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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Resuspension Processes and Seston Dynamics, Southern North Sea [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1993 **343**, 475-491
doi: 10.1098/rsta.1993.0060

Resuspension processes and seston dynamics, southern North Sea

By C. F. Jago[1], A. J. Bale[2], M. O. Green[3], M. J. Howarth[4], S. E. Jones[1], I. N. McCave[3], G. E. Millward[5], A. W. Morris[2], A. A. Rowden[2] and J. J. Williams[4]

[1] *School of Ocean Sciences, University of Wales Bangor, Marine Science Laboratories, Menai Bridge, Gwynedd LL59 5EY, U.K.*

[2] *Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth PL1 3DH, U.K.*

[3] *Department of Earth Sciences, University of Cambridge CB2 3EQ, U.K.*

[4] *Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead L43 7RA, U.K.*

[5] *Department of Environmental Sciences, University of Plymouth PL4 8AA, U.K.*

[Plate 1]

Coupling of physical, biological and chemical processes associated with particle resuspension and seston flux was investigated at three sites in the North Sea with contrasting water column (mixed/stratified) and seabed (cohesive/non-cohesive) characteristics.

Seston concentration was determined by a combination of local resuspension and advection of a regional horizontal concentration gradient. Model simulations of observations show that fair weather, the bed erosion rate was limited by the availability of suitable bed material. The resuspended particles were derived from a surficial veneer of material (fluff) that was relatively enriched in organic carbon. Sediment from the bed itself was therefore not resuspended by tidal currents even at a shallow water, sandy site. Bioturbation of the seabed by infauna significantly modified the properties of muddy sands at a deep water site in summer, but this was insufficient to cause tidal entrainment of the bed sediment.

Resuspension increased under combined wave/current flows during storms. However, model simulations predict that self-stratification of the boundary layer by resuspended fine sediment during storms reduces bed stress and limits further resuspension, so that storm resuspension of fine sediments may be self-limiting.

Seston was a mixture of: (1) particles relatively rich in organic carbon, with low settling velocities, in long-term suspension; (2) particles with less organic carbon (though still greater than that of the bed material), faster settling velocities, periodically resuspended; (3) particles that were very rich in organic carbon, with fast settling velocities, produced during plankton blooms. Particles in category 3 scavenged those in category 1 as they settled, so that seston concentrations diminished and deposition rates increased after blooms.

In stratified waters during blooms, deposition of organic-rich detritus gave rise to seabed anoxia and efflux of trace metals (Fe and Mn) from pore waters. Differential rates of metal exchange altered the particulate Fe/Mn ratio below the thermocline. Settling, deposition, and resuspension of fluff were therefore important controls of metal exchanges in the boundary layer.

Phil. Trans. R. Soc. Lond. A (1993) **343**, 475–491

Printed in Great Britain

16-2

1. Introduction

The mobilization and dispersal of suspended particulate matter (SPM or seston) are important in several chemical and biological processes that determine water quality in shelf seas (Burton *et al.* 1993; Tett *et al.* 1993). Biological processes in turn influence the size, structure, and settling rates of suspended particles (Postma 1973; McCave 1984; Puls & Sunderman 1990). All of these processes exhibit marked variability in time and space.

A principal aim of the resuspension experiments described herein was to provide data for development and evaluation of resuspension models. Hence simultaneous observations were made on tidal, spring/neap and seasonal timescales. This necessitated development and deployment of new autonomous instruments (see Green *et al.* 1992; Jago & Jones 1993; Williams *et al.* 1993) and, above all, a new interdisciplinary strategy for field measurements (see Morris & Howarth 1993).

2. Resuspension experiments

Observations were made at three sites chosen to encompass a range of water column structure (mixed and stratified), boundary layer dynamics (steady current and wave/current) and seabed properties (cohesive and non-cohesive); see figure 1 and table 1. Overall experimental strategies are given in Green *et al.* (1990, 1992) and Morris & Howarth (1993); further details of instrument deployments and analytical methods can be found in Bale & Morris (1993), Howarth (1993), Jago & Jones (1993), Millward *et al.* (1993), Rowden *et al.* (1993*b*), and Williams *et al.* (1993).

3. Resuspension of bed material

(*a*) *Resuspension by tidal currents*

Although Sites A and C are in shallow water, few of our observations encompassed times of significant wave/current interaction and much of the resuspension that we observed was due to steady currents.

Typical transmissometer time series for Site A are shown in figure 2. Quarter-diurnal maxima in seston concentration indicate resuspension by tidal currents. An additional semi-diurnal signal indicates advection past the site of a regional horizontal concentration gradient. Combination of the two signals produces a characteristic 'twin peak' time series in which there is an alternation of successive concentration minima (Weekes & Simpson 1991; Jones *et al.* 1993*b*). This characteristic signature has been simulated by a conceptual model which combines resuspension and advection components superimposed on a background concentration; in this model, resuspension is a function of current speed and advection is related to tidal displacement (Jago & Jones 1993). Figure 3 shows seston concentration predicted by this model against measured concentration at Site A in January. The twin-peaks concentration signature also characterized Site C (figure 7) but was only occasionally seen at Site B during plankton blooms (see below).

Resuspension of non-cohesive sediment can be modelled as a power relationship constrained by a threshold condition: thus $\epsilon = k(u_* - u_{*\mathrm{th}})^n$, where ϵ is erosion rate, u_* and $u_{*\mathrm{th}}$ are shear velocity and threshold shear velocity, respectively, k is an appropriate pick-up constant, and n is greater than 3. Time-averaged shear velocity

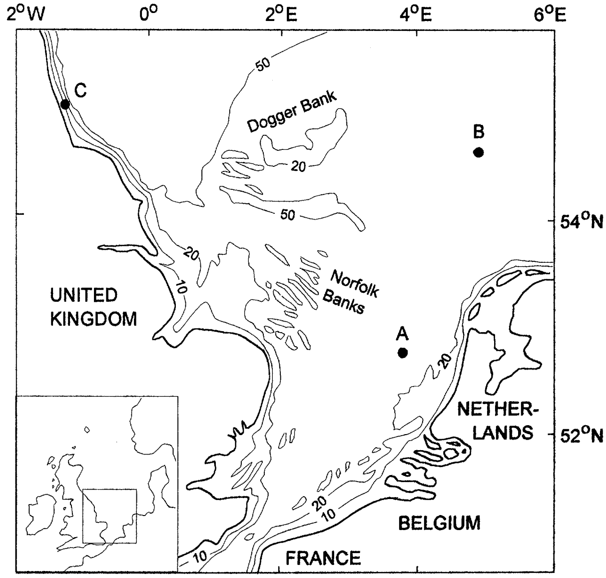

Figure 1. Geographical location of study Sites A, B and C.

