Gross sedimentation rates in the North Sea-Baltic Sea transition: effects of stratification, wind energy transfer, and resuspension

Sedimentation rates
Sediment traps
Stratification
Wind energy
Resuspension

Vitesse de sédimentation
Piège à sédiment
Stratification
Énergie du vent
Resuspension

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ABSTRACT

Gross sedimentation rates (GSR) were measured using sediment traps placed at different levels above the seabed (0.3, 0.5, 0.8, 1.0, 2.0, 4.0, 6.0, 8.0, 10.0 m) at a water depth of 17 m. The traps were deployed for 1.25 year. The study was carried out at a location in the semi-enclosed Aarhus Bay, in the southwestern part of the Kattegat, which forms the transitional zone between the highly saline (32-34) North Sea and the less saline (15-20) Baltic Sea. Hydrographic conditions in the Aarhus Bay are dominated by significant changes in salinity during the year, and the water column was stratified for 80 % of the time. High GSR values were recorded near the seabed with a mean of 114.8 (g m^{-2} day^{-1}) at 0.3 m above the seabed, whereas low GSR values were recorded in the upper traps with a mean of 5.5 (g m^{-2} day^{-1}) at 10 m above the seabed. The density difference between surface and bottom water was used as a stratification parameter. A strong negative correlation between stratification and wind energy transfer was found. The negative correlation was due to opposite seasonal components of in- and outflow of waters increasing the density difference, *i.e.* in- and outflow occurred predominantly in seasons with calm wind conditions. Correlation coefficients were high and positive between wind energy and GSR 6.0 m above the seabed due to enhanced turbulent diffusion of suspended particulate matter in periods of strong winds. Resuspension of bottom sediments by surface waves also occurred, increasing GSR at all trap levels. A net sedimentation rate given by the Pb-210 method (2.5 g m^{-2} day^{-1}) was low compared to the high GSR near the seabed (114.8 g m^{-2} day^{-1}), this difference being primarily due to resuspension by currents and waves.

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RÉSUMÉ

Taux de sédimentation brute dans le front Mer du Nord-Baltique : effets de la stratification, du transfert de l'énergie du vent et de la remise en suspension

Les taux de sédimentation brute (GSR) ont été mesurés à l'aide de pièges à sédiments placés à différentes hauteurs au-dessus du fond (0,3 ; 0,5 ; 0,8 ; 1,0 ; 2,0 ;

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4,0 ; 6,0 ; 8,0 ; 10 m). Les pièges sont restés en place pendant 1,25 année en un site où la profondeur est de 17 m, dans la baie semi-fermée de Aarhus, au sud-ouest du Kattegat ; cette région fait la transition entre les eaux salées (32-34) de la Mer du Nord et les eaux peu salées (15-20) de la Mer Baltique. Les caractéristiques hydrologiques de la baie de Aarhus sont marquées par des variations significatives de la salinité au cours de l'année, avec une stratification de la colonne d'eau pendant 80 % de la période d'observation. Les valeurs de GSR sont fortes au voisinage du fond (en moyenne 114,8 g $m^{-2} * j^{-1}$ à 0,3 m de hauteur) et faibles dans les pièges supérieurs (en moyenne 5,5 g $m^{-2} * j^{-1}$ à 10 m de hauteur). L'écart de densité de l'eau entre la surface et le fond caractérise la stratification. Ce paramètre est corrélé négativement avec la vitesse du vent en raison des composantes saisonnières opposées des flux entrant et sortant. L'écart de densité augmente avec ces flux, en particulier par régime de vent calme. Dans les périodes de vents forts, les corrélations positives entre l'énergie du vent et GSR à 6 m au-dessus du fond sont dues à l'augmentation de la diffusion turbulente de la matière particulaire en suspension. La remise en suspension des sédiments du fond par les vagues de surface contribue aussi à augmenter GSR dans tous les pièges à sédiments. Le taux net de sédimentation obtenu par la méthode Pb-210 (2,5 g $m^{-2} * j^{-1}$) est faible par comparaison avec les valeurs élevées de GSR au voisinage du fond (114,8 2,5 g $m^{-2} * j^{-1}$), la différence étant due à la remise en suspension par les courants et les vagues.

