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The effects of suspended sediment on turbulence within an estuarine turbidity maximum

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Abstract

Predictions of cohesive sediment transport are hampered by poor understanding of the effects of sediment suspensions upon the nature of near-bed turbulence. In this study, current velocities, associated turbulence and flow characteristics were measured within an estuarine turbidity maximum during two spring ebb tides. Measurements at two heights, both within and above a near-bed high concentration layer, show the importance of intermittent internal waves. The ratio of vertical to horizontal turbulence intensities exceeded 1.0 when waves were present. The waves were more significant above the layer than within it. Comparison between the turbulent kinetic energy and the Reynolds stresses showed 'inactive turbulence' occurring at stresses less than about 0.2 N m^{-2}. During these periods negative suspended sediment fluxes occurred, indicating that the turbulence could enhance settling of the sediment. The effect of the intermittent internal waves on the turbulent bursting structure, and their interaction with the concentration profile appears to increase the variability of the Reynolds fluxes of suspended sediment and cause downwards Reynolds fluxes, especially beneath the lutocline.

Keywords: partially mixed estuary; suspended sediment; turbidity maximum; shear stress; turbulence; internal waves; suspended sediment fluxes

1. Introduction

Accurate quantification of sediment transport processes is essential for predictions of the behaviour of estuaries. Erosion and deposition rates depend upon accurate specification of the shear stress exerted by the flow on the bed. Predictions of bed stress and sediment transport have traditionally made use of theory and results derived from steady flows using clear water and low suspended sediment concentrations, because of difficulties in obtaining accurate in situ measurements. However, these are not always appropriate for high rates of transport, or oscillatory tidal flows.

In clear water, turbulence is produced by friction at the bed, and the shear stress linearly diminishes with height above the bed. In this situation a logarithmic profile of velocity increase with height is appropriate for about 20–30% of the water depth. However, when density stratification is present the velocity profile becomes distorted and shear across the interface provides an additional source of turbulent mixing, and the turbulence distribution becomes complex. There is the added complication that internal waves may occur on the density interface and make specification of the shear stresses difficult.

When there are vertical gradients in concentration, two effects occur. The vertical density gradient will affect the turbulence characteristics in the same way that salinity or temperature would, and be expressible in terms of a gradient Richardson number. In addition, the presence of the suspended flocs absorbs energy from the flow as the flocs are disrupted, or when they collide, interact and exchange momentum. This is apparent as an increase in effective viscosity.

The vertical gradients in concentration cause an upward shift in the velocity profile and the associated

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turbulence, and an increasing fraction of the shear stress is carried by the effective viscosity. The velocity near the bed is relatively reduced, thereby 'buffering' the bed against erosion and therefore providing a negative feedback limiting the sediment transport. Additionally, the effect of the density profile will alter the turbulent structure of the flow, thereby affecting the sediment suspension. The physical conditions governing this important process in high suspended sediment concentrations are not well understood, as there have been few field measurements of turbulence in these conditions.

In the very narrow wall layer adjacent to the bed the phenomenon of drag reduction occurs. Gust (1976) and Gust and Walger (1976) have shown that dilute clay/seawater suspensions are able to produce turbulent drag reduction at what appears to be surprisingly low concentrations of only 150–380 mg l^{-1}. In testing an annular flume Amos et al. (1992) found that, for a constant mean velocity, the friction velocity decreased by up to 10% as the concentration increased to 200 mg l^{-1}. Later on, Amos et al. (1997) proposed a relationship between u_* and clay.

In more detailed flume experiments Best and Leeder (1993) found reductions of 32% in friction velocity with alleged homogeneous concentrations of up to 2.2 g l^{-1}. The drag reduction was achieved through modification of the near wall turbulence structure within the buffer region of the flow, the viscous sub-layer having a relatively passive role.

In other laboratory experiments Li and Gust (2000) compared directly measured shear in the viscous sub-layer with friction velocities derived from the logarithmic layer, and found reductions of up to 70% in friction velocities in concentrations between 4 and 8 g l^{-1}. For a given flow strength, the drag reduction increased with suspension concentration, and for a fixed concentration, drag reduction decreased as flow strength increased.

Field measurements on boundary layer turbulence at heights of at least 10 cm to about 1 m above the bed have been carried out by many workers, including Heathershaw (1979), Bowden and Ferguson (1980), Soulsby (1981), West et al. (1986), Shiono and West (1987), and West and Shiono (1988). West and Oduyemi (1989) measured mean and fluctuating velocities in the Tamar Estuary at concentrations of 0.05–4 g l^{-1}, and vertical gradients of up to 3.5 kg m^{-4}. They found a reduction in vertical sediment flux by up to 90% at Richardson numbers exceeding 0.25. The vertical momentum flux was reduced less, mainly because of the presence of internal waves, which produce velocity fluctuations, but little mixing. Van der Ham (1999) carried out turbulence measurements at three levels over an intertidal mudflat in the Dollard Estuary. He found a reduction in shear stress at a time when the mean velocity was constant, and when suspended sediment stratification effects were present at vertical gradients of up to 0.7 kg m^{-4}.

Modelling studies by Wolanski et al. (1988) and Sheng and Villaret (1989), indicate that the effects of concentration stratification depend upon the Richardson number, and Winterwerp (1999) has shown that, as a consequence, there is a critical saturation suspension concentration at which the character of the flow changes.

This paper presents field measurements of the velocity and turbulence properties of an estuarine flow in high concentrations from measurements obtained at two levels within the turbidity maximum of a partially mixed estuary. The results were obtained under spring tidal conditions, with concentrations ranging up to about 12 g l^{-1} and vertical gradients up to 18 kg m^{-4}. Turbulence was measured directly at two levels using miniaturised electromagnetic flow meters. The results show that the shear stresses and the turbulence characteristics are highly influenced by interfacial waves. The vertical sediment fluxes appear to be affected by 'inactive turbulence' occurring at low stresses, and by variations in the vertical structure as the suspended sediment concentrations and near-bed density gradients increased.