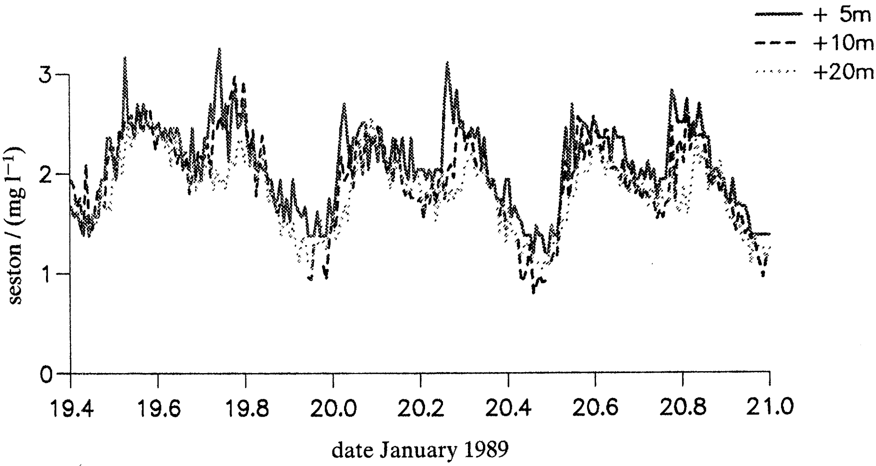

Figure 2. Seston concentration measured at three heights above bed at Site A. Note low concentrations (cf. figure 6 for Site C), 'twin peaks' seston concentration signature, and successive upward time delays in onset of the resuspension signal.

Table 1. *Summary of site characteristics*

variable	Site A	Site B	Site C
position	52° 39′ N 03° 40′ E	54° 35′ N 04° 50′ E	54° 59′ N 01° 21′ W
mean water depth/m	30	47	24
water column structure	mixed	seasonally stratified	mixed
approximate tidal range/m	1.2	0.6	3.6
maximum tidal current/ms^{-1}	0.6	0.2	0.3
median grain size/µm	250	100	100
bedform wavelength/m	0.15	—	—

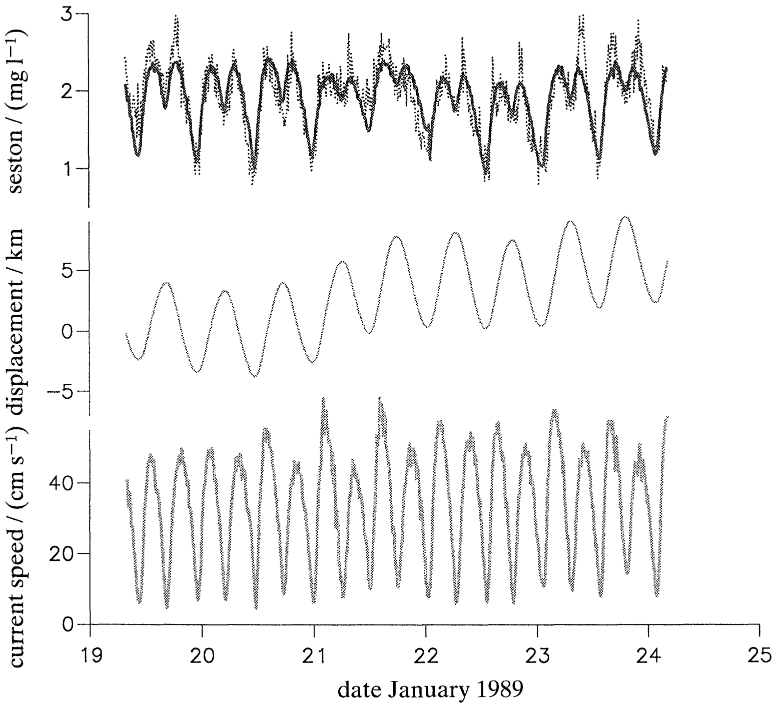

Figure 3. Combination of advection signal and resuspension signal gives twin peaks signature in seston concentration time series. For seston concentration, broken line, observations (Site A); solid line, model simulation.

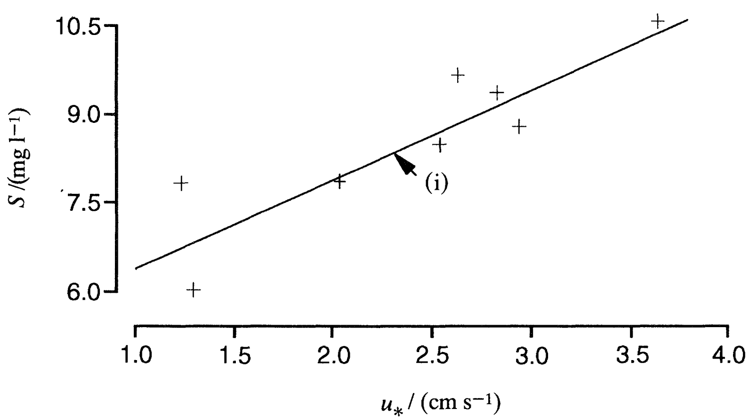

Figure 4. Relationship between time-averaged seston concentration and shear velocity at Site A. Shear velocity determined using the eddy correlation and turbulent kinetic energy methods over a typical 16 h period (eight burst measurements). (i) $S = 5.08 + 1.42\ u_*$ ($r = 0.875$).

u_* and seston concentration S (1 mab) at Site A in May are shown in figure 4. Interestingly, the relationship of u_* to S is essentially linear such that $n = 1$ in the foregoing entrainment relationship. This suggests that the suspended load was source limited.

This has been further investigated by using a one-dimensional turbulence model (Simpson & Sharples 1991; Jago & Jones 1993). Two model simulations of seston

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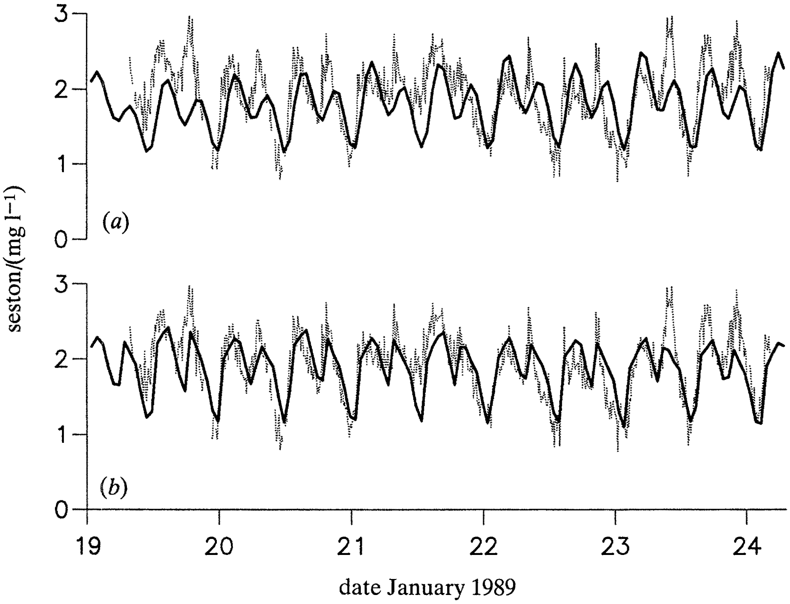

