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Depth dependence and intra-tidal variability of Suspended Particulate Matter transport in the East Anglian plume

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ABSTRACT

In order to derive an estimate of the net transport of Suspended Particulate Matter (SPM) in the East Anglian plume, we carried out a measurement campaign along two cross-sections within the plume. Selected stations were visited repeatedly to resolve the tidal cycle. By measuring profiles of currents and optical backscatter (from which SPM concentrations were estimated, via samples), both gross and net transports can be calculated, as well as intra-tidal and vertical variability. For the centre of the plume, we find a net transport of about 13millionkg over a tidal cycle. A comparison is made with maps of near-surface concentration of SPM from optical remote sensing. Some discrepancy is found in the values (of about a factor of two), but the spatial pattern agrees qualitatively.

1. Introduction

The East Anglian plume forms one of the pathways of Suspended Particulate Matter (SPM) in the southern North Sea (Dyer and Moffat, 1998). In Fig. 1a, the plume is visible by its relatively high concentrations of SPM at the surface, as observed by remote sensing. It leaves the East Anglian coast across the Norfolk Banks and then follows more or less an eastward direction along the Terschellinger Bank and the Frisian Front, in a range of water depths between about 30 and 40 m.

This frontal area is special in several ways. During summer, it marks the transition between well-mixed conditions to the south and stratification to the north (Pingree et al., 1978); a more detailed view was obtained from modelling results by van Leeuwen et al. (2015). In terms of bed composition in the southern North Sea, it forms the boundary between a generally low-silt content (¡2%) to the south, and high silt content (¿10%) to the north (Creutzberg and Postma, 1979), although sediment composition on the North Sea floor also shows a lot of patchiness due to its complex development during the Pleistocene (Eisma, 1987). Finally, the plume follows the general direction of the circulation (Otto et al., 1990), reflecting the presence of frontal jets (Hill et al., 2008); these flows show some variation with wind strength and direction (Nauw et al., 2015).

The overall distribution of suspended matter concentrations in the southern North Sea is known from extensive in-situ measurements, see, e.g., Eisma and Kalf (1987b). For surface values, optical remote sensing provides detailed maps, in which the East Anglian plume is often clearly visible (Eleveld et al., 2008; Pietrzak et al., 2011). SPM concentrations in the southern North Sea are persistently high at the head of the East Anglian plume, near the Humber Estuary, over the southern edge of the Norfolk Banks, and in the Greater Thames Estuary. Along the Belgian and Dutch continental coast, year-round high SPM concentrations occur over the Flemish Banks, and near the Wadden Sea and Weser-Elbe Estuary (Eleveld et al., 2008). Along both the shallow UK and the continental coasts ample fine sediment is available for resuspension by strong tidal currents from both older deposits and recent supply; besides, river discharge is a factor (de Jonge and de Jong, 2002).

The East Anglian plume crosses the North Sea from southeast England and occasionally even extends northward past the Dutch Wadden Sea and offshore from the Danish coast, most clearly so in October to March (Eleveld et al., 2008). In these months, surface SPM concentrations in the East Anglian plume are influenced by winds and waves in addition to tides; they produce increased advection

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and sufficient shear stress to also resuspend mud from the deeper (>35 m) regions (Pietrzak et al., 2011, Fig. 8) to the top of the well-mixed water column, where it can be detected with satellite sensors. In a modelling study, Stanev et al. (2009) also found wave-induced shear stress to be significant for resuspension at these deeper locations, besides current-induced shear stress, although there are additional factors, such as the local bottom composition.

The sources and sinks of fine sediment in the North Sea have been broadly identified (see Dyer and Moffat, 1998, for a short overview). In particular, Dyer and Moffat (1998) made an estimate of the total net eastward transport of SPM in the East Anglian plume by multiplying the residual current (obtained from a numerical model) with the depth-average SPM concentration. Their estimate was 6.6 Mton/year, with, however, an error range of 50%. We are not aware of studies on the fate of the SPM in the East Anglian plume, but given the general direction of the plume, the major deposition areas of the Kattegat and Skaggerak (Eisma, 1987) are likely candidates.

In this study, we calculate transports according to their actual definition, namely by multiplying instantaneous currents u (in m/s) and concentrations c (in g/m^3) at individual positions in the vertical, and then integrate this product over time and over the area of the transect (Notice that, in principle, the resulting transport may even be opposite to the residual current.) Moreover, our estimates are purely observation-based; we are not aware of similarly obtained earlier estimates for the East Anglian plume.

We consider the transport of water and SPM that occurs within a tidal period. Intensive measurements are needed to determine instantaneous current and concentration profiles throughout a full tidal period. The aim of this research is to identify the transport rates of SPM along this plume, and investigate variability in the vertical and with time (specifically the tidal cycle), across and along the plume. We start with an overview of the area and methods in Section 2. In Section 3, we present measurements made along two transects (T1 and T2), for each one a detailed spatial coverage was followed by repeated measurements at selected stations over a tidal cycle. Extensive measurements of current profiles, optical backscatter (OBS) and SPM concentrations allow us to establish a relationship between OBS and SPM, and hence to calculate the gross transports of SPM during the ebb and flood phases of the tidal cycle, as well as the net result over a tidal cycle. In Section 4, we compare near-surface values of SPM from in-situ measurements with estimates from optical remote sensing.

