Tidal and Meteorological Forcing of Suspended Sediment Flux in a Muddy Mesotidal Estuary

J. R. French · H. Burningham · T. Benson

Abstract Although the supply and fate of suspended sediment is of fundamental importance to the functioning and morphological evolution of muddy estuaries, reliable sediment budgets have been established in only a few cases. Especially for smaller estuaries, inadequate bathymetric surveys and a lack of intertidal sedimentation data often preclude estimation of the sediment budget from morphological change, while instrument-derived residual fluxes typically lie well within the errors associated with measurement of much larger gross tidal transports. Given suitably long-term records of continuously monitored suspended sediment concentration (SSC), however, analysis of the major scales of variation in sediment transport and their relation to hydrodynamic and meteorological forcing permits qualitative testing of hypotheses suggested by directly measured residual fluxes. This paper analyzes data from a 1-year acoustic Doppler profiler deployment in the Blyth estuary, a muddy mesotidal barrier-enclosed system on the UK east coast. Flux calculations indicate a small sediment import equivalent to just 1.5% of the gross flood tide transport. Little confidence can be assigned to either the magnitude or direction of such a small residual when considered in isolation. However, the inference that the sediment regime is finely balanced is qualitatively supported by the close similarity between flood-tide and ebb-tide SSC values. Singular spectrum analysis of the SSC time series shows the expectedly large contributions to the variance in SSC at intratidal and subtidal (semimonthly and monthly) scales but also picks out intermittent variability that is initially attributed to a combination of non-tidal surge and wind stress forcing. Closer examination of the data through cross-correlograms and event-scale analysis indicates that local meteorological forcing is the major factor. Acting through the resuspension of intertidal mudflat sediments at times of strong westerlies, meteorological forcing is directly implicated in episodic sediment export from the estuary. Thresholding of tide-averaged fluxes using a range of critical wind stress values further indicates that 'tide-dominated' (i.e., low wind stress) and 'wave-dominated' (high wind stress) conditions are associated with sediment import and export. Sediment balance is potentially sensitive to the frequency of high wind stress events, since the associated sediment exports are several times larger than the average import under calm conditions. Intermittent meteorological forcing may thus exert an important control on the sedimentary balance of otherwise tidally dominated muddy estuarine systems, and the role of wind climate should not be overlooked in studies of estuary response to environmental change.

Keywords Sediment budget · Cohesive sediment transport · Resuspension · Estuary waves · Singular spectrum analysis · Acoustic Doppler profiler · Climate change · Blyth estuary · Suffolk · UK

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Introduction

The supply and fate of suspended sediment is of fundamental importance to the functioning and morphological

evolution of muddy estuaries. Knowledge of the sediment regime is increasingly relevant for the management and restoration of estuarine ecosystems (e.g., Goodwin et al. 2001; Chen et al. 2005), monitoring of contaminant inventories (Schoellhamer 1996; Spencer 2002; Robert et al. 2004), and the prediction of estuary response to environmental change (e.g., Corbett et al. 2007). Translation of recent advances in the understanding of estuarine sediment dynamics into robust flux and budget estimates remains problematic given the range of scales of tidal, fluvial, and meteorological forcing and the difficulty of isolating a small residual flux from much larger flood and ebb transports (Lane et al. 1997; Simpson and Bland 2000; Townend and Whitehead 2003). Some of the more compelling analyses combine historic sedimentation information with instrumentation-derived sediment flux, possibly supported by physically based numerical modeling (e.g., Baird et al. 1987). However, the data required to support integrated analyses of this kind exist for only a fraction of estuaries, and estuary management problems frequently demand that an appreciation of the sediment dynamics be obtained from limited data acquisition campaigns.

The advent of optical backscatter sensors (Bunt et al. 1999; Lunven and Gentien 2000) and acoustic Doppler profilers (Land and Bray 1998; Holdaway et al. 1999; Hoitink and Hoekstra 2005; Kostaschuk et al. 2005) has enabled the acquisition of much longer time series of suspended sediment concentration (SSC) than would be possible by discrete sampling. Interpreted with care, long-term SSC time series provide valuable insights into the processes controlling sediment regime (Schoellhamer 1996, 2002) and, importantly, allow the evaluation of hypotheses originating from quantitative determinations of the residual flux.

This study analyzes data from a 12-month data acquisition campaign in the Blyth estuary, a muddy mesotidal estuary on the UK east coast. Suspended sediment concentrations and fluxes are estimated at the interface between the narrow outer channel and the more extensive middle estuary that accounts for most of the tidal prism. Analysis of the SSC time series is then undertaken to identify major scales of variability and their relation to hydrodynamic and meteorological forcing. The dynamic insights afforded by these analyses allow qualitative testing of hypotheses relating to the sediment balance and the relative contribution of tidal versus meteorological forcing. Wider implications for the sediment balance of muddy estuaries in the region and their potential sensitivity to climate change are briefly considered.

Study Location

Suffolk Coast Estuaries

The estuaries that indent the coast of Suffolk (Fig. 1a) receive small river inflows in comparison with a mesotidal influence. The coast is subject to the storm wave climate of the southern North Sea [mean offshore $h_s=0.96$ m, with modal directions from the northeast (50%) and southwest (32%); CEFAS 2004]. Northeasterly waves are the main factors controlling the large-scale littoral drift, which is
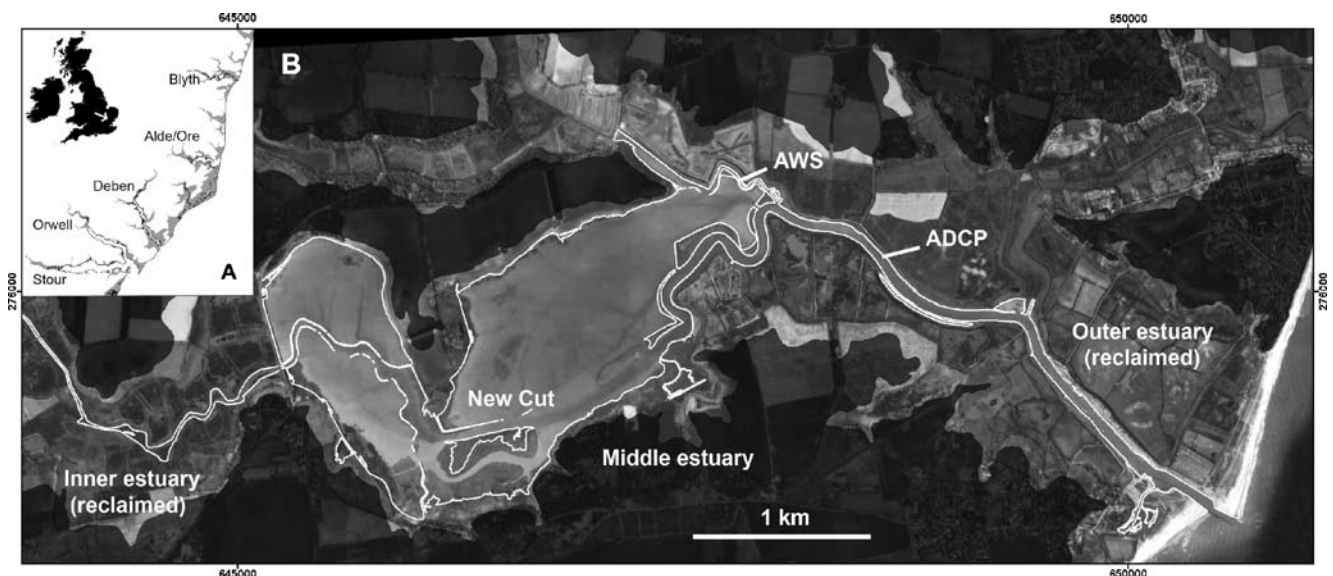

Fig. 1 a Location of Suffolk estuaries on east coast of UK; b aerial photo mosaic of Blyth estuary showing outer, middle, and inner estuary zones referred to in text and location of ADCP and AWS instrumentation (aerial photography flown by Natural Environment Research Council)

geographically variable in magnitude but generally from north to south (Wallingford 2002).

The littoral shoreline is dominated by gravel with a significant sand fraction (Pontee et al. 1994; Burningham and French 2007). Offshore, the shoreface is swept by strong tidal streams and comprises lag gravel pavements, with a complex arrangement of sand sheets and ridges. Exposures of London Clay and estuarine alluvium close to the modern shoreline (Lees 1980; HR Wallingford 2002) reflect the generally transgressive nature of this coast prior to widespread coastal protection that greatly reduced rates of retreat over the last century (Taylor et al. 2004). Gravel and sand deposits typically occur at the estuary mouths, most notably in the Alde/Ore and Deben estuaries, where large ebb-tidal deltas facilitate inlet bypassing and the long-term continuity of the littoral drift system (Burningham and French 2006, 2007). Estuarine sediments are predominantly muddy, and all the estuaries in the region once possessed extensive salt and brackish marshes that were largely reclaimed by the mid-nineteenth century (Beardall et al. 1991).

Large-scale suspended mud transport in the southern North Sea has been well studied. Offshore SSC is low (typically <10 mg l^{-1}) but increases in the winter, during which a distinct plume of suspended sediment extends from Norfolk in an easterly direction across the North Sea towards the island of Texel in The Netherlands (Eisma and Kalf 1987; Dyer and Moffat 1998; Gayer et al. 2006). Concentrations in estuarine and coastal waters are much higher. Data from the CEFAS archive (HR Wallingford 2002) also show several areas of elevated SSC, including a zone between Great Yarmouth and Lowestoft in which average concentrations exceed 65 mg l^{-1}. There is some association between elevated SSC and high spring tidal currents in this zone.