Figure 5. Observed and predicted (using one-dimensional turbulence closure model) seston concentrations at 10 mab with (*a*) infinite and (*b*) finite supply of particles for resuspension. Solid line, model simulation; broken line, observations. Note phase lag between model and observed peak concentration in (*a*) and much improved agreement in both phase and form in (*b*).

concentration time series at Site A in January are shown in figure 5. The first simulation uses an unlimited supply of resuspendable material; reasonable agreement is obtained with data at three heights in the water column but there is a distinct phase lag between model and observations with peak observed values occurring before peak predicted values (see figure 5*a*). The second simulation limits the supply of resuspendable particles by assuming that all available material is already in suspension at the start of the model run (which is at maximum tidal flow); agreement in both phase and form is much improved (figure 5*b*). It is this constraint on erosion rate which explains the apparent linear relationship of seston concentration and shear velocity (figure 4).

This model therefore confirms that the resuspended particles at Site A were derived from a source of finite supply that was exhausted during the entrainment process. This is because the resuspended material comprised particles ('fluff') which clothed the bed in a very thin veneer at slack water; seabed photographs at Site A show these particles in the troughs of ripples at slack water. Resuspension of these particles by the accelerating current quickly exhausted the supply so that further resuspension ceased. The bed sediment proper therefore contributed little to the resuspension population. A comparable source-limitation on resuspension was observed at Site B whenever tidal resuspension occurred.

(*b*) *Resuspension by combined wave/current flows*

Addition of even modest waves to a steady current should increase both the apparent bed roughness and the bed shear stress. This then boosts resuspension and dispersion of particles from the bed. Boundary layer measurements at Sites A and C during periods of wave activity confirm that the mean flow above the embedded

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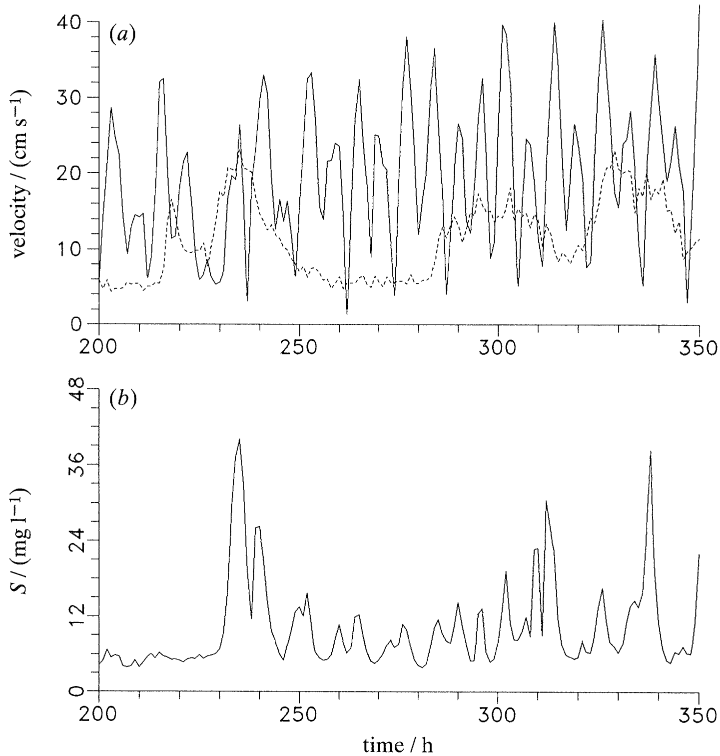

Figure 6. (*a*) Mean current speed (0.86 mab) and significant wave-orbital velocity and (*b*) seston concentration (2.0 mab), Site C. Note coincidence of peak in turbidity and plateau in orbital velocity at hour 235. (*a*) ----, u_0; ——, u_{86}.

wave boundary layer was retarded by an hydraulic roughness that was larger than can be attributed to the seabed (Green *et al.* 1990; Williams *et al.* 1993). Green *et al.* (1990) successfully simulated the enhanced bed shear stress in a wave/current flow at Site C and showed that the peak wave stress may be significantly increased by nonlinear interaction with the tidal current even under small waves in fairweather conditions. Increased resuspension of bed material due to wave enhancement of bed stress was observed at both Sites A and C. Thus at Site A there was a high level of correlation between u_0/u_z (i.e. significant wave-orbital velocity at the bed/mean current speed at height z above the bed) and seston concentration at 1 mab (Williams *et al.* 1993). The effect of waves at Site C is shown in figure 6; the largest peak in seston concentration (2 mab) is coincident with the plateau in orbital velocity. Wave/current interaction at Site C produced an order of magnitude greater seston concentration than at either of the other sites; such resuspension at this site probably involved entrainment of bed sediment (rather than a veneer of fluff).

This need not mean that increasing wave activity necessarily gives rise to ever-increasing seston concentration. Suspended particles may themselves suppress turbulence within the boundary layer and so limit further resuspension. With the right combination of particle settling velocity and turbulent mixing, the added mass of the suspended load can act to stably stratify the boundary layer (Glenn & Grant 1987). Model predictions show that such stratification is critically dependent on the settling velocity, and hence, the particle size spectrum of the bed material (figure 7):

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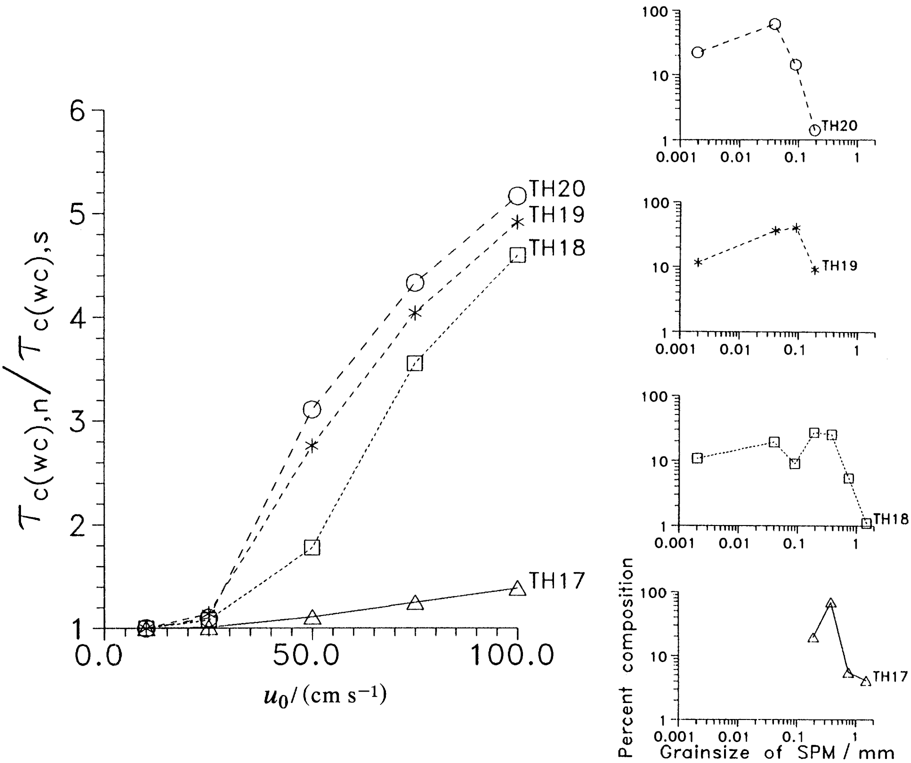