2. Methodology

Field measurements were obtained as part of the EC MAST III COSINUS programme in the Tamar Estuary, South-west England (see Dyer et al., 2002a). The estuary is partially mixed, with a flood dominated tidal flow, and a tidal range varying between 2.1 and 4.5 m at neaps and springs, respectively. Instrumentation was deployed from a four-point anchored pontoon at mid-channel Station A, located within a 1 km straight section of the estuary, near to Calstock boatyard. Measurements were obtained under both neap and spring conditions, from 15th to 23rd September 1998. Under average river flow conditions this reach is the centre of movement of the turbidity maximum during the tide (Uncles and Stevens, 1993). The estuary mean width and depth at Station A were 75 m and 4.5 m, respectively.

Eight sampling runs each of approximately 3 h duration were obtained during the two-week experimental period. The results presented here focus on measurements of turbulence properties obtained during well-developed ebb flows, particularly in the presence of high concentrations during spring tides on three consecutive days. The turbidity maximum was about 1 km up-estuary of the tip of the salt intrusion (Dyer et al., 2002a). Consequently, vertical stratification was entirely the result of suspended sediment concentration. The results concerning the overall structure of the flow and the turbidity maximum, and the distributions and the properties of the suspended sediment have been reported by Dyer et al. (2002a,b). These measurements provided a context for interpretation of the detailed measurements reported here.

2.1. Instrumentation

Through depth profiles of salinity, temperature and suspended solids concentration were taken at least every 15 min. Hourly water samples were taken for calibration of the optical backscatter (OBS) gauges in terms of suspended sediment concentration (SSC). Mean surface flow velocities were measured at a depth of about 0.5 m.

Measurements of the mean and fluctuating components of velocity and concentration within 1 m of the seabed were obtained with the POST system (Christie et al., 1997). The system consisted of four 2 cm diameter discus shaped electro-magnetic flow meters (EM) and five OBSs, two of which were mounted close to the EM sensors. The EM sensors were arranged in pairs to measure the streamwise u, cross-channel v, and vertical w components of the flow, at $z = 0.25$ m and 0.75 m above the bed (denoted by subscripts L and U, respectively). Water depths were measured using a Druck pressure transducer.

All these sensors, together with the floc size and settling velocity system INSSEV (Fennessy et al., 1994) were mounted onto a bed-frame that was lowered onto the estuary bed from a tautly moored pontoon. The orientation of the EM sensors relative to the bed-frame was adjusted before deployment, and the bed-frame was aligned with the flow direction using a large fin (further experimental details are given in reports at http://sun-hydr-01.bwk.kuleuven.ac.be/COSINUS/field.htm).

A compromise has to be made regarding the co-ordinate directions, whether to orientate relative to the bed, or to the vertical. An estimate of the vertical orientation in both the uw and the vw plane provided from comparison of the floc settling direction with the INSSEV settling chamber suggested that the bed-frame aligned correctly, but this was checked by calculation of the mean flow relative to the rig.

Turbulence data were collected with sensors being sampled simultaneously at 18 Hz, and low pass filtered to 5 Hz. A succession of time series files was produced, each record covering 4096 values, about 3 min 47 s. The deviations from the mean taken over each record define the turbulent velocity components.

2.2. Calibration

Laboratory testing has shown that the EMs could be deployed within 1 cm of the bed without any signal distortion, and that they are insensitive to suspended sediment concentration up to at least 15 g l^{-1} (Christie et al., 1997). They were calibrated in an annular flume, and zero flow offsets were measured in the field. The calibration and zero offset checks suggest the accuracy of the EMs is about $\pm 3\%$, but their resolution is about 0.004 cm s^{-1}.

The OBS were calibrated daily and suggest an accuracy of about $\pm 5\%$, but resolutions were better at about $\pm 0.5\%$.

2.3. Data analysis

Calculated variance values of turbulence can be altered by spurious data spikes, drift, and non-stationarity of the time series. Spikes were identified by detrending the time series data using a linear fit, and then replacing variations greater than 5 standard deviations with an interpolated value (French and Clifford, 1992). The resulting detrended and despiked time series were then used to calculate the velocity variances and the turbulent velocity values discussed later. The stationarity of each time series was examined by dividing it into 10 segments and applying a run test (Bendat and Piersol, 1971).

The instantaneous streamwise velocity component U is the sum of the fluctuating part u and the burst mean value $\overline{U}$. The root mean square (rms) value of the streamwise fluctuating part is denoted by u', whilst the variance is denoted by $\overline{u^2}$. Similar notations are used for the cross-channel (V) and vertical (W) flow components and the sediment concentration (C).

The shear stress was calculated in two ways: as the Reynolds stress and via the turbulent kinetic energy. The Reynolds stress was calculated as the mean over each record of the product uw. However, this approach is very sensitive to current meter alignment and can show large errors.

Turbulent shear stresses were also quantified from the turbulent kinetic energy (TKE) derived using the relationship

$$E = \frac{1}{2}\left(\overline{u^2} + \overline{v^2} + \overline{w^2}\right) \tag{1}$$

since the value of E was relatively insensitive to the orientation of the EMs. Calculated E values were converted into shear stress (τ) in N m^{-2} using

$$\tau = 0.19\rho E \tag{2}$$

The constant of proportionality applies to wide variety of flows (Soulsby, 1983). Water densities (ρ) were calculated using the equation of state, including suspended sediment concentration.

The velocity variances were not corrected for high frequency losses. However, the correction for the miniaturised EMs should be less than 5% (Van der Ham, 1999).

Illustrative gradient Richardson numbers (Ri_g) were calculated from the differences in velocity and density between the upper and lower EM pairs (i.e. $\partial z \approx 0.5$) and were calculated using:

$$Ri_{\rm g} = -\frac{(g/\rho)(\partial\rho/\partial z)}{(\partial u/\partial z)^2} \tag{3}$$

The calculated values are notoriously sensitive to the sensor spacing, as the concentration interfaces may only be a few cm thick. Therefore the quoted values of $Ri_{\rm g}$ may underestimate the actual values at the interface, and were only calculated for indicative purposes.