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INTRODUCTION

Vertical particle fluxes and sedimentation rates are important sedimentological parameters in coastal and estuarine environments, and have been studied with particular reference to sediment properties and transport (Swift *et al.*, 1972; Dronkers and Van Leussen, 1988). The hydrography of stratified waters has especially been studied with focus on the physical properties of the stratified water column (Turner, 1973), together with the development of the stratification (Simpson *et al.*, 1990; Simpson *et al.*, 1991) and the break down of the stratification (Kato and Philips, 1969; Wolanski and Brush, 1975; Kullenberg, 1977). Distributions of phytoplankton biomass (Pingree *et al.*, 1976; Cloern, 1984; Powell *et al.*, 1989), chlorophyll (Richardson *et al.*, 1985), and vertical fluxes of nutrients (Pingree and Pennycuick, 1975) have been studied in relation to stratification. In estuaries, vertical fluxes of particulate matter related to stratification and mixing have also been studied (West and Shiono, 1988; West *et al.*, 1991); less attention has, however, been given to the effects of stratification on vertical fluxes and sedimentation rates in coastal low- and nontidal areas.

This paper presents the results of a study of the variations in gross sedimentation rates (GSR), as measured by sediment traps, in relation to changes in wind energy transfer and stratification in a strongly stratified coastal area. GSR was also studied in relation to processes of resuspension by surface waves and currents, and the role of advection is discussed.

STUDY AREA

The study area is the semi-enclosed Aarhus Bay situated in the southwestern part of the Kattegat (Fig. 1). The Kattegat together with the Skagerrak, constitute the transitional zone between the highly saline North Sea waters (32-34) at the bottom and the northward flowing less saline waters (15-20) from the Baltic Sea (The Belt Project, 1981). Measurements of both GSR and hydrographic parameters have been carried

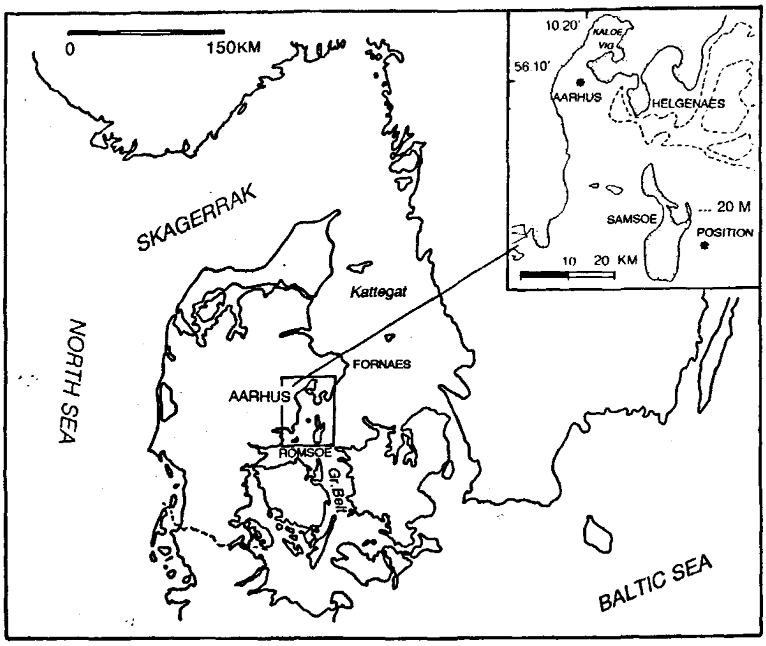

Figure 1

Location of study areas.

Situation de la région étudiée.