Figure 7. Model predictions of time-averaged bed shear stress in neutral wave/current flow ($\tau_{c(wc),n}$) and in stably stratified wave/current flow ($\tau_{c(wc),s}$) with the suspended load supplied by four different bed sediments (wave period is 7 s, bed roughness is 10^{-2} m, $u_{100} = 0.25$ m s^{-1}). Grain size spectra of the bed sediments are also shown.

fine sediments are most likely to stably stratify the boundary layer. This condition was not encountered during our periods of observations but must be important in shallow water, fine sediment areas like Site C during storms (cf. Huntley *et al.* 1993).

4. Properties of the suspended particles

(*a*) *A model of particle mixing*

Differences in particle characteristics in the two seston components (background and resuspension) were investigated at Sites A and B.

There was a nonlinear relationship between concentration of total particulate carbon (POC) and seston concentration S at Sites A and B (figure 8) which has been previously observed in estuaries (Morris *et al.* 1982; Balls 1990) and coastal seas (Cauwet *et al.* 1990).

A two-component mixing model (Morris *et al.* 1987; Bale & Morris 1993) illuminates this relationship. This uses the algorithm $[C = S_0(C_0 - C_r)/S + C_r]$, where C, C_0, and C_r are the concentrations of POC in the mixture, background and resuspension components, respectively; there is an inverse relationship between C and S. Regressions of POC on $1/S$ give significant relationships for all observational periods (see figure 8 for May).

As shown by Bale & Morris (1993), the significant regressions provide values of C_0 and C_r. During the observational periods, C_r varied from 1.9% to 4.5%; these were

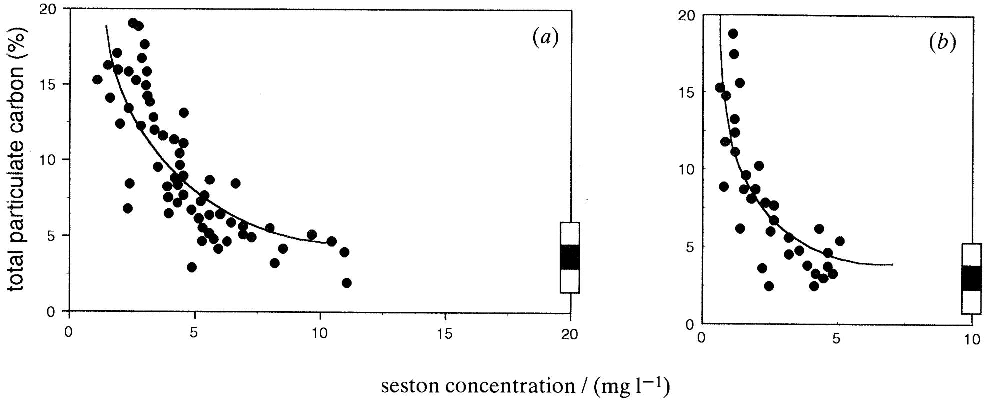

Figure 8. Scatter plots showing relationship between POC (% carbon) and seston concentration at (*a*) Site A and (*b*) Site B in May. Superimposed is the relationship generated from a linear regression of %C against 1/S (see text). Values of C_r predicted by the linear regressions are plotted on the right-hand vertical axis as solid squares with open rectangles showing the 95% confidence interval (i.e. ± 2 standard deviations).

five to ten times higher than for seabed sediments in these parts of the North Sea (Wirth & Weisner 1988; Rowden *et al.* 1993*a*). Thus the resuspension component was carbon-enriched compared with the bulk of the seabed sediment. This corroborates our view that the resuspended material at these sites was derived from a surficial layer of light, mobile, comparatively organic-rich particles (i.e. fluff).

C_0 varied from 8.5% to 57.4% (an order of magnitude greater than C_r), was greater in May (in the aftermath of the spring bloom) than in January or September, and was greater at Site A (which is nearer the coast). Significantly, C_0 was less than typical values for planktonic cells in January and September but not in May. The inference is that the carbon component of the background suspended fraction was dominated by degrading cells and colloidal organic matter except for short periods after blooms when it consisted of living cells.

(*b*) *Hydraulic properties of seston*

Further examination confirms that the two components also differed in physical and hydraulic properties. Particle settling velocity spectra measured 1 mab showed systematic changes within tidal cycles and during storms whenever resuspension occurred (Jago & Jones 1993; Jones *et al.* 1993*a*). Settling velocity increased from slack water to maximum flow and decreased from maximum flow to slack water. The development of the resuspension component as the current speed increases is very clear in settling velocity spectra (figure 9) from which distinct components of modal value ω can be obtained (table 2). The resuspension component settling velocity ω_r was consistently *ca.* 5×10^{-3} m s^{-1} at Site A and $O(10^{-3}$–10^{-4} m s$^{-1})$ at Site B (after storms and blooms). We consider that the same phenomenon occurred at the two sites: entrainment of biotic aggregates (fluff) at the seabed. The resuspension components had settling rates of $O(1$–10 m h$^{-1})$ that were sufficiently fast for temporary deposition at slack water.

The background component had ω_0 of $O(10^{-7}$ m s$^{-1})$, a rate so slow, $O(10^{-2}$ m d$^{-1})$, that significant numbers of such particles could effectively never settle to the bed; the background component was clearly in long-term suspension. This value was remarkably consistent at both sites and at all times (table 2).