Within this broader picture, details of the coastal fine sediment budget remain sketchy. While the role of cliff erosion as a major source of fine sediment has been variously quantified (McCave 1987; Gayer et al. 2006), the role of estuaries is less well understood. Fluvial influxes from the numerous low gradient rivers are low, and late Holocene estuary infilling has been dominated by sediments of marine origin (Brew et al. 1992). Whether or not all these estuaries presently function as a sink or a source for fine sediment is less clear. McCave (1987) assumed, as a first approximation, that estuary intertidal sedimentation tracked relative sea level rise and, on this basis, estimated a potential demand of 82×10^3 t year^{-1} for the Suffolk estuaries. However, the commercially important Orwell and Stour estuaries are extensively dredged, and both have experienced rapid erosion of their salt marsh during the twentieth century (Beardall et al. 1991). As part of an investigation into the impacts of an expansion of the Port of Harwich, HR Wallingford (2001) undertook a sediment bud-

get analysis based on bathymetric changes between 1976 and 1997. This showed the Stour to be sourcing sediment through intertidal erosion (estimated at 240×10^3 m^3 year^{-1}) with the adjacent Orwell estuary acting as a net sink (estimated at 20 to 30×10^3 m^3 year^{-1}).

Blyth Estuary

The Blyth estuary is barrier-enclosed (Fig. 1b) with a dune-backed sand and gravel beach extending southwards from an elevated headland. The narrow mouth is fixed by breakwaters, to the south of which extends an offset sand and gravel beach. Although coarse sand and gravel occur at the mouth, clastic sediments within the estuary are predominantly silt clays. A combination of a small rural catchment area, low regional rainfall (mean 576 mm year^{-1} at Lowestoft, 1971–2000; http://www.metoffice.gov.uk/climate, accessed 15 May, 2007), and abstraction of water for agriculture ensure that fluvial inflow is minimal (90% of mean monthly flows <0.9 m^3 s^{-1}; http://www.nwl.ac.uk, accessed 15 May, 2007). Tidal range at the mouth averages 2.0 m at springs and 1.2 m at neaps. Given that the mean spring tidal prism is about 2.6×10^6 m^3, the estuary is almost always well mixed. Longitudinal salinity profiles typically show depth-mean salinities in the range 30.7 to 33.9‰, although mid-ebb salinities as low as 26.3‰ have been recorded within the middle estuary after very heavy rainfall (French et al. 2005).

The inlet of the Blyth was historically prone to blockage during winter storms, a situation exacerbated by the reclamation of most of the intertidal area by the early nineteenth century (Simper 1994). This necessitated frequent dredging and successive harbor improvements that culminated in the jetties that presently maintain a narrow inlet channel. Tidal action was restored to a large portion of the middle estuary due to failures of some of the flood banks in the 1920s and 1940s. The increase in tidal prism created a strongly ebb-dominated tidal regime that has subsequently maintained the inlet. The outer and inner estuary zones remain almost completely reclaimed and confined within a narrow channel. In contrast, the middle estuary is characterized by extensive tidal flats and smaller areas of salt marsh flanking the low water channel (Fig. 1b).

The tidal hydrodynamics have been investigated in some detail (French 2008), and French et al. (2005) presented a preliminary analysis of sediment flux data that suggested that the estuary is presently importing sediment but with intermittent export during periods of wave resuspension. This hypothesis has implications for the future evolution of the estuary and for habitat management in this and other muddy estuaries in which extensive intertidal flats are subject to intermittent wave action.

Methods

Data Acquisition

A site seaward of the transition between the outer and middle estuary zones (Fig. 1b) was instrumented in order to investigate exchanges of water and suspended sediment between estuary the North Sea. Navigational requirements precluded deployment of instruments within the mouth and the inner harbor. The instrumented reach (marked ADCP on Fig. 1b) is approximately 60 m wide and of fairly simple section, with a mean depth of about 6.5 m at mean high water spring tide. Hydrodynamic and SSC data were obtained from an RDI 1.2 MHz upward-looking acoustic Doppler current profiler (ADCP) deployed on a bottom frame in the channel centre. Vertical velocity profiles were recorded at 15-min intervals (0.2-m bin width; 60 ping ensembles; standard error 18 mm s^{-1}). Water levels were recorded at the same 15-min intervals by a calibrated pressure sensor. An automatic weather station (AWS) was maintained at a site on the tidal flats of the middle estuary (Fig. 1b) for the duration of the instrument deployment, which lasted from June 2001 to July 2002.

The intensity of the raw backscattered signal for each of the four ADCP beams was calibrated to provide a measure of SSC (e.g., Reichel and Nachtnebel 1994; Land and Bray 1998; Holdaway et al. 1999). Calibration was undertaken using intensities for a single vertical bin and filtered bottle samples obtained from a co-located pump sampler intake. As reported in other studies (e.g., Alvarez and Jones 2002), a good correlation was obtained between Log(SSC) and backscatter intensity (Fig. 2). Particle size is known to vary over the tidal cycle (Benson and French 2007), and the influence of this variation was minimized through the derivation of separate flood and ebb calibrations. This
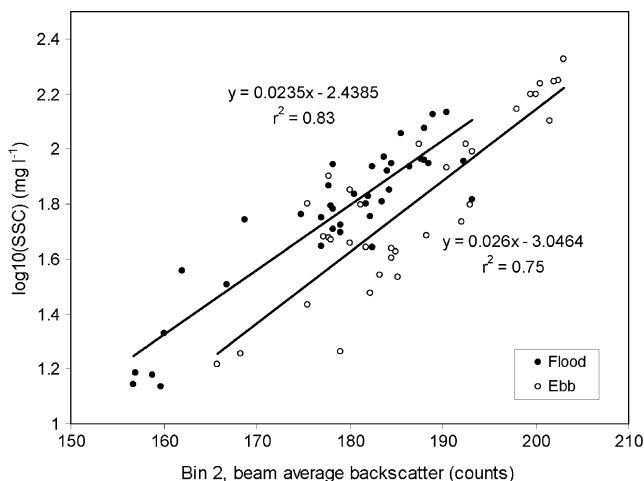
accounts for some of the expected variability associated with formation and breakup of composite particles (macroflocs) in response to time variation in concentration and turbulent shear (Benson and French 2007) and the larger proportion of the ebb suspended load that has undergone at least one cycle of deposition and resuspension within the estuarine intertidal. Such variability in the properties of the suspended material can be important even in the absence of a significant net flux. In order to obtain depth profiles of SSC, raw intensities recorded by the ADCP were range-normalized with respect to spherical spreading and absorption by the water (RDI 1999). Backscatter values for each depth bin were then calculated using the calibration for the reference bin level. Near-surface values were removed due to acoustic side-lobe interference, and wave effects and values from the first bin were not used due to the effects of near-field backscattering.

The ADCP frame was tipped over towards the end of the deployment with the result that 5 weeks of data were lost. Allowing also for brief gaps during data retrieval and instrument checking, record completeness was 92.1%, with good data being obtained for 648 complete tidal cycles. A fault with the AWS also resulted in the loss of meteorological data for the final 33 of these tides.

Sediment Flux Estimation

The mean spring tidal prism accounts for around 70% of the estuary volume, and the tidal excursion is comparable to the length of the outer and middle estuary zones. It is therefore more appropriate to estimate the sediment flux from direct integration of successive tidal transports than synoptically (see, for example, Jay et al. 1997). Continuous instantaneous water discharge, Q, was computed as the product of channel average velocity and cross-sectional area. Boat-mounted ADCP traverses of the entire cross-section at 30-min intervals over selected spring and neap tides yielded 'best estimates' of the channel average velocity. Linear transfer functions were obtained for the calibration of section mean values from the channel centerline data. Cross-sectional area was obtained from a nonlinear function of tidal level. Both flood and ebb transects showed lateral variation in SSC to be minimal in comparison with the vertical variation. Accordingly, the observed vertical SSC profile was extrapolated across the channel width. Instantaneous sediment flux, Q_s, was obtained as the product of Q and SSC and the residual flux estimated by integrating the opposing flood and ebb fluxes over the duration of the record.

A difficulty in flux estimation of this kind lies in the identification and correction of small systematic biases that are not easily removed through time averaging (Simpson and Bland 2000). In the case of the Blyth, it is possible to

Fig. 2 Calibration of ADCP backscatter against SSC determined from filtration of pump samples

exploit the small size of the system, the fact that tidal prism accounts for a large proportion of the overall volume, and the correspondingly short residence time. Neglecting the river inflow and in the absence of large non-tidal variations in level, the net water transport must be zero over a suitably long timescale (of the order of a few months or greater). Daily discharge data exist for the River Blyth, although gauging ceased at the end of 2001, necessitating the estimation of runoff from rainfall for the final portion of the record. On this basis, systematic bias in Q can be substantially eliminated by subtracting river inflow; linear de-trending of the cumulative Q (undertaken separately for data blocks of several months in duration punctuated by gaps for instrument retrieval for downloading and maintenance); addition of the river flow; and reconstruction of the Q series. Biases removed in this way were small but, uncorrected, sufficient to give a cumulated error in Q large enough to confound meaningful estimation of the associated net suspended sediment flux.

