MONITORING AND MODELLING OF THE IRISH SEA AND LIVERPOOL BAY: AN OVERVIEW AND AN SPM CASE STUDY.

V. Krivtsov[1*], M.J. Howarth[2], S.E. Jones[1], A. Souza[2], and C.F. Jago[1]

[1]*School of Ocean Sciences, University of Wales Bangor, Marine Science Laboratories, Menai Bridge, Anglesey LL59 5AB*

[2]*Proudman Oceanographic Laboratories, Joseph Proudman Building, 6 Brownlow street, Liverpool L3 5DA*

[*]Corresponding author. Present address: CECS, The Crew Building, King's Buildings, University of Edinburgh, West mains Road, Edinburgh EH9 3JN, Scotland, UK. email: e96kri69@netscape.net

Abstract

Suspended particulate matter (SPM) is an important constituent of marine ecosystems, and is involved in a wide range of biogeochemical processes. Because availability of light is dependent upon the concentration of suspended solids, correct representation of SPM dynamics is paramount for simulating the dynamics of primary producers, and therefore for simulating all the other ecological variables. This paper presents a brief overview of the Irish Sea/Liverpool Bay monitoring & modelling programme, and on the basis of a case study, discusses the ways how the models' explanatory and predictive powers may be further enhanced by taking detailed account of patterns and processes related to the SPM dynamics and particle size distribution. Here we identify (using the results of monitoring data combined with tidal predictions generated by POLPRED model, and a Matlab script specially written to carry out Stepwise Regression Modelling on these data) the meteorological and oceanographic variables especially important for the characterisation of SPM in Liverpool Bay. In particular, in the stepwise regression models, variables related to winds, waves, and tidal currents appear to explain considerable percent of the variance observed. Tides appear to matter more during springs than neaps, but overall show weaker relationships with SPM variables than winds and waves. These results are important for further developments and applications of the POLCOMS and ERSEM models, and may have implications for a number of ecological and oceanographic issues.

Key words: suspended sediment, size spectrum, biogeochemical cycling, LISST, statistical modelling, regression trees, flocculation, resuspension, indirect effects

1. Introduction

Suspended particulate matter (SPM) in the marine environment is represented by a mixture of organic and inorganic particles, and is characterised by complex structural and dynamical transformations (Jones et al., 1998, Richard et al., 1997, Jago and Jones, 2000). SPM is an important ecosystem constituent, and its characteristics influence overall ecosystem functioning through a wide range of biogeochemical processes (Tett et al., 1993, Guo & Zhang, 2005, Liu et al., 2005, Hill et al., 2006). Consequently, consideration of SPM has been useful in a number of ecosystem modelling studies (see, e.g., Hakanson & Eckhell, 2005, Huret et al., 2007, and references therein). A number of processes important for our understanding of the observed SPM patterns include, among others, advection, resuspension, sedimentation, flocculation, disaggregation, precipitation and dissolution. Of a particular interest is biological mediation of SPM aggregation during, e.g., phytoplankton blooms, resulting in increased particle size and settling flux of SPM to the seabed (Jones et al., 1998; Jago and Jones, 2000).

This paper presents some results from the joint investigations carried out by POL (Proudman Oceanographic Laboratories) and the School of Ocean Sciences (University of Wales, Bangor) in the Irish Sea, where a regular monitoring programme is being conducted with the aim to develop the underpinning science for marine management. The investigations are focused on the impacts of storms and eutrophication, the relative importance of events viz-a-viz the mean, and the implications for the modelling analysis of the overall ecosystem functioning, currently carried out by POL using ERSEM (European Regional Seas Ecosystem Model) component of POLCOMS (POL Coastal Ocean Modelling System).

