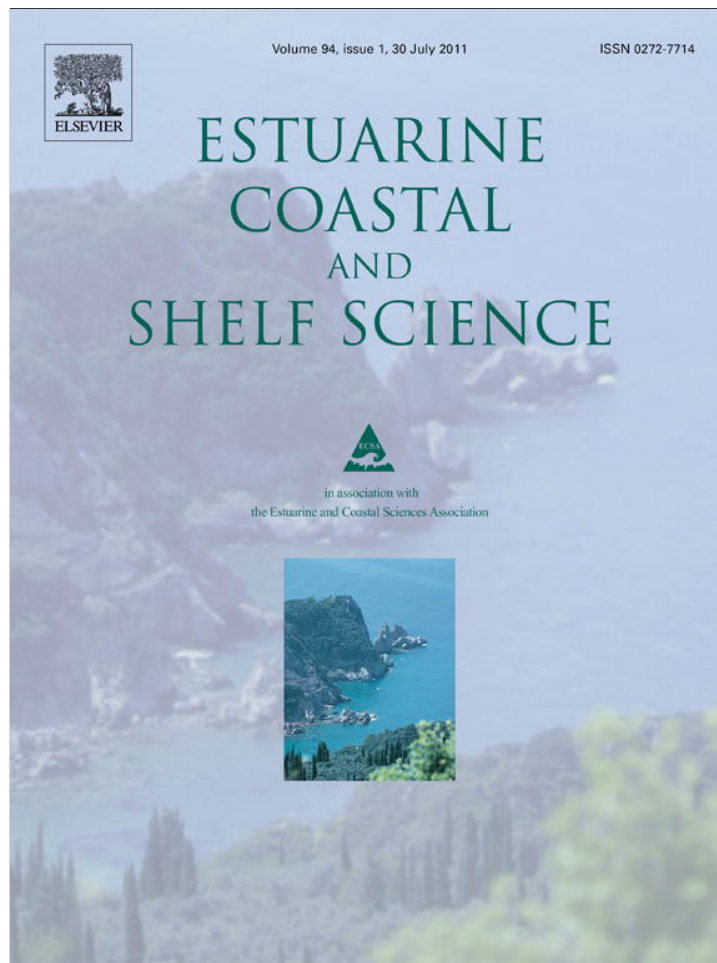


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Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecssIn situ flume measurements of resuspension in the North Sea[☆]C.E.L. Thompson^{a,*}, F. Couceiro^b, G.R. Fones^{b,**}, R. Helsby^c, C.L. Amos^a, K. Black^c, E.R. Parker^d, N. Greenwood^d, P.J. Statham^a, B.A. Kelly-Gerrey^e^a School of Ocean and Earth Science, University of Southampton, National Oceanography Centre, Southampton, Hampshire SO14 3ZH, UK^b School of Earth and Environmental Sciences, University of Portsmouth, Burnaby Building, Burnaby Road, Portsmouth PO1 3QL, UK^c Partrac Ltd, 141 St James Road, Glasgow G4 0LT, UK^d Cefas Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK^e NERC, National Oceanography Centre, Southampton, Hampshire SO14 3ZH, UK

ARTICLE INFO

Article history:

Received 10 March 2011

Accepted 26 May 2011

Available online 1 June 2011

Keywords:

sediment
resuspension
North Sea
annular flume

ABSTRACT

The in situ annular flume, Voyager II, was deployed at three sites in the North Sea in order to investigate resuspension events, to determine the physical characteristics of the seabed, to determine the threshold of resuspension of the bed and to quantify erosion rates and erosion depths. These are the first controlled, in situ flume experiments to study resuspension in the North Sea, and were combined with long-term measurements of waves and currents. Resuspension experiments were undertaken at two muddy, and one sandy site: north of the Dogger Bank (DG: water depths ~80 m, very fine, poorly sorted, very fine-skewed sediment experiencing seasonal thermal stratification of the water column along with oxygen depletion); the Oyster Grounds (OG: ~40 m, similar bed properties, year round water column thermal stratification, Atlantic forcing); and in the Sean Gas Field (SGF: ~20 m, moderately sorted, very coarse-skewed sand, and well mixed water column). The erosion thresholds of the bed were found to be 0.66–1.04 Pa (DG) and 0.91–1.27 Pa (OG), with corresponding erosion depths of 0.1–0.15 mm and 0.02–0.06 mm throughout the experiments.

Evaluation of a year of current velocities from 2007 indicated that at OG, resuspension of the consolidated bed was limited to on average ~8% of the time as a result of tidal forcing alone for short (<30 min) durations, but would potentially increase during the winter as a result of wave influences. At DG, under similar conditions this would increase to 13%, and in the SGF, wave-induced resuspension events occurred throughout the year, with the potential exceedance of the threshold for suspension greater than 50% in January and March.

Resuspension of bed material and erosion rates were closely related to applied bed shear stresses, and eroded depths were significantly correlated with the physical properties of the bed. Therefore, while complex variations in biogeophysical factors affected the critical threshold of erosion, once exceeded, erosion rates were related to the nature of the sediment.

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[☆] This paper forms part of the Sediment–Water Column Exchange project, a partnership project funded by the UK Natural Environment Research Council (NERC) and supported equally by Defra as part of the Marine Ecosystem Connections (MECs) project.

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1. Introduction

Coastal and shelf seas are energetic environments, undergoing frequent resuspension events as a result of the action of waves and currents (Van Raaphorst et al., 1998). The resuspension of bed material leads to the stirring up of nutrients, trace metals, and organic material from the sediments into the water column (Morris and Howarth, 1998), affecting the timing and types of nutrient fluxes (Blackburn, 1997), potentially inducing microbial and phytoplankton growth (Wainright and Hopkinson, 1997) and increasing primary production. Conversely, when suspended material remains in suspension for prolonged periods (Jago et al., 1993), it may attenuate available light, inhibiting phytoplankton growth (Tett and Walne, 1995; Schallenberg and Burns, 2004) even

in relatively shallow waters (Tett and Walne, 1995). However, the full scale of the influence that resuspension events have on these and other biogeochemical processes is still unclear.

Key to the assessment of these processes is determining the likelihood and potential frequency of resuspension events in a given area, based on the local sediment and hydrodynamic conditions. To do this, a thorough understanding of the physical resuspension process is essential, in particular the critical erosion threshold and the potential eroding depths of the sediments.

Making in situ measurements of resuspension is challenging due to the difficulties of predicting the timing of events, and the requirement to measure close to the sediment–water interface where suspended sediment concentrations are highest (Van Rijn, 1984; Nittrouer and Wright, 1994). Alternatively, collection of sediment for laboratory experiments of resuspension can result in disturbance of the sediment structure, leading to differences in experimental results in comparison to in situ measurements (Tolhurst et al., 2000). To address these issues, a comprehensive strategy was devised to combine in situ benthic flume deployments and long-term measurements of local hydrodynamic conditions. The use of an in situ benthic flume ensures that the natural bed structure and water conditions are maintained, but resuspension events can be induced by way of paddles driving a unidirectional current within the flume. In situ benthic flumes have been successfully used to investigate bed stability in the past in lakes (e.g. Droppo and Amos, 2001; Amos et al., 2003), intertidal areas (e.g. Widdows et al., 1998; Tolhurst et al., 2000; Amos et al., 2004) and coastal settings (e.g. Amos et al., 1992a,b, 1996; Sutherland et al., 1998b; Moreau et al., 2006). However, these kinds of controlled, in situ flume experiments have not been used before to assess the resuspension potential of sediments on an open shelf sea setting such as the North Sea, and are unique to this study.

Local resuspension from the bed is controlled by the threshold bed shear stress $\tau_{cr} = \rho u_*^2$ (Pa) where ρ is the density of the water and u_* the friction velocity at the bed. Resuspension is dependant

on the combined effects of waves and currents, the grain size and bulk characteristics of the bed material (its erodibility), the presence of bedforms, and any biogenic influences such as biostabilisation (Black et al., 2002) or bioturbation (Widdows et al., 2000). Once this threshold stress is exceeded, material will become entrained from the bed and enter suspension. If the settling velocity of the material is less than the upward-turbulent component of the velocity, the material will remain in suspension (Soulsby, 1997), otherwise it will be returned back to the bed.

