophys. Res. 117, C04036, http://dx.doi.org/10.1029/2011jc007420.

Van Alphen, J., 1990. A mud balance for Belgian-Dutch coastal waters between 1969 and 1986. Neth. J. Sea Res. 25 (1—2), 19—30, http://dx.doi.org/10.1016/0077-7579(90)90005-2.

Van der Molen, J., Bolding, K., Greenwoord, N., Mills, D.K., 2009. A 1-D vertical multiple grain size model of suspended particulate matter in combined currents and waves in shelf seas. J. Geophys. Res. 114, F01030, http://dx.doi.org/10.1029/2008jf001150.

Velegrakis, A.F., Gao, S., Lafite, R., Dupont, J.P., Huault, M.F., Nash, L.A., Collins, M.B., 1997. Resuspension and advection processes affecting suspended particulate matter concentrations in the central English Channel. J. Sea Res. 38 (1—2), 17—34, http://dx.doi.org/10.1016/S1385-1101(97)00041-5.

Velegrakis, A.F., Michel, D., Collins, M.B., Lafite, R., Oikonomou, E. K., Dupont, J.P., Huault, M.F., Lecouturier, M., Salomon, J.C., Bishop, C., 1999. Sources, sinks and resuspension of suspended particulate matter in the eastern English Channel. Cont. Shelf Res. 19 (15—16), 1933—1957, http://dx.doi.org/10.1016/S0278-4343(99)00047-3.

Warner, J.C., Sherwood, C.R., Signell, R.P., Harris, C.K., Arango, H. G., 2008. Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model. Comput. Geosci. 34 (10), 1284—1306, http://dx.doi.org/10.1016/j.cageo.2008.02.012.

Wozniak, S.B., 2014. Simple statistical formulas for estimating biogeochemical properties of suspended particulate matter in the southern Baltic Sea potentially useful for optical remote sensing applications. Oceanologia 56 (1), 7—39, http://dx.doi.org/10.5697/oc.56-1.007.