1.1 Site Description

The study site is located in Liverpool Bay in the Irish Sea. The Irish Sea is connected to the rest of the North West European Shelf through the North Channel and St. Georges Channel in the south and so experiences interaction and exchanges with the North East Atlantic Ocean. The study area is characterised by strong tides (0.75 – 1 m/s on springs), occasional large storm surges and waves, freshwater input (the principal rivers Mersey, Dee and Ribble, the average total input of freshwater approximately 220 m^3s^{-1}), stratification, intertidal regions with exposed banks, high suspended sediment concentration and complex biogeochemical interactions. Tides in the area take the form of a standing wave, resulting from reflection of the Kelvin wave at the Lancashire coast. Tidal ranges are considerable, and reach approximately 8 m at the mouths of Dee and Mersey. Maximum currents occur 3 hr after and before high water (Miller, 1985). The Bay is also under considerable human impact as regards river-borne nutrients and pollutants, and therefore of concern to regulatory agencies.

2. Monitoring & Modelling Programme

The Liverpool Bay research is part of a wider monitoring and modelling programme of the eastern Irish Sea, which integrates (near) real-time and supplementary measurements with coupled models in a pre-operational coastal prediction system. It is led by POL and carried out in cooperation with CEFAS and SOS amongst other universities and research intitutions. Real time current measurements are obtained from a sea-bed mounted Acoustic Doppler Current Profiler, deployment started in August 2002, data are transferred to land via acoustic modems and the Orbcomm satellite e-mail system, and from a shore based HF radar via telephone landlines. There are also real time measurements from a surface buoy and a directional wave buoy and from an instrumented ferry, all via Orbcomm.

An extensive array of complementary physical and biogeochemical measurements on differing space and time scales has been established with a particular aspiration of measuring vertical gradients to test the 3-D models (Fig. 1). In particular:

- A central mooring at 53º 32' N 3º 21.8' W, installed in August 2002, providing *in situ* time series of current, temperature and salinity profiles. The site is close to the Mersey Bar Light and 20 km from the mouth of the Mersey. The water depth is 20 m below lowest tide, with a range of 10 m at equinoctial spring tides. An Acoustic Doppler Current Profiler (ADCP) in a sea bed frame records the current profile in 1 m bins from 2.5 m above the bed, and in addition directional waves. Acoustic transmission of data from a separate ADCP to a surface buoy has been successfully tested and installation is in progress so that the data can be transmitted in real-time using the Orbcomm satellite system. Conductivity, temperature, turbidity and fluorescence are also recorded on the frame.
- A CEFAS surface SmartBuoy installed in November 2002. This records surface properties including salinity, temperature, turbidity, nutrients, irradiance and chlorophyll and transmits the data in real-time via Orbcomm

(http://www.cefasdirect.co.uk/monitoring). The buoy also collects daily water samples.

- A directional wave buoy installed in November 2002 transmitting spectral wave components in real-time (http://www.cefas.co.uk/wavenet). Both the SmartBuoy and the WaveNet are located adjacent to the central mooring.
- A second site was established in 2005, 21 km to the west of the first, at 53º 27´ N 3º 38.6´W for estimation of horizontal gradients with the deployment of an ADCP frame. A second SmartBuoy has also been deployed.
- Mooring maintenance is carried out by the RV Prince Madog at approximately six week intervals (four weeks in the summer to overcome biofouling of the SmartBuoy optical sensors). Spatial surveys of Liverpool Bay are carried out on each cruise (black crosses in Fig. 1, comprising 34 vertical profiles, on a 5 nautical mile (9.3 km) grid, of CTD, SPM, some bed sediment sampling, and, since October 2003, surface and bed nutrients).
- The Birkenhead – Belfast ferry has been equipped with instruments for near surface (5m depth) temperature, salinity, turbidity, chlorophyll. The measurements began in December 2003. The 135 mile crossing takes 7 hours and a round trip takes place each day. The data are recorded every 30 s and 15 minute values transmitted to the laboratory by Orbcomm. The route is scientifically varied passing through six completely different hydrodynamic regions, whose differences in hydrodynamics are also reflected in their ecological functioning. This ferry is one of the nine ferry routes under study in the EU FERRYBOX project (www.ferrybox.com).
- A phased array HF radar system measuring surface currents and waves on a 4 km grid which started operation in 2004. The two sites are at Llanddulas, in

North Wales, and at Formby. The data at all cells are recorded every 20 minutes and hourly values transmitted to the laboratory by telephone landline.

