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# Processes of Vertical Exchange in Shelf Seas (PROVESS)

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## Abstract

Papers in this and a companion issue report on an interdisciplinary study of the vertical fluxes of properties throughout the water column from the sea surface to the seabed. The project was centred on measuring and modelling for two contrasting sites in the North Sea of turbulence properties and their effects on particles, zooplankton and nutrient cycling, particularly the relative importance of cycling in the water column, the seabed fluff layer and the sediments. Turbulence activity was weaker at the northern site, which stratified in summer, and where measurements were obtained during the start of the autumnal breakdown of stratification. The southern site, where measurements were taken during and after the spring bloom, was much more dynamic both in terms of turbulence and of particles. The site was close to the Dutch coast and was well mixed throughout the year, except for the intermittent influence of the Rhine plume. The study contributes towards the long-term goal of developing robust water column plankton models applicable in the full range of turbulence environments encountered in continental shelf seas.

*Keywords:* Turbulence; Particles; Benthic exchanges; Measurements; Coupled physical-biological modelling; North Sea

## 1. Introduction

Vertical exchanges are central to many continental shelf sea processes, processes in which horizontal fluxes and gradients are of secondary importance and can often be neglected. Examples are the development and erosion of the pycnocline (particularly diurnal and seasonal thermoclines); the onset and decline of phytoplankton blooms, both in spring and, especially, in autumn; the chlorophyll mid-water maximum in summer stratified water; particle sedimentation and the remineralisation of particulate matter in the benthic boundary layer. Vertical exchanges are controlled principally by the turbulence characteristics of the water column, with three regions of special significance—the surface mixed layer, the pycnocline and the benthic boundary layer. Turbulence is generated both at the surface, by wind stress and waves, particularly by breaking waves, whitecapping and Langmuir circulations, and at the seabed, through the action of bottom friction on the current (tidal currents are often the most important). At the pycnocline turbulence levels are reduced and vertical fluxes can be inhibited, unless there is internal wave breaking. The turbulence characteristics at any location therefore depend on many factors—water depth, tidal current strength, nature and

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degree of stratification, surface heat flux, composition and shape of the seabed, strength of the winds and waves and on the presence of Langmuir circulation, inertial currents and internal waves. In turn, the nature and strength of the turbulence affect the local dynamics and thermodynamics.

The development of one-dimensional coupled physical-biological models is based on the premise that the dynamics of primary production and nutrient cycling in shelf seas can largely be explained by interactions between physical and biological processes in the vertical. Stirring plays two opposing roles in the life of phytoplankters: it can supply nutrients essential for growth whilst moving these photosynthetic organisms into or out of the equally essential light, the photic zone. 'Vertical-process' models linking physics with plankton biology must thus simulate, at least, a deep source of nutrient, the penetration of light into the sea, and vertical mixing represented either as an eddy diffusion or the entrainment of water into the surface mixed layer. Adding the sinking of remineralisable particles allows the local closure of the nutrient cycle, but in the case of continental shelf seas requires account to be taken of possible resuspension of particles from the seabed.

A considerable reliance is now placed on turbulence closure schemes to quantify fluxes in shelf sea environmental models. A crucial example for coupled physical-biological models is the entrainment of nutrients into the photic zone. Studies with coupled physical-biological models have shown that accurate modelling of physical processes in the water column, especially of vertical advection and turbulent mixing, is critical for predicting the dynamics of the plankton system (Sharples and Tett, 1994). In present models the entrainment of nutrients across the thermocline appears not to be correctly estimated a priori, with the result that predictions of autumn blooms and mid-water chlorophyll maxima are in error. This failure to estimate nutrient fluxes accurately stems from a lack of understanding in two areas—firstly the quantification of vertical fluxes in the vicinity of the thermocline, mentioned above, and secondly which processes control nutrient recycling in the benthic boundary layer. Physical—biological coupling involved in recycling includes (a) the agglomeration–sedimentation–deposition–resuspension of particulates, and (b) the mineralisation of nutrients, in relation to (i) bed stress and (ii) turbulence regimes in the bottom mixed layer. A key aspect is to distinguish processes occurring in the water column from those in the 'fluff layer' formed by freshly deposited particulates and those in the compacted sediment of the seabed (Stolzenbach et al., 1992). Our hypothesis is that the bottom mixed layer of the water column is the dominant region of mineralisation at sites where deposited material is regularly resuspended by tidal stirring (Lee et al., 2002).