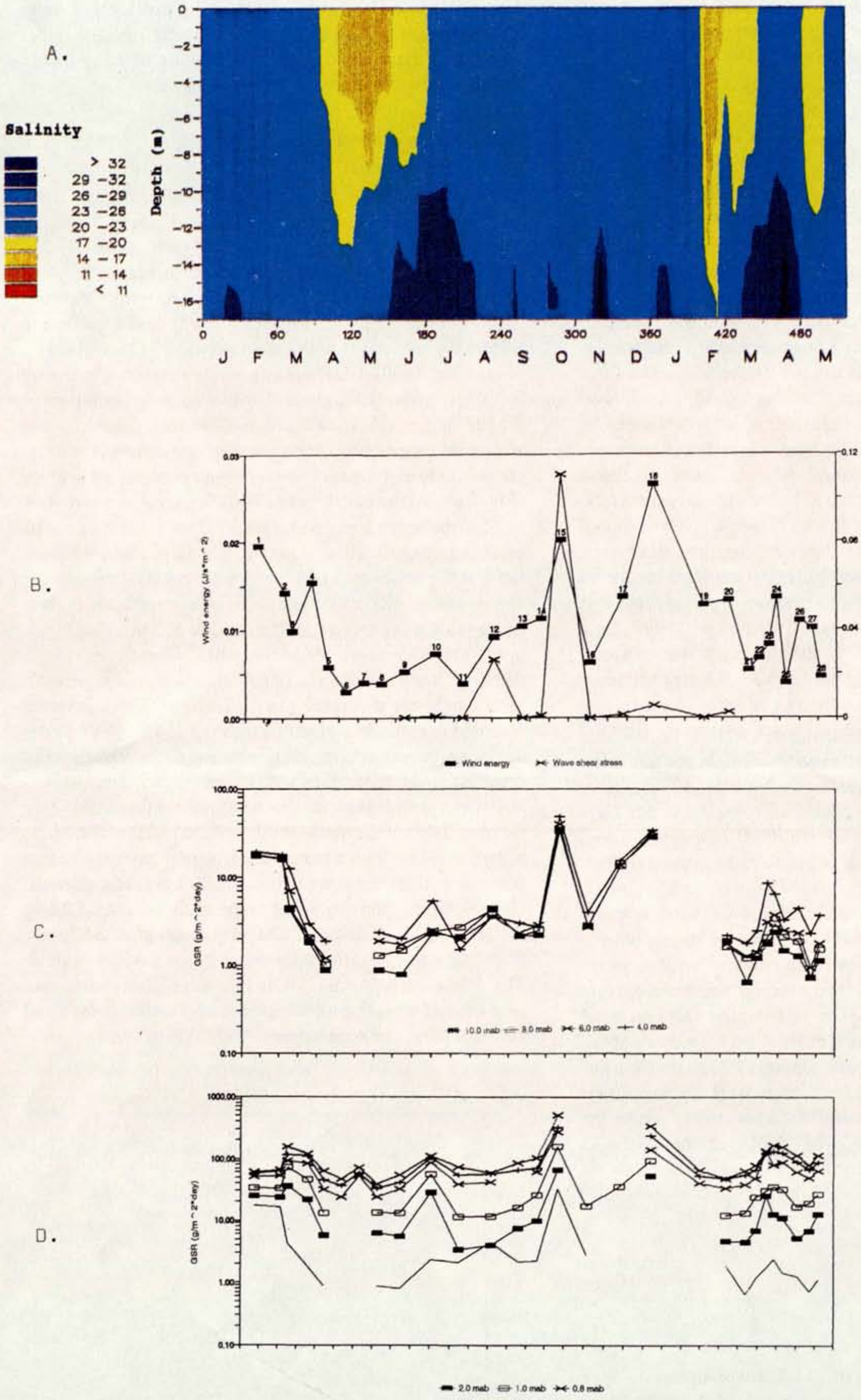

Figure 2

a: salinity distribution;
b: wind energy ($J\ s^{-1}\ m^{-2}$) and wave shear stress ($N\ m^{-2}$);
c: GSR 10.0, 8.0, 6.0, and 4.0 m;
d: GSR 10.0, 2.0, 1.0, 0.8, 0.5, 0.3 m.

a : salinité ; b : énergie du vent ($J\ s^{-1}\ m^{-2}$) et tension due au cisaillement des vagues ($N\ m^{-2}$) ; c : sédimentation brute (GSR) à 10, 8, 6 et 4 m ; d : sédimentation brute (GSR) à 10 ; 2 ; 1 ; 0,8 ; 0,5 et 0,3 m.

out at a fixed position (56°09.10 N, 10°19.20 E) in the Aarhus Bay. Water depth at the position is 17 m, and bottom sediments consist of silt and clay, and about 10 % organic matter (Lund-Hansen and Skyum, 1992). The bay has a tidal range of 40 cm, covers an area of approximately 250 km2, and contains a volume of water of 3.4 km3, which gives an average water depth of 13.6 m. To the south, Aarhus Bay is enclosed by islands and shallow water areas, and the main water exchange between Aarhus Bay and the Kattegat takes place at the deep-water (45 m) entrance situated at Helgenaes (Lund-Hansen and Skyum, 1992; Fig. 1).