Erosion of muddy sediments tends to begin with the movement of the organic-rich “fluff” layer, and erosion of the primary floc and aggregate bonds of the surficial bed material (Type 1a), before the onset of erosion of the bed material in the form of aggregates (Type 1b) characterised by an asymptotic suspended particulate matter (SPM) time series at a constant applied stress. Type II erosion is constant with time, where erosion continues as long as the applied stress exceeds the critical threshold and is characterised by mass failure of the bed (Parchure and Mehta, 1986; Amos et al., 1992a, 1997).

This paper forms part of the Sediment–Water Column Exchange project, a partnership project which aims to understand the effects of resuspension on nutrient fluxes within the North Sea. It describes the physical characteristics of the seabed at three project sites, determines the threshold of resuspension of the bed, quantifies the erosion rates and erosion depths and relates this to longer-term measurements of currents and waves in order to answer the questions: How frequently is resuspension of bed material in the Southern North Sea likely to be? How much material is likely to be resuspended during such events?

2. Methodologies

2.1. Site descriptions

The North Sea is a tidally dominated, semi-enclosed coastal shelf sea on the northwest European continental margin (Fig. 1). The

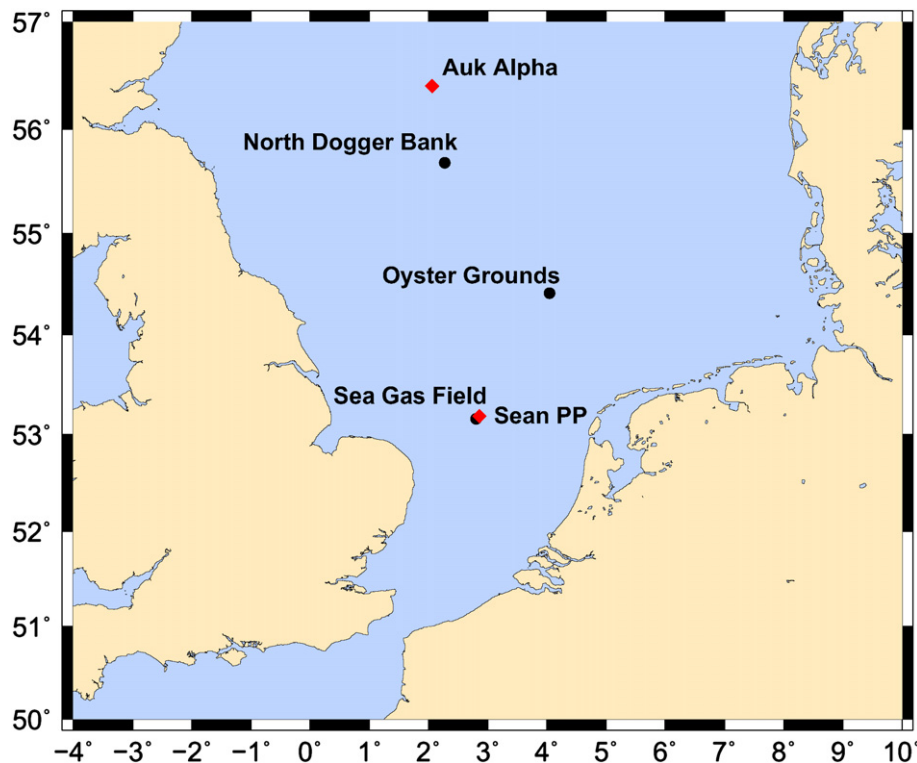


Fig. 1. Positions of Voyager in situ flume deployments (black circles), and wave buoys (red diamonds).

water column is completely mixed by waves in winter, and stratified in the northern regions by increased surface temperature in the summer (Rodhe et al., 1962). Rivers inputs range from 165 to 300 km³ annually (Rodhe et al., 1962; Gerritsen et al., 2000), and persistent patterns have been found in the sedimentary system (Stanev et al., 2009) with the predominant forcings being: astronomical tides, wind waves, currents and thermohaline fields, fresh water fluxes and external sources of suspended particulate material (Stanev et al., 2009).

Sediments are predominantly sand, with gravel and sandbanks in the shallower waters, and fine-grained beds in deeper waters (Rodhe et al., 1962). Sediment turnover is largely dominated by tidal forcing in the Southern Bight, and by waves in the deeper northern North Sea.

Temporal changes in suspended particulate concentration in the southern North Sea are largely decoupled from the local near-bed hydrodynamic conditions (Williams et al., 1998), and when local resuspension does occur, the suspended particulate matter is predominately composed of material from a “fluff” layer of biotic material rather than the underlying bed material (Jago et al., 1993, 2002; Van Raaphorst et al., 1998; Williams et al., 1998).

Three sites were chosen for the investigation (Fig. 1, Table 1), coinciding with sites visited by research cruises as part of the joint Centre for Environment, Fisheries & Aquaculture Science (Cefas) and Department for Environment, Food and Rural Affairs (DEFRA) Marine Ecosystems Connections Program, and chosen based on their physical, chemical and biological characteristics.

Oyster Ground (OG) (Fig. 1) is characterised by seasonally occurring, thermally induced, water column stratification and the occurrence of oxygen depletion near the bed. Water depths are typically ~40 m overlying a cohesive muddy sand substrate. Van Raaphorst et al. (1998) described the Oyster Grounds as a temporary deponent, which retains advected material for some time following deposition, until it is advected away after resuspension. North Dogger Bank (DG) north of the Dogger Bank, is the deepest site at ~80 m

depth, and consists of mainly cohesive sediment and fine sand. It is subject to thermal stratification and the influence of Atlantic forcing. This area typically sees relatively low suspended sediment concentrations (<10 mg l⁻¹) (Doerffer and Fisher, 1994), and high bed shear stresses in the area have been seen to coincide with low concentrations of suspended matter (Stanev et al., 2009), implying a limited sediment source. Sean Gas Field (SGF) in the southern Bight is well mixed throughout the year and influenced by riverine inputs. The sediment is permeable sand with an overlying water depth of ~20 m.

2.2. Long-term monitoring

Sustained monitoring of the sites has been carried out by Cefas since 2006, providing time series measurements of naturally occurring current velocities, suspended sediment loads and resuspension events. The monitoring has involved regular cruises to the sites, as well as fixed measurements in the form of bottom landers, tethered (mid-water) instruments and surface buoys (Greenwood et al., 2009). The instruments provide measurements of temperature, salinity, chlorophyll, suspended particulate matter and dissolved oxygen. Nutrient measurements are available from surface buoys at DG and OG.

At OG, a surface buoy and mid-water (35 m) instrument package have been in operation since March 2006, and a benthic lander has been in place from April 2007 to August 2008. Continuous ADCP records are available from 23 February 2007 until 29 October 2007 and from 19 January 2008 to 07 August 2008. At DG, all three instrument packages were in place from February 2007 to September 2008. A combination of Teledyne RDI's Workhorse Sentinel ADCP instruments (600 kHz and 300 kHz) were utilised at both OG and DG. At SGF, a benthic lander has been in place, providing continuous ADCP data from 21 February 2007 until 22 April 2008, from a combination of an RDI (300 KHz), and a Nortek Continental Current Profiler (470 kHz). ADCP data was recorded at 30 min intervals, and breaks in the data are the result of biofouling of the sensors, or instrument failure (Greenwood et al., 2009).

Wave data has been sourced from the closest Cefas wave buoys to the site locations (Fig. 1). Sean PP (WMO ID 62145) has been used to represent the Sean Gas Field Site. It is located at 53°11'.30N and 002°51'.75E in 31 m of water. The North Dogger and Oyster Ground sites are represented by Auk Alpha (WMO ID 62132). This buoy is located at 56°24'.03N and 002°3'.80E in 77 m of water. Data from both were recorded using a Saab® downward-looking wave radar.

2.3. Bed properties

When on station, a large (550 mm) and a small (300 mm) NIOZ Haja corer recovered sediment cores to assess the physical properties of the bed. The larger cores were sub-sampled using 60 ml syringe cores and flash frozen in liquid nitrogen. Cores were then assessed for bulk density and porosity using computed tomography (CT) on a Siemens Sensation 64 scanner based on the methodologies of Orsi et al. (1994), Amos and Sutherland (1996), and Burdige (2006) respectively.

