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Measurement strategy of PRISMA: design and realisation

Uwe H. Brockmann[1,*], Thomas Raabe[1], Klaus Nagel[2], Michael Haarich[3]

[1]Zentrum für Meeres- und Klimaforschung der Universität Hamburg, Institut für Biogeochemie und Meereschemie, Martin-Luther-King-Platz 6, D-20146 Hamburg, Germany

[2]Institut für Ostseeforschung an der Universität Rostock, Seestr. 15, D-18119 Rostock-Warnemünde, Germany

[3]Bundesforschungsanstalt für Fischerei, Wüstland 2, D-22589 Hamburg, Germany

ABSTRACT: To approach the aims of the German research project PRISMA, an integrated measurement strategy was developed, following the nesting principle: (i) drift experiments which involved sampling in a defined water mass aiming at the analyses of transfer and transformation processes were supplemented by (ii) analyses at 3 equidistant drifting positions 3 n.m. (nautical miles) apart, which were performed in (iii) a grid of equidistant stations at fixed positions 10 n.m. apart, covering the German Bight, to identify hydrodynamic and biogeochemical changes or interferences affecting the drift area. In this way, the spatial representativeness of frequent point measurements at drifting stations could be estimated, as well as the short-term variability during the 4 d duration of each grid survey in the German Bight. The latter also provided data sets for transport modelling. In addition time series data were collected at 6 mooring stations equipped with current meters, CTD and transmission meters. Some of the modelling was already performed during the experiment with a daily operational model (used by BSH, Bundesamt für Seeschiffahrt und Hydrographie, Hamburg) comprising atmospheric and ocean models. The output provided nearly real-time information on the drift direction of the defined water masses. The results of more extensive model calculations allowed the subsequent description of water mass transports in different depths of the German Bight. A great number of samples were taken for the estimation of bulk parameters in order to define the status of the ecosystem. Taking account of the time and position of these measurements, selected samples were processed for the analysis of contaminants, which required more effort. Some examples are discussed that illustrate the advantages and disadvantages of the measurement strategy. These focus mainly on hydrographic measurements and nutrient data, reflecting the dominant biological processes investigated during PRISMA.

KEY WORDS: Measurement strategy · Drift experiment · Nitrate

INTRODUCTION

Ecosystem analyses using sampling in station networks in the German Bight were first performed in 1935-36 (Kalle 1937) and since then have been repeated several times on seasonal and monthly scales (Anonymous 1992, Heyer et al. 1994). Sampling repeated in stationary grids over several days has also been conducted to detect current-related processes affecting the measured gradients (Brockmann 1987); in addition, drift experiments combined with mesocosm experiments and lasting several days have been performed (Brockmann 1991, 1992).

The main investigations during the German research project PRISMA, running from 1990 to 1993, were conducted during April and August 1991. Here, results mainly from the April cruise will be discussed, illustrating the advantages and limitations of the applied measurement strategy. Since changes in nutrient concentrations reflect net biological turnover processes, and nutrient gradients are indicative of different water masses and their motion (Brockmann & Eberlein 1986),

*E-mail: brockmann@rrz.uni-hamburg.de

these components were chosen to illustrate the integrated measurement strategy.

Stratification of the water column is controlled (1) by the freshwater discharge of the Elbe and the Weser (Frey & Becker 1986), amounting to about 500 $m^3 s^{-1}$ during spring 1991 (ARGE 1992), and (2) by heating of the water surface, resulting in formation of a thermocline between late spring and fall, which sometimes even reaches shallow areas of 25 m water depth. Frontal systems, such as tidal mixing fronts, upwelling fronts and especially the river plume fronts of the Elbe, separate water masses of different origin (Krause et al. 1986). Due to variable discharges and wind directions, the Elbe plume can spread over large areas of the German Bight (Brockmann & Eberlein 1986). The prevailing westerly winds often press the plume along the eastern coast and large parts traverse the Wadden Sea (Brockmann et al. 1994).

In spite of an estimated residence time on the order of months for the German Bight water in the North Sea (Smith et al. 1997), strong or changing wind pressure may completely change the gradients in the German Bight within 5 to 10 d. This is another reason for process studies being so difficult to conduct in this area. Other problems are caused by the inhomogeneous topographic structure, which enhances local upwelling (Elbe valley, Helgoland), formation of eddies (Schrum 1994), vertical mixing and separation of water masses in tidal basins, along banks and island chains. The variable and high load of nutrients and contaminants discharged into the German Bight (ARGE 1992) affects the gradients and ecosystem processes as well.

MEASUREMENT STRATEGY

General. One of the main aims of the project was the estimation of biogeochemical processes, including phase transfer of selected contaminants such as heavy metals and pesticides, in the German Bight. The phase transfer is linked to the production and decomposition of phytoplankton biomass, which is fertilised by the river discharges into the coastal water.

Another aim was the quantification of mass transports in the German Bight, including dissolved and particulate material. The following 2 processes interfere containing these transports: (1) advection of water masses containing significant gradients of interacting constituents superimposed upon biological processes, and (2) biogeochemically controlled phase transfer, which affects the transport characteristics of individual compounds.