A comprehensive error analysis is not possible given the difficulty in quantifying some of the terms. However, a preliminary analysis indicated mean absolute errors arising from the best estimate of Q from the ADCP transects (2%) and use of these data to calibrate the continuous channel centerline data from the upward-looking ADCP (6%); calibration of the ADCP backscatter for SSC (32%); and the laboratory error in the analysis of the bottle samples for SSC (estimated at 4%). Budgeting these as a quadratic sum gives an overall error of around 33% in the estimation of Q_s. This assumes that the various terms are truly independent and ignores the unknown effect of extrapolating calibrations based on intensive measurements over a few tides over the duration of the entire dataset. However, the main point here is that even a well-constrained measurement campaign in an estuarine section of minimal complexity can only resolve a very substantial net sediment flux with statistical confidence.

Time Series Analysis

Time series of SSC and hydrodynamic and meteorological variables were analyzed to obtain further insight into the processes influencing sediment exchanges between the middle estuary and the sea. As a first step, singular spectrum analysis (SSA) was applied to the SSC series. SSA is essentially a principal component analysis performed in the time domain (Broomhead and King 1986; Vautard et al. 1992; Schoellhamer 1996). First, an autocorrelation matrix is formed by lagging a standardized time series of interest over zero to M-1 time steps (Vautard et al. 1992). Eigenvalues, $\lambda_{k\ k=1\ldots M}$, and eigenvectors (empirical orthogonal functions) of the lagged autocorrelation matrix are then computed and sorted in descending order of λ_k.

The eigenvalues, λ_k, contain successive fractions of the variance of the raw time series, and a plot in order of their decreasing magnitude typically exhibits a steep initial slope containing the signal components, which is terminated by a flatter floor that represents the noise level (Vautard and Ghil 1989). Principal components are calculated for each eigenvector, and a set of reconstructed components (RCs) are then obtained by multiplying the principal components and their corresponding eigenvectors. SSA thus provides a powerful tool for decomposing a time series into a set of independent components that represent slowly varying trend, periodic and quasi-periodic variation, and noise. Typically, one or two RCs contain variations at periodicities greater than the lag window size, M. Periodic components are represented by paired RCs with similar λ_k, and periods in the range $0.2M$ to M can generally be identified (Schoellhamer 2002). Here, SSA was applied to the SSC time series using the modifications to handle missing data suggested by Schoellhamer (2001), who also provides a more comprehensive description of the method.

Cross-correlation was used to explore the delays associated with tidal and meteorological forcing of estuarine SSC. This analysis distinguished between flood tide SSC, as an indicator of sediment input from the North Sea via the short outer estuary channel, and ebb tide SSC, as an indicator of processes of deposition, resuspension, and erosion within the estuary. Tidal forcing was quantified through series of tidal range and depth-mean current velocity. Meteorological forcing was quantified in terms of wind stress (and its westerly and northerly components) obtained from AWS data using drag coefficients given by Smith (1988).

Results

Quantitative Estimation of SSC and Sediment Flux

Instantaneous water discharge, Q, (Fig. 3a) greatly exceeds the fluvial inflow to the estuary (2001–2002 mean 0.6 m^3 s^{-1}; maximum 5.5 m^3 s^{-1}). Following adjustment for small systematic biases integration of Q over the duration of the study period yielded a seaward directed residual water transport of 17.9×10^6 m^3. Of this, 17.6×10^6 m^3 can be accounted for by the calculated freshwater inflow. The discrepancy of 0.3×10^6 m^3 is equivalent to about 11% of the gross water transport on an average spring tide and is just 0.0003% of the total gross ebb transport (approximately 1.17×10^9 m^3) over the same period. The 3-day low-pass-filtered discharge, $<Q>$, is generally ebb-directed with a mean of 0.62 m^{3}s^{-1}, which corresponds to the river inflow. Minor excursions can be attributed to high river flow or oscillations in mean level within the estuary (associated with semimonthly tidal variation and meteorological effects).
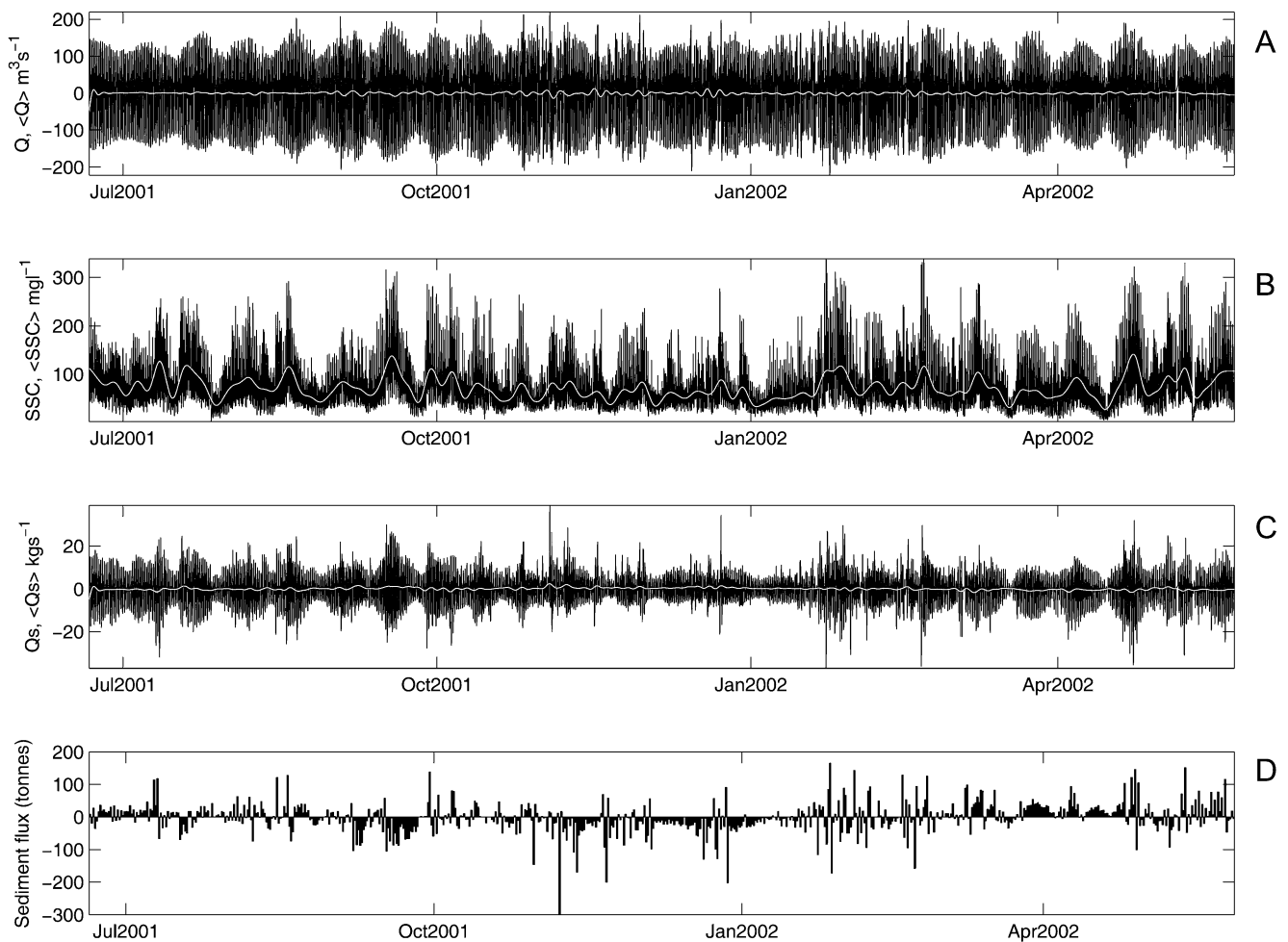
Fig. 3 Time series of instantaneous of instantaneous and low-pass-filtered discharge, Q and <Q> (a); instantaneous and low-pass-filtered SSC (b); instantaneous and low-pass-filtered suspended sediment flux, Qs and <Qs> (c); tide-integrated sediment flux (−ve = import; +ve = export) (d)

The time series for acoustic backscatter-derived SSC is presented in Fig. 3b. This exhibits variability at tidal and spring–neap timescales (most clearly shown by the low pass filtered data, <SSC>). Seasonal variability is less obvious, although the highest SSC are recorded in the winter. Related summary statistics are given in Table 1, from which it is clear that SSC is significantly higher

during spring tides and slightly higher and more variable during ebb tides than for flood tides. Consistently higher ebb concentrations might lead us to expect a net sediment export from the estuary. However, the closeness of flood and ebb SSC suggests that the magnitude of the net sediment flux is likely to be small, with the direction of the net flux being determined by the intratidal variation in

Table 1 Summary of SSC and tidal current data derived from ADCP deployment (648 complete tidal cycles)

		SSC (mg l^{-1})	Tidal current speed (m s^{-1})	Mean slack water duration (min)	
		Median (interquartile range)	Mean peak	HW	LW
All	Flood	60.1 (41.7–85.3)	0.69	37	88
	Ebb	61.7 (41.5–97.5)	0.85		
Spring	Flood	67.5 (49.5–94.5)	0.78	34	59
	Ebb	69.9 (45.9–108.3)	0.94		
Neap	Flood	52.6 (34.6–75.9)	0.60	40	118
	Ebb	54.1 (38.4–83.4)	0.78		

SSC and by the relative contribution of sediment transporting events of different frequency and magnitude.