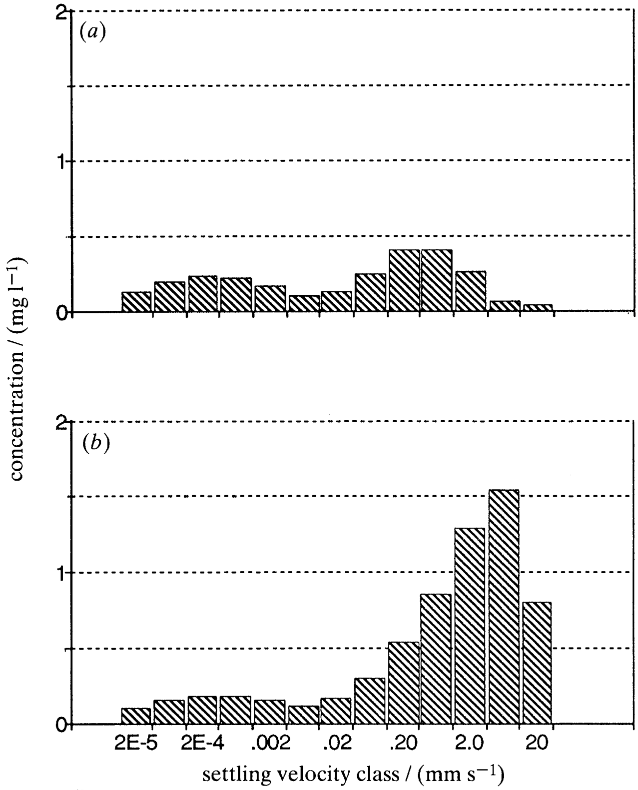

Figure 9. Typical settling velocity spectra at Site A in January at (*a*) slack water and (*b*) maximum flow. Note increased settling velocities at maximum flow due to resuspension components ($\omega_r \approx 5 \times 10^{-3}$ m s^{-1}). Background component has ω_0 of $O(10^{-7}$ m s$^{-1})$.

Table 2. *Settling velocities of seston components*
(Order of magnitude values in m s^{-1}.)

site/month	resuspension	background	primary production
A/Jan	5×10^{-3}	10^{-7}	—
A/May	5×10^{-3}	10^{-7}	10^{-4}–10^{-5}
A/Sep	5×10^{-3}	10^{-7}	—
B/Jan	2×10^{-4}	10^{-7}	—
B/May	1×10^{-3}	10^{-7}	—
B/Sep	3×10^{-4}	10^{-7}	3×10^{-3}

Extra fractions appeared during plankton blooms. Thus, for example, additional contributions with ω of $O(10^{-5}$ m s$^{-1})$ appeared at Site A in May. These settling rates, $O(1$ m d$^{-1})$ coupled to high values of C_0 and POC, and low C/N ratio, suggests that these fractions consisted of living and degrading cells and aggregates of *Phaeocystis*. Furthermore, as these particles settled, background seston concentrations declined even though maximum currents were increasing (from neaps to springs). Thus settling *Phaeocystis* cells were scavenging other particles and carrying them to the bed.

6. Properties of the bed

Benthic organisms intensively rework the upper few centimetres of the bed so that bed erodibility and bed roughness may be significantly enhanced or diminished (Rhoads & Boyer 1982).

There was little evidence of benthos control of bed properties and resuspension at the sandy Site A. However, the macrobenthic community of the muddy sands of Site B was dominated by large population densities of several active burrowers, principally *Amphiura filiformis*, *Echinocardium cordatum* and *Callianassa subterranea*. Measurements in box cores identified significant temporal changes in both community structure and bed properties (Rowden *et al.* 1993*b*). The greatest influence in the upper 0.05 m of the bed was exerted by the brittle star *A. filiformis* whose abundance was significantly correlated with sediment water content and acoustic shear wave velocity (figure 10), bulk sediment properties which are related to the rigidity of the bed (Jones & Jago 1992). Increasing numbers of *A. filiformis* were therefore related to decreasing bulk density and decreasing shear modulus. Furthermore, the bed was least rigid in May when *A. filiformis* was most abundant. With increased organism numbers, bulk density reduced by 3.5%, shear wave velocity reduced by 25%, and rigidity (shear modulus) reduced by 45%. The widespread abundance of this species (it occurred at 70% of the stations sampled by Kunitzer *et al.* (1992) in their survey of the North Sea) emphasizes the possible spatial scale of this effect. A reduction in the density and rigidity of such a cohesive bed should lower the threshold of movement and increase the potential erosion rate of the bed.

The members of the *Amphiura-Echinocardium* community at Site B also influence the surface roughness of the bed. Modelled and observed roughness length z_0 increased by a factor of 400 between January and September (Howarth 1993; Rowden *et al.* 1993*a*). The values suggest that in January ($z_0 \approx 3 \times 10^{-6}$ m) the bed was flat, featureless, and hydraulically smooth; this could be the result of reworking of the bed in winter by storms or by epifauna. The increased bed roughness in September ($z_0 = 10^{-3}$–10^{-4} m) must be imposed by biological rather than hydraulic processes. Box cores and bottom photographs confirm that the increased activity in summer of the abundant infauna, especially *Callianassa subterranea*, gave rise to extensive burrows and excavation mounds.

Biological modifications to bed properties and bed roughness between January and September at this site would have increased the susceptibility of the bed to resuspension. However, none of the modifications sufficiently lowered the threshold of movement for resuspension to occur. Nevertheless, these biological effects must become important when wave/current interaction boosts the bed stress.

7. Seasonal variation of seston dynamics

Important changes occurred in early summer at Site B with the onset of water column stratification and plankton blooms (see figure 11, plate 1, where the horizontal axis shows the day of month, May 1989).

Onset and development of these phenomena were recorded over several tidal cycles at Site B in May (figure 11). At the beginning of the observational period (15 May), thermal stratification was muted and a bloom was present in surface and mid-depth waters (high chlorophyll *a* concentrations). Seston concentrations were high near the

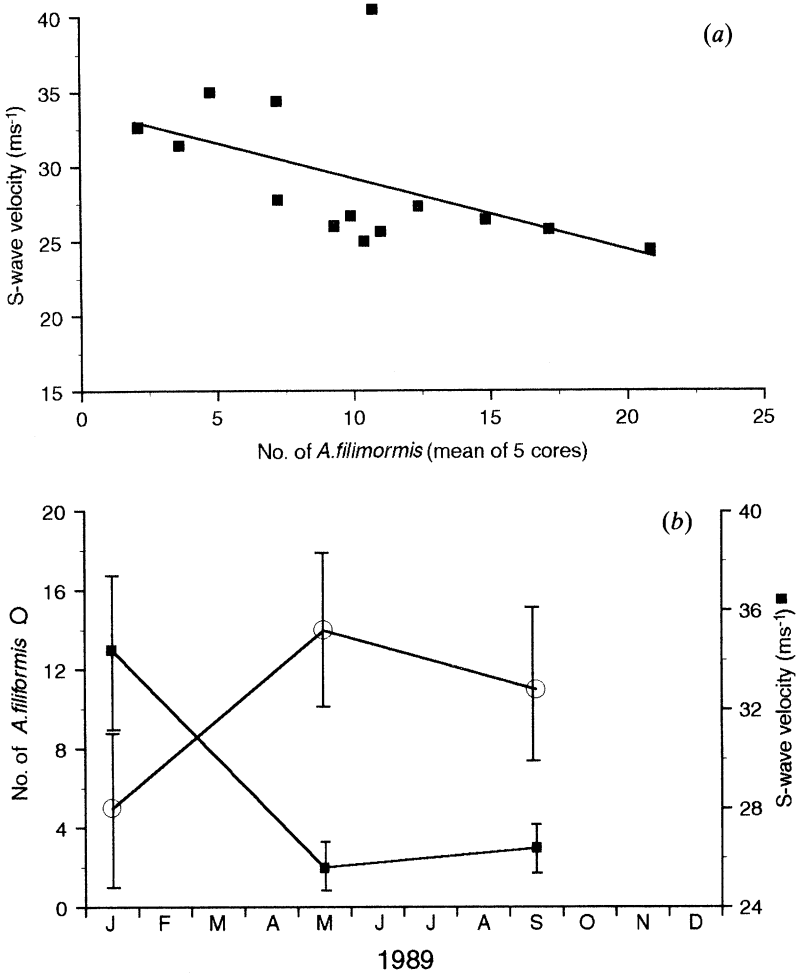

Figure 10. Modification of bed properties by bioturbating fauna. (*a*) Relationship between numbers of *Amphiura filiformis* and acoustic shear wave velocity. (*b*) Seasonal variability of shear wave velocity and numbers of *A. filiformis*.