- The UK Tide Gauge Network has been upgraded to allow real-time transmission of data from all tide gauges around the UK. The tide gauges in the Irish Sea, with additional sensors for met, waves, temperature and salinity where appropriate, are being incorporated into the Observatory.
- Bidston Observatory has been a meteorological recording station since 1867. This provides local real-time weather information (atmospheric pressure, wind speed and direction, cloud cover, rainfall). The station stopped recording in 2004 and has been superseded by a new station on Hilbre Island in the Dee Estuary, 10 km to the north west of Bidston Observatory, which also includes a web camera.
- Satellite data - infra-red (for sea surface temperature) and visible (for chlorophyll and suspended sediment) is provided by the Remote Sensing Data Acquisition Service (RSDAS, Plymouth) of NERC. Daily and weekly composite images are obtained via ftp but the extensive cloud cover over the Irish Sea means the daily images are often of little use. Weekly composite images are usually 90-100% complete.

The measurements are integrated with a suite of nested 3-dimensional hydrodynamic and ecological models run daily, focusing on the Observatory area by covering the ocean / shelf of northwest Europe (at 12 km resolution), the Irish Sea (at 1.8 km) and Liverpool Bay (at 200-300m resolution). All measurements and model outputs are displayed on the web-site (http://coastobs.pol.ac.uk).

The Coastal Observatory uses POLCOMS (the **P**roudman **O**ceanographic **L**aboratory **C**oastal **O**cean **M**odeling **S**ystem, see www.pol.ac.uk/home/research/polcoms), a 3-dimensional modelling system whose main elements are a 3-dimensional baroclinic hydrodynamic model (Holt & James, 2001) linked to a surface wave model (Wolf et al., 2002, Osuna et al., 2007), a sediment resuspension and transport model (Holt & James, 1999) and an ecosystem model (ERSEM – the European Regional Seas Ecosystem Model – Barreta et al., 1995; Blackford et al., 2004) with benthic and pelagic components. This modelling system has been developed primarily to investigate physical-biogeochemical interactions in shelf seas, see for example Allen et al. (2001), Proctor et al. (2002) and Proctor et al. (2003) for a fuller description of the system, although brief details are given below.

Operational nested 3-dimensional models covering the NE Atlantic ocean / shelf of northwest Europe (the Atlantic Margin Model (AMM) with 12 km resolution), the NW European Shelf (Medium Resolution Continental Shelf model (MRCS), 7km) and Irish Sea (Irish Sea model (IRS), 1.8 km) have been set up, and one is being set up for Liverpool Bay (LB, at 200 m resolution); a schematic of these domains is shown in Fig. 2. At the UK Met Office, POLCOMS on the AMM (Atlantic Margin Model) ocean/shelf domain (20ºW - 15ºE, 40º - 65ºN), driven by surface fluxes from the Met Office mesoscale (12 km) unified meteorological model and lateral ocean fluxes from the North Atlantic 1/3rd degree FOAM (Forecast Ocean Assimilation Model, Cattle et al. (1998)), has been operational since December 2002. This model produces daily hindcasts (24-hour) and forecasts (48-hour) and provides the boundary conditions (temperature, salinity, elevations, currents) for both the MRCS and the Irish Sea model. The Irish Sea model, was brought on-line in July 2003 and the

MRCS in February 2005 to run in pre-operational mode. Both AMM and IRS are now operational on the POL 192 processor (Pentium P4) Linux cluster. Models run daily in near-real time, either at the Met Office or at POL with the necessary forcing information transferred by ftp between the two computers. The Irish Sea model in turn provides boundary conditions to the Liverpool Bay model which is currently under development and includes wetting and drying processes to accommodate the significant intertidal regions which arise from the 12 m spring tidal range. Local river discharges are planned for inclusion in real-time through a link-up to the Environment Agency river-flow network; at present monthly climatological inflows are prescribed.