Grain size analysis was performed on the material collected with the smaller corer at each site, using a combination of dry sieving (for sizes >1 mm) and laser analysis (<1 mm). X-ray diffraction (XRD) was performed to determine the mineralogy of the fine fraction for the muddy sites, using a Phillips XPert Pro diffractometer. A copper tube was used and run from 2°2θ–215°2θ at a scan rate of 1.2°2θ/min with a step size of 0.02°2θ. Each sample was saturated with magnesium chloride before slide preparation, and run four times under the following conditions: (1) air dried; (2) soaked overnight in ethylene glycol at 55 °C in a humidifier (run at 2°2θ–40°2θ) to detect the presence of swelling clay; (3) oven dried

Table 1

Summary of Voyager II deployments and bed parameters at the 3 deployment sites. Porosity (uppermost 1 cm of sediment), chlorophyll *a* (1 cm), particulate organic carbon (10 cm). All organic data (italicised) is for April 2007: for full methodologies of organic data collection see Teal et al. (2010). Locations, water depths and dates of all Voyager II deployments.

	DG	OG	SGF
Water depth (m)	83	46	30
Voyager deployment dates	28/04/08 29/04/08	26/04/08 07/08/08	22/04/08
Voyager deployment locations	55°40.814, 02°19.426, 55°41.032, 02°19.573	54°24.684, 04°02.461, 54°24.747, 04°02.448	53°09.683, 02°48.225
Mean grain size (mm)	0.065 (V. fine sand)	0.071 (V. fine sand)	0.279 (Medium Sand)
Sorting	1.60, poorly sorted	1.65, poorly sorted	0.72, moderately sorted
Skewness	1.46, S. fine-skewed	2.00, S. fine-skewed	-0.5, S. coarse-skewed
Smectite (%)	21	21	–
Illite (%)	47	43	–
Kaolinite + chlorite (%)	32	36	–
Bulk density (kg m ⁻³)	1625	1716	1804
Porosity (%)	0.50 ± 0.04	0.51 ± 0.01	0.371 ± 0.01
Chlorophyll <i>a</i> (mg m ⁻²)	<i>6.54 ± 0.40</i>	<i>18.08 ± 7.16</i>	<i>5.39 ± 2.25</i>
Organic carbon (g ⁻²)	<i>27.7 ± 7.78</i>	<i>48.5 ± 5.05</i>	<i>9.87 ± 2.7</i>
Epifaunal carbon (g ⁻²)	<i>0.05 ± 0.029</i>	<i>0.22 ± 0.11</i>	<i>0.18 ± 0.05</i>
Infafaunal carbon (g ⁻²)	<i>6.89 ± 4.58</i>	<i>0.856 ± 0.795</i>	<i>0.094 ± 0.113</i>
Oxygen penetration depth (cm)	<i>0.64 ± 0.43</i>	<i>1.03 ± 0.2</i>	<i>3.08 ± 0.29</i>
Bioturbation potential	103	3178	14.24

overnight at 375 °C; and (4) dried overnight at 550 °C (to confirm the presence of a chlorite peak). Scanning Electron Microscope (SEM) analysis of frozen, filtered water samples was carried out using a Hitachi TM1000 Tabletop Microscope to assess the properties of the suspended particulate matter at 10 min intervals throughout the experiments.

Sediment Profile Images (SPI) from the three sites, were taken to assess the different bed types, and biological influences in situ. SPI is a high resolution imaging technique, which takes vertical profile pictures of the upper 20 cm of the sediment system (Ocean imaging, US). Within soft sediments this technique can be used to derive the boundary in the sediment between Fe^{3+} and Fe^{2+} reduction (Teal, 2008), or aRPD (apparent Redox Potential Discontinuity) (Teal et al., 2009, 2010).

2.4. Resuspension experiments

Voyager II, an in situ benthic annular flume (Fig. 2A) was provided by Partrac Ltd for use on Cefas cruises from 21 to 29th April 2008 (SGF, OG, DG: CEnd 08-08) and 5 to 11th August 2008 (SGF, OG: CEnd 15-08). It undertook a series of controlled resuspension events in situ. It is based on the designs and dimensions of Amos et al. (1992b),

consisting of an aluminium channel 0.3 m high and 0.15 m wide, with a total diameter of 2.2 m. Eight equidistantly spaced paddles induce a current via a chain drive, driven by a 0.6 hp, 24 V DC submarine motor and gearbox. The flume is instrumented with 3 optical backscatter sensors (OBS) which measure turbidity at three different heights, a Nortek Vectrino Velocimeter measuring velocity in the along channel (u), across channel (v) and vertical (w) directions 0.15 m above the nominal bed level, and an automated syringe sampling system taking calibration samples for the OBS. Data are logged directly to an onboard data logger, and an inboard computer controls the lid rotation and direction. The flume was lowered to the seabed, and the ship kept on station with the use of dynamic positioning to allow for easy deployment onto an optimum site, or repositioning if the flume did not seal with the seabed. A settling period of 30 min was given to allow for settling of any fluff material resuspended by deployment. The flume was pre-programmed with lid rotations in a stepwise increasing fashion, designed to resuspend and erode the bed in the manner followed by Amos et al. (1992a, 2003, 2004) and Sutherland et al. (1998a,b). Videos were taken of the experiments in progress through a window in the flume wall.

Table 1 and Fig. 1 detail the times and locations of the in situ flume deployments. All three sites were visited in April 2008.

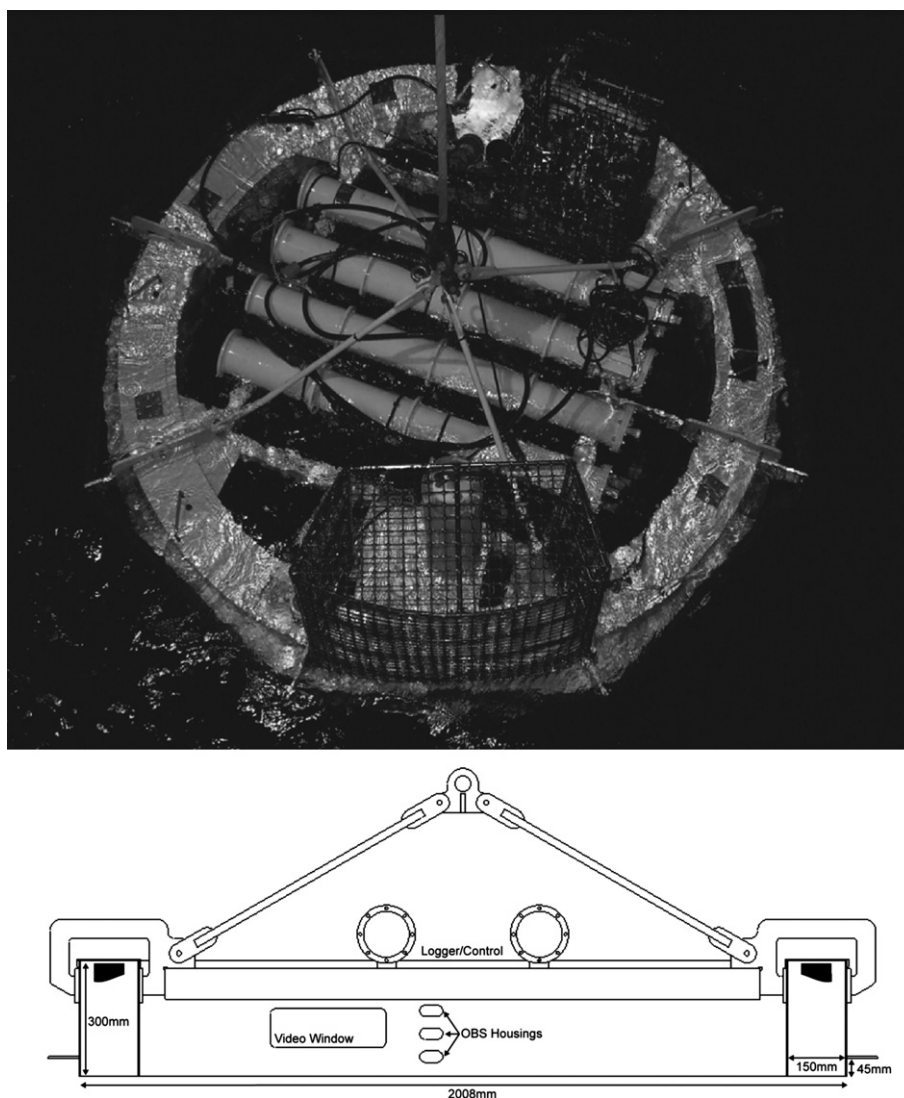


Fig. 2. The annular flume Voyager II during deployment (top); schematic of key flume dimensions (bottom).