Simple tests of the models can be made against bulk properties of the water column. The accurate simulation of the evolution throughout the year of vertical temperature structure is, moreover, of critical importance for the prediction of phytoplankton dynamics. Here many models cannot correctly simulate the surface mixed layer depth and the sharpness of the thermocline without the imposition in the thermocline region of a limiting condition, one consequence of which is a background diffusivity (for instance Holt and James, 1999). This highlights a significant deficiency of these models which is that internal wave dynamics and specifically mixing associated with internal wave breaking is lacking. In stratified regions the layer below the thermocline also provides a good test of the models since it is isolated from surface exchanges and over the period of stratification values result from integrating any fluxes across the thermocline. One example is the near-bed temperature, where, however, advection may also be important. Another, for coupled physical-biological models, is the concentration of dissolved oxygen below the thermocline, of practical concern in regions where oxygen levels become depleted. The dissolved oxygen level is an integration of both biological effects and exchanges across the thermocline.

A more direct test of the physical models is against measurements of turbulence properties (for instance Simpson et al., 1996). Since turbulence also directly affects the environment perceived by particles, including living biota, detritus and suspended sediment, studies were made of aggregation, flocculation and sedimentation of particulate organic and inorganic matter and of trophic interactions. Zooplankton are directly influenced both passively and actively by turbulence. Passively, turbulence affects zooplankton through vertical mixing, encounter rate, detection abilities and feeding current efficiency.

However, many zooplankton species are also actively able to mitigate turbulence effects by modifying behaviour, for example vertical migration, prey switching and habituation to hydromechanical stimuli. Observations at the northern site (see below) show both that some copepod species actively migrate to avoid high turbulence levels in surface waters and also that there is a negative relationship between turbulence and zooplankton ingestion rates (Visser and Stips, 2002).

## 2. Project outline and summary of results

Measurements of turbulence dissipation rate throughout the water column and turbulence intensity over a wide frequency range in continental shelf seas were at the heart of the project. These, together with particle and biological measurements concentrating on fluxes near the seabed, were made at two contrasting sites in the North Sea—a deep, low-energy site (north) and a shallow high-energy site (south) (Fig. 1 and