The implementation of the MRCS has fully coupled hydrodynamics-sediments-ecosystem 3-D interaction. This model runs in near real-time as a 7-day hindcast once per week. The components of the coupled model are shown in Fig. 3. The hydrodynamic component of POLCOMS is the three-dimensional baroclinic B-grid model described by Holt and James (2001) and Proctor and James (1996). It is a primitive equation finite difference model, solving for velocity (u,v,w), surface elevation, ζ, potential temperature, T, salinity, S and turbulent kinetic energy, q^2 in spherical polar s-coordinates (Song and Haidvogel, 1994). The model uses forward-time-centred-space differencing, with time splitting between external (fast) and internal (slow) modes. It employs a sophisticated advection scheme (the "Piecewise Parabolic Method", James, 1996) to minimize numerical diffusion and ensure the preservation of features even on coarse grids under oscillatory flows. This scheme also ensures positivity, is not subject to a vertical CFL restriction on the time step (James, 2000), and a flux matching scheme gives conservation of volume over both the internal and external time steps. Horizontal pressure gradients are calculated by interpolation (using a cubic-spline) onto horizontal planes to avoid the errors associated with calculating these on s-coordinates where the topography is steep. Turbulent viscosities and diffusivities are calculated using a Mellor-Yamada level 2.5 turbulence closure, but with an algebraically specified mixing length. In shelf-sea applications, such as considered here, the model is run without (imposed) horizontal diffusion since the parameterization of these processes is poorly understood and even with a sophisticated advection scheme, there is sufficient numerical diffusion to account for horizontal diffusion on the shelf.

The POLCOMS system includes the suspended particulate material (SPM) model described by Holt and James (1999) and Souza et al., 2007, which describes the deposition and resuspension of inorganic fine suspended material. This implementation uses two sediment classes with settling velocities of $5x10^{-5}$ ms^{-1} and $1x10^{-3}$ ms^{-1}; SPM size distributions (according to settling velocities) in the southern North Sea tend to approximate a bimodal distribution (Jago and Jones, 1998). The fine SPM class is initialized with a constant suspended load of $1.5gm^{-3}$ and is not transported in the horizontal. The coarser class is initialised with a bed load of $100gm^{-2}$ in water depths less than 20m. It is also supplied by riverine sources where data is available and by coastal erosion sources from the east coast of Great Britain. This is taken to occur from October to February and the total source is 3.8 M tonnes per year, a value that lies between the estimates of McCave (1987) and Odd and Murphy (1992).

ERSEM is a generic ecosystem model, which was originally developed and applied in the context of the North Sea. This model takes the ‘functional group approach’; the biota in the ecosystem is divided into three functional types: primary producers, consumers and decomposers, which are subdivided on the basis of trophic links and/or size. Each functional group is defined by a number of explicitly modelled components: carbon, nitrogen and phosphorous and, in the case of diatoms, silicon, and the physiological and population processes are described by fluxes of these between the functional groups. Detailed descriptions of the model and its pelagic and benthic sub-models are given by Blackford et al. (2004), Baretta et al. (1995), Baretta-Bekker et al. (1998) and Ebenhöh et al. (1997), and will not be repeated here. The parameter set used for this model simulation is the same as used in previous studies (Allen et al., 2001, Holt et al., 2004) and can be found at http://www.pml.ac.uk/ecomodels/ersem.htm. The POLCOMS-ERSEM system is considered the state of the art in North Sea ecosystem modeling (Moll and Radach, 2003).The ERSEM model is coupled as a subroutine in the hydrodynamic model: the 52 pelagic state variables are advected (by the "Piecewise Parabolic Method"), diffused and the ERSEM equations integrated at the same time step as the baroclinic physics model (300s). Example outputs of MRCS for the 30 April 2005 are shown in Fig. 4.

3. Case study: Suspended Particulate Matter

Currently, the sediment submodel of POLCOMS realistically reproduces a number of SPM patterns in the Irish Sea in general, and in Liverpool Bay in particular (see an example of model simulations in Videoclip 1; for further details and more videoclips of simulations contact A. Souza, http://www.pol.ac.uk/home/staff/?user=SouzAlex). This includes, e.g., elevated concentrations around the Liverpool Bay coast line and an SPM plume from the major freshwater inputs (rivers Dee, Mersey, Ribble) into the bay. There are also frequent occasions of elevated concentrations in Morecambe Bay (and adjacent area) and off Hollyhead. The events of higher SPM concentrations appear to be dependent both on high river discharges (which tend to bring a lot of suspended solids from the catchments, especially during and after storm events), and on the periods of windy weather (in particular westerly high winds and gales), which cause mixing of the water column and sediment resuspension.