Spatial heterogeneity was examined with three deployments at DG in April, and seasonal variability was examined by re-visiting OG in August of 2008.

Flow velocities (u, v, w, ms^{-1}) collected within the annular flume were filtered for quality following procedures recommended by Nortek AS. Data with a signal to noise ratio (SNR) lower than 15 and/or a correlation less than 85% were discarded.

Bed shear stress (τ_0, Pa) was calculated from the following empirical calibrations of shear velocity (Amos et al., 1992b; Thompson and Amos, 2002), where $\tau_0 = \rho u_*^2$

$$\bar{u}_* = 0.0167 + 0.097\bar{u} \quad (1)$$

Due to intermittent problems with the automated water sampler, the OBS data was calibrated to suspended particulate matter concentration (SPM, mg l^{-1}) against water samples taken during a subsequent laboratory based calibration, using bed material collected on-site. The SPM time series (S) was then time averaged every 20 s to eliminate high frequency short-term variability in the record (Widdows et al., 2007), and erosion rates were calculated. An equivalent depth of erosion (z_e) was calculated every 20 s based on the measured dry bulk density of the bed (ρ_b), the

total dry volume of material (M) in the water column and the bed area (A).

$$\frac{dz_e}{dt} = \frac{dM}{dt} \frac{1}{A\rho_b} \quad (2)$$

A stress reduction algorithm was applied to the shear stresses following the work of Amos et al. (1992a, 2003); Li and Gust (2000) to compensate for increasing sediment concentrations ($S, \text{mg l}^{-1}$) over time within the water column:

$$u_{*s} = u_* - \left(0.2267[\log_{10}S] \left(\frac{u_*}{6.35}\right)\right), \text{cm s}^{-1} \quad (3)$$

The critical erosion threshold is interpreted as the point of initial erosion of the bed, and has been determined following the method of Sutherland et al. (1998a), Amos et al. (2003) and Widdows et al. (2007) as the value at which the sediment concentration, reaches ambient conditions in the flume, based on a regression line of suspended particulate matter vs. log (bed shear stress). This has been found to be accurate even in cohesive sediments with high proportions of fine sands (Sutherland et al., 1998a).

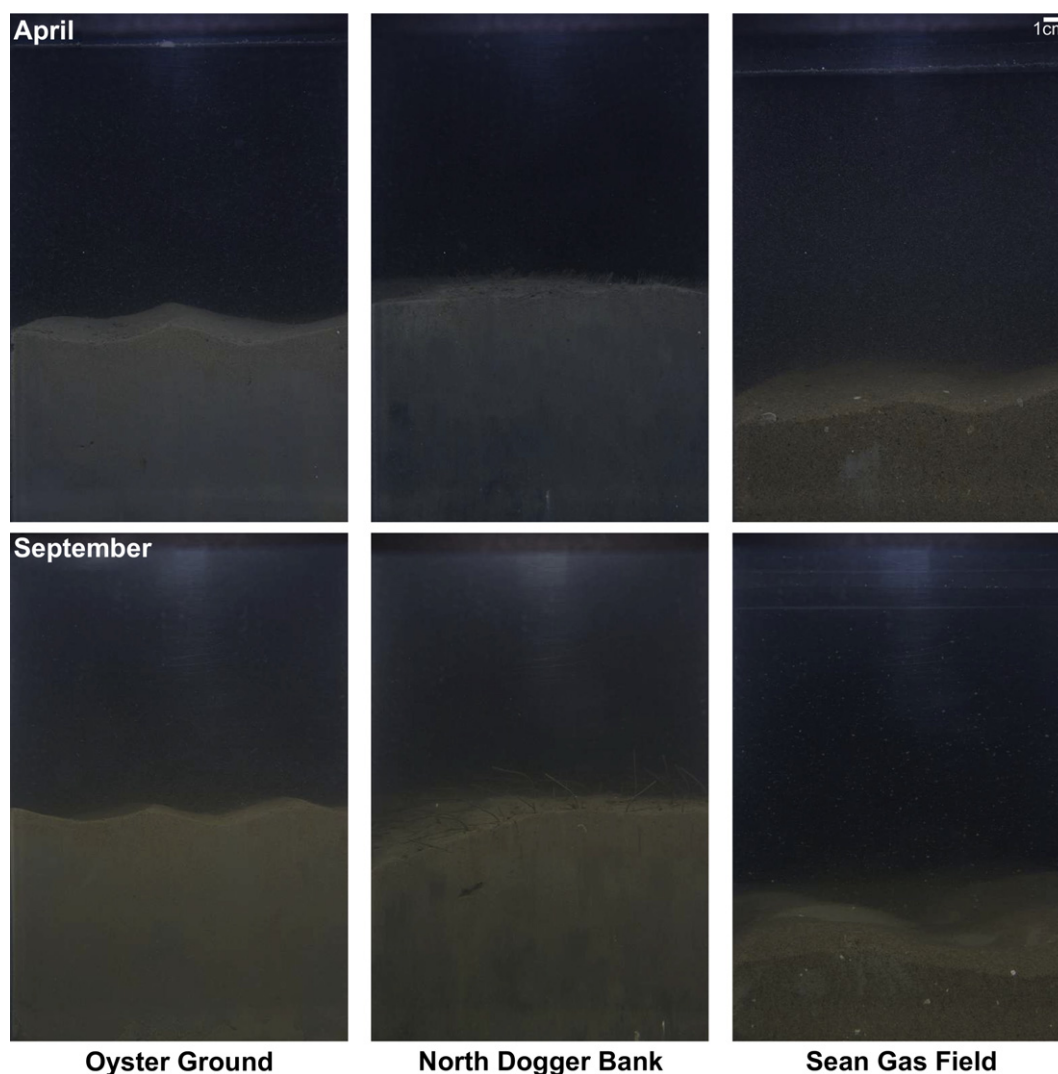


Fig. 3. SPI images (15 × 21.5 cm) of the sediments at Oyster Ground, North Dogger Bank and Sean Gas Field taken in April 2007 and September 2008, courtesy of Cefas.

3. Results

3.1. Bed properties

The bed properties assessed from the sub-sampled box core sediments are summarised in Table 1. The sediments of the OG and DG sites were largely similar muddy sands (based on the Folk, 1954 sand:mud ratio classification OG = 4:1, DG = 2.3:1), with median grain sizes falling into the very fine sand range, exhibiting poor sorting and with strong fine skewness. The mineralogy of the sites was similar given the error associated with the technique (10%), being composed predominately of illite, with a large proportion of kaolinite and chlorite. The porosity (%) of the sites was similar (0.51 ± 0.01 and 0.50 ± 0.04), and the wet bulk density differs by only ~5% (1716 and 1625 kg m^{-3} , respectively).

SGF on the other hand, was composed of moderately sorted medium sand, with strongly coarse skewness. The wet bulk density of the bed (1804 kg m^{-3}) is approximately 11% higher than DG, and 5% higher than OG, and the porosity is lower (0.371 ± 0.01).