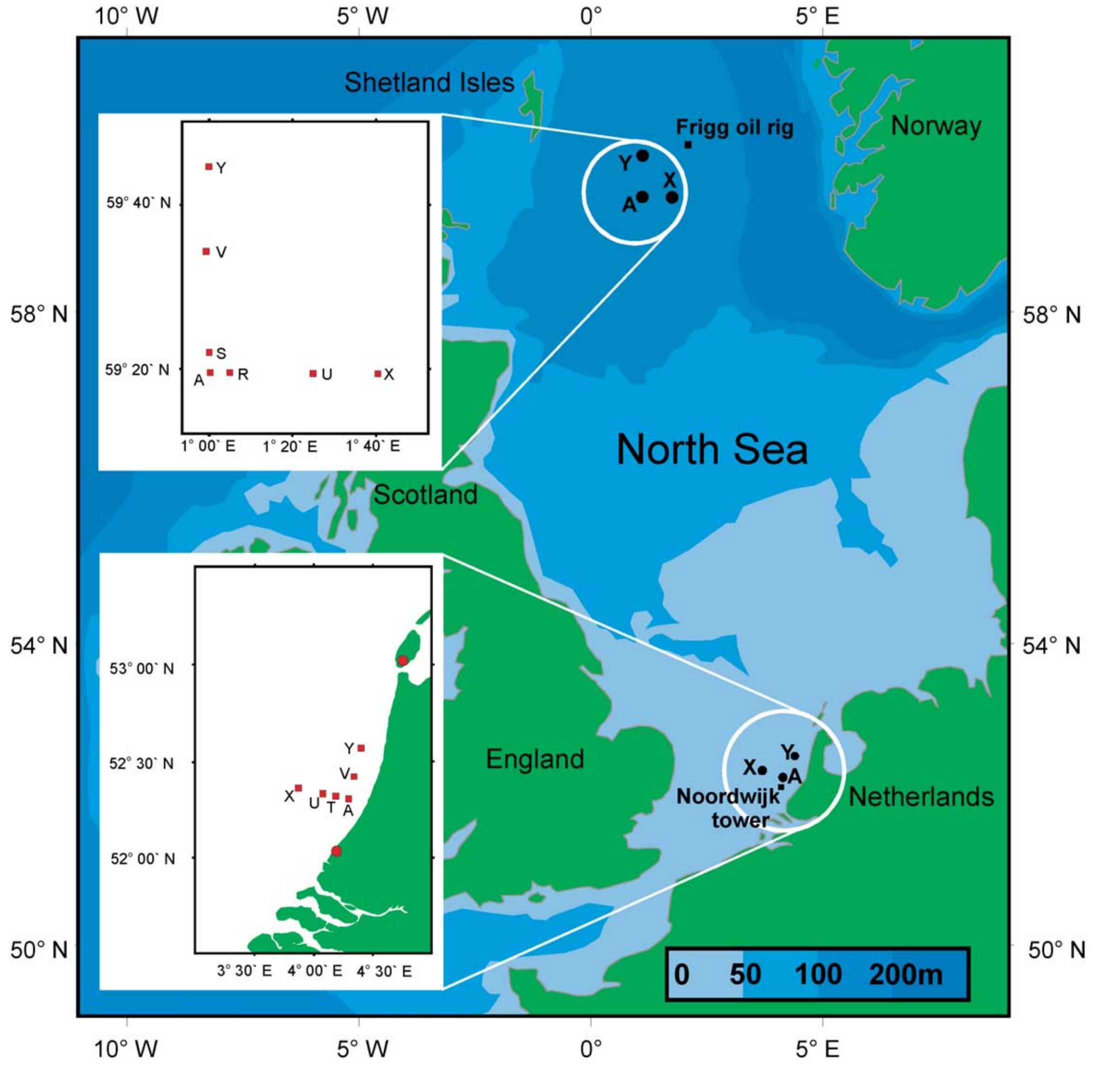

Fig. 1. Map of North Sea with insets showing the mooring arrays at the northern and southern sites.

Table 1
The salient conditions at each site

| | Northern | Southern |
|---|---|---|
| Dates | 5 September to 9 November 1998 | 29 March to 21 May 1999 |
| Central position | 59° 20′ N 1° E | 52° 18′ 22″N 4° 18′ 1.3″E |
| Situation | 150 km from nearest land (Shetland Isles) | 11 km from the Dutch coast |
| Water depth and maximum tidal range | 110 ± 0.8 m | 19 ± 1.25 m |
| Tidal wave | Progressive | Progressive |
| Max amplitude of the depth-averaged $M_2$ | 0.15 m s$^{-1}$ | 0.65 m s$^{-1}$ |
| Max amplitude of the near-bed $M_2$ | | 0.30 m s$^{-1}$ |
| Spring tides on | 22 September, 6, 20 October 1998 | 1, 18, 30 April, 17 May 1999 |
| Inertial currents | Episodes on 20–24 September; 15–19 October; 20–26 October (largest); speeds $<=$ 0.15 m s$^{-1}$ | |
| Mean current | $<=$ 0.02 m s$^{-1}$ | |
| Near-surface mean current | | 0.07 m s$^{-1}$ (northward) |
| Near-bed mean current | | 0.02 m s$^{-1}$ (towards coast/south/south-east) |
| Height above bed of zero mean flow | | 9 m |
| Wind speed, maximum | 20 m s$^{-1}$ | 17 m s$^{-1}$ |
| Weather | First half settled, with 3 storms; from 9 Oct. sustained winds 10–15 m s$^{-1}$ | Mainly $<$ 12 m s$^{-1}$, wind from south-west,but from north-east 26 April–4 May |
| Wave height, maximum | 5 m | 1.8 m |
| Water column structure | Temperature and salinity stratified | Well-mixed, apart from plume events, below |
| Surface temperature, $T_s$, start | 13.0°C | 7.2°C |
| Surface temperature, end | 9.5°C | 12.8°C |
| Bottom temperature, $T_b$ | ~ 7.4°C | |
| Depth of bottom of surface mixed layer, $[(T_s - T(z)) < 0.1°C]$ | 25–50 m | |
| Height of top of bed mixed layer, $[(T(z) - T_b) < 0.1°C]$ | 40–50 m | |
| Distance between layers | 5–40 m | |
| Pycnocline depth, [max. Brunt-Väisalä frequency, N] | 35–65 m | |
| | Approx. constant in first half, deepens episodically in second | |
| Thickness of pycnocline, $[N(z) > 0.015\ s^{-1}]$ | 5–20 m | |
| Surface salinity, start | 34.55 ppt | |
| Surface salinity, end | 34.81 ppt | |
| Bottom salinity | ~ 35.22 | 29–33 ppt, at 13 m below the surface |
| Near surface salinity | | 25–33 ppt, at 3 m below the surface |
| Significant near-surface salinity stratification on | | 30 March–2 April, 8–11, 25–29 April (surface temperature also up to 1.5°C warmer) |
| Annual mean discharge for Rhine (predominant source) | | ~ 2800 m$^3$ s$^{-1}$, high in March 1999 and slightly above annual average from 14–30 April, 1999 |
| Nutrients | Depleted in surface layer | |
| Near-bed Nitrate | | Decreasing from 50 μmol l$^{-1}$ to 16 μmol l$^{-1}$ on April 7 and thereafter |
| Phytoplankton | Small flagellates, typical of late summer, no evidence of autumn diatom bloom; chlorophyll $<$ 1 μg l$^{-1}$, largest values near surface, small below the pycnocline | Spring bloom peaks 26 April–6 May, with chlorophyll concentrations 35–40 μg l$^{-1}$ higher values near-bed |