METHODS

Sediment traps were deployed for measuring gross sedimentation rates (GSR) at nine different levels above the seabed (0.3, 0.5, 0.8, 1.0, 2.0, 4.0, 6.0, 8.0, 10.0 m). GSR is defined as the total amount of material sampled in a sediment trap with a known cross-sectional area over a known length of time. The traps above 0.8 m were mounted on a wire and held in position by a concrete block at the bottom, and a sub-surface buoy at the top of the wire. The three lower traps (0.3-0.8 m) were placed in stands pressed down into the seabed. The traps consisted of polyethylene pipes closed at the lower end. The inner diameter of the pipes was 8.0 cm and the inner length 40.0 cm, giving an aspect ratio of 5, which is considered to be the optimal aspect ratio for measuring GSR in horizontal flows, where maximum speeds infrequently reach 0.2 m s^{-1} (Hargrave and Burns, 1979; Gardner, 1980 *a*; 1980 *b*). The traps were recovered by divers, and the pipes were sealed *in situ* to prevent loss of material during recovery (*see* Valeur *et al.* (1992) for a more detailed discussion of the sediment trap design). Samples were filtered using preweighed (0.1 mg) Millipore GEM filters (0.45 µm). The filters were dried for 24 hours at 60°C and weighed. Sediment cores were collected near the position in order to determine a sediment accumulation rate based on the Pb-210 method (Robbins, 1978). CTD-measurements were carried out at the position with a fully automated CTD-measuring device (GMI-Instruments), and data from depth intervals of 0.2 m have been used for further treatment. CTD-measurements were carried out by the Aarhus County, and were obtained once per week in general, and twice per week in the periods of spring bloom. Measurements of current speed and direction 1.0 m above the seabed were obtained by a moored Aanderaa current meter (RCM 7) at intervals of 10 minutes. Data on wind speed and direction, recorded every third hour, were obtained from Fornaes Lighthouse, situated 50 km northeast of the position (Fig. 1). Sediment traps were deployed between 20 February 1990 and 23 May 1991, while the Aanderaa current meter was deployed between 23 September 1990 and 23 May 1991.

RESULTS

Salinity

On basis of a total number of 83 CTD-measurements, time *versus* depth contours of salinity between 1 January 1990 and 5 July 1991 have been compiled (Fig. 2 *a*). Low salinity waters (14-17) are present at the surface in April and May 1990, followed by high salinity bottom waters (29-32) in June and July 1990. Low salinity waters (14-17) are also present in February 1991, again followed by high salinity bottom waters (29-32) in March and April 1991. Due to these changes in salinity the stratification of the water column is maintained, although periods of fully mixed water column occur during winter and autumn.

Gross sedimentation rates

Sediment traps were recovered 28 times during the study period at 16 day intervals on average (range 6-39 days). The variation of GSR at the different levels above the seabed during the study period is shown in Figure 2 *c* + *d*. GSR ranges between a minimum of 0.65 g m^{-2} day^{-1} at 10.0 m in period 21 (11-27 March 1991), and a maximum of 505.0 g m^{-2} day^{-1} at 0.3 m in period 15 (16 October-1 November, 1990). Numbers of periods are shown in Figure 2 *b*. GSR varies strongly and with a seasonal component which, in general, shows a high GSR during autumn and winter and a low GSR during spring and summer. A comparison between the time *versus* depth contours of salinity (Fig. 2 *a*) and the variation of GSR (Fig. 2 *c* + *d*) shows that GSR at the upper trap levels (10.0-2.0 m) is low in periods of strong stratification (low surface salinities), whereas GSR at the lower trap levels showed no correlation to the changes in stratification. The correlation coefficient (r) between GSR measured at 10.0 m and at 8.0 m is high (r = 0.99), and decreases continuously to 0.77 at 0.3 m, which demonstrates a high degree of covariation between the sediment trap levels with respect to GSR. High GSR values were recorded near the seabed with a mean of 114.8 (g m^{-2} day^{-1}) at 0.3 m, whereas comparatively low GSR values were recorded in the upper traps with a mean of 5.5 (g m^{-2} day^{-1}) at 10 m. A typical vertical GSR distribution - period 14 (2-16 October, 1990) - shows that GSR between 10.0 and 4.0 m is nearly constant with a mean of 2.6 (g m^{-2} day^{-1}), whereas below 4 m GSR increases exponentially towards the seabed (Fig. 3). GSR in the upper part of the water column of 2.6 (g m^{-2} day^{-1}) is equal to the net sedimentation rate of 2.5 (g m^{-2} day^{-1}) near the position, determined by the Pb-210 method. The difference between GSR and the net sedimentation rate near the seabed is due to resuspension by surface waves and currents, as will be seen below.