Stringent quality controls were applied to the data. In particular, to limit the errors in the calculated Reynolds stresses, data were only accepted when the calculated mean vertical and horizontal velocities indicated sensor orientation at both heights were less than $\sim 5°$ from the vertical. This led to rejection of the whole of the data from the 22nd Sept, despite the visual indications of rig orientation being satisfactory. Also inspection of the time series showed a few anomalous traces that probably were affected by fouling by weed. These were omitted.

3. Results

3.1. Mean velocity and concentration

Spring tide ebb flow measurements obtained on the 21st and 23rd Sept 1998 will be considered. In terms of the ebb tidal phase, the sequence of measurements ran from 2:50 h–5:08 h after HW on the 23rd and 5:18 h–6:38 h after HW on the 21st. The maximum tidal range occurred on the 21st Sept, but there was a gradual increase in the suspended sediment concentrations over the three days.

3.2. Currents

On the 21st Sept the velocities were gradually decelerating, with those at the upper level about double those at the lower level, except for the final 40 min (Fig. 1A).

The current velocities on the 23rd Sept at the upper height rose from about 0.35 m s^{-1} to about 0.85 m s^{-1}, with velocities at the lower height of 0.05–0.2 m s^{-1}.

3.3. SSC

There was a period of almost an hour between the disappearance of the saline intrusion, and the appearance of the turbidity maximum, when significant vertical density gradients were generated by high near-bed concentrations. This delay is equivalent to a distance of about 1 km (Dyer et al., 2002a). On the 21st Sept the upstream end of the turbidity maximum was observed, as the flow decelerated and the turbidity maximum advected downstream. The concentration decreased from 4.0 g l^{-1} to 1.5 g l^{-1} at the upper level, and decreased from 2.5 g l^{-1} to 1.2 g l^{-1} at the lower (Fig. 1B). On the 23rd a distinct turbidity maximum was measured in which near-bed concentrations exceeded 12 g l^{-1}. Concentrations were at most 2 g l^{-1} at 0.75 m above the bed, with strong vertical concentration gradients (7–16 kg m^{-4}) within 1.0 m of the bed. Concentration profiles suggested that there were two fairly distinct layers on the 23rd, with one of the EM sensor heights being in each layer. The upper layer was very similar to the whole flow on the 21st, when the upper, lower concentration layer encompassed both.

3.4. Richardson number

The $Ri_{\rm g}$ values (Eq. (3)) depend upon U, C, ρ and possibly of most importance is the value of ∂z (which is defined as 0.5 m by the separation of the EM sensor pairs). With a sharp interface the $\partial u/\partial z$ term is likely to be underestimated, and both the $\partial\rho/\partial z$ term and resulting $Ri_{\rm g}$ value would have been underestimated. Thus it is likely that the calculated values are lower than the maximum present at the lutocline. Consequently only illustrative values can be used. $Ri_{\rm g}$ values were less than 0.13 on the 21st, but often exceeded 0.2 during the sample periods on 23rd. On the 23rd the $Ri_{\rm g}$ decreased towards the end of the record as the vertical SSC decreased, despite the increasing velocity shear. Thus it is likely that at peak concentrations the $Ri_{\rm g}$ was in excess of the limit of 0.25.

3.5. Shear stress

The shear stress was calculated both from the turbulent kinetic energy (Eq. (2)), and as the Reynolds stress. Fig. 2 shows the TKE shear stress plotted against the Reynolds stress, for both tides. At the lower height (Fig. 2A) there is a reasonable relationship between them, but with a deviation at lower stresses where there is 'inactive turbulence' (Gordon and Dohne, 1973) equivalent to a TKE shear stress of about 0.2 N m^{-2}. This is the result of essentially isotropic turbulence at low intensities not contributing to the Reynolds stress. For the upper height (Fig. 2B) the same phenomenon occurs, as well as there being considerable deviation from equality at higher shear stresses. Inspection of the records shows that this is due to the incidence of internal wave motions that can contribute to the Reynolds stress, because of correlation between the u and w fluctuations. The motions appear to be a mixture of progressive and standing waves, with the proportion and amplitudes varying at different times. They mainly affect the water motions above the lutocline and not below it.

A time series of TKE shear stress is shown in Fig. 3. On the 21st the $\tau_{\rm L}$ values were always a factor of about 2 greater than $\tau_{\rm U}$, and were fairly constant over the record, despite the changing current velocities and

