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Suspended sediment signatures induced by shallow water undulating bottom topography

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ABSTRACT

Near-surface signatures of suspended sediment concentration (SSC) related to submerged bed forms displayed in visible band data gathered by space-borne imaging sensors are described. Detailed Acoustic Doppler Current Profiler (ADCP) data of vertical current velocity component, echo intensity, modulation of SSC and related oceanographic and meteorological observations in a tidal inlet of the North Sea have been analyzed. To understand the associated hydrodynamics of the optical imaging mechanism theoretical considerations based on the Navier–Stokes and sediment continuity equations have been carried out. As a first approximation these theoretical results explain signatures of enhanced SSC of in situ measurements and analyzed space-borne images. Strong currents flowing over steep bottom topography are able to stir up the sediments to form both a general continuum of SSC and localized pulses of higher SSC in the vicinity of the causative bed feature itself. The "strain rate" equivalent to the current gradient is an important parameter describing near water surface oceanographic and meteorological phenomena in the visible and microwave part of the electromagnetic spectrum observed by shore- and ship-based as well as air- and space-borne remote sensing systems. Significant disagreements between theoretical results of the "strain rate" generated by the surface current and in situ observations at the crests of submerged ridges and sand waves were identified. Possible explanations could be: first, the current velocity may not be barotropic near the crests of such bed forms and second, mass conservation may not only be maintained through an acceleration or deceleration of the flow. This implies that active up- and downwelling effects of the three-dimensional current field can also play a significant role for hydrodynamic interaction between current and underwater bed forms.

1. Introduction

In this paper the focus is on the variation of oceanographic parameters caused by interaction of currents with sea bottom topography. It is well known that a strong coherence exists between fluctuations of oceanic structures and disturbances of current velocity. The analysis of marine remote sensing data gave a special contribution for explanation of different imaging mechanisms in the visible, infrared and microwave parts of the electromagnetic spectrum. Acoustic methods such as the Acoustic Doppler Current Profiler (ADCP) made also distinct contributions for measuring oceanographic parameters in the water column. The dominant oceanic sound scatters of ADCP transmission frequencies are zooplankton, suspended sediment, turbulence-induced sediment fluctuations, detritus, bubbles and density gradients.

Already Stewart and Jordan (1964) observed suspended sediment in the water column when diving just over crests of submerged sand ridges on Georges Shoal of Georges Bank, Gulf of Maine, USA. The current direction was normal to the ridge during these observations. Nearly 20 years later Harden Jones and Mitson (1982) published measurements of large submerged sand waves between Sandettie and Outer Ruytingen Banks in the Southern Bight of the North Sea which showed enhanced noise levels at their crests. They called these features "plume-like traces" which have been recorded by 30 kHz and 100 kHz echo sounders as well as by 300 kHz sector-scanning sonar. They discussed that underwater sound sources might be used by fish shoals as indicators of tidal flow or as acoustic beacons by migrants on passage. It has been concluded by these authors that the noise was generated by the movement of bottom sediments which might be detected by marine species such as herring and plaice shoals. Furthermore, Harden Jones and Mitson (1982) showed also the relation between the intensity of measured 300 kHz bottom noise and water current velocity associated with a group of small sand waves located 150 m to 160 m to the southwest of the Outer Ruytingen anchor station at position 51° 06.2′ N and 1° 53.1′ E. Noise from sand waves increased with current velocity whereas bottom noise was not detected at current velocities below 0.4 m s^{-1}. This was an important result because the lower limit of the current velocity of 0.4 m s^{-1} coincides with the lower limit of current velocity when observing significant Normalized Radar Cross Section (NRCS) modulations due to submerged sand

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waves two years later by Alpers and Hennings (1984). Again 10 years later, Stolte (1994) showed distinct links between NRCS and sea surface sonar conditions.

A suspended sediment front in the Severn Estuary, United Kingdom, was investigated by Kirby and Parker (1982). The authors concluded that the front may be due to an interaction between the regional and local topography, Coriolis effects and lateral phase differences in tidal elevation across the estuary, which set up secondary water circulation cells in the plane of the cross-section, leading to convergence along the main channel axis. A pair of light streaks observed on aerial photos had been associated with crests of submerged ridges in the sea area of Nantucket Shoals, Massachusetts, USA (Smith, 1986). It was assumed that these streaks are caused by suspended sediment stirring by large tidal current velocities. The streaks often coincided with a boundary between rougher and smoother sea surface water depending on the tidal current phase. A strong correlation between water properties and water depth was found out across the Well Bank and the Broken Bank of the Norfolk Sandbanks in the North Sea (Huntley et al., 1993). High suspended particulate matter (SPM) concentrations are located over the crests of the banks. A Coastal Zone Color Scanner (CZCS) image of the sea area of Georges Bank at the eastern North Atlantic coast of Maine, USA, showed band like patterns in the water-leaving radiance at 550 nm wavelengths in the visible part of the electromagnetic spectrum (Yentsch, Phinney, & Campbell, 1994). These high-reflectance bands appear to be related to the large sand dunes and ridges which dominate the sea bottom topography in this sea area. Soulsby, Atkins, Waters, and Oliver (1991) showed that the near bed region above the trough of an asymmetric sand wave in the tidal estuary of the river Taw, southeast England, has largest values of turbulent kinetic energy, Reynolds stress and sediment concentration. The sand wave trough acts as a source of these quantities. At peak flow no flow separation was observed, but during the decelerating phase flow has been reversed up to 40% of the time. Until now strong acoustic scatter has been often observed within the water column expected to be turbulent, but it has never been absolutely clear if this is due to higher plankton or suspended matter concentration or other effects. A review of acoustic measurement of small-scale sediment processes were presented by Thorne and Hanes (2002). In particular, Ross and Lueck (2003) showed that turbulent microstructure strongly scatters sound at 307 kHz. An overview of oceanographic phenomena caused by interaction of currents and bottom topography based on historical notes and theoretical modeling was presented by Hennings (2009). Many in situ measurements of water constituents in the ocean such as suspended sediment concentration (SSC), its analysis and modeling efforts have been carried out and discussed during the last three decades (see e. g. Fugate & Friedrichs, 2002; Gartner, 2004; Hoitink & Hoekstra, 2005; Gemein, Stanev, Brink-Spalink, Wolff, & Reuter, 2006; Chanson, Takeuchi, & Trevethan, 2008; Lee et al., 2010; Shi, Wang, Li, & Pichel, 2011). Finally, a summary of new light into optical oceanography was given by Dickey, Kattawar, and Voss (2011).