2. Measurements

2.1. Research area and cruise plan

The cruise took place on board NIOZ R/V Pelagia, from 6 to 15 March 2013 (days of year 65–74). We carried out in-situ measurements at two transects across the plume, indicated by the blue lines in Fig. 1. The first transect (T1) lies in the middle of the Southern Bight, spanning from 52°54.0′N 3°15.0′E to 53°53.4′N 3°15′E. The location was determined using a map of surface values of SPM estimated from a remote-sensing image from the 4th of March (day of year 63), two days prior to the start of the cruise, see Fig. 1a.

The SPM maps were produced from the Level-1 images acquired by the Moderate-resolution Imaging spectroradiometer (MODIS) onboard of the NASA spacecraft Aqua. These data, processed by the Ocean Biology Processing Group, are available from the NASA Ocean Color website (http://oceancolor.gsfc.nasa.gov). The Level-1 images were then atmospherically corrected using the near-infrared atmospheric correction algorithm implemented in the SeaDAS software, yielding images of water-leaving reflectance (ρ_w). Finally, SPM concentration is retrieved from ρ_w data at band 667 nm, using the algorithm of Nechad et al. (2010). The algorithm is applied here because 1) this semi-empirical model has been calibrated and validated using measurements taken in the southern North Sea (2001–2006), and 2) it is designed for use in the case of turbid waters (SPM >1 mg/l, up to SPM 100 mg/l). The choice of this algorithm using band 667 nm has the advantage to estimate SPM concentrations with the best accuracy from MODIS band 667 (relative error < 30%). For the 1–200 mg/l concentration range, this band has a higher signal-to-noise ratio than the longer infrared bands, while the significant contributions from CDOM and Chl absorption to reflectance at shorter wavelengths can lead to larger uncertainties in SPM retrieval. The disadvantage is that estimation of SPM from band 667 nm may show larger uncertainties (>33%) in the case of extreme chlorophyll concentrations (>10 μg/l), but this effect should be reduced for the East Anglian plume in March; the mean seasonal Chl concentrations from 1988 to 2011 range between 1 and 7 μg/l approximately (Capuzzo et al., 2015).

The image in Fig. 1a shows a relatively wide but low-intensity plume, beyond the initial higher SPM concentrations close to the UK coast. The second transect (T2) was located at the eastern edge of the plume, from 53°24.0′N 5°9.0′E to 54°15.6′N 4°10.9′E. Later remote-sensing images are also shown in Fig. 1b–d; they will be discussed in Section 4.

The main objective is to determine the vertical and intra-tidal variability in SPM concentration and transport rates in the East Anglian plume. In initial surveys, measurements were conducted to locate the centre of the plume, where concentrations are highest. For T1, this survey was carried out on the 7th of March (day of year 66), and for T2 on the 12th of March (day of year 71). In the ensuing days at each transect, more detailed measurements would follow by repeatedly visiting selected stations near the centre of the plume. This involved measurements over a 14-hour period, to resolve the variability in SPM dynamics over a tidal cycle; additionally, longer transects were conducted to monitor the location and width of the central part of the East Anglian plume.

The high-frequency measurements included either two or three stations, at a distance of 5 km from each other. Measurements were then conducted every 45 min at a different station. For a 2-station session, this means that every 1.5 h each station was visited, resulting in 10 or 11 data-points during a 14-hour period. When three stations were included during a day, the central station would be visited every 1.5 h, and the outside stations only every 3 h. These outside stations were however visited more frequently (10 or 11 times during the 14 hour session) during the previous or ensuing day (see Tiessen, 2013, for the detailed cruise program).

New Moon was on 11 March and the strongest currents (according to the Oregon State University model) occur about two days later in this area. At spring tides, maximum currents in the east-west direction are similar for both transects (according to the model), but the tidal cycles were covered on different days: on 8 March for T1 and 14 March for T2. So, for T1, the condition was in between neap and spring tides, whereas T2 was right after spring tides. This is confirmed by Fig. 5e,f, where currents are stronger in the latter. Regarding the diurnal inequality (again according to the model), for the eastward component at T1, the maximum flood just prior to the measurements was equal to the one at the end of the measurements. For T2 on 14 March, the second flood (right after the measurements) was only slightly higher (a few cm/s). In short, the diurnal inequality does not seem to play an important part here; the beginning and end of the measurements closes a nearly periodic cycle.

Weather conditions during the cruise were variable: mild conditions were experienced prior to departure as well as during the first day of the cruise, which was mainly spent in transit. Subsequently, cold weather and strong easterly to northeasterly winds persisted during the first half of the measurement campaign, but the wind dropped considerably during the second half of the cruise and turned northerly to northwesterly. Fig. 2 shows the wind conditions as