surface due to living plankton. Seston concentrations were also high near the bed but the high C/N ratio (*ca.* 21) of the suspended particles is indicative of plankton cells in poor physiological condition (Graf *et al.* 1982) so these near-bed particles must have been generated during an early phase of the bloom taking place in the surface waters; some tidal resuspension of these particles was taking place. The water column then stratified, by which time (20 May) chlorophyll production in the surface waters had ceased. Plankton-rich seston had settled below the thermocline and much had reached the bed. There was enhanced tidal resuspension but the material resuspended was now plankton-rich (high chlorophyll *a*). Tidal resuspension was unusual at this site; its occurrence at this time indicates that the resuspended material (living cells plus recently formed fluff) was readily entrained. Due to suppression of vertical mixing, no resuspended particles were able to penetrate the thermocline. Surface waters were therefore very clear, so enabling sufficient light penetration to maintain the bloom now active below the thermocline. This situation continued till the end of the observation period (23 May) by which time seston

Table 3. *Mean concentrations of trace metals at Site B*

(Concentrations of dissolved constituents in nmol l^{-1}; concentrations of particulate constituents in $\mu g\ g^{-1}$.)

date	cadmium	copper	iron	manganese	nickel	lead	zinc
dissolved							
Jan 89	0.188	3.78	ND	12.54	4.41	0.089	5.56
May 89	0.210	3.75	ND	19.73	5.32	0.105	7.06
particulate							
Jan 89	1.4	9.9	6800	554	ND	101	63
May 89	ND	10.2	9100	311	5.4	31	53

concentration below the thermocline had declined. Tidal resuspension of settled plankton-rich material, still living, continued. The bloom was therefore active for at least nine days, though its focus had shifted from surface to bottom waters.

Clearly there was a marked decoupling of both the physics and biology of surface and bottom waters at Site B. This has important implications for models of particle-related biogeochemical processes in shelf seas.

8. Benthic biogeochemical processes

While atmospheric and aquatic transport (from the coastal boundary zone) and direct biological input (from plankton tissue) are important for some metals, biogeochemical processes at the sediment/water interface control the behaviour of the redox-sensitive metals Co, Fe and Mn (Graf *et al.* 1982; Hunt 1983; Millward *et al.* 1993). This was most apparent at the seasonally stratified Site B where sedimentation of organic debris from plankton blooms gave rise to benthic anoxia and flux of Fe and Mn.

Marked temporal variations in dissolved and particulate Fe and Mn were observed at Site B. There is good evidence for efflux of metals across the sediment/water interface, particularly in spring (May): (i) relatively high bottom water dissolved Mn concentrations were observed with the highest dissolved concentrations in bottom waters coinciding with maximum current speeds; (ii) in May 1990 at this site, pore water Mn and Fe concentrations were three orders of magnitude greater than the dissolved metal concentrations in the overlying water column.

In May, settling plankton trapped below the developing thermocline gave rise to anaerobic decay of cells and oxygen depletion near the seabed, thereby stimulating the release of solubilized Mn and Fe (and Co) from the bed. Thus as the thermocline developed (15 May), limited resuspension by tidal currents of degraded organic-rich particles was taking place (figure 11 and previous section). The degraded condition of the organic matter (due to anaerobic decomposition of cells), indicates that near-bed oxygen depletion was already established. Hence solubilized trace metals were released across the sediment/water interface. Because of differential rates of removal of Fe and Mn, the particulate Fe/Mn ratio increased at this time (15 May). There was therefore a strong seasonal signal in the particulate Fe/Mn ratio which was 12 in January and 29 in May (table 3).

Cycling of these metals at Site B was therefore dependent on water column structure and on production, settling, and resuspension of biotic particles. The interplay of stratification and plankton blooms and the decoupling of surface and bottom water processes are crucial: in stratified waters, the thermocline traps carbon-rich seston in the bottom waters so the supply of benthic POC and the development of benthic anoxia are maintained; the thermocline then confines sorbed metals to bottom waters.

9. Summary and conclusions

Resuspension of bed material by tidal currents occurred at the shallow water Site A and C. Tidal resuspension was observed at the deeper water Site B only during plankton blooms when there was an enhanced production of light, readily entrained particles to the seabed. Much of the tidal resuspension was of organic-rich fluff rather than of bed sediment. The activities of benthic infauna produced significant seasonal changes to bed properties and bed roughness at Site B, but no increase in tidal resuspension of bed sediment was observed due to these effects. Increased resuspension by combined wave/current flows was observed at all three sites, notably at Site C where fine sediments occur in shallow water.

These results support the view that significant resuspension of bed sediment in European shelf seas occurs only in areas of strong tidal currents and/or during storms. However, stable stratification of the boundary layer by suspended sediment may occur during storms so that resuspension should be a self-limiting process; this is most likely to occur in shallow water areas of fine sediments.

When tidal resuspension occurred, seston concentration comprised a resuspension component superimposed on an advecting background component. Modelling of seston concentration profiles over tidal and spring/neap cycles shows that, at Sites A and B, resuspension was constrained by a finite supply of material; once this material (fluff) was entrained, further resuspension ceased.

The composition of seston depended on the relative contributions of the background component (high POC) and the resuspension component (lower POC). The resuspension component consisted of fluff and so contained more organic carbon than the seabed sediment. The background component in long-term suspension settled so slowly that it was effectively conservative; hence its behaviour was that of a dissolved tracer (Prandle *et al.* 1993). A seasonally generated biotic fraction scavenged particles in long-term suspension as it settled to the bed where, in part, it joined the resuspension component until it was advected away, deposited, mixed into the bed, and/or biodegraded. The resuspension component had a site-specific settling rate that was remarkably consistent in time.

Simultaneous onsets of water column stratification and plankton blooms produced complex patterns of seston behaviour. Decoupling of surface and bottom waters during blooms gave rise to distinctive particle characteristics and behaviour. Enhanced deposition of living cells and degrading fluff during blooms produced seabed anoxia and boosted efflux of redox-sensitive trace metals; there was therefore a significant seasonal signal in particulate Fe/Mg. Thus metal fluxes were strongly modulated by particle characteristics and dynamics at the seasonally stratified Site B during plankton blooms.