Correct representation of SPM is paramount for simulations of a marine ecosystem, as SPM dynamics will directly affect light availability for primary producers, alter physical characteristics of pelagic and benthic habitats, and influence biogeochemical cycling via adsorption/desorption of chemicals to/off particles. Clearly, these direct effects will propagate through a multitude of environmental interactions, thus indirectly affecting many other processes and components of the ecosystem (Krivtsov 2001, 2004). Below we present some of the SPM monitoring results from 3 separate cruises on the RV ‘Prince Madog’ and use the patterns observed together with the results of regression tree analysis and stepwise regression modelling, to discuss implications for the overall ecosystem functioning and further improvements in the representation of the SPM submodel of POLCOMS.

3.1 Observations and data mining

The selection of data presented below to illustrate some typical patterns (Figures 5-13) were collected on 29-30 Oct 2004, 31 Jan-4 Feb 2005, and 15-17 Jun 2005 during 3 separate research cruises. Principally, the observational evidence comes from applying two methods: gravimetric determinations using GFF filters, and the

LISST_100 (Laser In-Situ Scattering and Transmissometry, Sequoia Ltd.) technique. The former technique enables measurements of SPM mass concentrations, e.g. in mg/l, whilst the latter provides estimates of volumetric concentrations (in microlitters per litter) for 32 size classes corresponding (on a log scale) to particle median diameters between 2.5 and 500 microns. Due to the space constraints only a small number of graphs can be reproduced here; however, more graphs are available on request and, at the time of writing, can be found at the first author's home page (http://www.sos.bangor.ac.uk/~oss00d/).

To investigate whether the total SPM volume could be consistently described in terms of a few size classes, we applied the data mining method of regression trees using a Matlab function 'treefit'. Regression trees are a representation for piece-wise constant or piece-wise linear functions, and models are given in a form of hierarchical structures of their elements. The models predict the value of a dependent variable (i.e. in our case, total SPM volume measured by LISST) from the values of a set of independent variables (i.e. volumes of 32 size classes). The space of examples is partitioned into axis-parallel rectangles and a model is fitted to each of these partitions. A regression tree has an inverse hierarchical structure with a test in each inner node (junction from were two links go to the lower hierarchical levels). Each node tests the value of a certain independent variable, and each leaf (the lowest level of hieratical tree) displays a linear equation or (in the analysis presented here) just a constant for predicting the value of the dependent variable.

3.1.1 October

The rivers' plume is a typical feature of the Liverpool Bay's oceanography. There appear (both from filtering, and LISST results) to be elevated concentrations off Dee/Mersey/ Ribble, and also at the west and North East (the latter possibly relating to the SPM load from Morecambe Bay). There also appear to be differences in the contributions of different size classes towards bottom and surface SPM, as visualised in the regression trees (Figures 8-9).

It is noteworthy that LISST and filtering results correlated well (Table 1a). However, there was no conclusive increase in correlation strengths whilst using beam attenuation or volume/diameter ratio in comparison with using the total SPM volume measured by LISST, hence no solid evidence that particles behaved like fractal aggregates. Improvement of statistical relationships between filtering (i.e. mass concentrations) and LISST data whilst using Beam Attenuation or V/d (as opposed to the volumetric concentration) would have been indicative of fractal behaviour (for more information on modelling of SPM fractal aggregates see Winterwerp, 1998, and references therein).

Interstingly, median diameter showed an inverse relationship with SPM for bottom data, whilst no significant relationship for the surface data was found. Consequently, the spatial distribution of the median diameter was markedly different from the distributions of SPM total weight and volume.

3.1.2 January-February

Due to a bad weather in winter only a limited number of sampling stations (16) have been visited during the cruise, which imposes limitations on the dataset collected. However, elevated concentrations off Mersey/Ribble (noted previously) are apparent in the winter data as well (both filtering and LISST, although the latter more prominent as regards surface data). Like before, there also appear to be differences in the contributions of different size classes towards bottom and surface SPM, as visualised in the regression trees (Figures 10-11). It should be noted, however, that the regression trees obtained for this data set also differed considerably from the ones obtained for Oct 2004. Interestingly, the strength of the correlations between filtering and LISST data was improved by using beam attenuation or Volume/diameter ratio variables, hence indicating that particles might have been behaving as fractal aggregates.