Table 1 (*continued*)

| | Northern | Southern |
|---|---|---|
| Oxygen | 85% of saturation below the pycnocline | Supersaturated (up to 190%),<br>peak > 20 mg $l^{-1}$ at 1.5 m above the bed;<br>concentration decreasing towards the surface |
| Depth of euphotic layer (1% surface irradiance) | 50–60 m | 8–10 m |
| Biology | Oligotrophic | Eutrophic |
| Seabed | Muddy-sand<br>at start signs of benthic activity;<br>at end reworked/rippled-waves | Muddy-sand with fluff layer<br>during neap tides |
| Surface suspended sediment | 1 mg $l^{-1}$ (surface mixed layer) | < 25 mg $l^{-1}$ at 7 m above the bed |
| Near-bed suspended sediment | < 2 mg $l^{-1}$ (bottom mixed layer) | < 20 mg $l^{-1}$ at 1.5 m above the bed |
| Median particle diameter | 165–205 μm | 100–190 μm |
| Settling velocities, long-term | | |
| suspension component | $2\times10^{-4}$–$2\times10^{-3}$ mm $s^{-1}$ | $10^{-4}$–$10^{-3}$ mm $s^{-1}$ |
| resuspension component | 0.2–5.7 mm $s^{-1}$ | $10^{-2}$–$10^{-1}$ mm $s^{-1}$ |

Table 1) each for a two-month period. The measurements were applied principally to testing the robustness of parameterisations and starting to establish the domain of validity of turbulent physics (Burchard et al., 2002; Luyten et al., 2002) and integrated biological-physical water column models (Lee et al., 2002; Grenz et al., submitted).

### 2.1. Modelling

A one-dimensional integrated model PROWQM (PROvess Water Quality Model) was constructed and validated with existing data and with the turbulence and biological measurements from the northern site. The main objective of PROWQM was to provide a common framework and user-platform for the testing and validation of new and existing schemes for turbulence and of modules for biology and sediments prior to their implementation in three-dimensional numerical prediction models. The basic concept, structure and programming techniques are similar to the ones used in the extensively documented COHERENS model (Luyten et al., 1999), with the addition of the input of turbulence at the sea surface due to breaking waves (Craig, 1996; Luyten et al., 2002).

The coupled biology-physics modules within COHERENS (Luyten et al., 1999) have been developed further. The former model contained a single microplankton compartment and a single detritus compartment, and cycled carbon, nitrogen and oxygen. PROWQM's pelagic biological sub-model, of medium complexity, divided the microplankton compartment into 'diatomy' and 'flagellatey' microplankton, thus including the cycling of silicon as well as of nitrogen, and fast-sinking phyto-detritus as well as slow-sinking detritus. Phyto-detritus is formed by shear-driven aggregation of particulate material. Each microplankton compartment includes heterotrophic bacteria and protozoa as well as phytoplankton. The microbiological system is closed by mesozooplankton grazing pressures determined from observed zooplankton abundance. The benthic boundary sub-model includes a superficial 'fluff' layer and nutrient element reservoir in the consolidated sediment. Particulate material in the fluff layer can be resuspended (in response to bed stress by near-bed flows), mineralised or carried by bioturbation into the underlying, consolidated, sediment, where it is mineralised and its nutrients returned to the water-column at a rate mainly dependent on macrobenthic pumping (Lee et al., 2002; Grenz et al., submitted).