The work at Sites A and B was supported by the Natural Environment Research Council within its North Sea Community Programme. C.F.J. and S.E.J. were supported by a NERC Special Topic research grant (GST/02/276). Additional support to A.J.B., A.W.M. and A.A.R. was provided by the Department of the Environment (Contract PECD 7/8/141). The boundary layer work at Site C was supported by the Ministry of Agriculture, Fisheries and Food (Project BEC3) and by the Department of the Environment (Contract F22). MOG and INMcC acknowledge the other members of the COSEDS group and the MAFF Fisheries Laboratory, Lowestoft for technical and field support. Department of Earth Sciences, University of Cambridge, Contribution 2490.

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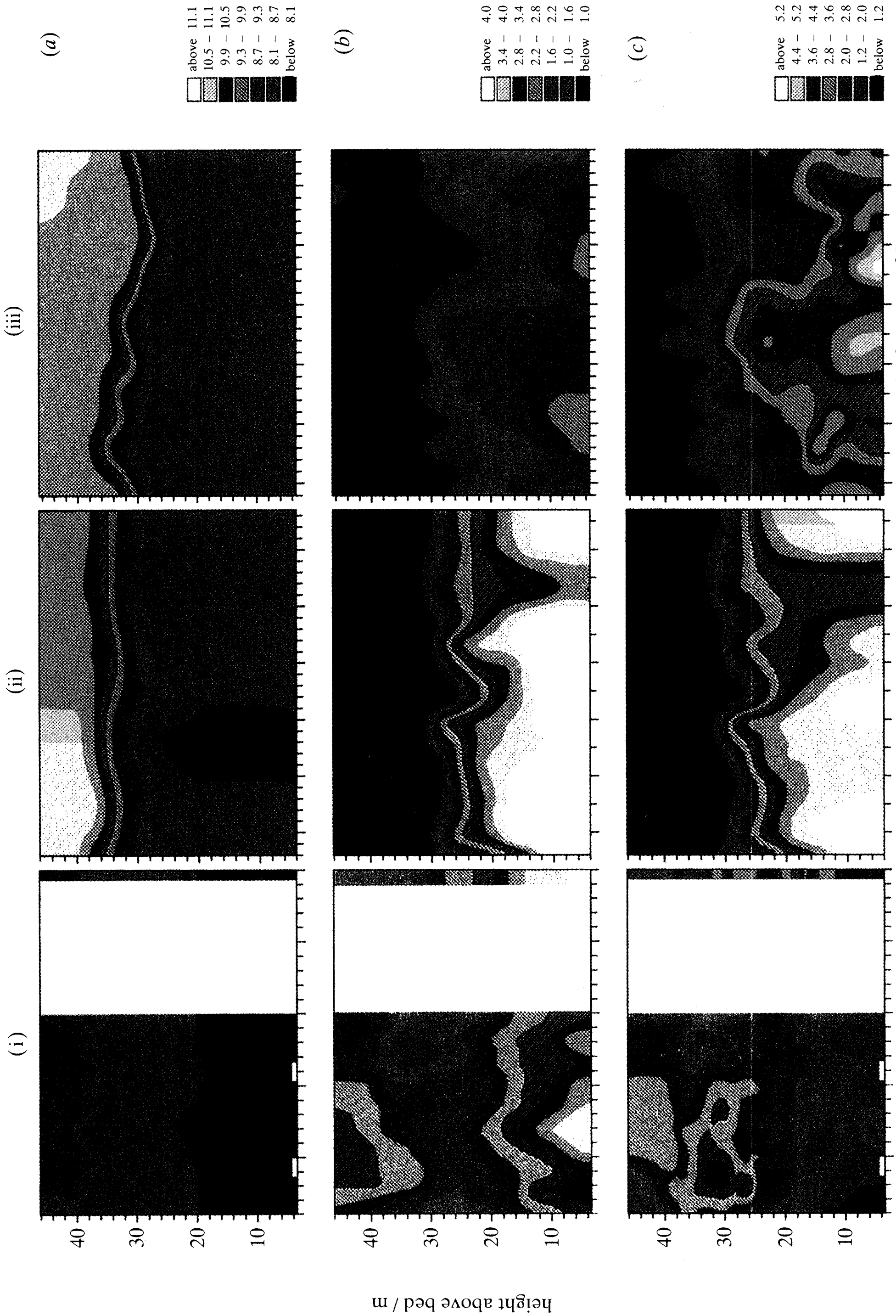

Figure 11. Tidal cycle observations of (*a*) temperature (°C), (*b*) seston (SPM) concentration (mg l^{-1}) and (*c*) chlorophyll *a* concentration (µg l^{-1}) at Site B in May 1989 during plankton bloom. (i) Tide A, (ii) tide B, (iii) tide C.

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Discussion

D. Hydes (*Institute of Oceanographic Sciences, U.K.*). It is suggested that on average the bed of the North Sea is turned over by trawling activities three times a year. Did Dr Jago see any indications of such a high rate of activity in his observations? Would he like to comment on the comparative magnitude of biological turn over?

C. F. Jago. Both bottom photography and side scan sonar surveys were conducted at the study sites, though no indications of trawling activity were recorded. However, such indications were not being specifically sought and the areas of seafloor observations were relatively small. It is generally agreed that in the North Sea trawling gear physically disturbs the sediment to a depth of just a few centimetres: Estimates vary depending on the characteristics of the gear and the sediment (e.g. 1.5 cm, 8–10 cm (Margetts & Bridger 1971); 1–3 cm (Bridger 1972); 6 cm (BEON 1990)). The frequency of such disturbance in the North Sea is highly variable, some areas of seabed being trawled at extremely high rates (e.g. 10 times per year), while others receive relatively little or no attention; an average value for the North Sea is 3–5 times per year (Messieh *et al.* 1991). The influence of biological activity upon the physical nature of the sediment was investigated at Site B (Rowden *et al.* 1993*a*) and an estimate for sediment reworking was determined for one species of the benthic infauna (*Callianassa subterranea*, the mud shrimp); this organism can rework the bottom sediment at a rate of 11 kg m^{-2} a^{-1}, equivalent to a sediment turnover rate of approximately 1 cm m^{-2} a^{-1}. This is numerically less than the estimated sediment turnover due to trawling, but it must be emphasised that organisms such as *Callianassa* rework sediments from depths of 20–30 cm and their activity is probably spatially and temporally less variable than trawling activity. Bioturbation rather than trawling may therefore be more significant to, for example, nutrient cycling.

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A. Turner (*BMT Southampton Ltd, U.K.*). Has Dr Jago considered applying the carbon resuspension model to Fe and Mn, and would he anticipate different trends bearing in mind their redox properties?