3.1.3 June

This time the weather was calm, and most sampling stations (34) have been visited. However, being summer, the range of the concentrations recorded for this data set was much smaller, which might have weakened the correlations revealed.

The LISST and filtering results correlated significantly, but the strength of the relationships obtained was limited (see Table 1). Similar to the Oct 2004 results, but in contrast with the winter data, the correlations were not improved by using beam attenuation or Volume/diameter ratio variables, hence providing no evidence that particles were behaving like fractal aggregates.

Consistent with the previous occasions, elevated concentrations were noted off Dee/Mersey and Ribble. Like before, there also appear to be differences in the contributions of different size classes towards bottom and surface SPM, as visualised in the regression trees, whilst the regression trees obtained for this data set (Figures 12-13) also differed considerably from the ones obtained for the previous occasions.

Finally, LISST Total V (i.e. the sum of volumetric concentrations of all the 32 size classes expressed in microlitres/l) and median diameter were positively correlated, whilst the relationships between SPM ppm (i.e. mass concentration expressed in mg/l) and median diameter were not significant. That contrasts remarkably with the previous occasions when inverse relationships were found.

3.2 Stepwise regression modelling

User-written Matlab programs were used to carry out Stepwise Regression Modelling analysis on the dataset containing bottom and surface SPM concentrations, median diameters, volume over diameter ratios (i.e. V/d), and a wide range of oceanographic variables. The final models (see examples in Tables 2-3) expressing relationships between SPM and environmental variables were of variable strength, and were generally better for SPM concentrations than for median diameters. In many cases models for beam attenuation and/or V/d were stronger than models for SPM volumes, thus providing evidence that particles might have been behaving like fractal aggregates (see Winterwerp, 1998, and references therein).

Despite the acknowledged complexity, our analysis helps to identify environmental variables important for the SPM characterisation. In particular, in the stepwise regression models, variables related to winds, waves, and tidal currents appear to explain considerable percent of the variance observed. Tides appear to matter more during springs (Table 2) than neaps (Table 3) but overall (i.e. on the basis of a number of cruises in addition to the ones illustrated here) show weaker relationships with SPM variables than winds and waves. Due to the Bay's geography and meteorological patterns (i.e. relatively long fetch from the West and predominance of Westerly winds), winds and waves are expected to be especially important during stronger, in particular W winds. Waves appear to be a significant predictor for a number of cruises, and influence the SPM in their own right (i.e. in addition to the purely wind effect). In Summer, the situation is especially complicated by the concurrent biological activity, and the patterns observed are likely to be a combined result of the superimposed direct and indirect interactions (Krivtsov, 2004). The most important predictor for the SPM variables in June appeared to be salinity, thus emphasising the importance of the inshore-offshore gradient.

3.3 Discussion

Although the patterns obtained using the simulation model simulations broadly represent the patterns observed in the total SPM volume, there is still scope for improvement. A number of previous studies have emphasised the difficulties involving modelling the SPM patterns (see, e.g. Tappin et al., 2002, Allen et al., in press, and references therein) and addressed errors in the simulations of the

POLCOMS-ERSEM complex (e.g. Lewis et al., 2006, Allen et al., in press). It should be noted that the aim of this paper is not to investigate the errors in the modelling simulations, but rather to use the patterns observed in the monitoring programme, together with the results of regression tree analysis and stepwise regression modelling, to further our understanding of the SPM characterisation, and to suggest possible improvements to the simulation models.

It has previously been shown (Jago and Jones, 1998) that the particle size distribution in the Irish Sea can be approximated as bimodal. Consequently, the current representation of the SPM submodel of a typical POLCOMS application considers only 2 size classes. The study of Holt and James (1999) considered 4 size classes, but they only covered diameters up to 35 microns. However, considering the regression trees presented here and the profiles of observed particle diameters, it appears that the dynamics of particle size distribution is rather complex, and a large proportion of SPM is present in flocks larger than 100 microns (see also Fig. 6). There is evidence (data not shown) that in the Irish Sea a number of processes are affecting particle size distribution, including, e.g., advection, resuspension, sedimentation, flocculation, disaggregation, precipitation and dissolution. Some of these processes (advection, resuspension, sedimentation) are currently represented in the POLCOMS; the others, however, remain the scope for future work.