The eventual aim is to incorporate the improved understanding gained with the water column models into 3-D coupled physical-biological models capable of simulating the annual cycle, but this is beyond the scope of the project since major field experiments are required to test such models. However, concentrating on 1-D models has the potential to cause difficulties when testing model simulations against measurements, however carefully the experiments were planned, through the neglect of advection, horizontal gradients and variability and their effects (Umgiesser et al., submitted; Grenz et al., submitted). The compensation is that significant processes are isolated and model development and testing is speedy. Some of the difficulties were overcome by using measurements to specify the horizontal gradients and initial conditions, by running the models for a limited period only and by adjusting the models to conform with observations.

### *2.2. Measurements*

At both sites measurements were concentrated at a central position, with additional measurements being made to estimate horizontal gradients and transports, essential for the interpretation of the vertical exchange observations. Eighteen moorings were deployed at the northern site and 10 at the southern site (Tables 2 and 3, which also list the cruises to each site). The data can be displayed through , www.pol.ac.uk/provess and are included on the PROVESS data set CD-ROM (BODC, 2002).

The main measurements were of

Turbulence dissipation using repeated profiles over 13 or 25 hours of the FLY (Dewey et al., 1987) and MICSOS (Stips et al., 2000) free-fall microstructure probes deployed from a research vessel, measuring from ~ 10 m below the surface to close to the bed (0.15 m for FLY).

Turbulence intensity from fast sample current measurements from instruments mounted in seabed frames—electro-magnetic current meters, 8Hz, or from Acoustic Doppler Current Profilers (ADCP), 0.5 Hz-and a high resolution thermistor chain (1 m spacing, 0.05 Hz, Van Haren et al., 2001).

Non-turbulent dynamics with ADCPs, current meters and pressure recorders.

Meteorological and wave information were obtained from the Frigg oil rig at 59° 54′N 2° 6′E (90 km from the main mooring site for the north experiment) and the Noordwijk tower at 52° 16.5′N 4° 18′E (4 km from the main mooring site for the south experiment) after attempts to make in situ measurements were unsuccessful.

Water column biology and physics

Moored instrumentation—thermistor chains (+conductivity chains at the south site); fluorometers; nutrient (nitrate and silicate) analysers

CTD fitted with sensors for suspended sediment, chlorophyll, dissolved oxygen, irradiance.

Water samples for CTD sensor calibration; nutrients (nitrate, nitrite, ammonia, silicate, phosphate); pigments; particulate organic carbon, nitrogen and phosphorus; inorganic suspended particulate matter.

Optical properties of the water column (north site—Sagan et al., unpubl. ms.)

Pumped zooplankton samples and underwater video camera (north site)

Benthic exchanges

Respiration and mineralisation fluxes multi-corer (north site); benthic chamber (south site)

Near-bed water sampler.

Suspended sediment/particles with recording transmissometers; particle size spectra from a LISST 100 mounted on the CTD, and a GALAI (Latter et al., unpubl. ms.); settling velocity tubes.

### *2.3. Northern site*

The experimental sites in the North Sea (Fig. 1) were chosen to satisfy specific turbulence regimes. The sites' salient characteristics are listed in Table 1. The northern site, centred at 59° 20′N 1° E, is in a low-energy region, where the water depth (110 m) is sufficient for there to be clearly distinct surface and benthic boundary layers, separated by a strongly stratified layer, the pycnocline, varying in thickness from 20 to a few metres. The site's position was chosen to minimise the significance of advection, horizontal gradients, topography and other processes, such as fronts. It was situated in the middle of the northern North Sea, away from coasts and the Norwegian Trench. The site also avoided the main circulation paths in the region which follow the 100 m isobath and the shelf edge or are associated with the Norwegian Trench and the Norwegian Coastal Current (Turrell, 1992). Despite this, two small events in the bottom temperature record (magnitude 0.25 °C, duration a couple of days) and 1-D and 3-D modelling both indicate that advection was at times important for the temperature field (Burchard et al., 2002; Luyten et al., 2002; Umgiesser et al., submitted).