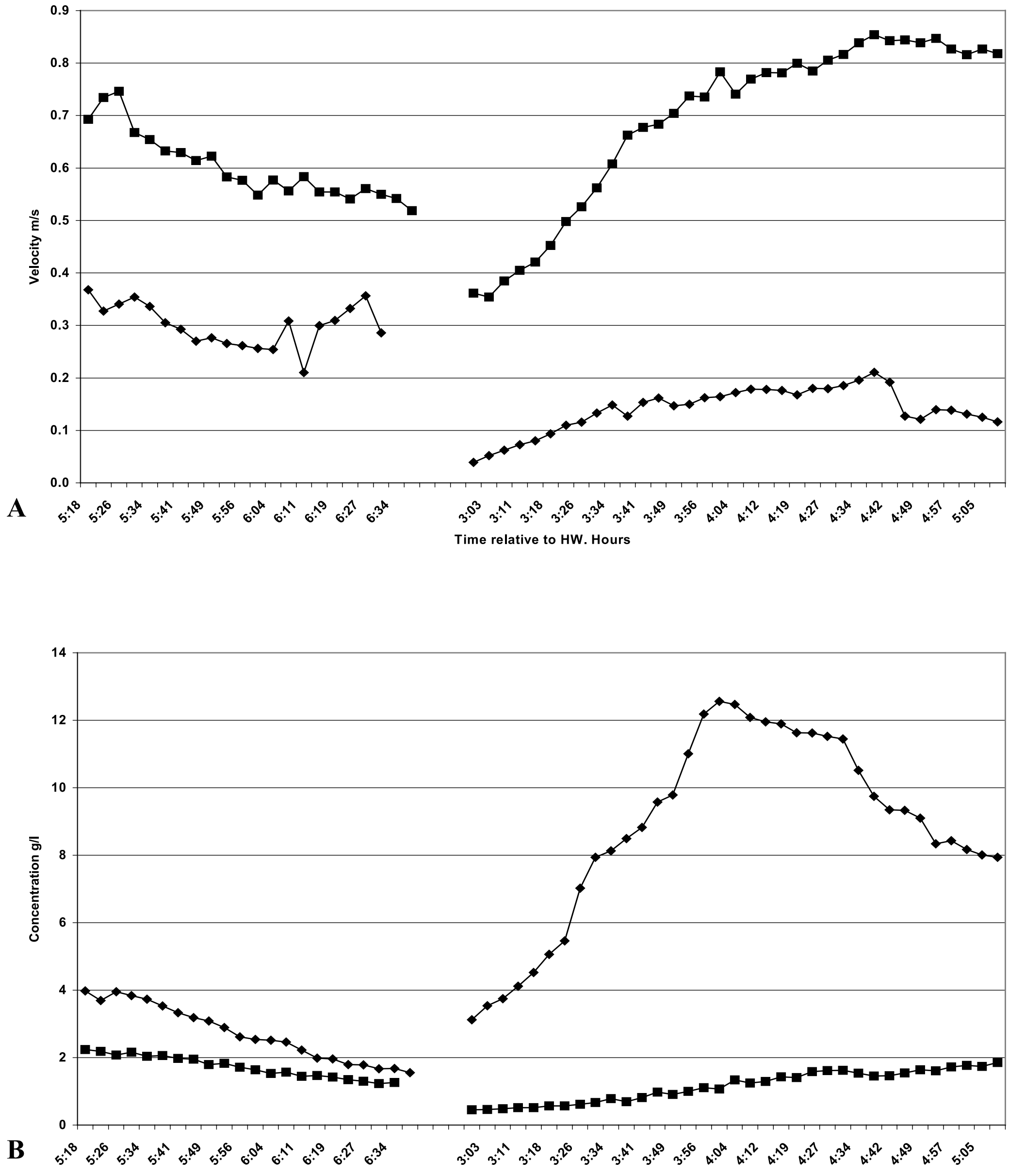
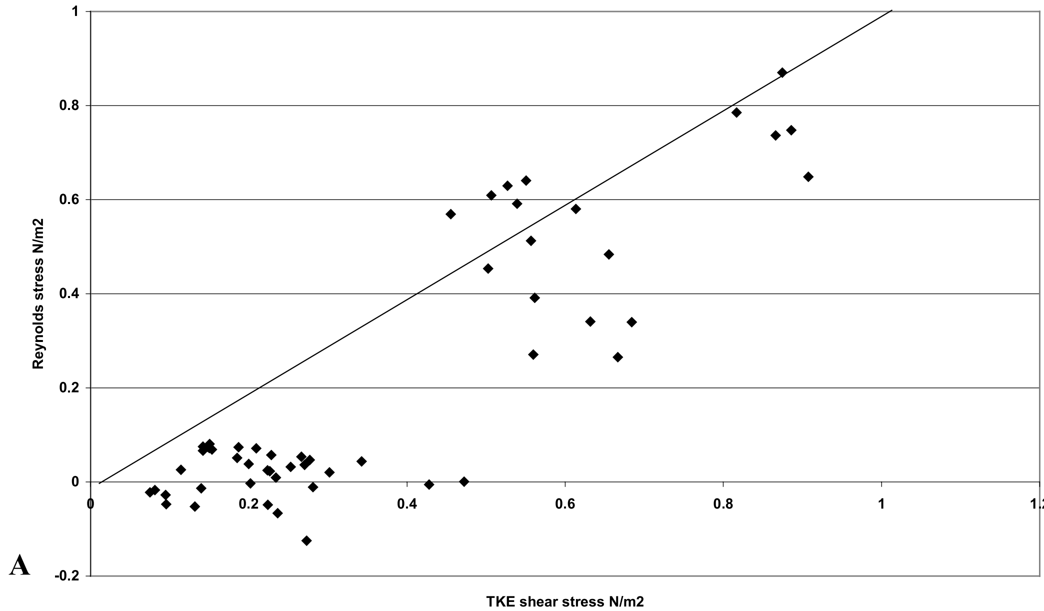


Fig. 1. Time series of (A) mean velocity and (B) mean concentration for the 21st Sept (left) and the 23rd Sept (right). Diamonds, lower height; squares, upper height.

relative depths. On the 23rd the τ_U were always greater than those at the lower height, reaching a factor of 3 difference and indicating the greater influence of internal waves above the lutocline. These measurements and those taken at neap tides suggest that internal waves cause τ_U to exceed τ_L when the density gradients exceed 4 kg m^{-4}.

3.6. Turbulence properties

Studies by many authors on the turbulence characteristics in unstratified conditions in clear water have shown that the horizontal rms intensity u' is generally 8–10% of the mean flow speed, and the ratio of vertical to longitudinal turbulent intensities w'/u' varies between 0.4 and 0.6. As stratification develops the vertical turbulent fluctuations are suppressed, and an increasing proportion of the turbulent energy goes into the longitudinal component. However, if internal wave motion is present on the interface, the vertical turbulence is relatively enhanced. Additionally, turbulent intensities near the boundary are affected by the pressure gradients associated with acceleration and deceleration in the flow (Gordon and Dohne, 1973). Consequently, there are likely to be significant variations during the tidal cycle.