Aspects of the tidal current regime are also summarized in Table 1. In terms of peak current speeds, this part of the estuary is always ebb-dominated, although the ebb dominance is slightly stronger at neap tides. A more thorough investigation of the tidal flows (French 2008) showed that while most of the middle and outer estuary are ebb-dominated, flood dominance does occur within the channel that connects the most extensive tidal flats of the middle estuary with a smaller up-estuary area of tidal flat and salt marsh (labeled as the New Cut in Fig. 1b). The relative duration of high and low slack water is arguably more meaningful as an indicator of likely net sediment transport in systems dominated by cohesive sediments, with flood-directed sediment transport favored when high water slack duration is greater (Dronkers 1986). Using 0.2 m s^{-1} as an arbitrary threshold tidal current speed, low water slack in the Blyth estuary significantly exceeds high water slack in duration (Table 1). This difference is greater on neap tides than at springs. Together with the tidal velocity asymmetry, these data imply that the hydrodynamic regime, in the outer estuary at least, is not conducive to the import and retention of fine sediment.

Figure 3c shows the time series for both instantaneous and 3-day low-pass-filtered sediment transport, Q_s and $\langle Q_s \rangle$. As expected, tidal variation in Q_s is very strong, while $\langle Q_s \rangle$ is very small and flood-directed (with a mean of just 0.03 kg s^{-1}). The gross suspended sediment transport of 84.2×10^3 t over the 648 flood tides sampled provides a measure of the potential marine sediment supply available to the middle and inner estuary. Integration of the opposing flood and ebb transports yields a net import of just 1.2×10^3 t, equivalent to 1.5% of the gross flood transport. Residual fluxes computed for successive tidal cycles are plotted in Fig. 3d. Some of the alternations between import and export are the result of short-term variability in tidal range and mean level. However, there is some suggestion of more significant import through late summer and autumn, with greater volatility that includes some large exports in the winter and a tendency to export in the spring also.

Despite a moderately high turbidity, large gross flood and ebb transports under a mesotidal regime appear to be very similar in magnitude such that the calculated residual flux lies well within the measurement uncertainty. Without further interpretation, it is therefore unrealistic to place too much weight on the inference that the estuary is functioning as a small sediment sink or even that the sediment budget is close to neutral. The main question here is whether further analysis and interpretation of the time variation in Q_s and the underlying SSC data, and their relation to major forcing factors, can lend qualitative support to such inferences.

Scales of Variability in SSC

SSA provides a convenient means of identifying major scales of variability in the underlying SSC series as a prelude to investigating in greater detail the linkages between sediment flux and likely forcing mechanisms. Application of SSA to the complete 15-min series (Fig. 4a) with a 30-h ($M=120$) window identified significant subtidal variability in two RCs. RC1 (Fig. 4b) accounts for 28.0% of the variance in SSC and contains variability primarily due to semimonthly and monthly tidal cycles. RC6 (Fig. 4c; 3.5% of the variance) contains intermittent oscillations with various periodicities (days to months) that may be associated with non-tidal surges or wind effects.

Approximately 35% of the variance in SSC is accounted for by four components (RC2-5; Fig. 4d) which contain periodic M_4 and M_2 tidal forcing. A further 3.5% of the variance is explained by M_6 tidal forcing (RC7–8; Fig. 4e). Together, these eight components contain about 75% of the variance in the raw series, with most of the remaining components containing mixtures of frequencies present in the higher components or noise. The application of SSA confirms the importance of tidal modulation of SSC at both subtidal and intratidal timescales and also hints at a smaller but potentially important meteorologically driven source of variation in SSC. Each of these can be investigated through more detailed analysis of the raw SSC series and, where appropriate, the derived Q_s series.

Intratidal Variation in SSC

Figure 5 shows the variation in depth-averaged SSC, tidal current speed, U, and level, H, over selected spring and neap tides. Spring tides are characterized by marked settling and subsequent resuspension events either side of low water slack (Fig. 5a,b). SSC increases slowly over the flood tide but decreases to a minimum well before high water. A smaller resuspension peak is evident after the short high water slack, and this is followed by a more progressive increase in SSC over the ebb. Maximum SSC is attained towards the end of the ebb. This lags the peak in U and is possibly associated with the advection of sediment-charged water draining the mid-estuary tidal flats where tide-averaged SSC often exceeds 100 mg l^{-1} and concentrations as high as 600 mg l^{-1} were observed in an earlier study by French et al. (2000).

Neap tides show lower SSC overall and a closer correspondence between SSC and U (Fig. 5d,e). The absence of well-defined settling and resuspension peaks may reflect an absence of larger composite particles (flocs) under lower sediment concentrations and turbulence intensities (Benson and French 2007).
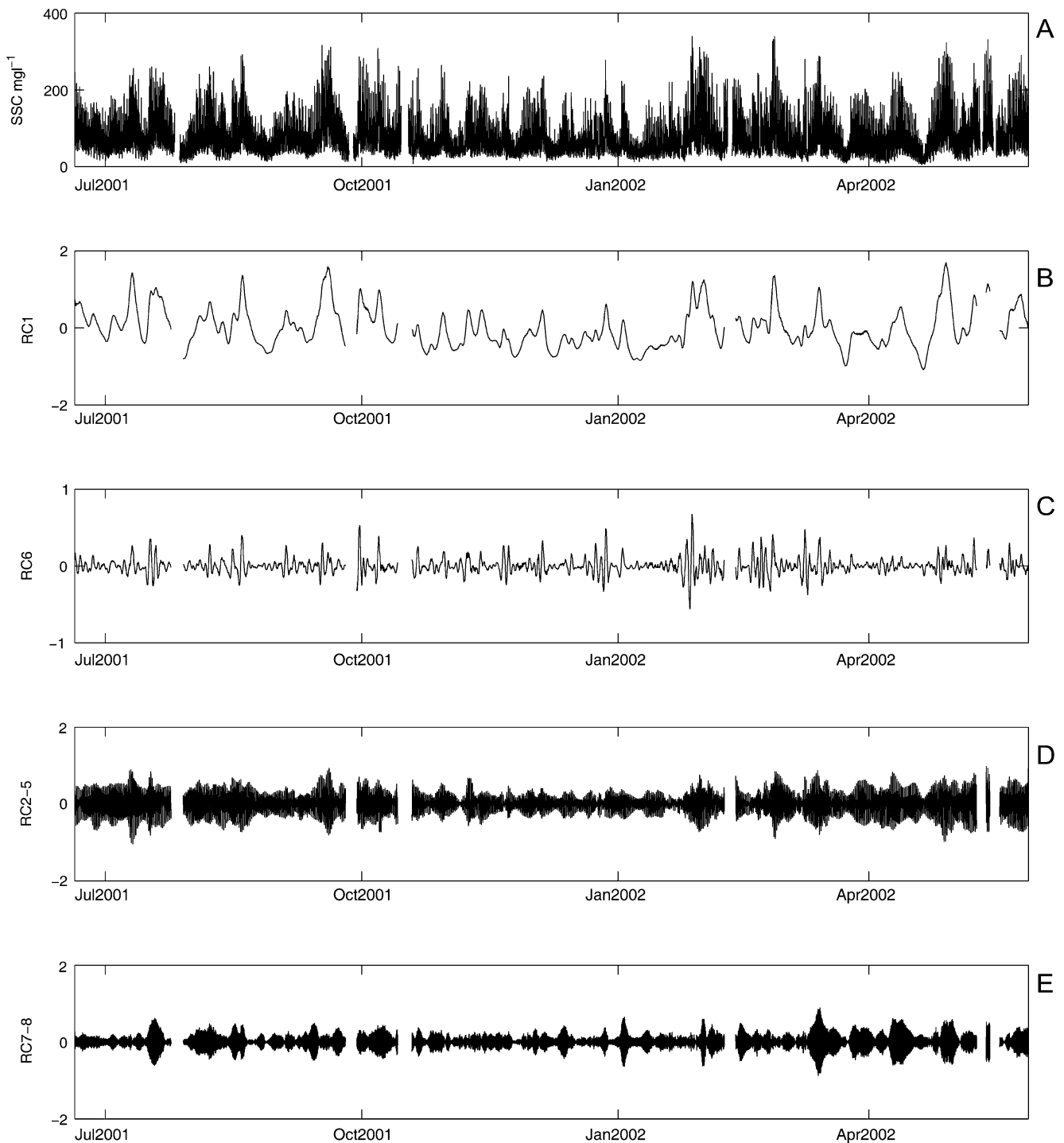
Fig. 4 **a** Time series of SSC; **b–e** reconstructed components (RC) of SSC obtained from singular spectrum analysis

Figure 5c–f shows the instantaneous sediment flux, Q_s, over the same tides. Variation in SSC due to settling and resuspension is less evident in the Q_s series, since these processes tend to occur when Q is small (especially around low water slack). Also, peak ebb U occurs at a slightly lower H and leads the maximum of SSC. Accordingly, the tidal transports are quite closely balanced: about 53% of the

648 tides for which data are available showed a net import and 47% a net export.