The experiment took place during the autumnal erosion of the thermocline, in September and October 1998. A main objective was to study exchanges across the thermocline, particularly as it deepened and with

Table 2
Cruise and moorings details for the northern experiment, 1998 (mab = metres above the bed)

| Ship | Start | End |
|---|---|---|
| Valdivia | 05 September | 17 September 1998 |
| Dana | 14 October | 26 October 1998 |
| Pelagia | 19 October | 30 October 1998 |
| Challenger | 22 October | 09 November 1998 |

| Rig | Instrumentation | Deployed | Recovered | Latitude (N) | Longitude (E) | Depth (m) |
|---|---|---|---|---|---|---|
| A | 150 kHz ADCP + pressure recorder | 08 Sept | 02 Nov | 59° 19.70′ | 1° 00.22′ | 105 |
| B | 1.2 MHz ADCP | 08 Sept | 01 Nov | 59° 19.54′ | 0° 59.99′ | 105 |
| Ca | 1.2 MHz ADCP | 08 Sept | 15 Sept | 59° 19.42′ | 1° 00.08′ | 107 |
| Cb | 1.2 MHz ADCP | 24 Oct | trawled | 59° 18.79′ | 1° 00.74′ | - |
| D | STABLE, bottom lander | 08 Sept | 01 Nov | 59° 19.89′ | 1° 00.06′ | 110 |
| E | Surface current, 4 and 10 m below the surface | 09 Sept | 01 Nov | 59° 19.21′ | 1° 00.02′ | 112 |
| Fa | Surface current, 4 and 10 m below the surface | 09 Sept | 15 Sept | 59° 19.10′ | 0° 59.99′ | 107 |
| Fb | Surface current, 4 and 10 m below the surface | 24 Oct | 03 Nov | 59° 18.72′ | 0° 59.80′ | 118 |
| G | Meteorological buoy | 08 Sept | 03 Nov | 59° 20.61′ | 0° 59.73′ | 104 |
| H | Waverider | 08 Sept | lost | 59° 20.45′ | 1° 00.87′ | 104 |
| I | Surface nitrate + fluorometer + transmissometer | 10 Sept | 26 Oct | 59° 19.38′ | 1° 00.62′ | 104 |
| J1 | Nitrate + fluorometer + transmissometer, 50 m above bed | 10 Sept | 05 Nov | 59° 19.59′ | 1° 00.65′ | 103 |
| J2 | Nitrate + silicate + fluorometer + transmissometer, 9 mab | 09 Sept | 01 Nov | 59° 19.74′ | 1° 00.58′ | 103 |
| L | Thermistor chain, 25–75 mab + temp. sensors + INFLUX | 10 Sept | lost | 59° 19.95′ | 1° 00.62′ | - |
| M | 600 kHz ADCP + 1.2 MHz ADCP + thermistor chain | 21 Oct | 03 Nov | 59° 19.05′ | 1° 00.52′ | 110 |
| R | Thermistor chain, 25–75 m above the bed + temp. sensors | 10 Sept | 01 Nov | 59° 20.00′ | 1° 05.00′ | 105 |
| S | Thermistor chain, 35–75 m above the bed + temp. sensors | 10 Sept | 01 Nov | 59° 22.45′ | 1° 00.00′ | 107 |
| U | 150 k Hz ADCP + pressure recorder | 07 Sept | 02 Nov | 59° 19.97′ | 1° 25.07′ | 100 |
| V | 150 kHz ADCP | 09 Sept | 03 Nov | 59° 32.64′ | 0° 59.62′ | 110 |
| X | Pressure recorder | 07 Sept | 02 Nov | 59° 19.93′ | 1° 40.43′ | 113 |
| Y | Pressure recorder | 08 Sept | 03 Nov | 59° 45.00′ | 1° 00.08′ | 114 |