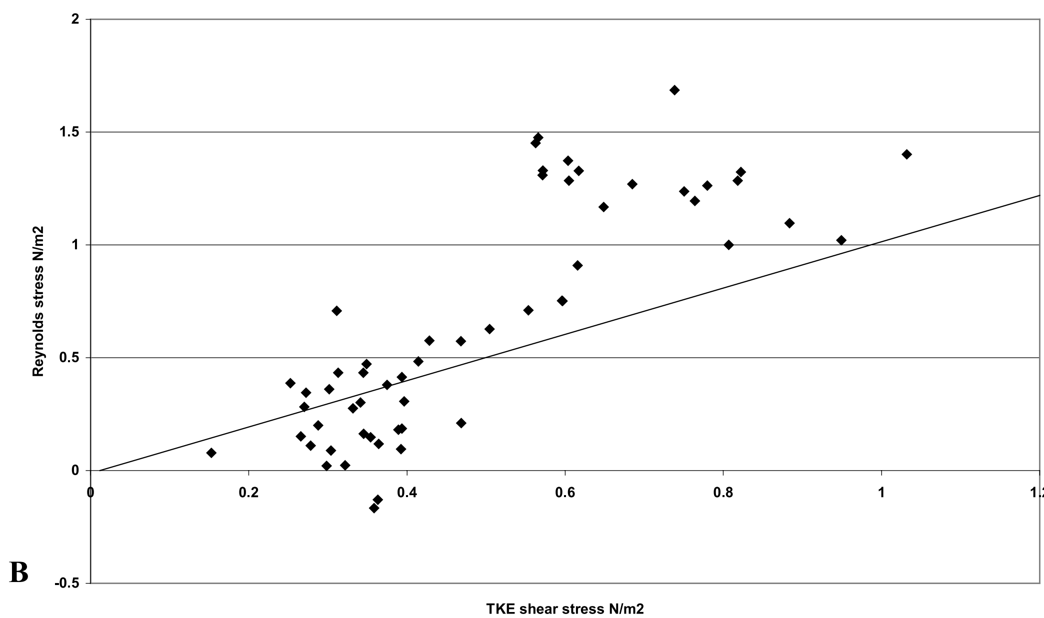


Fig. 2. TKE shear stress vs Reynolds stress. (A) Lower height and (B) upper height. The lines show equality.

On the 21st Sept at the end of the ebb tide, the intensity ratio values (w'/u') at the end of the ebb were between about 0.4 and 0.7, and were slightly larger at the upper height (Fig. 4) reflecting the increased relative height above the bed. These results are to be expected in a flow with relatively low Richardson numbers, and without significant internal waves.

On the 23rd Sept the ratio of the intensities w'/u' at the lower level was about constant at 0.4 until near the end of the tide when it rose to 1.2. At the upper height the ratio was generally 1.0–1.2, but it rose to reach 1.7 later in the tide. The increased ratio was the result of internal waves contributing to the deviations from the mean. Thus it appeared again that the waves were only effective above the lutocline.

Soulsby (1983) quotes a number of sources of marine turbulence measurements taken in clear water with values for the ratio of the intensities w'/u' of 0.46–0.66. West and Oduyemi (1989) and West et al. (1991) found in the Tamar that the ratio increased with the density gradient, rising from 0.6 to 0.9, because the decrease in the horizontal intensities was greater than in the vertical.

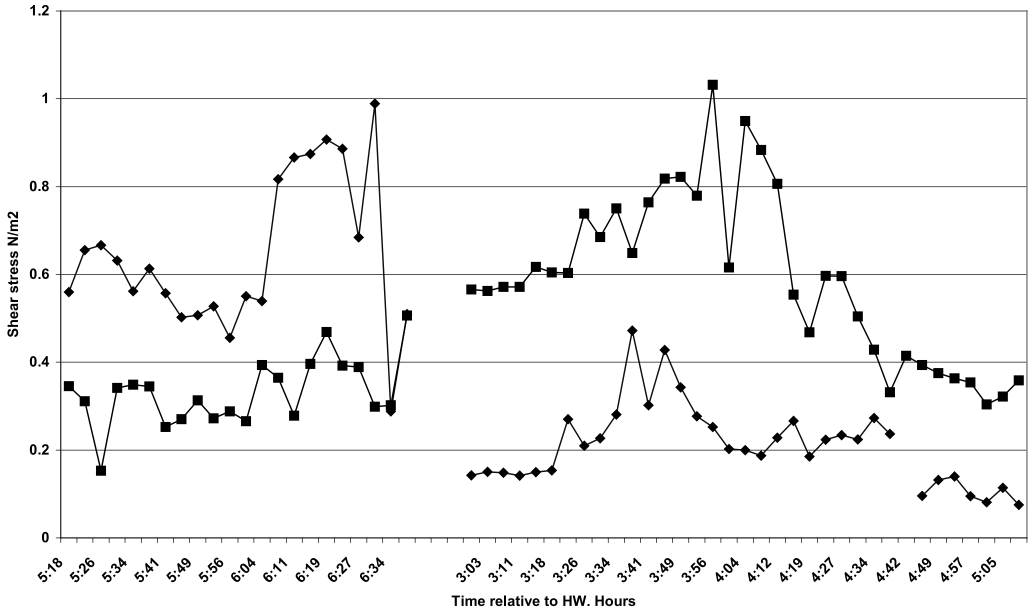


Fig. 3. Time series of TKE shear stress on 21st Sept (left) and 23rd Sept (right). Diamonds, lower height; squares, upper height.

The results here suggest that the internal waves can increase the turbulent intensity ratio by a factor of 2.0–2.5 for both low and high concentrations.

3.7. Turbulent variations in concentration c'

On both days wave-like fluctuations in concentration were present, being in phase at the two levels on the 23rd, but occasionally being out of phase on the 21st. As is to be expected, the turbulent variations in c' at the upper and lower levels are generally related to the mean SSC, with relative intensities of about 8–10% in the lower concentrations. At the upper level the values of c' rose fairly steadily in line with the mean SSC, from a relative intensity of about 10% to about 20%. At the lower level, however, once the concentration exceeded about 8 g l^{-1}, there were limited fluctuations in concentration. When the sensor was located close to the lutocline, the extent of the fluctuations was maximum.

These values are in agreement with those of West and Oduyemi (1989), who found that c'/C values increased to 0.1 at vertical concentration gradients of 3.5 kg m^{-4}.