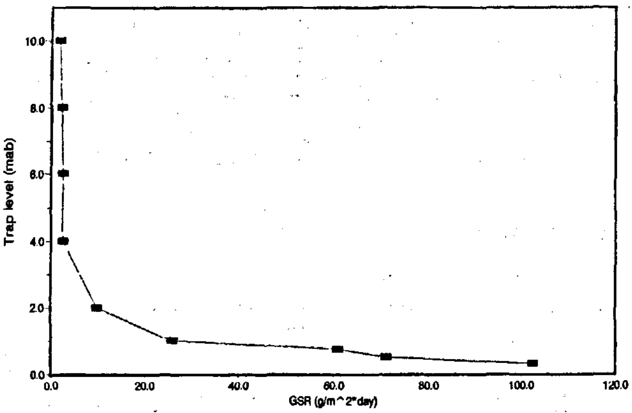

Figure 3

Typical vertical distribution of GSR.

Distribution verticale type de GSR.

Stratification

The mean wind energy (J s^{-1} m^{-2}) transferred to the water in each of the 28 periods has been calculated according to Kullenberg (1977) by

$$E_w = kC_d\rho_aU^3 \quad (1)$$

where k is a wind factor ($1.8*10^{-2}$), C_d a drag coefficient ($1.1*10^{-3}$), ρ_a the air density (1.2 kg m^{-3}), and U the wind speed (m s^{-1}) measured at 10 m above the surface. The variation of (1) during the study period shows a seasonal component with high rates during autumn and winter, and low rates during spring and summer (Fig. 2 *b*).

The stratification of a water column can be expressed by the Brunt-Väisälä frequency (Kullenberg, 1977), a function proportional to the density gradient $D\rho/Dz$ with z as the depth parameter. The density difference between the surface and bottom waters may be used to parameterize the stratification of the water column. The average density difference ($\Delta\sigma_t$) between surface and bottom water in each of the 28 periods has been compared to the mean wind energy transfer (E_w) given by (1) for the same periods (Fig. 4). The months covering approximately the periods of sediment trap deployment are also shown. A distinct negative correlation (r = - 0.69) is recognized between wind energy transfer and density difference.

Mixing of the water column can also be due to the shear stress at the bottom boundary, *i. e.* the bottom current. The current shear stress is calculated by

$$\tau_c = C_d\rho_wU^2 \quad (2)$$

where C_d is a drag coefficient ($1.1*10^{-3}$) for current speed measured at 1.0 m above the seabed (Sternberg, 1972), ρ_w the water density (1020 kg m^{-3}), and U is the current speed (m s^{-1}). Shear stress is proportional to the amount of energy derived from either the wind or the current, apart from some coefficients of proportionality. For comparison between wind and bottom current, in terms of shear stress, the mean wind shear stress in the fourteen periods of Aanderaa current meter deployment has been calculated by

$$\tau_w = C_d\rho_aU^2 \quad (3)$$

with definitions of C_d, ρ_a, and U as in (1). The mean wind shear stress during the fourteen periods is 6.9 ± 2.4 STD (N $m^{-2}*10^{-2}$), whereas the corresponding mean current shear stress is 4.3 ± 1.2 STD (N $m^{-2}*10^{-3}$), which gives a mean wind/mean current shear stress ratio of 16. The comparison shows that the energy transferred to the water column from the wind far exceeds that derived from the current.