Fig. 3 shows the SPI images from the three sites for April 2007 and September 2008. From these images it is possible to see the depth of biological influence at the three sites, with a biological mixing depth (due to bioturbation) and associated colour change (aRPD) of only 2–3 cm at DG, and 5–8 cm at OG where a greater number of burrows have been identified. SGF images illustrate

a mobile sand bed. Redox transition cannot be measured from this image by SPI, but separate measured oxygen penetration (Table 1) and nutrient profile measurements (Parker, Pers. Comm.) indicate a redoxcline of 10–13 cm in April, although this is likely due to physical mobility of the sediment and advection of pore-waters through the upper layers. Clear changes can be seen in the apparent redox potential discontinuity at the OG and DG between April and September, although measured oxygen penetration depths remained largely constant except at the Sean Gas Field where it shallowed to approximately 3–4 cm due to a high influx of fine material (Parker, Pers. Comm.).

3.2. In situ flume experiments

Fig. 4 shows the time series of applied bed shear stress and SPM for all five Voyager II deployments. For all the deployments the current velocity was increased in a series of 5 steps of 11 min each (comparable to Amos et al., 2004), up to a maximum of $\sim 0.4 \text{ ms}^{-1}$, followed by a period of settling. This equates to a maximum bed shear stress of $\sim 2.5 \text{ Pa}$. Increasing levels of SPM with time shows evidence of erosion, with SPM following a typical asymptotic pattern where the rate of increase in SPM decreases with time until a constant value is reached (Type 1b erosion).

SPM was adjusted for the ambient flume background levels to zero at the initiation of the experiments for easier inter-comparisons

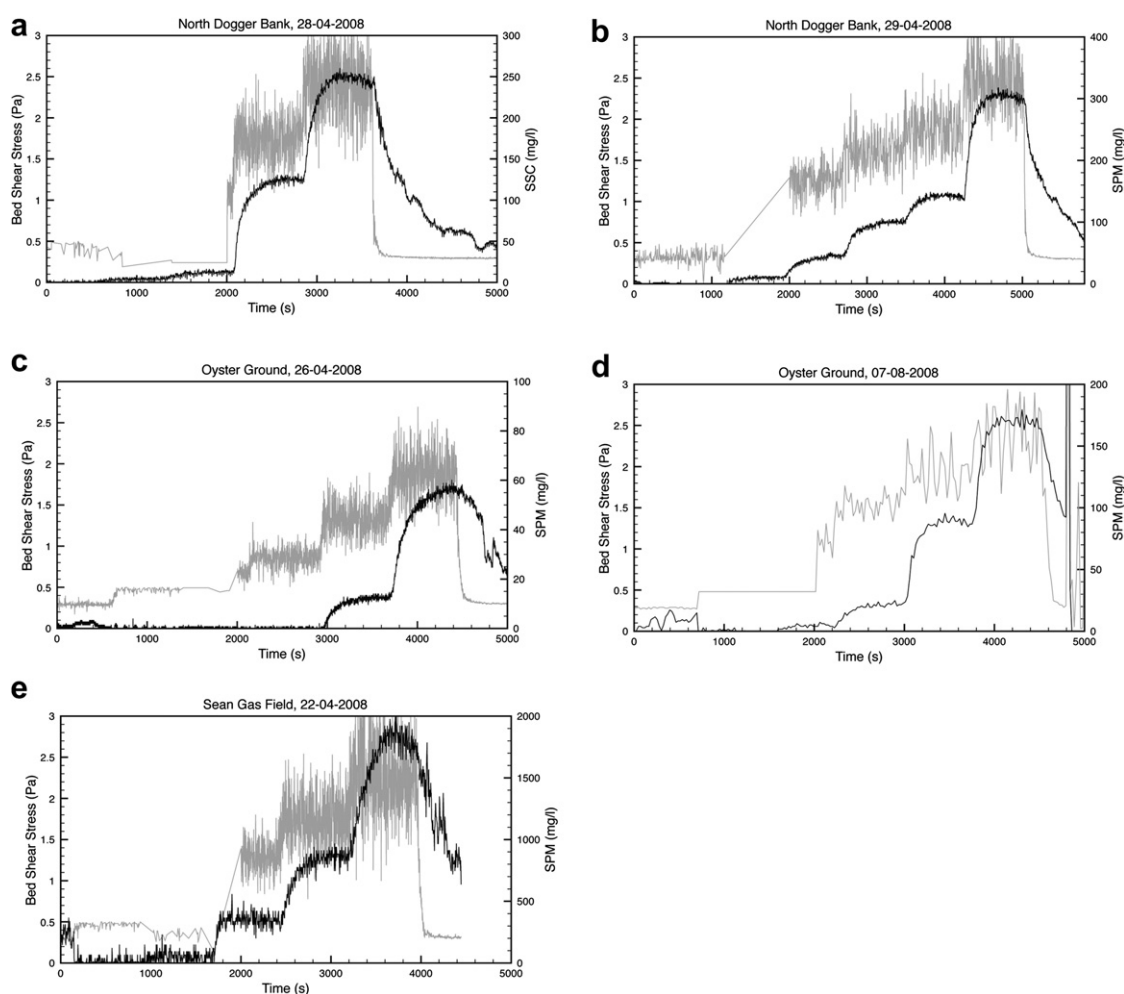


Fig. 4. Applied bed shear stress (Pa, solid black line) and total suspended solids (mg l^{-1} , solid grey line) of (a) and (b) DG April 2008, (c) OG April 2008, (d) OG August 2008, and (e) SGF April 2008.

between sites. Resuspended SPM levels were consistent between the two DG sites, peaking at levels of 250 and 300 mg l⁻¹ at the highest applied stresses. At OG, SPM levels remained lower, reaching only 60 mg l⁻¹ in April, but increasing in August to levels of 170 mg l⁻¹.

Dispersion has been noted to occur from similar flumes (Amos et al., 1992a,b), but was not observed in video taken during the experiments. If present, dispersion would be evident by a decrease in SPM at the end of a time step, with no associated velocity decrease. This effect was noted only when concentrations were in excess of 200 mg l⁻¹ (the last time step the two DG deployments), and may also be associated with flocculation and subsequent settling of the material in suspension. The reduction is minimal in all cases (<5%) and would not have a significant impact on further analysis.

Erosion rates peaked at the beginning of each velocity increment, reducing thereafter (Fig. 5). Peak erosion rates increased with increased flow velocity for all sites except SGF, which has a predominantly sandy bed and exhibits much greater variability in both SPM and erosion rates. Erosion rates for DG (peak erosion rate = 0.6 mg m⁻² s⁻¹) were an order of magnitude larger than those at OG in April (peak erosion rate = 0.04 mg m⁻² s⁻¹).

At the two DG sites, the critical erosion thresholds (Table 2) were found to be 0.66 and 1.04 Pa, respectively ($R^2 = 0.33$; 0.66 , $p < 0.01$). The critical erosion threshold for OG was 0.91 Pa in April ($R^2 = 0.41$, $p < 0.01$), and 1.27 Pa in August ($R^2 = 0.61$, $p < 0.01$). For SGF, this method of threshold determination is not valid, as bedload transport began some time before suspension occurred.

Fig. 6 shows the equivalent depth of erosion for all 5 deployments. These depths were very shallow, restricted to 0.1 and 0.14 mm for DG, reduced to 0.02 and 0.06 mm for OG, and reaching 0.6 mm in SGF.

3.3. Relationships between bed properties and measured erosion characteristics

A principal component analysis (PCA; Table 3) of the sites visited for the in situ deployments shows that 96.5% of the variance between the sites can be described by two principle components. Of these PC1 is largely composed of the physical sediment properties (mean grain size, sorting, percentage clay, bulk density and porosity) along with benthic carbon and the oxygen penetration depth. PC2 is mainly composed of the skewness, Chlorophyll *a* and the bioturbation potential. Multiple linear regression analysis was therefore performed between the measured erosion characteristics and these variables (Table 4). Significant ($p < 0.05$) negative relationships were found between the eroded depth and the sediment sorting

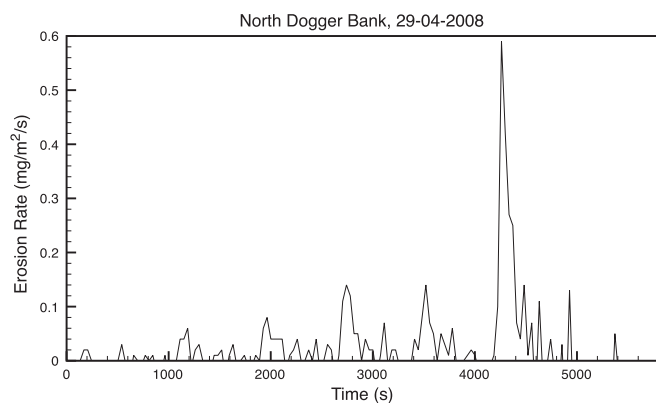


Fig. 5. Erosion rates (mg m⁻² s⁻¹) for DG April 2008.

