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A 3D SPM model for biogeochemical modelling, with application to the northwest European continental shelf

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ABSTRACT

An SPM resuspension method was developed for use in 3D coupled hydrodynamics-biogeochemistry models to feed into simulations of the under-water light climate and and primary production. The method uses a single mineral fine SPM component for computational efficiency, with a concentration-dependent settling velocity to parameterize the effect of settling of different size fractions. The SPM is resuspended in response to combined wave and current conditions. Wave conditions were calculated using a simple set of equilibrium equations, which allows computationally cheap inclusion of the large-scale spatial and temporal trends of the wave field. The development was carried out using 1D water-column implementations of GOTM-ERSEM-BFM for two sites for which multi-year time series observations from autonomous moorings (SmartBuoy) were available. A sensitivity study is included to illustrate the effect of the main variables controlling the exchange with the sea-bed and the settling velocity. The method was applied to a 3D model implementation of GETM-ERSEM-BFM for the north-west European continental shelf, comparing mineral fine SPM concentrations at five sites with SmartBuoy observations, and shelf-wide using remote sensing. The 3D implementation included a simple fitting method to generate gridded sea-bed composition information for use in the sea-bed boundary conditions. The results showed that the model produces reasonable simulations of seasonal SPM concentrations across the north-west European continental shelf.

1. Introduction

1.1. Background

Suspended (mineral) particulate matter (SPM) can contribute significantly to the turbidity of coastal seas, and as such modify the attenuation of sun light penetrating from the surface through scattering and absorption. Because phytoplankton require light to grow, SPM can constitute a significant modulating factor for primary production and associated nutrient cycling. Hence, the effects of SPM on the under-water light climate are usually included in biogeochemical models used in the coastal ocean, in addition to contributions by clear water, coloured disolved organic matter (CDOM) and phytoplankton self shading (Jerlov, 1976; Baker and Lavelle, 1984; Campbell and Spinrad, 1987; Gallegos and Correll, 1990; Apel, 1995; Bowers et al., 2004). These other three factors are fairly well understood, and relatively easily included in biogeochemical models, and will not be further discussed here.

Because SPM models can be computationally expensive additions to already expensive biogeochemical models and SPM concentrations are notoriously difficult to model, the current implementations of SPM in biogeochemical models tend to contain significant simplifications. These could be i) climatologies based on observations (ECOHAM4, Lenhart et al., 2010) ii) climatologies based on monthly satellite composites (MICRO&COHERENCE-3D, Lenhart et al., 2010), iii) a relaxation to weekly satellite composites (POLCOMS-ERSEM, Lenhart et al., 2010), iv) a combination of monthly satellite composites and a current-based SPM model (ECO-MARS3D, Lenhart et al., 2010), v) a current-based SPM transport model (WES-CH3D, Xu and Hood, 2006; Delft3D-GEM, Lenhart et al., 2010; Van Kessel et al., 2011; ROMS, Feng et al., 2015) or vi) proportionalities with local wave-induced bed-shear stress (GETM-ERSEM-BFM, Lenhart et al., 2010; Van der Molen et al., 2014). As biogeochemical models are increasingly in demand for what-if scenarios in coastal seas to address questions relating to eutrophication, renewable energy generation, climate change and carbon and nutrient budgets and cycling, a good representation of dynamic, water-column resolved SPM concentrations in response to changes in forcing

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associated with the scenarios in question is becoming increasingly important. This can only be achieved with a model.

In an earlier study using 1D water column models in combination with high temporal resolution time series of SPM concentrations in coastal waters, Van der Molen et al. (2009) showed that inclusion of both current and wave effects on resuspension is necessary to simulate SPM concentrations. Moreover, they demonstrated that, because of their different settling velocities, a range of size fractions (at least four) is needed to to simulate SPM concentrations both in high temporal detail, and over seasonal cycles. As separate size fractions need to be advected separately in 3D models, and spatial advection constitutes the main computational cost for state variables in 3D models (four additional state variables would consume approximately 10% of the compute time in ERSEM-BFM; moreover if a sand fraction were included explicitly the model time step would have to be reduced), limiting the computational burden of an SPM model leaves more compute time for biological processes in any particular application.

Hence, here, we here present and investigate the implementation of a variant of the method of Van der Molen et al. (2009) in 1D and 3D biogeochemical models using a single SPM fraction, but with a parameterization to adjust the settling velocity to the instantaneous SPM concentration based on the assumption that the average grain size (and hence settling velocity) at high concentrations is larger than at low concentrations. As it contains only a single advected state variable, the method is computationally as cheap as it can be made, while containing continuous (rather than discrete) size-dependent settling, and giving a reasonable simulation of SPM concentrations induced by a combination of currents and waves in a wide range of hydrodynamic conditions including seasonal and riverine stratification. For the remainder of this paper, SPM is defined as fine, mineral material (clay and silt).