Resuspension-wave

On basis of the recorded wind speed and fetch at the position (Beach Erosion Board, 1975), orbital velocities at the seabed due to surface waves have been calculated (Komar and Miller, 1973). The bottom shear stress derived from the orbital velocities have been calculated according to Larsen *et al.* (1981) by

$$\tau_w = 0.5\ \rho_wf_w\ U^2 \quad (4)$$

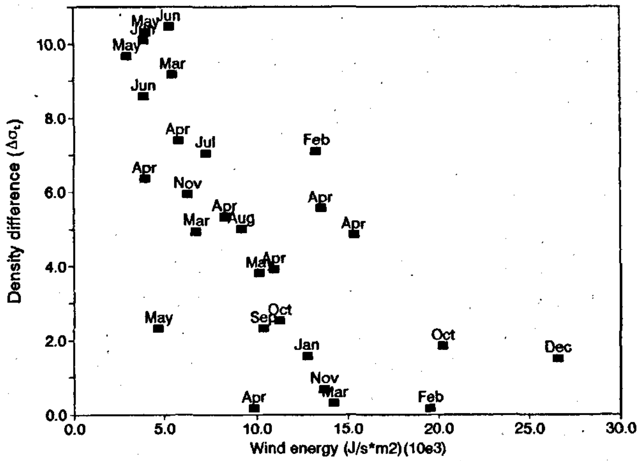

Figure 4

Wind energy (J s^{-1} m^{-2}) and density difference ($\Delta\sigma_t$) between surface and bottom waters.

Énergie du vent (J s^{-1} m^{-2}) et différence de densité ($\Delta\sigma_t$) entre de l'eau de surface et l'eau de fond.

where ρ_w is the water density (1020 kg m^{-3}), f_w a wave friction factor (0.004; Jonsson, 1966), and U the maximum orbital velocity (m s^{-1}). Wind speeds and directions were recorded at a three-hour interval (*see* Methods), and Figure 2 *b* shows the maximum bottom shear stress due to surface waves corresponding to maximum wind speed and optimum fetch, in each of the 28 periods where (4) is above 0.01 (N m^{-2}).

The maximum shear stress induced by surface waves (Fig. 2 *d*) is high in period 15, corresponding to a high GSR at all trap levels in this period (Fig. 2 *c* + *d*), which strongly indicates that the high GSR in this period is due to resuspension by surface waves. However, GSR is also high at all trap levels in period 18, during which the highest mean wind speed occurred, although the calculated wave shear stress is low. Period 15 was dominated by strong winds from the southeast giving the optimum fetch for surface wave development in Aarhus Bay (Fig. 1), whereas period 18 was dominated by winds from southwest giving a very low fetch although wind speed is high. The high GSR in period 18 is supposedly due to advection of suspended particulate matter brought in from the shallow water areas surrounding the bay.

DISCUSSION

Salinity

The changes in surface salinities are due to outflow towards the Kattegat of low saline waters (12-15) from the Baltic Sea in spring, where there is a high rate of fresh water runoff into the Baltic Sea (Kullenberg, 1981). However, the occurrence of low salinity waters (14-17) in February 1991 is due to winds with easterly components associated with the high pressure located over southern Scandinavia during that period. In general, the low salinity of the surface waters is followed by inflow of high salinity bottom waters 1-2 months later. The occurrence of the high salinity bottom waters, present in July and June 1990 and in March and April 1991, preceding the low salinity surface waters, is due to the inflow of bottom waters from the Kattegat. The northward outflow towards the Kattegat of low salinity waters produces the southward movement of a compensating return flow in the Kattegat, *i. e.* an estuarine circulation (Jacobsen, 1980).

During the summer months, a thermocline develops in Aarhus Bay (Aarhus County, 1990), although the stratification of the water column is dominated by both the buoyancy flux of low salinity waters and the inflow of high salinity bottom waters resulting in the strong stratification. The vertical and time-scale salinity distribution during the study period represents average conditions, although the occurrence of outflow in February 1991 is somewhat atypical (Aarhus County, 1990).