Table 2

Critical erosion thresholds and equivalent depths of erosion for the in situ flume deployment sites.

	DG	DG	OG Apr	OG Aug	SGF
Measured Critical Erosion Threshold (Pa)	0.66	1.04	0.91	1.27	-
Equivalent Depth of Erosion (mm)	0.1	0.14	0.02	0.06	0.6

($r^2 = -0.934$, $p = 0.01$), and porosity ($r^2 = -0.993$, $p < 0.001$), and there was a significant positive correlation with mean grain size ($r^2 = 0.963$, $p = 0.004$) and the oxygen penetration depth ($r^2 = 0.996$, $p < 0.01$). However, the sample size is small ($n = 5$) and it should also be noted that further strong relationships exist ($p < 0.1$) between the critical shear stress and the sorting ($r^2 = 0.718$, $p = 0.086$); mean grain size ($r^2 = -0.695$, $p = 0.096$); and the oxygen penetration depth ($r^2 = -0.765$, $p = 0.066$) and between eroded depth and sediment distribution skewness ($r^2 = -0.796$, $p = 0.054$).

3.4. Long-term hydrographic data

Monthly bed shear stresses were calculated for the ADCP data at OG assuming a logarithmic velocity profile (Soulsby, 1997), and are presented in Table 5 along with monthly averaged significant wave heights and zero crossing periods. The magnitudes of the mean bed shear stresses were relatively low, ranging from 0.21 (± 0.31) ms⁻¹ in June to 0.43 (± 0.72) ms⁻¹ in September. The wave data show peaks of significant wave height and peak periods in the winter months, with associated increased bottom orbital velocities.

Fig. 7 shows the monthly averaged SPM levels from the lander at OG. SPM levels are generally low, increasing in November 2007 (related to increased daily maximums from 12 to 14th November averaging 992.15 mg l⁻¹, and a sustained increase for the remainder of the month ranging from 80 to 180 mg l⁻¹) and in June–August 2008. There is some yearly variation in SPM level, with the summer 2008 values being considerably higher than those from summer 2007. During flume deployment, the natural background SPM values were 10.77 and 65.94 mg l⁻¹ in April and August 2008, respectively.

4. Discussion

Due to the limited ship time, only a small number of deployments could be made with Voyager II. Ideally, a larger range of spatially and temporally varying deployments would have been made, however, this is the first study of this kind ever to have been undertaken in the North Sea, and as such the results are noteworthy. The supply of SPM to the North Sea from resuspension events at the bed is not well constrained (Puls et al., 1997; Gerritsen et al., 2000), being dependant on available observational and experimental data (Gerritsen et al., 2000). As such, a critical parameter in modelling, and for the understanding of biogeochemical, ecological, and pollutant processes is often associated with large uncertainties.

4.1. A comment on fluff layers

It should be noted that a 'fluff' layer is not apparent in the in situ flume data, but may have been resuspended by the deployment of the flume; ambient SPM levels in the flumes prior to the resuspension experiment are significantly higher than the background water column levels (DG = 252–256 \pm 2.2 mg l⁻¹; OG = 90 \pm 1.05 mg l⁻¹ (April) and 196 \pm 1.29 mg l⁻¹ (August) and Fig. 7, respectively), and a peak of SPM is sometimes recorded at the point of flume impact in the OBS data. The data discussed herein is therefore

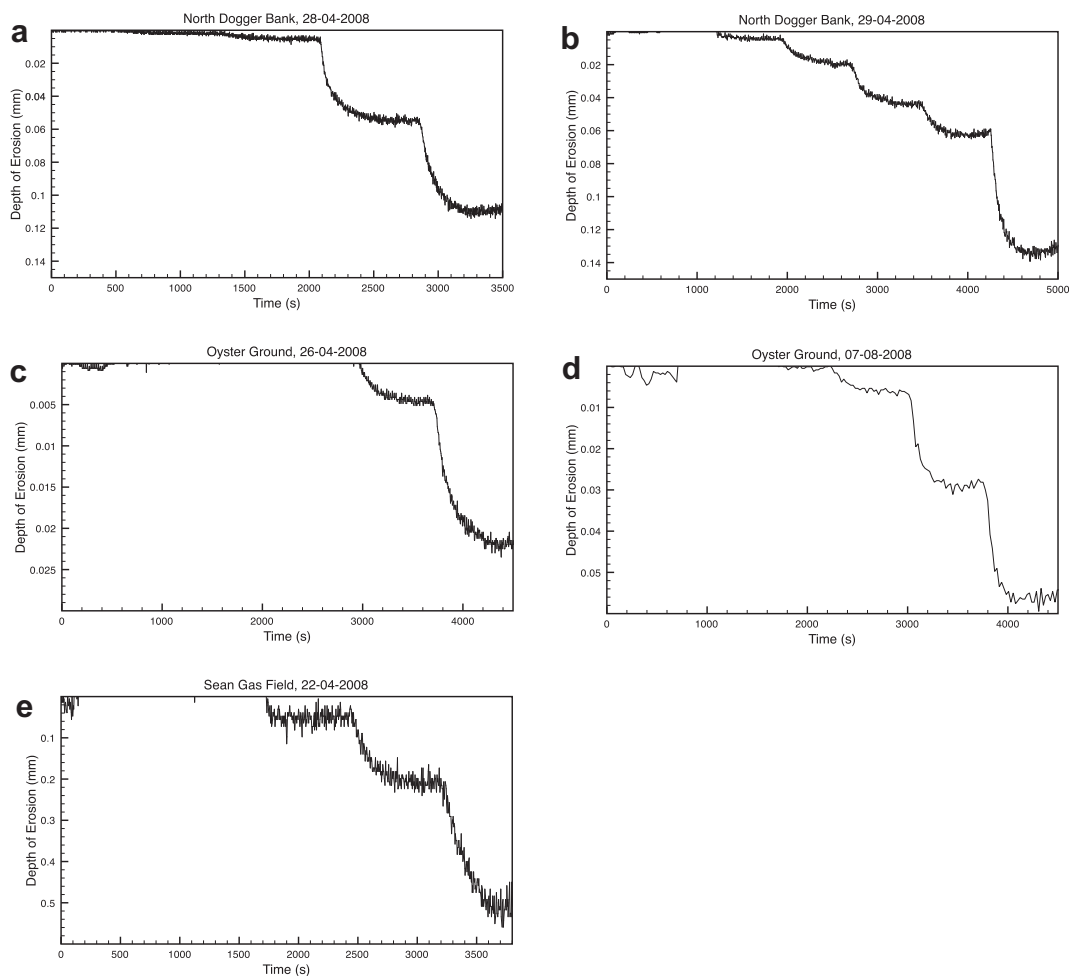


Fig. 6. Erosion depths (in mm) of (a) and (b) DG April 2008, (c) OG April 2008, (d) OG August 2008, and (e) SGF April 2008.

related to erosion of the underlying bed, and do not address the ‘fluff’ layer directly, although one should bear in mind that due to its low shear strength, benthic ‘fluff’ would be more readily resuspended on the shelf (Jago et al., 2002).

4.2. Bed stability

Bed erosion type can affect the net erosion of a system considerably (Amos et al., 1992a). The resuspension experiments indicate that all three sites exhibit classic Type 1b erosion patterns in situ

Table 3
Principle component analysis results for the five in situ flume deployment sites figures in bold indicate those variables which contribute most strongly to the variance.