C. F. Jago. The particle mixing model presented in this paper is essentially a mass balance equation which is dependent on conservative behaviour by the tracer constituent in relation to the timescale of the mixing process. The model was originally used in relation to relatively stable components of seston, e.g. Si, Cu and Mg within the detrital 'fabric' of the particle or otherwise firmly associated with the surfaces, e.g. some Fe and Pb, but not Mn (Morris *et al.* 1987). The problem with Fe and Mn in natural sediments is that the behaviour of a significant proportion of the species is greatly affected by redox processes which influence stability of these components in going from sedimented to suspended phases (the oxides tending to be insoluble and associated with particle surfaces whereas the reduced forms are soluble). We can anticipate that Mn might be more usefully predicted by the model since it is kinetically stable on a timescale of days; Fe would be more difficult since reduced Fe is kinetically unstable on a timescale of minutes. Certainly, application of such a simple mixing model to redox-sensitive particulate Fe and Mn would not be straightforward.

D. Huntley (*University of Plymouth, U.K.*). Sediment modelling involves several parameters (the 'pick-up' constant, the power of velocity relevant to sediment response and so on). How were these parameters estimated, and how do their values compare with the generally accepted values?

C. F. Jago. There are two tunable parameters (α and n) which describe the erosion rate (E) as a function of bed shear stress (τ) for a particular (measured) settling rate class: $E = \alpha|\tau|^n$. The model is run for a range of values of n to identify that which best simulates the form of the observed resuspension signal. Then α is adjusted until simulated mean concentration profiles match observed values. Different values of α and n were chosen for the two sites: there also appears to be seasonal variation at each site, although modelling of the full data set is not yet complete. Our values of n range from 1 to 3; α ranges from 0.06×10^{-3} to 2.5×10^{-3} g m^{-2} s^{-1}. There are no 'generally accepted' values for the organic-rich fluff particles involved here. Published values fall in the range 1 to 5 for n; 0.02×10^{-3} to 40×10^{-3} g m^{-2} s^{-1} for α (Lavelle *et al.* 1984).

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W. van Leussen (*Tidal Water Division, The Netherlands*). During periods of maximum current velocities the presented settling velocities reached values of several millimetres per second. Are sand grains also responsible for these relatively high values? If not, large aggregates should be formed to arrive at such values. Are they formed by flocculation of the fine-grained particles in the water column, or were they already formed at the bottom before resuspension, for example by biological mechanism?

C. F. Jago. A few grains of sand were occasionally observed on filters from Site A samples, but sand resuspension (at 1 m above bed) was low even during maximum flow. Most of the observed high settling rate particles must therefore have been in aggregate form. During May at Site A and both May and September at Site B, these were primarily produced in the water column by flocculation of particles from phytoplankton blooms (via differential settling/entanglement), resulting in large aggregates which settled to the bed and were subsequently resuspended and deposited over several tidal cycles. Faecal pellets produced within the seabed by benthic macrofauna may also have been present at Site B. During January at Site A, chlorophyll *a* levels were very low and aggregates must have comprised fine inorganic particles and degraded organic material.

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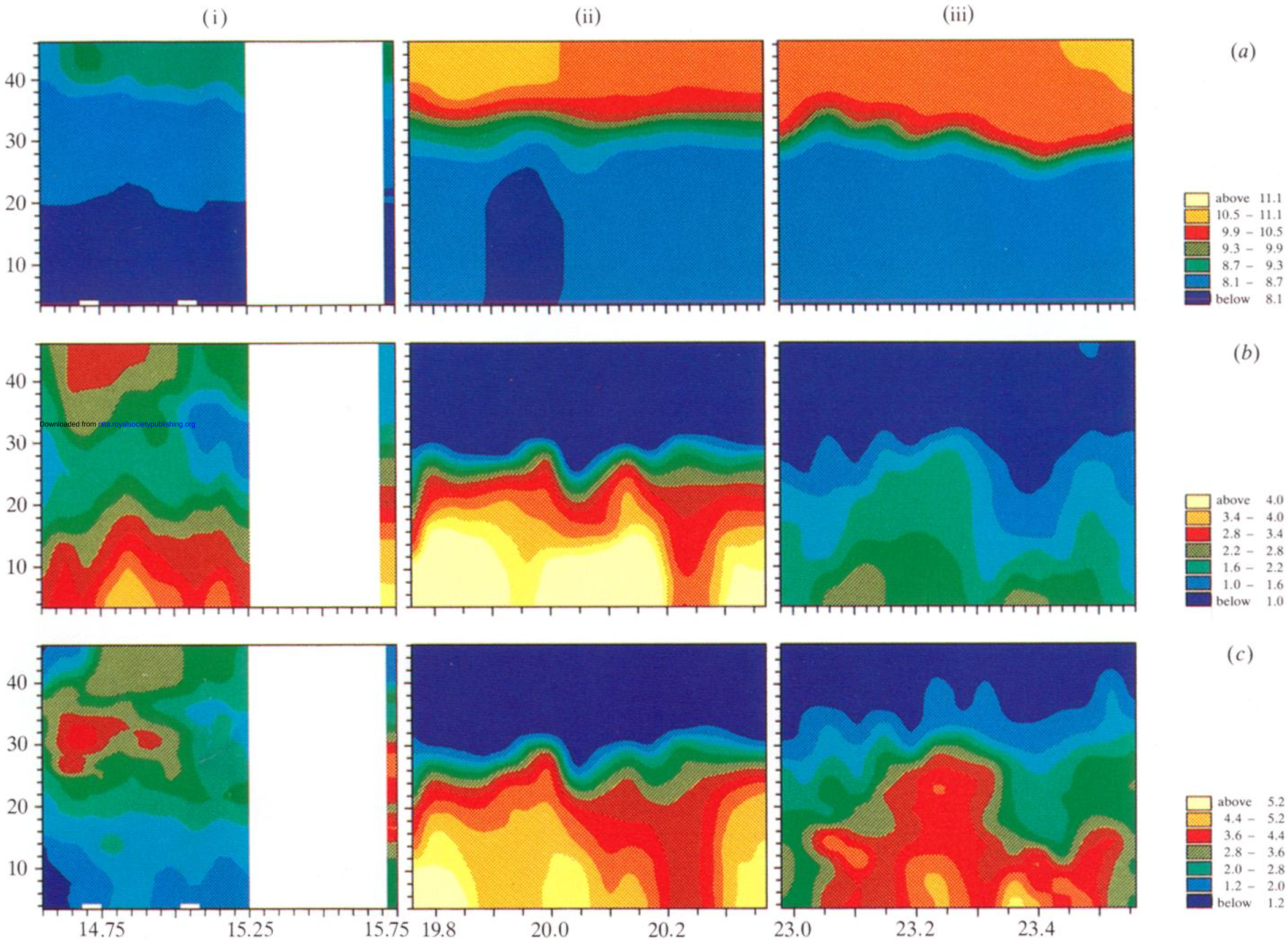
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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