the possibility of an autumnal bloom. This section of the seasonal cycle has been less well studied than the formation of the thermocline and the spring bloom. The water column was still stratified at the end of the experiment—complete overturning usually does not take place here until about a month later. The site was both temperature and salinity stratified with the thermocline and halocline coincident. The initial surface to bed salinity difference was 0.7 (Table 1). The source of the fresher surface water was presumably Norwegian Coastal or Baltic water spreading westward across the North Sea. However, salinity stratification does not always occur here, since there was none in 1991 when measurements were also made. Temperature differences contributed twice as much as salinity differences to vertical variations in density. The presence of salinity gradients had a significant impact on the Brunt-Väisalä frequency in the surface and bottom layers and on the buoyancy sink term in the turbulent kinetic energy transport equation (Luyten et al., 2002). The near-bed temperature and salinity remained approximately constant during the measurements, indicating little or no downward mixing across the thermocline (or removal of mixed water by advection). This was despite reworking of the seabed so that its characteristics were completely changed, from one of abundant benthic biological activity at the start to a biologically featureless rippled

Table 3
Cruise and mooring details for the southern experiment, 1999 (mab = metres above the bed)

| Ship | Start | End | |
|---|---|---|---|
| Pelagia | 29 March | 09 April 1999 | |
| Mitra | 19 April | 30 April 1999 | ( + Dissipation measurements from the Noordwijk Tower) |
| Belgica | 17 May | 21 May 1999 | |

| Rig | Instrumentation | Deployed | Recovered | Latitude (N) | Longitude (E) | Depth (m) |
|---|---|---|---|---|---|---|
| A | STABLE, bottom lander | 30 March | 19 May | 52° 18.38′ | 4° 18.01′ | 20 |
| M | 600 kHz ADCP + pressure + thermistor chain, 1 – 11 mab | 29 March | 08 April | 52° 18.13′ | 4° 18.02′ | 19 |
| B | 1.2 MHz ADCP + pressure recorder | 30 March | 19 May | 52° 18.14′ | 4° 18.40′ | 20 |
| B | Thermistor/conductivity chain, 3 – 13 m below the surface | 30 March | 19 May | 52° 18.14′ | 4° 18.40′ | 20 |
| D | Surface currents, 4 m below the surface | 30 March | 18 May | 52° 18.20′ | 4° 17.67′ | 19 |
| G | Surface nitrate + fluorometer + transmissometer | 29 March | 18 May | 52° 17.88′ | 4° 17.98′ | 19 |
| H | Near-bed nitrate + silicate + fluorometer + transmissometer | 30 March | 18 May | 52° 18.01′ | 4° 18.01′ | 18 |
| T | 1.2 MHz ADCP + pressure recorder | 30 March | 18 May | 52° 19.19′ | 4° 11.72′ | 22 |
| T | Thermistor/conductivity chain, 3 – 13 m below the surface | 30 March | 18 May | 52° 19.19′ | 4° 11.72′ | 22 |
| U | Current meters at 3 and 13 m above the bed | 30 March | lost | 52° 20.10′ | 4° 05.12′ | 23 |
| V | Current meters at 3 and 9 m above the bed | 30 March | 18 May | 52° 26.31′ | 4° 21.02′ | 19 |
| X | Pressure recorder | 29 March | 18 May | 52° 21.79′ | 3° 52.02′ | 24 |
| Y | Pressure recorder | 30 March | 19 May | 52° 34.09′ | 4° 24.01′ | 19 |

bed at the end, presumably by the impact of wave activity (in 110 m of water). Maximum shears occurred during periods of inertial currents, up to 0.04 $s^{-1}$ across the thermocline based on a 4 m depth resolution, giving a minimum associated Richardson number (Ri) of slightly less than 1 (Knight et al., 2002). Evidence for the importance of inertial shear for diapycnal exchange was found in sudden enhancement of near-surface nutrient levels, coinciding with the period of persistent low Ri (van Haren et al., 2002).

For one 24-h period simultaneous measurements of turbulence microstructure were obtained from the two systems-FLY and MICSOS, operated from two different ships about 2 km apart- and their results have been compared with estimates from several different turbulence model formulations. The differences between estimates of turbulence dissipation rate from these two sets of observations were significantly larger than the equivalent measures between the model results. Probable reasons are the stochastic character of turbulence microstructure in connection with under-sampling and the distance between the two ships, the movement of the vessels and instrument errors. The models on the other hand, although closed on different levels, were all based on the same assumptions and driven by the same external forcing, and therefore showed only relatively small differences (Burchard et al., 2002).