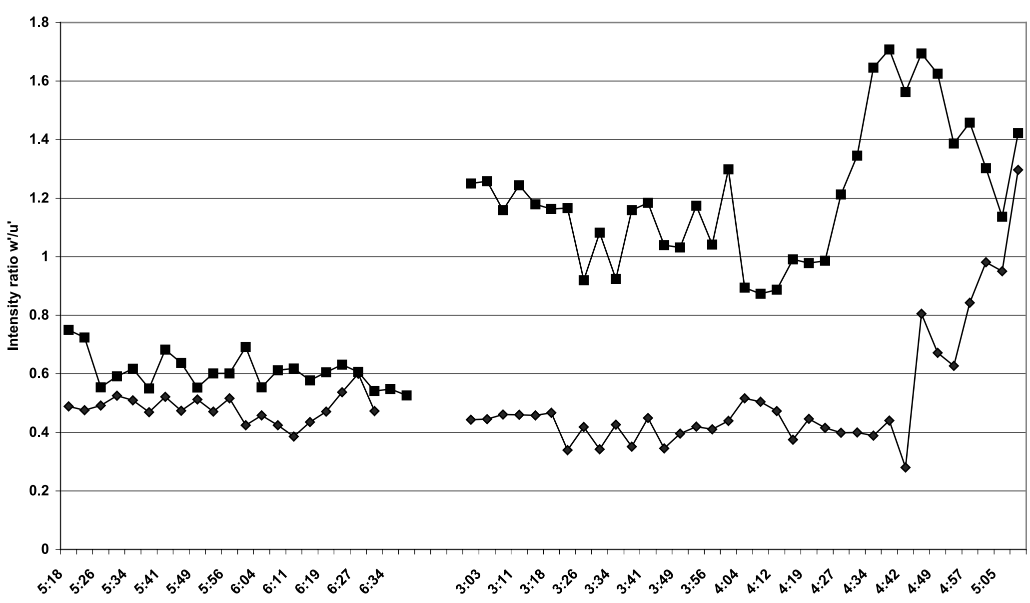


Fig. 4. Time series of ratio of turbulence intensities w'/u' on 21st Sept (left) and 23rd Sept (right). Diamonds, lower height; squares, upper height.

Van der Ham (1999) also found relative intensities of between 10 and 20% at mean concentrations up to about 0.5 g l^{-1}.

3.8. Suspended sediment fluxes

The cross product of the turbulent variations in vertical velocity and in SSC (i.e. $\overline{wc}$) give the turbulent or Reynolds fluxes of suspended sediment. An upward or positive contribution to the Reynolds flux occurs when an upward velocity is correlated with an increase in SSC, and a downward velocity with a decreasing SSC. The average of these motions causes a net upward transfer of mass. The reverse situation of an upward velocity coinciding with a decrease in SSC, and a downward velocity with an increase in SSC would produce a downward (negative) mass flux of suspended sediment. The presence of internal waves, where the vertical velocity and concentration fluctuations are 90° out of phase, produces no contribution to the vertical fluxes.

On the 21st Sept the fluxes at the upper level were consistently positive with values gradually decreasing with the decrease in mean SSC and as the flow slowed down. At the lower level the fluxes were near zero and largely negative. Conversely, on the 23rd Sept the flux was the same at both levels until a TKE shear stress of about 0.7 N m^{-2} after which the flux at the higher level increased, as upward entrainment of sediment occurred, until the time of the maximum turbidity. The flux at the upper height then reduced and subsequently became negative. This agrees with Linden (1979) and McEwan (1983) who suggest that the vertical fluxes reach a maximum at a gradient Richardson number of 0.25.

The experimental variability in both the Reynolds flux and the Reynolds stress is understandably large. Within the lower layer there was effectively no mean trend between the flux and stress (Fig. 5A), but negative fluxes frequently occurred. At the same time in the upper layer (Fig. 5B) the flux was upwards, increasing to a maximum of about 0.0015 g l^{-1} m s^{-1} at a stress of about 1 N m^{-2}, followed by a decrease towards zero. During the period of inactive turbulence, below a Reynolds stress of about 0.2 N m^{-2} (a TKE of 0.0002 m^2 s^{-2}), fluxes may be frequently negative, raising the possibility that sediment settling is enhanced by inactive turbulence.

The turbulent eddies are composed of bursting events containing sweeps, downward and forward water movements, and ejections, upward and backward movements. Together these form more than 100% of the exchange of momentum and the balance is made by the weaker inward and outward interactions, that act in the opposite sense but last relatively longer. For an upward suspended sediment flux, the sweeps would need to be correlated with lower concentrations and the ejections with higher concentrations.

The effect of the stratification on the bursting cycle has been examined by quadrant analysis. Typical results are presented for a record on the 23rd Sept at a time when the mean velocities were 0.87 and 0.39 m s^{-1} at the upper and lower heights, respectively, the calculated Reynolds stresses were 1.32 and 0.04 N m^{-2}, and the Reynolds fluxes were 0.00138 and 0.00123 g l^{-1}m s^{-1}. Thus the lower layer should exhibit the properties of inactive turbulence. The profile of mean concentrations is shown in Fig. 6A. The lutocline was about 0.4 m above the bed. The minimum gradient Richardson number based on the measurements 0.5 m apart was 0.15, but the value based on the steepest gradient is likely to exceed the critical value of 0.25.