Therefore, processes of tranport, phase transfer and transformation of chemical compounds had to be investigated simultaneously at scales corresponding to the extent and velocities of the different interacting processes. Due to the overlapping of transports on different scales (tidal cycles, residual and wind-driven currents), involving different media (air, water, suspended matter), with biogeochemical processes affecting the dissolved and particulate chemical constituents and the plankton community, we had to combine sampling scales in space and time, from meters (gradients in the water column) up to 100 km (spreading of water masses and atmospheric forcing), and from hours (diurnal signals) to weeks (variation of advective effects), respectively.

In Fig. 1, an overview of the experimental setup is given:

(1) By sampling a grid of about 50 stations spaced 10 n.m. (nautical miles) apart, the gradients and boundary conditions over 4 d periods in the German Bight were identified.

(2) At 6 stations moorings were launched to measure currents, salinity, temperature and turbidity at a 5 min sampling rate, providing information for hydrodynamic models and on tidal effects.

(3) At 4 stations, meteorological measurements were performed, partly combined with sampling of dry and wet precipitation products to monitor the atmospheric inputs into the environment.

(4) Drift experiments, each lasting a few days, were performed in 2 areas, with sampling occurring every 6 h at 4 drifting positions to quantify the biogeochemical processes in this Lagrangian field.

Satellite data (NOAA) were collected for identification of sea surface temperature to quantify some frontal structures.

Fig. 2 shows the different parallel activities over the time course of the experiment, together with the wind situation, reflecting the variability of one of the main forcing functions. At the meteorological stations, sampling of airborne chemical compounds was performed parallel to the ship-based measurements. Moorings were anchored from April 14 to May 1, 1991. The station grid in the German Bight was sampled on 4 surveys between April 17 and 30. During the first survey, 2 ships worked parallel to each other, analysing the ecosystem components as well as contaminants. After this, RV 'Gauss' continued the grid sampling, whereas RV 'Valdivia' carried out 2 drift experiments, from April 19 to 23 and 23 to 29. At the same time, RV 'Atair' checked the moorings and analysed transects in the area surrounding the drift stations and moorings, relating these sampling locations to the adjacent grid stations by hydrographic data sets.

For the meteorological forcing of the hydrodynamic models and the calculation of deposition rates, data from the German Meteorological Service in Offenbach