Spring-Neap Variation in SSC

Time series of low-pass-filtered tidal range and SSC show some correspondence between the spring–neap variation in
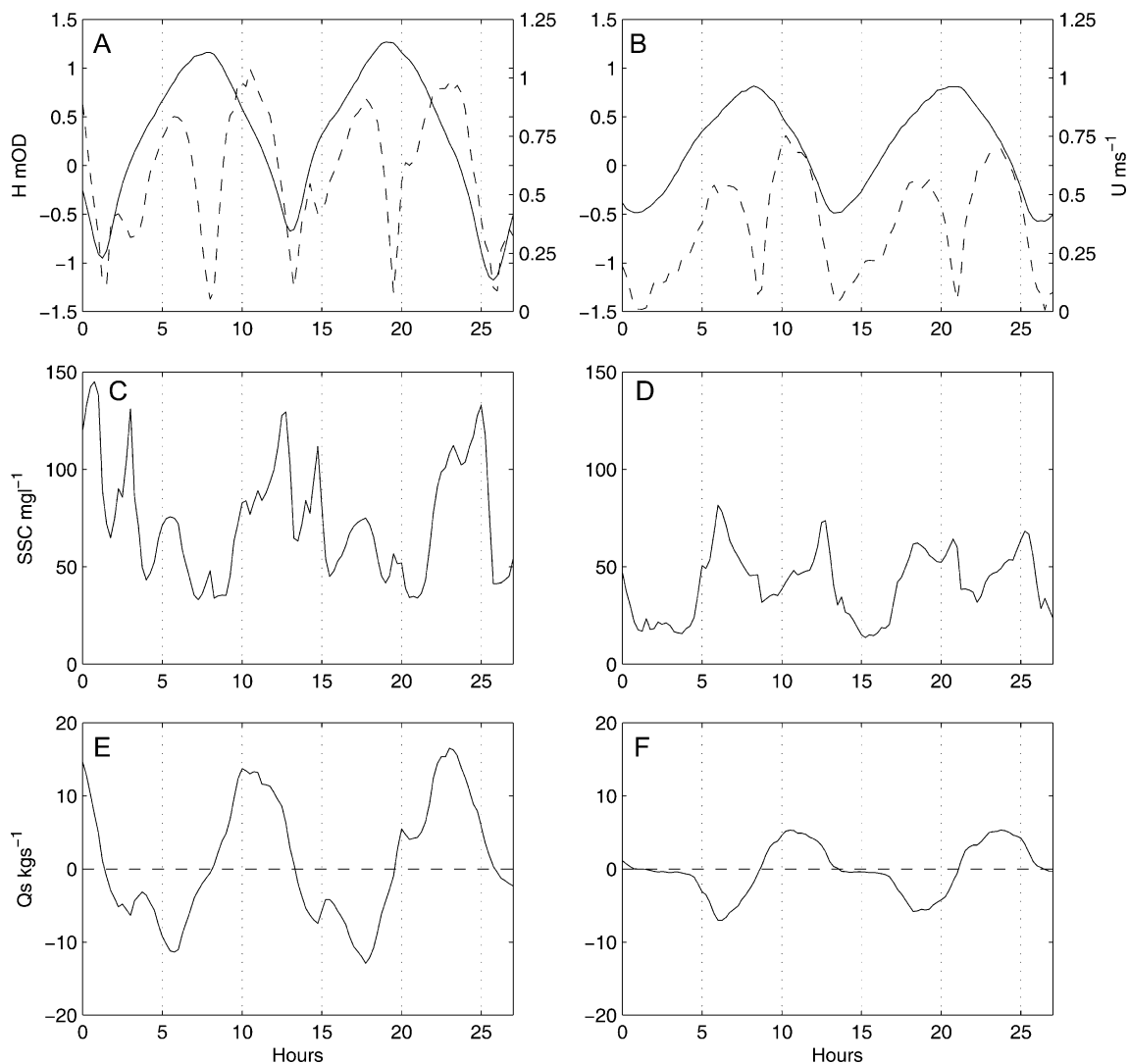
Fig. 5 Intratidal tidal variation in level and velocity, SSC, and Qs for spring (**a**, **c**, and **e**, respectively) and neap (**b**, **d**, and **f**, respectively) tides

range and SSC, although SSC is clearly subject to additional sources of variation (Fig. 6). In general, SSC at spring tides is about 1.5 times that at neaps, and the range of concentrations is similar to that reported for inshore waters (Wallingford 2002). Spring-neap variation is also evident in tide-averaged gross and residual transports (Table 2). These data suggest import during neap tides and a rather smaller export at springs, although it must be emphasized that the magnitude of the residual transport is extremely small in both cases.

Previous studies of muddy estuaries have found systematic hysteresis in the relation between SSC and tidal range over the spring–neap cycle. Guezennec et al. (1999) in the Seine, France and Grabeman and Krause (2001) in the Weser estuary, Germany observed consistently higher SSC during periods of falling tidal range (i.e., during the spring to neap transition) than under rising range (i.e., the neap to spring

transition). Both sets of authors attributed this to consolidation of deposited material during preceding tides and a lagged resuspension during springs once some critical tidal shear stress is exceeded. The Seine and Weser estuaries are both quite large systems, with much longer residence times and a more complex interaction between marine and fluvial processes than is the case for the Blyth estuary. This difference is reflected in a much less consistent relationship between SSC and tidal range, with some spring–neap cycles exhibiting virtually no hysteresis and others showing either clockwise or anticlockwise hysteresis loops (Fig. 7). This absence of consistent spring–neap cycling of suspended sediment is probably due to more direct influence from variations in marine sediment input. Also, exchanges between the narrow subtidal channel and extensive intertidal zone may be more important than subtidal deposition and consolidation during neap tides.

Fig. 6 Variation in tidal range (**a**) and SSC (**b**) for a 100-day period
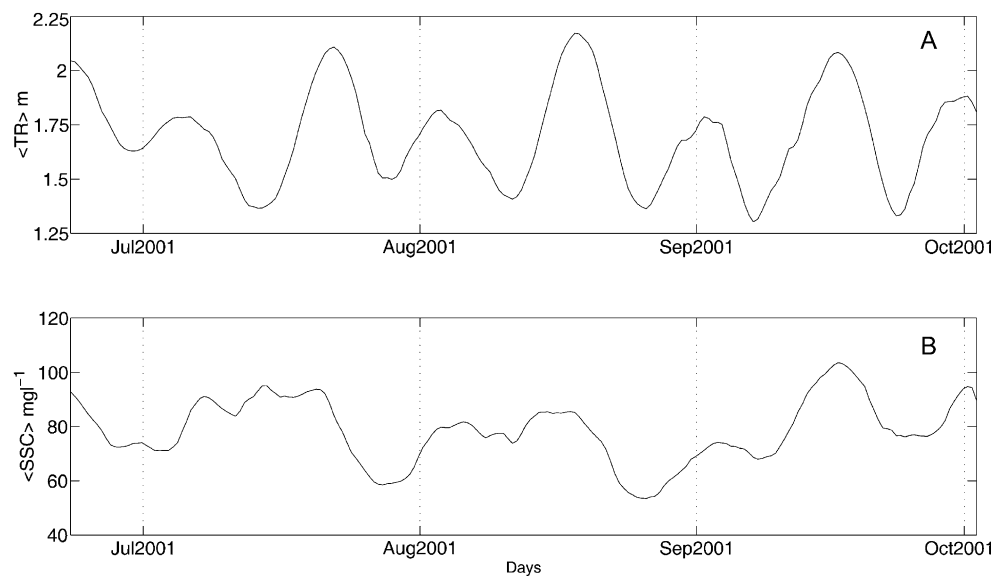
Relation of SSC to Meteorological Forcing

Tidal forcing accounts for most of the observed variance in SSC within this mesotidal estuary. However, application of SSA revealed additional variability that exhibits intermittent excitation that does not appear to be tidal in origin. As illustrated in Fig. 8, there is a good correspondence between the episodic excitation in RC6 from the SSA and time series of the non-tidal residual water level (surge component) and wind stress obtained from the AWS. This correspondence is not immediately apparent from inspection of the raw SSC series where it is masked by the much larger variance at intratidal and semimonthly periodicities.

A previous study by French et al. (2000) showed that moderately strong winds can generate significant wave heights (h_s) of 0.3 to 0.4 m over the tidal mudflats of the middle estuary and that these conditions are associated with elevated SSC. No gale force winds occurred during

their data acquisition periods. However, moderately strong winds of 10 to 14 m s^{-1} coincided with SSC in the range 500–600 mg l^{-1}. On such occasions, distinct plumes of sediment-charged water may be observed exiting tidal flats and entering the low water channel. Given that the prism associated with the tidal flats is large (around 80% of the total mid-estuary prism), it is reasonable to expect that major episodes of wind-driven wave resuspension should show up within the SSC time series obtained from the outer estuary channel and be most evident on the ebb tide.