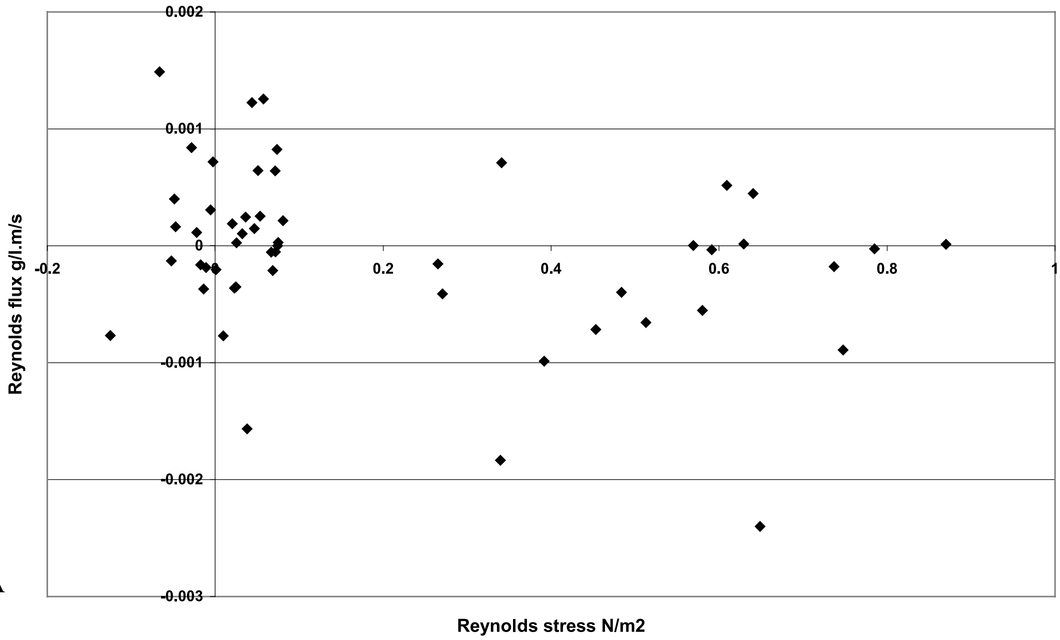
The quadrant plot for the upper height above the lutocline is shown in Fig. 6B. The sweeps (+ve u', −ve w') and ejections (−ve u', +ve w') dominate, with both sectors containing about 33% of the total values. The other 30% is occupied by the inward and outward interactions. In contrast, below the lutocline (Fig. 6C), the distribution has been rotated and all four quadrants now have almost identical contributions of 24–28%. Thus the structure of the turbulence below the lutocline is much more isotropic than above, accounting for the turbulence being ‘inactive’. These results agree with the quadrant analysis of West and Oduyemi (1989).

The same type of quadrant analysis can be carried out using the concentration fluctuations. For the upper height (Fig. 6D) the distribution is flattened, since the concentration variation is limited higher in the flow, and the downward velocity fluctuations cannot contribute much to negative fluctuations in flux. Likewise at the lower level (Fig. 6E), the distribution is similarly restricted by the availability of higher concentrations. In terms of the mean profile, the extent of the contributions to the flux at each level is shown in Fig. 6A.

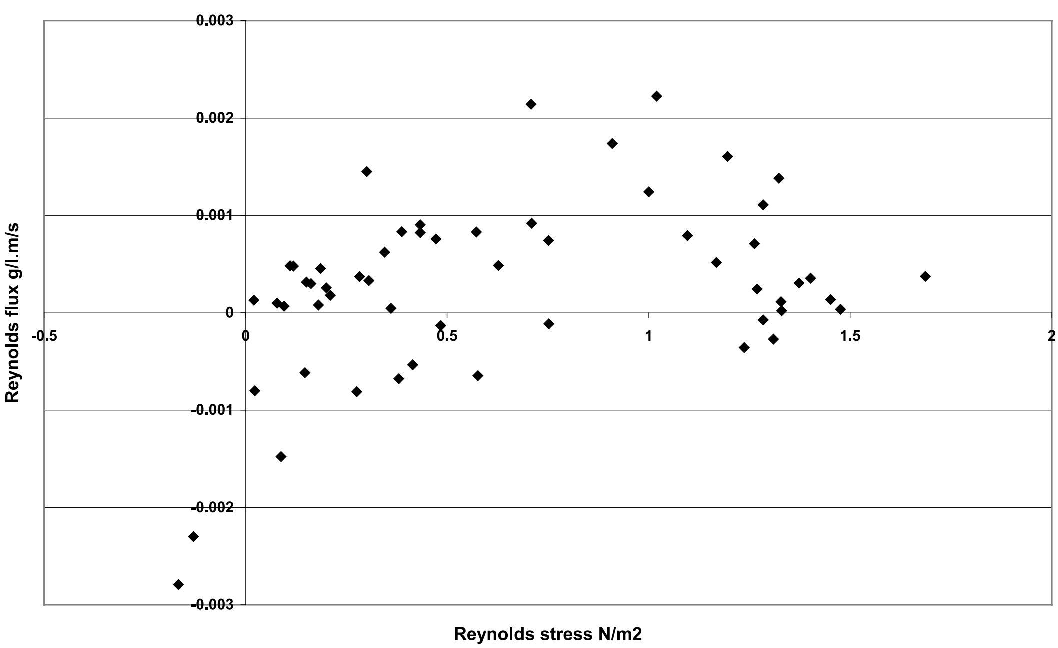
Results for other records have shown that, at the lower level, variation in the gradient of the concentration around the sensor height due to proximity to the lutocline has a major effect on the magnitude and the sign of the turbulent fluxes, particularly at low stresses. This appears to lead to alteration in the relative phases of the fluctuations. Additionally, the longer duration of the periods of the inward and outward interactions would provide time and relative weak motions during which the flocs could settle. Thus, when the turbulence is relatively weak the flocs will attempt to settle separately and become decoupled from the turbulent water motions.

4. Discussion

We have to assume that the turbulence was determined by the local flow velocity, with higher flow speeds generating more turbulence through friction effects,



A



B

Fig. 5. Reynolds flux vs Reynolds stress. (A) Lower height and (B) upper height.

primarily at the boundary between the bed and the flow. Bed roughness would affect the turbulence properties but measurements were not obtained of bed conditions, and as a first approximation it has to be assumed that bed roughness remained unchanged between tides. Other parameters such as flow history and conditions upstream may have secondary effects, but we were unable to quantify these effects.

Visual inspection of time series and comparison between the turbulent kinetic energy and the Reynolds stresses have shown that internal waves are important in the processes adjacent to high concentration near-bed layers. It is apparent that their effect is greater above the high concentration layer than within it, relatively enhancing the apparent Reynolds stress. These effects are likely to swamp any effects there may be of drag reduction.