At this stage, the model only conserves sediment that has been suspended, and does not track deposited sediment, for a number of reasons. Firstly, the primary aim was to improve the light climate calculations, making a good representation of SPM concentrations in the upper water column the most important criterium. Earlier experience with a much simpler implementation relating SPM concentrations directly to the bed-shear stress suggested this a viable approach (Van der Molen et al., 2014). Secondly, not including a dynamic bottom pool imposes a useful control on the SPM model: concentrations in the fixed bottom pool will remain at 'observed' levels, ensuring that the SPM model will continue to perform in the same way throughout the simulations to provide concentrations for the light calculation. Making this dynamic would enable the bottom pool to diverge from 'observed' levels as material is washed away or accumulated. If such changes in the bottom SPM pool were unrealistic, eg. through an accumulation of inaccuracies in the hydrodynamics and SPM calculations, they would over time lead to reduced performance in terms of the desired light climate calculations. It was decided that adding a dynamic, mass-conservative bottom pool was better left for a next stage of work. A limitation of assuming a static bottom pool is that the model can not self-adjust deviations in the bottom pool, and has limited ability to carry SPM across areas with low concentrations in the bottom pool.

An application that clearly demonstrates the utility of this method in a biogeochemical context by identifying an SPM-dominated response mechanism can be found in a study of the potential environmental effects of tidal energy generation by Van der Molen et al. (2016).

1.2. Study area

The shelf to the west and north of the UK (Fig. 1) is typically one to several hundreds of km wide, and has a depth of 100–200 m, in contrast to the North Atlantic Ocean to the west, which reaches depths of several thousands of m. The Celtic and Irish Seas separate Ireland from the mainland of the UK, and the English Channel separates the UK from the continent in the south. The North Sea to the east, between the UK and the European continent, has typical depths of over 100 m in the north, and <50 m in the south. The North-west European shelf, and in particular the North and Irish Seas, support a high biological production, but are at the same time used heavily for a range of economic activities including shipping, fishing, oil and gas extraction, pipe lines, and aggregate extraction, while also containing a large number of marine protected areas of various types (see, e.g., Paramor et al., 2009, OSPAR, 2010).

On the shelf, the tides interact with the topography, wave climate and river runoff to create a range of stratification and mixing conditions (Pingree et al., 1978; van Leeuwen et al., 2015), and sea bed disturbance, sediment resuspension and transport mechanisms (e.g., van der Molen, 2002; Aldridge et al., 2015). The shelf seas support a high level of primary productivity, which, during the last decades, has been augmented by varying and gradually reducing levels of anthropogenic riverine nutrient loads, and which depends on local SPM concentrations that affect the availability of light (e.g., Lenhart et al., 2010). Current- and wave-induced SPM concentrations on the northwest European continental shelf display a high level of spatial and temporal variability, in particular in more shallow waters, as is becoming increasingly evident from satellite observations (e.g., Eleveld et al., 2008; Dobrynin et al., 2010).

For five sites (Fig. 1), time-series observations of SPM from SmartBuoy (Greenwood et al., 2010) were available. Site 1, Warp Anchorage, is situated in well-mixed conditions at 15 m water depth in a channel in the Thames Estuary. Site 2, Liverpool Bay, was situated in intermittently stratified, river-influenced conditions (e.g., Verspecht et al., 2009) at 23 m water depth in the eastern Irish Sea, and formed part of the Liverpool Bay Coastal Observatory (http://cobs.pol.ac.uk/cobs). Site 3, West Gabbard, is situated in well-mixed conditions in 32 m water depth in the southern bight of the North Sea. Site 4, Oyster Grounds, was situated in mostly seasonally stratified waters in 45 m water depth. Site 5, North Dogger, was situated in seasonally stratified waters in 80 m water depth. Sea bed composition varies between the sites, with West Gabbard and Liverpool Bay having coarser sand beds (355 and 250 μm), and Warp Anchorage, Oyster Grounds and North Dogger having finer beds (125, 1E2 and 1E2 μm). Sites 4 and 5 were studied extensively as part of the Marine Ecosystem Connections programme (see Painting and Forster, 2013 and references therein).

2. Methods

2.1. SmartBuoy observations

Time series of near-surface optical back scatter were obtained from a routine monitoring programme at the Warp Anchorage (2002-present), Liverpool Bay (2001-present), the West Gabbard (2002-present), Oyster Grounds (2006–2013) and North Dogger (2007–2008) sites using SmartBuoy (Mills et al., 2003; Greenwood et al., 2010; www.cefas.defra.gov.uk/monitoring; see Fig. 1 for locations). The buoy consists of a 1.9 m wide toroidal float with a purpose built stainless steel frame for mounting instruments below surface. The payload includes, among others, an OBS sensor (OBS, Seapoint Sensors, Inc., New Hampshire, USA), of which the results were used here, has a manufacturer-specified linear response up to concentrations of 500 mg l^{-1}. For a detailed study of the response of the sensor, see Green et al. (1999). A Cefas purpose built solid state logger (ESM2) samples each sensor at 1 Hz for two 10-minute bursts each hour. A burst average is calculated from quality-assured data. The quality assurance procedure includes, among others, rejection of data from periods when bio-fouling is suspected. An automated water sampler (Aqua Monitor, EnviroTech, Virginia, USA) is used for collection and storage of up to 50 water samples of 150 ml each for subsequent gravimetric analysis of SPM. In general 2–3 water samples are collected at pre-set times for each week of deployment using this method. Sensors and the water sampler are held at fixed depths between 1 and 2 m. The optical back scatter readings from SmartBuoy were calibrated using SPM observations from a combination of water samples collected in situ by the on-board water sampler of

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