Table 2 Mean flood and ebb gross and residual suspended sediment transports

		Gross transport (t tide^{-1})	Residual transport (t tide^{-1})
All	Flood	141.4	2.5 (import)
	Ebb	138.9	
Spring	Flood	164.5	0.5 (export)
	Ebb	165.0	
Neap	Flood	117.8	5.4 (import)
	Ebb	112.4	
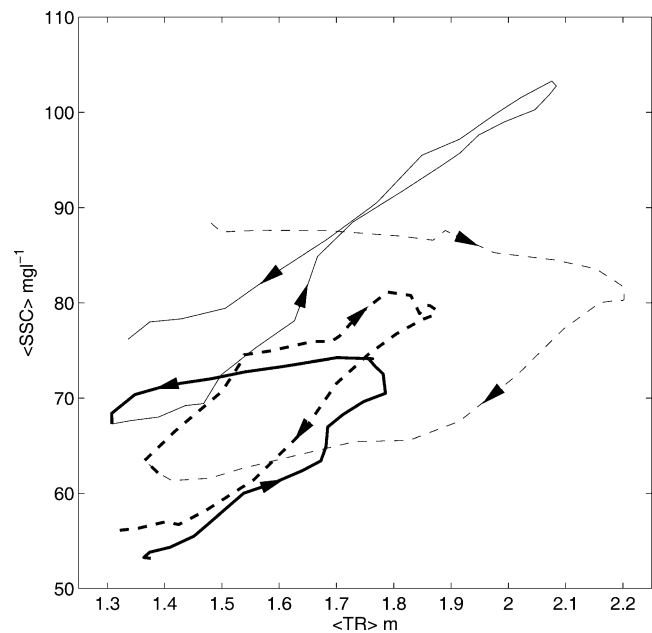
Fig. 7 Hysteresis in 5-day mean suspended sediment concentration, <SSC>, versus tidal range, <TR>, for four spring–neap cycles

Sustained periods of strong winds can also elevate SSC in coastal waters, and this will likely influence flood tide concentrations within the estuary, but at some temporal lag with respect to the meteorological forcing.

As a basis for such an analysis, median flood and ebb SSC was computed for all 648 tides in the sample, along with the tide-averaged wind stress. Cross-correlograms of flood and ebb SSC against wind stress and tidal range are presented in Fig. 9a,b. These show statistically significant ($p=0.01$) peak correlations between SSC and wind stress, with a qualitative difference between the flood and ebb datasets. Ebb tide data show the strongest correlation ($r=$ 0.63), and this is at zero-lag. For the flood data, the peak correlation is weaker ($r=0.38$) and lags wind stress by a single tide. The cross-correlogram is also less peaked. This provides clear evidence that wave resuspension within the estuary is a source of variability in SSC and a potential mechanism for the export of muddy sediments brought into the estuary by tidal action. Figure 9c,d shows the equivalent cross-correlograms for SSC versus tidal range. These cross-

correlograms are smoother and more symmetrical but have lower peak correlations ($r=0.41$ and 0.31 for flood and ebb SSC, respectively) that actually lead tidal range (by one tide in both cases).

The importance of non-tidal variation in SSC is also clear from an examination of individual events in the data record. Figure 10 shows data from a 2-day period in January 2002 characterized by spring tides and a positive surge coinciding with low water on the second day (Fig. 10a). The latter caused a setup in estuary water level and some disturbance to the tidal flows (Fig. 10b), but had no obvious impact on SSC (Fig. 10d). Strong southwesterly winds also occurred over this period (Fig. 10c), and these do appear to cause elevated SSC especially on the ebb tide on the evening of the first day (Fig. 10d). SSC is also high on the subsequent flood tide, presumably due the increased wave resuspension of sediment off the coast. The wind resuspension has a clear signature in the sediment flux series for this period (Fig. 10e), with a substantial export of material occurring on the second tide.

Fig. 8 Time series of non-tidal surge, H_{resid} (a); wind stress, τ (b); RC6 from singular spectrum analysis of SSC (c); and SSC (d)
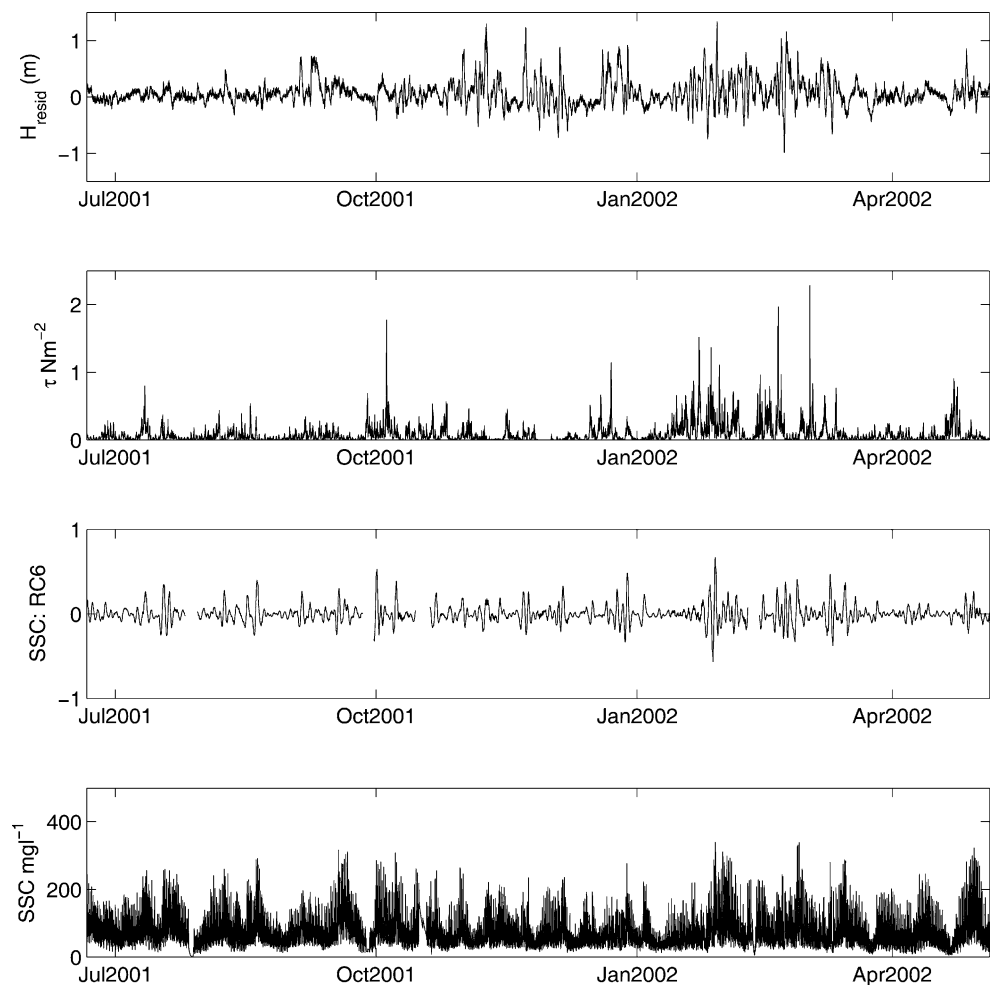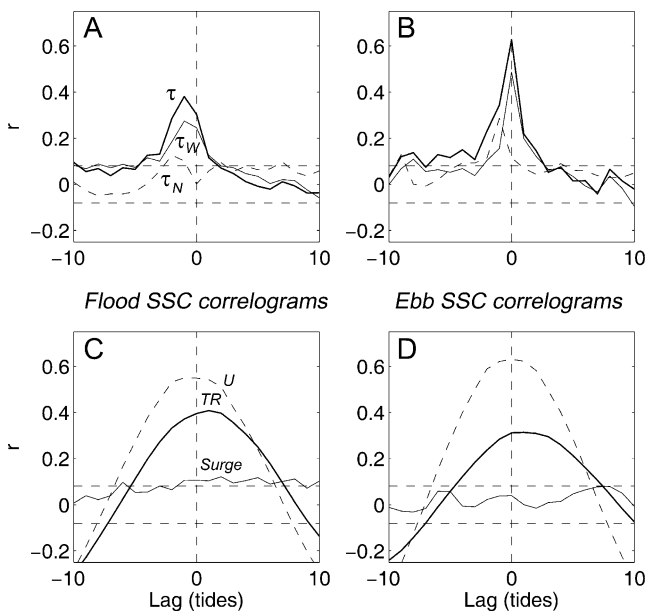
Fig. 9 Cross-correlograms of wind stress, τ, and its westerly and northerly components (τ_W and τ_N) versus flood (**a**) and ebb SSC (**b**) and tidal current velocity magnitude, U, range, TR, and non-tidal surge H_{resid} versus flood (**c**) and ebb SSC (**d**). Lags refer to complete tidal cycles (i.e., −10 to +10 corresponds to roughly −125 to +125 h). Where peak correlations occur at negative lag, SSC within the estuary exhibits a delayed response to the forcing variable

Discussion

Efforts to quantify contemporary estuarine sediment budgets through instrumentation of selected cross-sections have often been hampered by the inherent difficulty of extracting a statistically significant residual (or tide-averaged) flux from much larger flood and ebb transports (e.g., Kjerfve and Proehl 1979). In large systems, where residence times are typically long relative to tidal variations, attention has accordingly shifted towards indirect methods for the derivation of net fluxes from the relevant terms in an integral scalar conservation balance equation (Jay et al. 1997). In smaller estuaries that are subject to strong tidal flushing and short residence times, however, our understanding remains substantially reliant upon direct measurements and the dynamic insights that these afford.