Stratification and GSR

Energy for vertical mixing of the water column comes from either external or internal sources (Kullenberg, 1977). Internal tidal waves have been observed in Aarhus Bay (Lund-Hansen and Skyum, 1992) but are not considered to be of any significance for the vertical mixing. Also the mixing due to tides is minimal as the tidal range is only 0.4 m. The comparison between the shear stress of the wind and the bottom current showed that the wind shear stress, on the average, was about 16 times higher, whereas the density difference between the surface and bottom waters was negatively correlated to the wind energy transfer (r = - 0.68), indicating that the stratification is controlled by the wind-energy transfer. However, outflow from the Baltic Sea in spring, recognized by the low salinities of the surface waters in Aarhus Bay, coincides with more calm wind conditions during spring, which shows that density difference and wind energy transfer are not independent variables. The outflow from the Baltic in spring is followed by a compensating return flow at the bottom one-two months later, and during summer when wind conditions are calm. This indicates that the negative correlation between wind energy transfer and density difference is primarily due to the seasonal components of wind speed distribution and the seasonal component of the density difference variation, which are in opposite phase. However, the barotropic fields forcing water from the Skaggerak towards the Kattegat due to low pressure and winds from the western sector have been shown to force high salinity bottom waters into the Aarhus Bay (Lund-Hansen and Skyum, 1992; Skyum and Lund-Hansen, 1992). The prevailing wind directions in the study area are southwest and west (Danish Meteorological Institute, 1971), but which, as described above, by barotropic forcing, drive high salinity bottom waters into Aarhus Bay and thereby increase the density difference. Following the arguments by Pedersen (1986) it will take about 3.8 days to raise the potential energy to a maximum, *i.e.* fully break down the stratification of a typical water column in Aarhus Bay with a steady wind of 10 m s^{-1} and an efficiency of 5 %. A typical water column consists of a 10 m thick surface layer with a density of 1015 kg m^{-3} (20 ppt, 10°C), and a 7 m thick bottom layer with a density of 1020 kg m^{-3} (28 ppt, 6°C).

These results show that the stratification in Aarhus Bay in general is controlled by the in- and outflow caused by changes in the transitional zone, although in periods of high wind speeds of 10-15 m s^{-1} it is supposed that breakdown of the stratification takes place by wind mixing of the water column, for instance during autumn and winter. As Aarhus Bay is sheltered with respect to prevailing winds from the west (Fig. 1), the mixing of the water and breakdown of the stratification are supposed to take place outside the bay in the Kattegat area in periods of strong frontal movements (The Belt Project, 1981).

Density differences strongly inhibit vertical mixing of the water (Turner, 1973; Wolanski and Brush, 1975), whereas transfer of wind energy enhances vertical mixing and subsequent break down of the stratification (Kullenberg, 1977). The diffusion coefficient of suspended particulate matter has been shown to be proportional to that of fluid mass (Dyer, 1986; West *et al.*, 1990); *i. e.* when the vertical mixing of the water column increases by wind energy

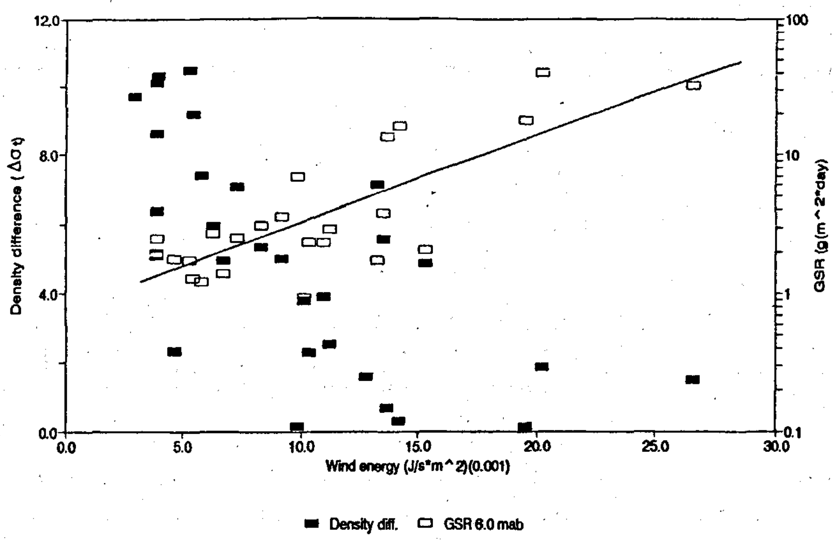

Figure 5

GSR at 6.0 m and wind energy (J s^{-1} m^{-2}) and density difference ($\Delta\sigma_t$) between surface and bottom waters.