The motivation for this study was given by the cited publications above, especially by the imaging of water surface signatures related to submerged bed forms viewed in visible-band imagery and the further development of the theoretically description of the associated hydrodynamics of the responsible imaging mechanism. A central question is whether localized pulses of higher SSC in the vicinity of the causative sea bed features rise high enough in the water column and become resolvable to the extent that they create distinct signatures in space-borne optical imagery. To illustrate such features, two examples of different spatial resolutions have been selected and are described in Sections 2 and 3, respectively. Section 4 presents the ADCP measurement configuration. The theoretical formulation is outlined in Section 5. ADCP data and related oceanographic as well as meteorological observations are described in Section 6. Calculation of the "strain rate" and its different components are presented in Section 7 for ebb and flood tidal current phase, respectively. Finally, the discussion and conclusions are given in Section 8.

2. Coastal Zone Color Scanner (CZCS) image

Our first example for distinct features in space-borne optical imagery has been primarily selected to show a subsurface radiance signature related to shallow water bottom topography on a larger spatial scale and to present the locations of the other two study areas of lower spatial scale described in Sections 3 and 4, respectively, as an overview. The picture shown in Fig. 1 is a CZCS image from onboard the Nimbus 7 satellite of orbit 4384 acquired at 1054 UT on 6 September 1979. A multi-channel scanning radiometer measured the reflected solar energy from the near ocean surface in six channels. The center wavelengths of the sensor are 443 nm (channel 1), 520 nm (channel 2), 550 nm (channel 3), 670 nm (channel 4), 750 nm (channel 5) and 11 500 nm (channel 6). A brief description of the CZCS sensor is given by Hovis and Clark (1980). The geometrically and atmospherically corrected CZCS image presented in Fig. 1 is a color composite of channels 1, 3 and 4. Superimposed on the image is a relative Mercator grid projection with a latitude difference of $\Delta\phi = 1°$ and a longitude difference $\Delta\lambda = 1°$, respectively. A spatial resolution of 825 m was achieved at nadir of the satellite scene. The image views the North Sea between the English, Dutch, German and Danish coasts. Both locations of the Marsdiep tidal inlet of the coast of the Netherlands and the Lister Tief tidal inlet of the coast of Germany described in Sections 3 and 4 are indicated each by black arrows in Fig. 1. Complex features of enhanced subsurface radiance are shown on the composite image which is created by the circulation regime and the transport of suspended matter in the North Sea. For a detailed discussion see e. g. Eisma and Kalf (1979). The focus of this image is on the green semicircle shaped signature located 192 km easterly of the English coast above the southern shallow part of the Dogger-Bank area. The CZCS image was acquired 26 min after spring high water at Dover, United Kingdom. A mean tidal current speed of 0.4 m s^{-1} and a mean tidal current direction of 311° were observed in the sea area of the Dogger-Bank (United Kingdom Hydrographic Office, 1976). The wind speed varied between 8 m $s^{-1} \leq U_W \leq 10$ m s^{-1} and the wind direction was from 158° (east southeasterly). The shallowest water depth of the Dogger-Bank is 13 m. A first comparison between CZCS signature and bathymetric data of the bank showed that the enhanced subsurface radiance feature is located above the shallow part and at the steep sea bed slope region in the southern part of the Dogger-Bank. The radiance signature is associated with that part of the Dogger-Bank which is caused by the tidal current velocity acting as a source at the boundary layer between the water and the sediment layer of the submerged bank. Bottom sediments could be moved upwards in the upper layer of the water column. Both the tidal current direction as well as the wind direction are creating a significant sea wave direction and are acting in a common way as sources for sediment suspension at the sea floor rising up in the water surface layer. However, at this stage of analysis it cannot be excluded that the radiance signature can be also explained by a localized enhancement in phytoplankton production or other water substances around the mixed waters near the Dogger Bank. In addition, in all of this one needs to rule out the possibilities that the light is coming directly from reflection at the sea bed itself or that sun glint at the surface is involved.

3. Kodak Digital Camera image

The second example shown in Fig. 2 is a Kodak Digital Camera DCS760C image of identification ISSO15-E-5977 (mission: ISSO15/roll: E/frame: 5977/mission ID on the film or image: ISSO15) of orbit number 341 acquired from onboard the International Space Station (ISS) at 1354 UT on 1 May 2007 with a spacecraft altitude of 326 km (data file: NASA_20070501_Den_Helder_NL.jpg). The camera tilt angle was 43° describing the calculated look angle away from a straight nadir view. Camera focal length was 800 mm. The film consists of a