	PC1	PC2
Mean Grain Size	-0.968	-0.249
Sorting	0.977	0.190
Skewness	0.395	0.912
% Clay	0.936	-0.352
Bulk Density	-0.944	0.305
Porosity	0.914	0.405
Chl A	0.166	0.978
Benthic Carbon	0.939	-0.318
Oxygen Penetration Depth	-0.880	-0.475
Epifauna	-0.671	0.693
Infauna	0.818	-0.574
Bioturbation Potential	0.114	0.987
% Variance	62.2	36.5

(Parchure and Mehta, 1986; Amos et al., 1992a, 1997), typified by an asymptotic decrease in the rate of change of suspended particulate matter with time, and peaks of erosion rate at the initiation of each velocity step (Figs. 4 and 5). This erosion type is typical of the upper 0.5 mm of the bed (Amos et al., 1992a), in agreement with the erosion depths recorded (maximum 0.14 mm) and typical of the majority of bed erosion scenarios where erosion occurs in the top few millimetres of the bed (Amos et al., 2010). Type II erosion was absent, which may be the result of low applied stresses (Amos et al., 1997) or indicative of a uniform sediment microfabric (Amos et al., 1992a,b) and the absence of a significant bedload component. Measurements of sediment transport at a shallower North Sea site (Marsden Bay; Green et al., 1995) indicate that the erosion depths required to support observed suspended sediment loads during storms are at most a centimetre, and usually sub-millimetre indicating our measurements are of the correct scale.

The critical erosion thresholds for OG and DG are higher than often used to represent the North Sea (Van Raaphorst et al., 1998: 0.07 Pa, Gerritsen et al., 2000: 0.05–0.4 Pa from Mehta et al., 1982, 0.1–0.5 Pa from Winterwerp, 1989), but are comparable to observations in the German Bight (Gayer et al., 2006: 0.8 Pa from Pohlmann and Puls, 1994) and other marine settings with similar bulk densities (Amos et al., 1992a, 1996; Mitchener and Torfs, 1996). The high erosion thresholds for the muddy sites, observed erosion type, and the shallow depths of erosion (Fig. 6) indicate erosion of the consolidated bed material is limited at the applied stresses used in the experiments.

Table 4

Correlation matrix (Pearson's linear correlation coefficients) between the bed properties and measured erosion characteristics ($n = 5$). From multi linear regression analysis, significance values given in brackets. *Significant at $p < 0.10$; bold * significant at $p < 0.05$.

	τ_c	ErD	MGS	SOR	SKW	%C	BDe	POR	Chl a	Ben C	OPD	Epi	In
Eroded depth	-0.715*												
Mean grain size	-0.695*	0.963*											
Sorting	0.718*	-0.934*	-0.992*										
Skewness	0.669	-0.796*	-0.612	0.548									
% Clay	0.359	-0.641	-0.819*	0.847*	0.050								
Bulk density	-0.335	0.679	0.840*	-0.851*	-0.109*	0.991*							
Porosity	0.742	-0.993*	-0.986	0.967*	0.733*	0.714*	-0.742*						
Chl a	0.673	-0.613	-0.402	0.360	0.943*	-0.190	0.158	0.544					
Benthic carbon	0.325	-0.668	-0.832*	0.844*	0.096	0.992*	-1.00*	0.733*	-0.172				
Oxygen penetration depth	-0.765*	0.996*	0.971*	0.971*	-0.782*	-0.675	0.687	-0.997*	-0.609	-0.677			
Epifauna	-0.138	0.225	0.472	0.472	0.370	-0.870*	0.811*	-0.326	0.534	-0.816*	0.258		
Infauna	0.192	-0.426	-0.648	-0.694*	-0.205	0.967*	-0.941*	0.514	-0.421	0.945*	-0.446	-0.958*	
Bioturbation potential	0.642	-0.574	-0.355	0.310	0.933*	-0.241	0.207	0.501	0.999*	-0.221	-0.568	0.578	-0.469

Measured critical erosion thresholds can vary by an order of magnitude both temporally and spatially (Thomsen and Gust, 2000) as a result of complex interactions between their physical and biological properties, and there is still a lack of detailed observations of the hydrodynamic, sedimentological and biological influences on erosion in shelf seas (Thomsen and Gust, 2000). No in situ measurements such as these have previously been carried out in the North Sea, and as such, several physical and biological properties of the bed were measured in this study, to determine the factors controlling erosion. However, the limited number of sites visited, along with their spatial separation has resulted in a lack of consistent significant correlations between the measured erosion thresholds and the physical and biological bed properties. This is common where sites are characterised by large differences in benthic assemblages (Widdows et al., 2007) and biological processes (Defew et al., 2002; Tolhurst et al., 2003) and illustrates the complex nature of bed stability (Table 1). The large biological differences between the sites can best be represented by the bioturbation potentials (Table 1: defining the role of the fauna in sediment turnover; Solan et al., 2004), which are seen to vary by an order of magnitude or more between sites. Nevertheless, once erosion has been initiated, the depth of erosion is closely related to the physical bed properties: the mean grain size, sorting, porosity, and the oxygen penetration depth, which is itself a function of the physical bed properties. This agrees with previous findings that the erosion rate is often more closely correlated to the excess bed shear stress ($\tau_0 - \tau_c$) than the applied bed shear stress (Amos et al., 1992a, 2010), i.e. complex variations in biogeophysical influences on the bed have the greatest impact on the critical threshold of erosion, but once this has can be

accounted for, erosion rates are predictable based on the nature of the sediment. In this case, the depth of erosion refers to the amount of material removed from the bed (and carried in suspension), as type 1b erosion is dominated by suspension (Amos et al., 2003) and storm transport of sediment in the coastal North Sea is also predominantly in suspension (Green et al., 1995). However, for sites with a high sandy component (for example SGF), bedload transport would simultaneously occur along with suspension, resulting in movement/reworking of the sediments below the erosion depth. This depth of reworking could not be measured in the context of these in situ experiments, but may be crucial when considering the wider biogeochemical implications of sediment resuspension (especially if this depth of reworking exceeds the redox layer.

4.3. Resuspension potential

Because of the difficulties with predicting critical shear stresses a priori from easily measured bed parameters as discussed in Section 4.2 above, in situ tests are necessary when considering the potential for resuspension in the field (Maa et al., 1998; Sutherland et al., 1998a,b). Similar studies have successfully related laboratory based measurements of critical erosion thresholds with field observations (Schaaff et al., 2006) and the methodology by which the critical shear stresses are found ensures that these processes are considered as an average over the area of the flume bed (0.95 m^2) and are not point measurements.

The resuspension potential was determined from a comparison of the in situ critical erosion thresholds and the ADCP derived bed shear stresses every 30 min. The tidal currents exceed the erosion

Table 5

Monthly averaged ADCP and wave buoy data (± 1 standard deviation), starting in January 2007. Current induced bed shear stress (OG, τ), Percentage of data where applied current induced bed shear stress exceeded the threshold shear stress (OG, %), significant wave height (H_s), peak period (T_p) and bed orbital velocity (u_b) for wave buoys at Auk Alpha (DG and OG) and Sean PP (SGF).

Month	τ (Pa)	% Exceedance	Auk Alpha			Sean PP		
			H_s (m)	T_p (s)	U_b (ms^{-1})	H_s (m)	T_p (s)	U_b (ms^{-1})
Jan	–	–	4.79 ± 0.49	7.65 ± 0.49	0.09	2.06 ± 0.79	4.68 ± 0.50	0.074
Feb	0.26 ± 0.37	6.8	–	–	–	1.45 ± 1.03	4.16 ± 1.05	0.024
March	0.29 ± 0.43	7.8	2.58 ± 1.11	5.88 ± 1.16	0.0059	2.09 ± 0.99	4.87 ± 0.99	0.094
April	0.37 ± 0.53	12.1	1.20 ± 0.52	4.57 ± 0.92	0.000075	1.00 ± 0.52	3.69 ± 0.77	0.006
May	0.22 ± 0.31	4.6	0.91 ± 0.58	4.32 ± 0.93	0.0000189	0.92 ± 0.57	3.52 ± 0.86	0.003
June	0.21 ± 0.31	4.4	0.49 ± 0.27	3.61 ± 0.73	0.00000011	0.90 ± 0.51	3.76 ± 0.91	0.065
July	0.31 ± 0.35	5.8	–	–	–	0.88 ± 0.51	3.50 ± 0.77	0.003
Aug	0.31 ± 0.45	8.6	1.44 ± 4.70	4.70 ± 0.64	0.00015	1.14 ± 0.56	3.72 ± 0.74	0.007
Sep	0.43 ± 0.72	13	–	–	–	1.24 ± 0.72	3.81 ± 0.90	0.010
Oct	0.23 ± 0.35	4.4	–	–	–	1.74 ± 0.77	4.49 ± 0.91	0.049
Nov	0.28 ± 0.42	7.5	–	–	–	1.93 ± 1.00	4.69 ± 1.00	0.071
Dec	0.29 ± 0.43	7.8	–	–	–	1.36 ± 0.68	4.05 ± 0.86	0.019
Jan	0.31 ± 0.45	9.3	–	–	–	–	–	–