Sédimentation brute (GSR) à 6 m et énergie du vent (J s^{-1} m^{-2}) et différence de densité ($\Delta\sigma_t$) entre de l'eau de surface et l'eau de fond.

transfer, the turbulent diffusion of suspended particulate matter is also increased. Figure 5 shows both the variation of GSR measured at 6.0 m and density difference between the surface and bottom waters against wind energy transfer as in Figure 4. A strong positive correlation ($r = 0.81$) between wind energy transfer and GSR at 6.0 m was found (Fig. 5), which shows that GSR is low in periods of strong stratification, whereas GSR strongly increases with increasing wind energy transfer and breakdown of the stratification. Analogous analysis applied for GSR measured 0.3 m showed no dependence on either density difference or wind energy transfer (Lund-Hansen *et al.*, 1992). The vertical flux of both organic carbon and particulate carbon (POC) have also been shown, in Aarhus Bay, to increase during periods without stratification (Valeur *et al.*, 1992).

The average GSR for the entire study period is 6.1 g m^{-2} day^{-1} at 2.0 m, which approximately equals the net sediment accumulation rate determined by the Pb-210 method of 2.5 g m^{-2} day^{-1}, whereas the average GSR of the three lower trap levels is 91.2 g m^{-2} day^{-1}. Sediment traps measure a gross sedimentation rate (GSR), whereas a net sediment accumulation rate is given by the Pb-210 method (Lund-Hansen, 1991; Valeur *et al.*, 1992). The difference between the net sedimentation rate and GSR increases exponentially towards the seabed (Fig. 3). Using a multitrap with the aperture opening placed at 1.5 m above the seabed, Floderus and Lund-Hansen (1992) measured GSR per day in Aarhus Bay, and a significant positive correlation between GSR and the mean current shear stress per day was found. In the present study, GSR represents an average of a period between 6 and 39 days, and the correlation coefficients between the mean current shear stress, calculated by (2), and GSR range between 0.25 at 0.8 m and 0.37 at 0.5 m. In the present study it has been shown that GSR increases due to resuspension by surface waves as in period 15 (Fig. 2 *b*), and it is thus supposed that the high GSRs near the seabed (0.3-1.0 m) are due to both resuspension by surface waves and currents. The low correlation coefficients between GSR and current shear stress, in the present study, are in contradiction with the results of Floderus and Lund-Hansen (1992), but this is supposed to be primarily due to differences in the time scale of obtaining GSR of the two methods.

The concentrations of suspended particulate matter in the surface waters of Aarhus Bay, in general, are 1-2 mg l^{-1}, whereas the bottom waters contain 3-4 mg l^{-1}. However, during an inflow of high salinity bottom waters (32.0) into the Aarhus Bay in April 1991, the concentrations of suspended particulate matter were 4-5 mg l^{-1} at the surface and 10-12 mg $^{-1}$ near the seabed (Lund-Hansen and Skyum, 1992). Both the increased bottom salinities and the increased GSR at all trap levels are recognized during that period in the present study (period 23; Fig. 2 *a*, *c*, *d*). Increased GSRs are at the lower trap levels also recognized in period 10 (Fig. 2 *c* + *d*) during an inflow of high salinity waters (Fig. 2 *a*). GSR is the product of a concentration C (kg m^{-3}) of suspended particulate matter and a particle settling velocity (m s^{-1}; Dyer, 1986), and by increasing C the GSR increases proportionally, on the probable assumption that particle settling velocity is nearly constant. These results show that advection with transport of suspended particulate matter to some extent takes place between Aarhus Bay and Kattegat, and that the difference between GSR and the net sediment accumulation rate is not accounted for by resuspension alone, although a quantification of the advective transport, based on the present data, is not justified.

CONCLUSION

Stratification in Aarhus Bay was entirely due to changes in salinity, driven by outflow from the Baltic Sea and inflow from the Kattegat. A strong negative correlation between density difference between surface and bottom waters and wind energy transfer was found. The negative correlation is in general due to opposite seasonal components of wind speed distribution and in- and outflow of waters derived from changes in the transitional zone. GSR was high in periods without stratification and low in periods with stratification. GSR was positively correlated to the wind energy transfer when turbulent diffusion of suspended particulate matter was enhanced by the vertical mixing. The vertical variation of GSR showed low values at the upper trap levels compared to trap levels near the seabed. Comparison between GSR at the seabed and the net sediment accumulation given by the Pb-210 method showed a high difference, primarily due to resuspension by waves and currents, although advective transport also takes place.

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