Particle sizes tend to increase offshore but the trend is often complicated, also spectra from the same station sampled at different stages of the tide may be very different (e.g. stations 1 and 9, which have the same location, see Figure 6). In Summer, increases in median diameter are sometimes evident at the picnocline. In the Dee estuary, increases in particle diameter have been observed during the slack water, when particles may be behaving like fractal aggregates. Once the current increases, disaggregation occurs and the flocs tend to be broken down. Alterations in particles' diameter will inevitably result in the alterations of density, and hence alter the rate of sedimentation.

Particle size distribution and hence the dynamics of SPM may be complicated further by the activity of biota. In particular, flocculation may be enhanced by particle agglutination due to increased concentrations of mucus secreted by algae (see, e.g. Jones et al., 1998; Jago and Jones, 2000, and references therein), with a consequent effect on particle settling velocity (Jago et al., 2002). In the aftermath of blooms, the enhanced settling flux gives rise to low density, organic-rich, benthic fluff on the bed (Jago et al., 1993), which influences a number of physical and biological processes.

SPM ingestion by zooplankton will be followed by egesting of faecal pellets, thus dramatically increasing SPM sedimentation (Krivtsov et al., 2001). On the other hand, trophic activity of shredders may increase inputs of smaller-sized particles. Furthermore, considering that much SPM settles to the bottom during slacks and is resuspended during periods of larger currents, it is inevitable that the bottom processes (e.g. sediment consolidation, bioturbation and ingestion by benthic fauna) will have an important role to play for improving representation of the SPM dynamics. Considering the above, whilst the current representation of modelled processes and the simple bimodal approximation of particle size diameter are logistically convenient, it seems likely that explanatory power (and hence the value as a predictive tool) of model simulations may be further enhanced by considering processes outlined above.

Ecosystem dynamics in an aquatic environment is characterised by a multitude of direct and indirect interactions (Richard et al., 1997, Krivtsov, 2001, 2004, Krivtsov et al., 2001), and this complexity often leads to the scatter in the data, making modelling rather challenging (Tapping et al., 2002). However, SPM is an important ecosystem constituent, and its characteristics influence overall ecosystem functioning through a wide range of biogeochemical processes (see, e.g., Tett et al., 1993, Krivtsov et al., 2002, and references therein). Thus correct representation of SPM dynamics is crucial for representation of biogeochemical cycles of nutrients, in particular N, P, and Si (Krivtsov et al, 1998, 2001). It should also be noted that the availability of light is dependent upon the concentration of suspended solids (Krivtsov et al., 2000). Hence, correct representation of SPM dynamics is paramount for simulating the dynamics of primary producers, and therefore for simulating all the other variables of ERSEM.

Furthermore, light penetration into the water column depends on the profile of particle size spectrum (with smaller particles being particularly efficient in light attenuation). As our analysis has shown, the characteristics of the SPM-related variables are particularly influenced by wind and wave induced turbulence, and it is therefore expected that during rough weather light penetration into the water column should decrease due to the combined effect of resuspension and disaggregation of flocks. However, changes in particle size distribution due to flocculation and disaggregation are not currently represented in the POLCOMS-ERSEM complex. In a recent study (Lewis et al, 2006) it was reported that the observed spring peak of diatoms (data collected by continuous plankton recorders) occurred considerably later than the peak simulated by ERSEM. Consequently, the authors suggested that the phytoplankton response to light may have to be recalibrated. However, it is likely that light availability in winter and spring has partly been affected by changes in particle size distribution. We, therefore, suggest that further developments of the POLCOMS-ERSEM complex should benefit from a more detailed representation of the SPM dynamics.

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Appendix: Videoclip 1. Example of the sediment submodel simulations (to see the simulation please go to the Elsevier or ScienceDirect website).