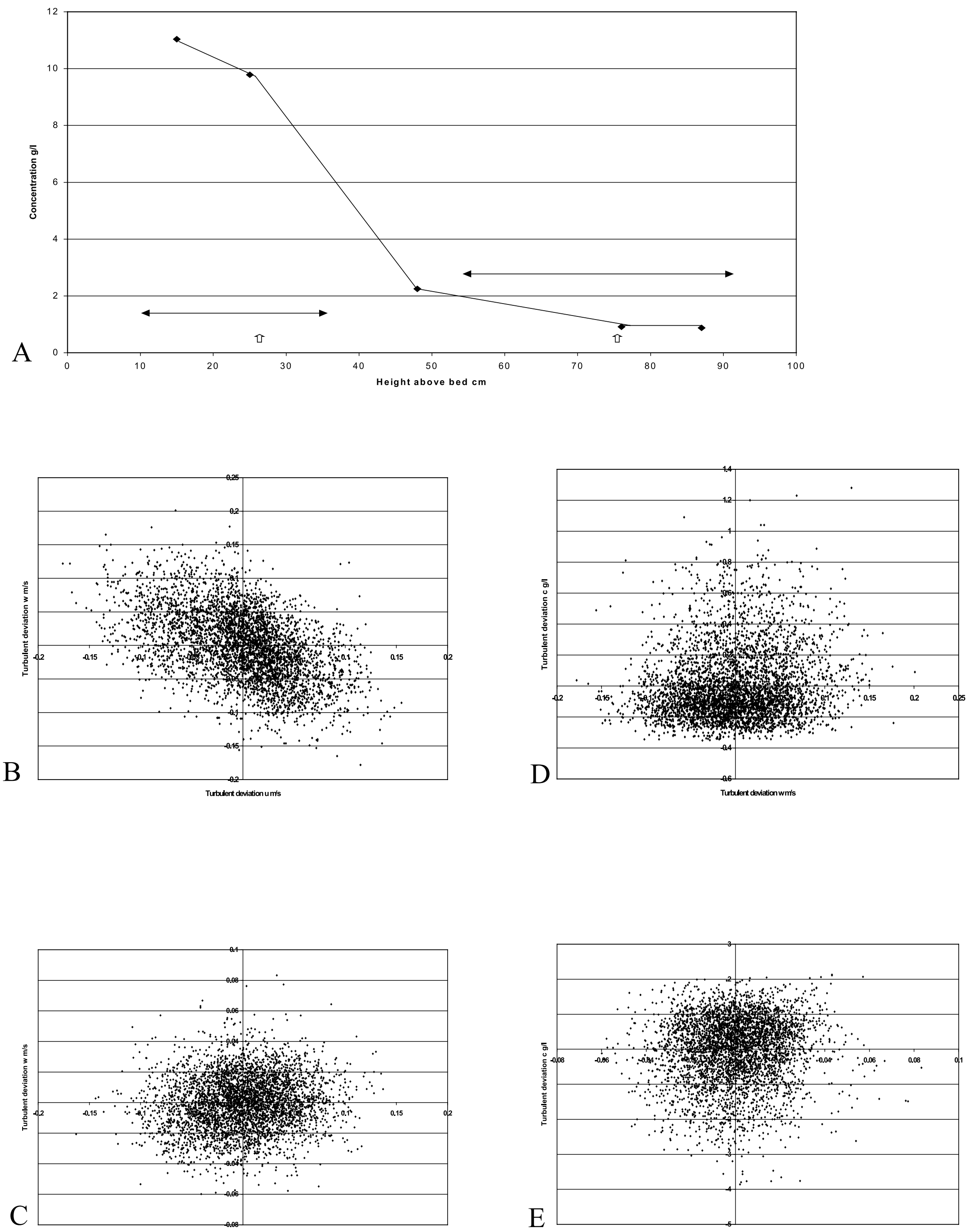


Fig. 6. Quadrant analysis for record 23,9121 on 23rd Sept. (A) Concentration profile, thin arrows show extent of concentration fluctuations, broad arrows heights of turbulence measurements. (B) Quadrant plot for u and w upper height. (C) Quadrant plot for u and w lower height. (D) Quadrant plot for c and w upper height. (E) Quadrant plot for c and w lower height. Note the scale differences.

During the acceleration phase of the measurements, the trends in the Reynolds fluxes agree with what would be expected by entrainment, from the changes in shear stress and concentration. It appears also that reduction of the fluxes occurred at the upper level at maximum stratification. West and Oduyemi (1989) note that there are negative contributions to the flux terms when intermittent wave-like motions are present. The wave-like motions appeared as u and w, and w and c being approximately 90°, and u and c approximately 180° out of phase. Our measurements show a variety of phase relationships were present and a slight change of phase could have important effects on the sign and magnitude of the turbulent SSC fluxes. This, together with the intermittency in the occurrence of the internal waves, may account for the great variability in the Reynolds fluxes, with intermittent negative fluxes at quite high shear stresses, especially within the bed layer.

In both the Tamar and the Conway Estuaries, West and Oduyemi (1989) suggest that the time fractions due to the sweep and ejection contributions to the vertical suspended sediment flux seem to be reduced, both tending towards 25%, as against 30% for homogeneous conditions. However, the time fraction spent in sweeps and ejections decreased when wave-like motions were present. A result is that a greater proportion of the total time may be spent in the relatively weaker interactions, during which time the settling of the grains and flocs separately from the flow could be more active. These suggestions are supported by the data presented here, which shows the extensive occurrence of negative fluxes at all stresses.

Additionally, below a TKE of about 0.0002 $m^2\ s^{-2}$ there is turbulent activity that does not contribute to the Reynolds stress. During these periods the incidence of negative fluxes is higher, leading to the possibility of turbulence enhanced settling at low shear stresses. These processes may be important in the vertical transport of suspended sediment in highly turbid estuarine flows. One of the crucial factors appears to be the large apparent intermittency in the shear stresses and the production of downward turbulent fluxes due to internal waves, especially in the lower layer. This emphasises the importance of adequately parameterizing the turbulence in transport models.

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