The flux measurement campaign in the Blyth estuary was able to exploit the restricted dimensions of the outer estuary channel and correction of systematic biases in the estimation of instantaneous water transport was facilitated by knowledge of the (small) fluvial input. Even so, the implied import amounts to just 1.5% of the potential supply, and that one cannot have statistical confidence in the direction of the residual transport let alone its magnitude. It is thus entirely possible that the estuary could actually be exporting rather than importing sediment at an annual timescale on the basis of the flux data considered in

isolation. Technological refinements alone are unlikely to resolve this difficulty. Improved calibrations of acoustic backscatter for SSC might potentially take account of in situ particle size measurement (e.g., Benson and French 2007), but extrapolation of short-term calibrations over much longer data records is likely to remain an issue.

The explanatory value of any sediment budget depends on the extent to which it can be grounded in an understanding of component terms and associated processes. Independent estimation of known source and sink terms can help to constrain the overall budget. However, this is difficult where repeat bathymetric surveys and spatially representative measurements of contemporary erosion and deposition are lacking. Crudely annualized, the residual import of 1.23×10^3 t for 648 tides amounts to 1.34×10^3 t year^{-1}, rather less than the 5×10^3 t year^{-1} assigned in McCave's provisional budget. The potential annual sediment supply amounts to 92.3×10^3 t. Fluvial sediment supply is likely to be at least an order of magnitude smaller. No sediment yield data are available for the Blyth catchment, though Frostick and McCave (1979) estimated a yield of 234 t year^{-1} for the nearby Deben estuary. The Deben has a higher mean flow (1.65 m^3 s^{-1} for 2001) and a larger catchment, and it is difficult to envisage the River Blyth sourcing more than this amount.

Estimation of intertidal sources and sinks is also difficult. French et al. (2005) reported salt marsh elevational gain of about 4 mm year^{-1}. The sediment mass required to sustain this depends upon assumptions regarding the dry bulk density: indicative values of 600 to 750 kg m^{-3} extrapolated over 60 ha of salt marsh give a requirement in the range 1.4 to 1.8×10^3 t year^{-1}. Based on comparison of modern mudflat elevations with land levels surveyed in 1840, French et al. (2005) concluded that overall sedimentation in this zone has been low following restoration of tidal exchange in the early twentieth century. However, around 10 ha of salt marsh has formed since the 1940s, and direct measurements of elevation change from 1997 and 2001 showed increases of about 4 to 9 mm year^{-1} on the upper mudflat according to the degree of exposure to waves. Past sedimentation may have been higher on account of material derived from reworking of sources within the estuary. About 100×10^3 t of mud must have been released into the middle estuary by the near-complete destruction of the old earth flood embankments by wave erosion (this figure is a revision of the 140×10^3 t estimated by French et al. 2005 based on measurements of seawall dry bulk density). This alone is sufficient for several centimeters of sedimentation across the flats (depending on assumptions regarding the dry bulk density of the tidal flat sediments, which shows considerable variability: our own limited measurements suggest a typical value of 500 to 600 kg m^{-3}). On the basis that there is no direct evidence for widespread erosion of
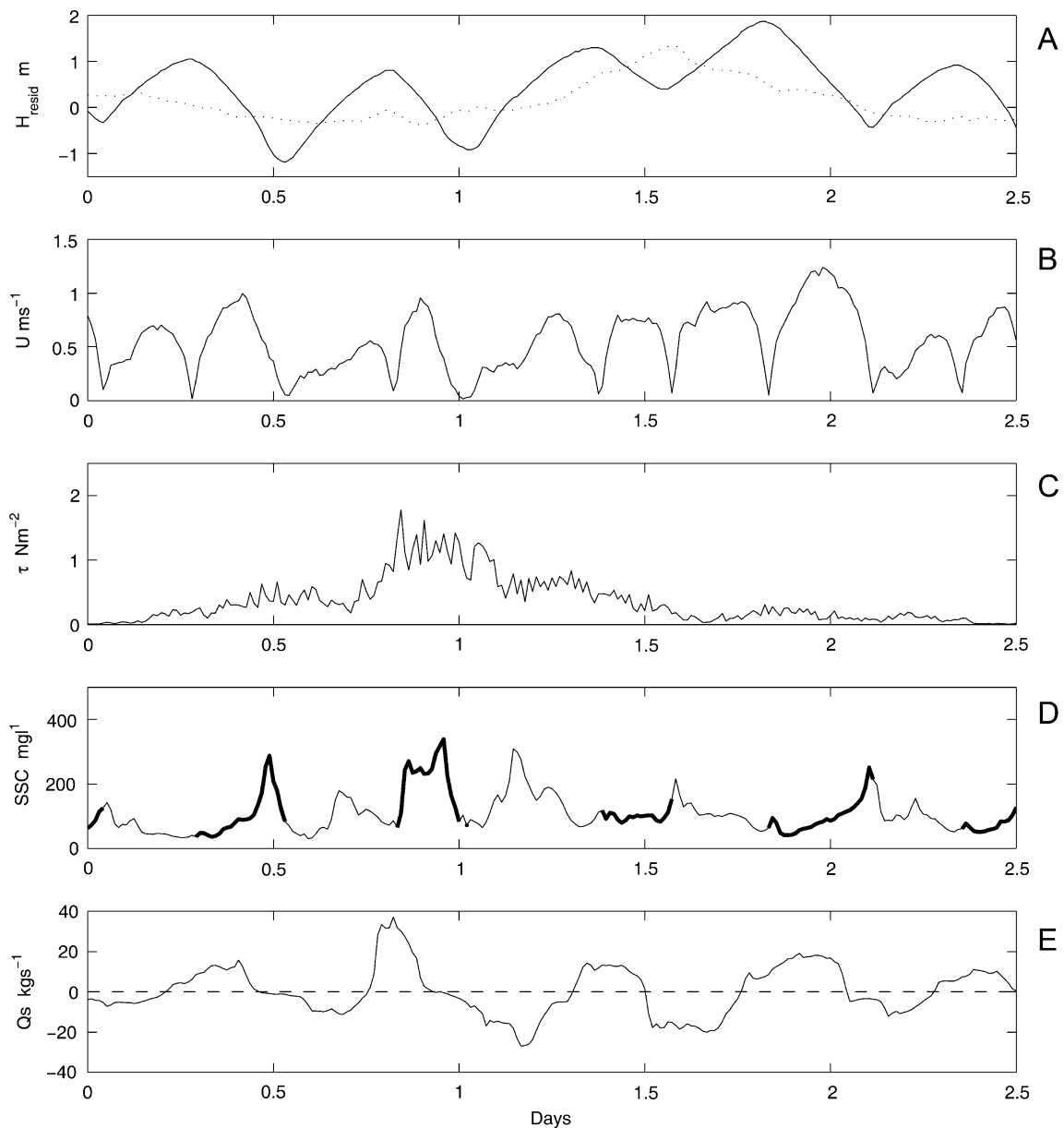
Fig. 10 Detail of non-tidal surge and wind stress event in early January 2002. Time series show non-tidal surge, H_{resid} (**a**); tidal current velocity magnitude, U (**b**); wind stress, τ (**c**); SSC (**d**); and instantaneous sediment flux, Q_s (**e**)

the tidal flats at the present time, it seems likely that the estuary is indeed importing sediment. Given that the direct flux estimate of approximately 1.34×10^3 t year^{-1} is barely sufficient to sustain the salt marshes, the actual import is presumably rather larger.

Analysis of the underlying SSC data provides insights into sediment dynamics that, calibration issues notwithstanding, are much less affected by the systematic errors that complicate interpretation of the estimated fluxes. A major inference from the flux data is that flood and ebb transports are finely balanced, and this is qualitatively supported by both the acoustic backscatter-derived flood and ebb SSC values (Table 1) and those obtained from

analysis of discrete bottle samples. Samples acquired over a number of tidal cycles (and used for ADCP calibration) showed median flood and ebb SSC of 61.5 ($n=40$) and 74.7 ($n=84$) mg l^{-1}, respectively. Frostick and McCave (1979) reported lower SSC values for the Deben estuary (mean concentrations around 30 to 40 mg l^{-1}), but their data also show slightly higher mean concentrations on ebb tides.

SSA is a useful tool for the exploratory analysis of geophysical time series as a prelude to more detailed investigation and modeling of the underlying processes. The application of SSA to estuarine suspended sediment datasets has been pioneered by Schoellhamer (1996, 2002) in San Francisco Bay. Applied to the Blyth estuary data,

SSA reveals expectedly large contributions to the variance in SSC at intratidal (chiefly M_4, M_2, and M_6 periodicities) and subtidal (semimonthly and monthly) scales. In addition, SSA picks out intermittent variability due to non-tidal forcing that is not evident from purely visual inspection of the raw SSC series.

The southern North Sea is highly susceptible to non-tidal surges (Pugh 1987). Although the surge variance on the Suffolk coast is less than that further south in the approaches to the Thames estuary, modification of astronomical tides under a low mesotidal regime can be quite significant. While important from a hydrodynamic (and flood defense) perspective, surge effects do not appear to directly influence suspended sediment concentrations in the Blyth estuary (Figs. 9 and 10). Of greater importance is local meteorological forcing, which acts through the resuspension of intertidal mudflat sediments especially under strong westerlies that exploit the maximum fetch within the estuary. Cross-correlograms of flood and ebb SSC versus wind stress cross-correlograms (Fig. 9), and event-scale analyses of wind stress, SSC, and sediment flux time series (Fig. 10) lend support to the hypothesis that episodic export of fine sediment is possible as a result of wave resuspension within the middle estuary.