Suspended particulate matter comprised two modes, one a slow-settling mode in long-term suspension, the other a fast-settling resuspension mode which appeared only during major hydrodynamic events. Mean particle size was remarkably uniform in the surface mixed layer, with little vertical variation. It increased upwards from the seabed towards the base of the thermocline where it reached a maximum value. It is proposed that these observed variations were caused by aggregation and disaggregation forced by variations in turbulence dissipation. In the surface mixed layer, dissipation was high and shear stresses were sufficient to overcome the shear strength of large aggregates; particle size was therefore small. In the thermocline, dissipation decreased dramatically so mixing and vertical exchange were reduced; this increased the residence time of particles which had time to form large, faster-settling, aggregates in a region where shear stresses were insufficient to break them up. Dissipation then increased towards the seabed, and particle size decreased as aggregates were progressively ruptured. These observations suggest a mechanism whereby suspended particulate matter can be more rapidly transferred to the bottom mixed layer and lost to the surface mixed layer (Jago et al., submitted).

### 2.4. Southern site

The southern site, in a high energy, shallow, tidally dominated region, was centred at 52° 18′ 22″ N 4° 18′ 1.3″ E, about 11 km from the Dutch coast (Fig. 1). The main focus here was the interaction between turbulence and particles and the consequence for nutrient fluxes. Whilst satisfying the criteria for a homogeneous region would have been desirable, this is not fully possible in tidally dominated, shallow coastal waters. The site was 50 km downstream from the mouth of the Rhine and consequently horizontal density gradients had a strong impact on the local dynamics. There were also intermittent incursions of Rhine plume water at the site, which resulted in significant vertical density gradients. The mean currents were sheared in the vertical, with a strong surface flow approximately along shore and a weaker near-bed flow onshore, suggesting a density-gradient driven estuarine type circulation. In view of the site's proximity to the coast the transverse dynamics at all frequencies maintained zero net transport to first order, so that the onshore/offshore component of current was in anti-phase about an approximately mid-depth level (across the strongest stratification, when present).

The strong tidal currents interacted with the offshore salinity gradient with the result that strain-induced periodic stratification dominated, with the water column switching between being totally mixed and stratified. Both the tidal flow and wind appeared to contribute to the rate of turbulence dissipation, with high levels of dissipation throughout the water column also attributed to shear-generated instabilities resulting from differential advection by the tide, a process also observed in the Liverpool Bay area of the Irish Sea (Fisher et al., 2002; Rippeth et al., 2001). Momentum fluxes and, very exceptionally, heat fluxes were estimated and compared with turbulence dissipation measurements. Surprisingly, the heat (buoyancy) fluxes contributed little to the production (suppression) of turbulent kinetic energy, despite strong stratification at times. Most kinetic energy production was observed near tidal frequencies and associated with stratification, being largest near mid-depth, albeit varying strongly with time (Gemmrich and van Haren, 2002).

The experiment took place during and after the spring bloom in April and May 1999 (with the water column warming up throughout the period) in order to investigate the effects of biology on particle dynamics, particularly in relation to the benthic fluff layer. In the relatively turbid waters at the site vertical mixing periodically resuspended optically active particles from the bed fluff layer throughout the water column and into the near surface layer, and was the single most important factor controlling the distribution of suspended particulate matter. Hence, although the euphotic layer was only 8–10 m deep, complete vertical mixing of the water column ensured that all phytoplankton had access to sufficient light for growth (Wild-Allen et al., 2002). One aim of the experiment was to study particle processes in a high energy environment—flocculation and sedimentation of material, the development of near-bed layers of aggregated phytodetrital fluff which occurred only during calm neap tide periods, resuspension and the remineralisation of nutrients in flocs and the benthic layer (McCandliss et al., 2002). The supply of organic material to the sediment only occurred during low tidal energy periods when reduced turbulence allowed particles to settle to the seabed. Comparing observed and simulated sediment oxygen demands with water column respiration measurements it can be stated that the mineralisation processes mainly took place in the water column during the study period in this shallow area of the southern North Sea (Grenz et al., submitted).

## 3. Conclusions

Two high-quality data sets (BODC, 2002) aimed at studying processes of vertical exchange in shelf seas and including turbulence dissipation, particle size spectra, zooplankton and nutrient cycling have been obtained from contrasting sites and used to test physics and coupled physics-biology water column models.

The results have been summarised in Section 2 above and are given in detail in the papers in this and a subsequent volume of the Journal of Sea Research.

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