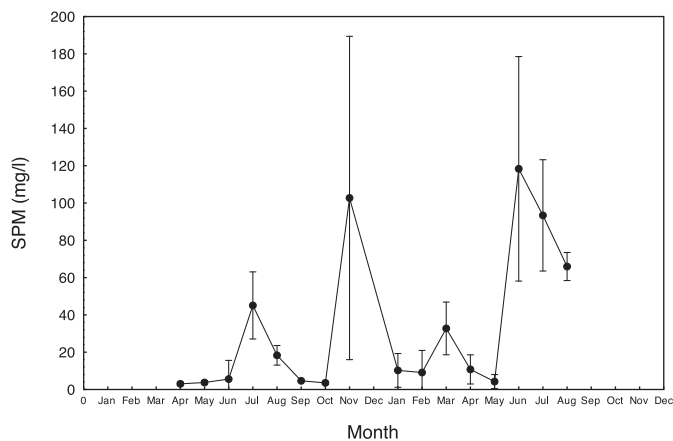


Fig. 7. Monthly averaged SPM levels (mg l^{-1}) with 1 standard deviation (SD) for period 2007–2008 from benthic lander at OG.

threshold of the sediment as measured in the Voyager experiments on average only 8% of the time at OG which is stratified year round, peaking in September and April. These periods are short lived, generally limited to less than 30 min in duration and often with several hours between re-occurrences. Both observation and modelling agree that there would be a rapid resettling of material post-resuspension (Puls et al., 1997; Van Raaphorst et al., 1998). Under the same conditions, resuspension events would be expected at most 13% at DG, which is seasonally stratified. The majority of large resuspension events at both of these sites are instead induced by storm action during the winter months. This is to be expected in the deeper regions of the North Sea where tidal currents are relatively weak with bed shear stresses often less than 0.06 Pa (Jago et al., 2002), and is supported by observations of storm sediment transport on the British North Sea Shelf (Green et al., 1995). Fig. 8 shows the percentage of the available wave data (Table 4), which exceeds the measured (DG, OG) or theoretical (Bagnold, 1966, sand suspension criterion (SGF)) threshold shear stresses for suspension of the bed material. Due to the shallow water depths at SGF (30 m, Table 1), wave conditions will be strong enough to resuspend the bottom sediment all year round, with peaks indicating resuspension 51% and 60% of the time in January and March, and generally increased potential resuspension in the winter months

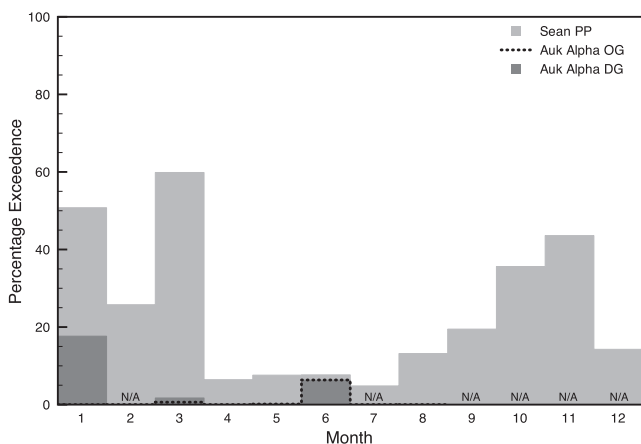


Fig. 8. Percentage of available wave data, which exceeds the threshold for erosion. Auk Alpha (Black) shear stresses were compared with DG measured threshold condition, and Sean PP (Grey) with SGF theoretical threshold for suspension. N/A indicates months where no data was available from Auk Alpha.

from September to March. At DG (~83 m), there is less available data, but resuspension is possible 18% of the time in January, 1.7% of the time in March and 6.3% of the time in June. Given the higher critical erosion thresholds of OG, this resuspension reduces to 0.6% in March and 6% in June, it is also likely that for these two sites in the winter months, when data are unavailable, increased wave-induced resuspension would occur during storm events.

Thus, at DG and OG, both tidally driven currents and wave conditions are often insufficient to resuspend material from the bed, indicating that locally induced resuspension events will be limited. Changes in SPM in the southern North Sea have been found to be decoupled from the local near-bed hydrodynamic conditions (Williams et al., 1998), so this is not surprising. The results found here agree with the work of Van Raaphorst et al. (1998), which described OG as a temporary depocentre, retaining material that has been advected in until removal by winter storms. The use of an enclosed annular flume in these experiments ensures that advecting particles can be excluded during the measurement period, and hence will not influence the measurements of erosion threshold. Jones et al. (1998) also found that tidal current were not sufficient to erode at OG during the summer, although a smoothing of the bed in winter months indicated combined wave and tidal action in the winter was capable of smoothing the bed. Van Raaphorst et al. (1998) claim that resuspension is limited to the very organic-rich “fluff” layer, and modelled increases in TSM are the result of advection rather than local resuspension. We have found that even with high erosion thresholds, occasional short-term resuspension events are likely, year round. However, the amounts likely to be eroded in these short periods are relatively small, with erosion depths limited to sub-millimetre scales. Stanev et al. (2009) noted a similar de-coupling of local SPM levels at DG, with high stresses at the bed coinciding with low concentrations of suspended matter and suggested this may be the result of a lack of erodible sediment. We can confirm that the high critical erosion thresholds and high stability of the sediments found here limit local erosion.

These experiments have illustrated the high bed shear stresses necessary to induce erosion at both OG and DG, and the shallow depths to which this erosion occurs. More significant erosion would only be possible under sustained periods of high bed shear stresses greater than those seen in the data, and are unlikely to erode through the redox layers at these locations, confirming the view that significant resuspension of bed sediments in the North Sea occurs only in areas of strong tidal currents and/or during storms (Jago et al., 1993; Puls et al., 1997). These are important findings when considering the effect that resuspension events may have on the wider biogeochemical processes in the North Sea, indicating that any such events are likely to be limited in both frequency and magnitude.

5. Conclusions

The bed sediments at the two muddy sites Oyster Grounds (OG) and North Dogger Bank (DG) both exhibit high critical erosion thresholds, with those at the OG being higher than those at DG during April. A typical type 1b erosion of the consolidated bed itself is seen after erosion is initiated, and at the applied bed shear stresses used in this study, which encompass the range of stresses experienced in situ; erosion rates were low and erosion depths less than 1 mm. The critical erosion thresholds varied due to the large spatial and biological variations between the sites, and no significant relationship was found between the measured erosion properties of the sites and the local biological properties (chlorophyll a, carbon, fauna or bioturbation potential). However, once erosion began, the erosion depth was significantly correlated with the

physical bed properties (mean grain size, sorting, and porosity) and the oxygen penetration depth.

Comparisons with local current and wave measurements confirmed that current induced bed resuspension events are likely to occur on average 8% of the time at OG (which is stratified year round) or 13% at DG (seasonally stratified), for short durations (< 30 minutes), but that storm action has the potential to significantly increase resuspension during the winter months. Resuspension is more common at SGF (well mixed water column), as suggested by its shallow depth and coarser grain size.

Acknowledgements

This partnership project was funded equally by the UK Natural Environment Research Council (NERC NE/F003293/1 and NE/F003552/1) and Defra as part of the Marine Ecosystem Connections (MECs) project. We would like to thank the crew and scientists of the RV Endeavour (Centre for Environment, Fisheries and Aquaculture Science [Cefas], cruises CEnd 08-08, CEnd 15-08, CEnd 16-08 and CEnd 01-09).

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