The fine sediment regime of the Blyth estuary has been impacted by the unplanned restoration of tidal action to around 250 ha of reclaimed marshland at various stages between the 1920s and 1940s. Other estuaries in the region have different histories, but may also exhibit some similarities in terms of the relative importance of tidal and meteorological forcing of fine sediment transport. The Alde-Ore estuary, 15 km to the south, has extensive tidal mudflats that also result from failure of defensive embankments in the 1950s. However, these contribute a smaller proportion of the overall tidal prism, and their location towards the head of a much longer estuary means that episodically resuspended intertidal sediments are more likely to be retained within the system than is the case in the Blyth. The Deben estuary has a large subtidal channel that is flanked by extensive mudflats. Frostick and McCave (1979) reported seasonal exchanges in sediment between intertidal and subtidal zones. Wave action within the estuary was cited as the main agent of mudflat erosion, with algal growth promoting accretion on the flats during summer and erosion occurring during the winter. The tidal flats in the Blyth appear to be rather lower in elevation such that algal growth is restricted to their margins. It is possible that a seasonal cycling of sediment between the high and low mudflats occurs, although the seasonal variation in flux through the outer estuary indicates the strongest import in autumn. The Stour estuary, 50 km to the south, has also seen a significant increase in intertidal volume over the twentieth century, in this case due to widespread erosion of

salt marsh and a lowering of the intertidal flats (Beardall et al. 1991; Roberts et al. 1998). The present sediment budget, determined from historic bathymetries, appears to be negative (Wallingford 2001), with sediment being sourced from continuing wave-driven erosion of the intertidal zone. Like the Blyth, the Stour has an ebb-dominated mesotidal regime (enhanced by dredging), and the fact that the tidal excursion is comparable to estuary length means that resuspended material can readily be exported. The adjacent Orwell estuary, in contrast, appears to be functioning as a net sink (HR Wallingford 2001) and may sequester some of this material.

Bearing in mind the errors inherent in the flux calculations, a semi-quantitative insight into the relative contributions of tidal versus meteorological forcing in the Blyth can be obtained by examining the variation in flux over the range of wind speeds encountered during the field campaign. Figure 11a shows the variation in the individual tide-averaged net fluxes with tide-averaged wind speed. There is a tendency both for increased variability in net flux as wind speed increases and for more large net exports to occur at times of high wind speed. Figure 11b shows the
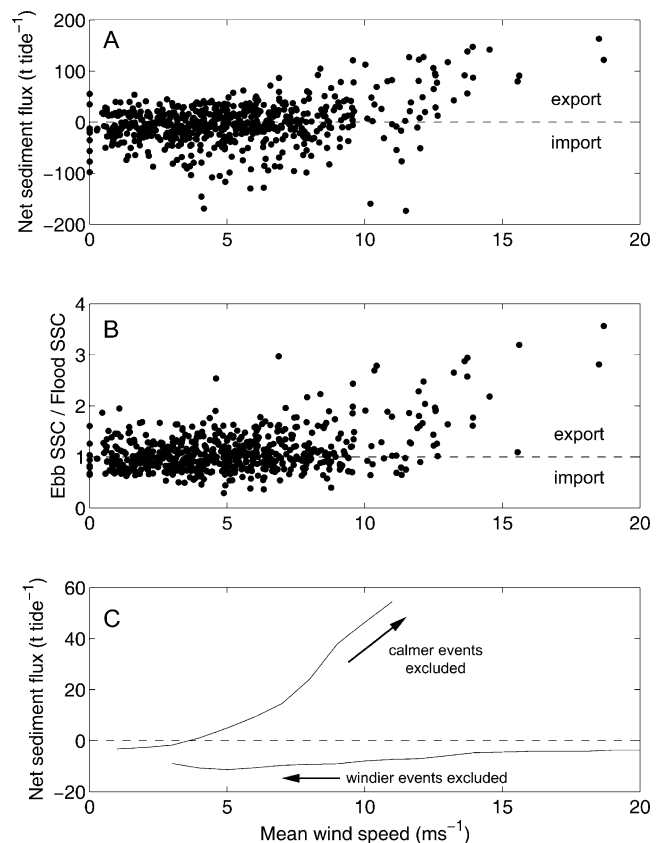

Fig. 11 **a** Variation in tide-averaged net sediment fluxes with tide-averaged wind speed; **b** ratio of ebb median SSC/flood median SSC versus tide-averaged wind speed; and **c** effect on the mean net tide-averaged sediment flux of progressively excluding tides below (*upper curve*) and above (*lower curve*) a given threshold wind speed

ratio of ebb median SSC/flood median SSC similarly plotted against tide-averaged wind speed. This shows the tendency for ebb SSC to exceed flood SSC during periods of high wind speed. An alternative way of looking at this is presented in Table 3 and Fig. 11c, which show the effect of filtering tide-average residual fluxes according to different threshold wind speeds, W. If a progressively larger proportion of wind stress 'events' are excluded (lower curve in Fig. 11c), the average import increases from a baseline of around 3 t tide^{-1} to over 9 t tide^{-1} when only tides experiencing $W < 7$ m s^{-1} are considered. Again, this implies that 'tide-dominated' conditions (i.e., low wind stress) are associated with sediment import and that the magnitude of this import is reduced by episodic wave action. Conversely, if the same calculation is performed using progressively windier conditions (upper curve in Fig. 11c), the baseline import rapidly evolves into a much larger export. 'Wind-dominated' tides for which $W > 10$ m s^{-1} are associated with a large export that averages 47 t tide^{-1}, although such conditions account for $<7\%$ of the total time. While we would not wish to place too much emphasis on the quantitative aspects of this analysis, it does highlight the potential sensitivity of this and other wave-influenced muddy estuaries to changes in wind climate.

Impacts of climate change on estuaries have hitherto often been evaluated largely in terms of the loss of intertidal habitats through 'coastal squeeze' and the implications of sea-level rise for flood defense (e.g., Townend and Pethick 2002; Winn et al. 2003). The translation of climate change predictions into regional wind regimes is clearly a work in progress, and UK scenarios are presently restricted to indicative changes in the mean wind speed and the frequency of gale-force winds and contain no directional information. Recent UK Climate Impacts Programme 2002 scenarios (Hulme et al. 2002) indicate small increases in mean winter wind speed (up to 6% by the 2080s) for eastern England, with winters generally becoming wetter, windier, and more strongly influenced by westerly weather

systems under a medium-high climate change scenario. Summer and autumn wind speeds may decline, however, by up to around 6% to 8%. These changes are small, and Hulme et al. (2002) stress that it is much harder to attach confidence to climate model predictions of surface wind speed change than to other climate variables such as temperature or precipitation. However, our analysis shows that suspended sediment dynamics in muddy estuaries may be sensitive to quite small changes in the frequency of moderate to high wind speeds. On this basis, further investigation of estuary sensitivity to likely future variations in wind regime might usefully complement the present focus on sea level rise as the primary agent of coastal and estuarine environmental change.

Conclusions

Data from a 1-year acoustic Doppler profiler deployment in a muddy mesotidal barrier-enclosed estuary on the UK east coast have been used to quantify sediment flux and obtain dynamic insights into tidal and meteorological forcing of SSC. In quantitative terms, the estimated residual sediment flux corresponds to an import of just 1.5% of the gross flood tide transport. Little statistical confidence can be assigned to either the magnitude or direction of such a small flux when considered in isolation. However, the inference that the sediment regime is finely balanced is qualitatively supported by the close similarity between flood-tide and ebb-tide SSC values. Singular spectrum analysis of the SSC time series reveals unsurprisingly large contributions to the variance at intratidal and subtidal (semimonthly and monthly) scales but also picks out intermittent variability that is initially attributed to a combination of non-tidal surge and wind stress forcing. Cross-correlograms and event-scale analysis suggest that local meteorological forcing is the more important of these factors. In particular, resuspension of intertidal mudflat sediments at times of strong westerly winds appears to be associated with episodic sediment export from the estuary. Thresholding of tide-averaged fluxes using a range of critical wind stress values further indicates that 'tide-dominated' (i.e., low wind stress) and 'wave-dominated' (high wind stress) conditions are associated with sediment import and export, respectively. Overall, estuary sediment balance is potentially sensitive to the frequency of high wind stress events, since the associated sediment exports are several times larger than the average import under calm conditions. Intermittent meteorological forcing may thus exert an important control on the sedimentary balance of otherwise tidally-dominated muddy estuarine systems, and the role of wind climate should not be overlooked in studies of estuary response to environmental change.

Table 3 Tide-mean residual sediment flux filtered against various critical tide-mean wind speeds

'Tide-dominated' conditions ($W < W_{crit}$)		'Wind-dominated' conditions ($W > W_{crit}$)	
W_{crit} (fractional time)	Mean flux (t tide^{-1})	W_{crit} (fractional time)	Mean flux (t tide^{-1})
2 (0.16)	−9.0	2 (0.84)	−2.4
5 (0.53)	−11.2	5 (0.47)	**5.4**
7 (0.75)	−9.5	7 (0.25)	**15.0**
10 (0.93)	−7.7	10 (0.07)	**47.1**

Negative fluxes indicate import and positive fluxes (highlighted in bold) indicate export. Data cover 615 tides, for which unfiltered tide-mean flux is −3.0 t tide^{-1}.

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