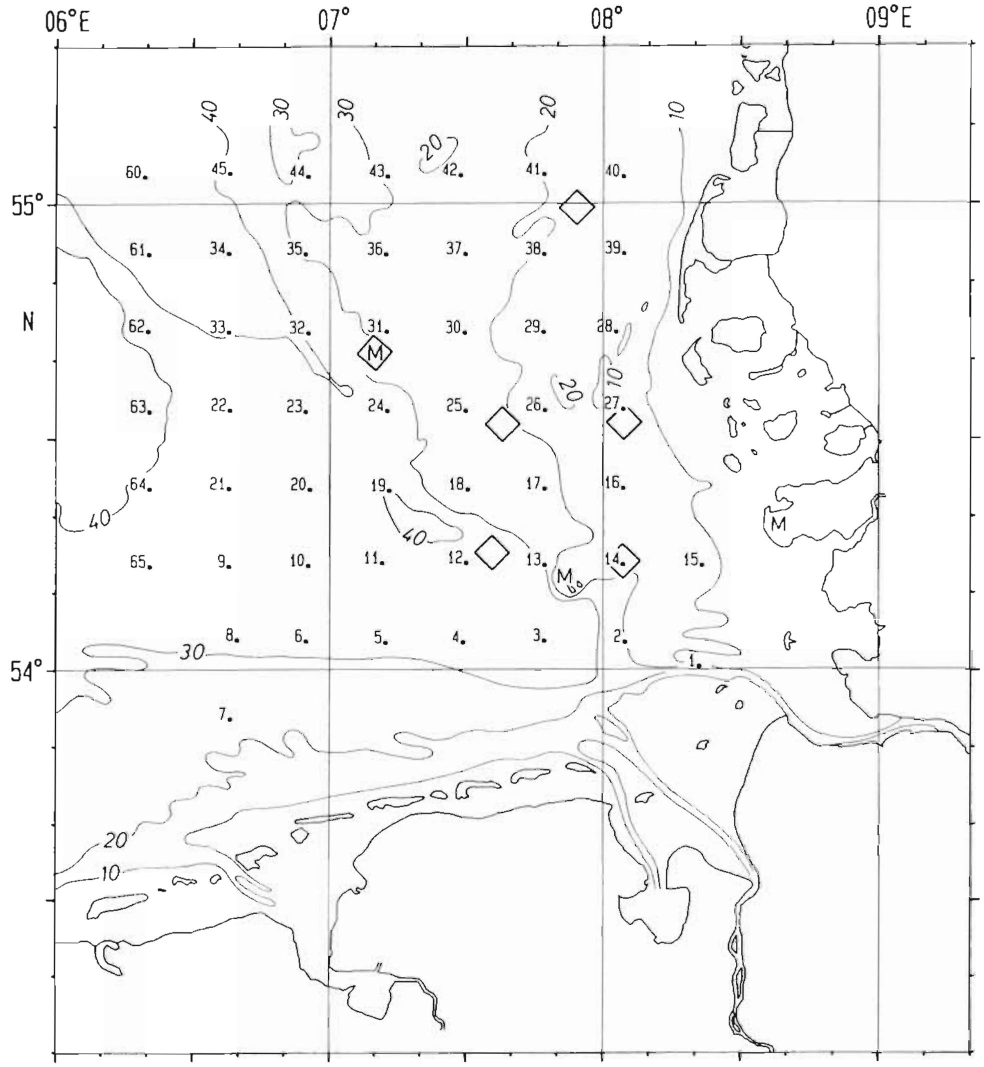

Fig. 1 Map of measurement activities during the PRISMA experiment in April 1991 in the German Bight. Numbers mark regular field stations; (◇) mooring; M: meteorological station. The contours are isobaths in meters

were used. The sampling strategy for atmospheric measurements and modelling in PRISMA is described by Schlünzen et al. (1997, this volume).

Drift experiments. In order to study transfer and transformation processes in the Elbe river plume and in the outer German Bight, the main drift experiments (D2 and D3) were performed between April 20 and 29, 1991, following a drifter in a water mass which had been previously identified. Taking into account the shortcomings due to the slippage of the drifter (Booth 1981), which may occur especially in shallow coastal waters, this type of measurement was considered to provide the most realistic process data. Even just a few days with frequent measurements would allow a rough estimate of production processes in the selected water masses, if advective interference could be detected and considered for the data interpretation.

The dominant chemical signal in the German Bight is the discharge of nutrients and contaminants by the Elbe River. For this reason the succession of processes occurring in the propagating river plume of the Elbe were of more interest than processes outside the plume. To identify the position and extent of the Elbe plume, a station grid was sampled which covered a large area of the German Bight (see below). From the determined gradients of salinity, temperature, nutrients and chlorophyll, possible locations for the drift experiment were defined.

These areas were (1) in the Elbe river plume, at a steep nitrate and salinity gradient, and (2) outside these gradients in an area where other gradients were dominant. Salinity and nitrate isopleths demonstrate the extent of the river plume well (Fig. 3). During April 1991 the Elbe plume was spread northward along the

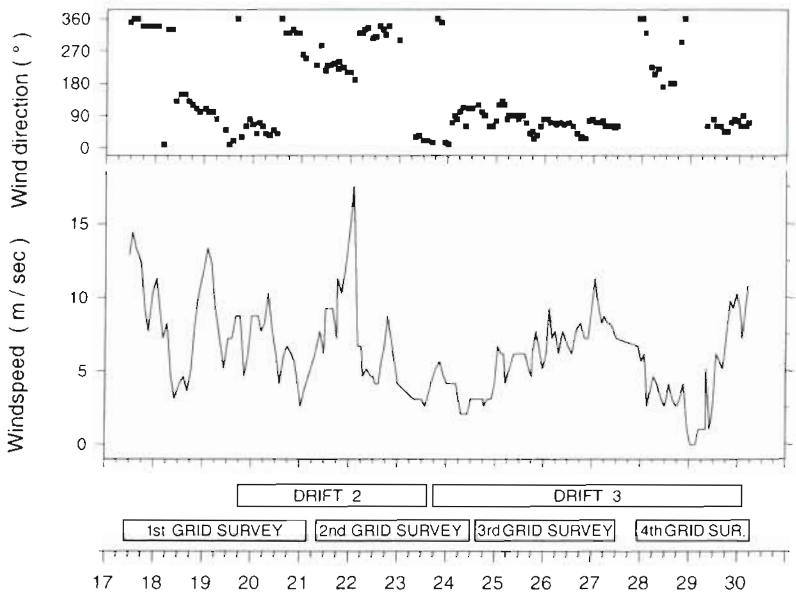

Fig. 2. Measurement activities of the PRISMA experiment in the German Bight during April 1991, together with wind direction and speed

and to the northwest, respectively, of the actual drifter position at the start of sampling (Fig. 4). By this strategy it was possible (1) to sample all stations every 6 h at the same times each day and (2) to detect immediately changes of gradients in the neighbourhood. By (1) diurnal effects could be identified, by (2) interfering advection of gradients could be considered in process calculations.

When the vessel was separated from the drifter, its current position was identified by radar measurements. The drift tracks are given for the third drift experiment (D3) as Lagrangian and Eulerian positions in Fig. 5. In the Eulerian plot, the effect of tidal action superimposed on the wind drift to the south can be seen clearly.

Sampling was performed at standard water depths of 1, 5, 10, 20, 30 and 40 m and 2 m above the bottom, combined with continuous vertical profiling by CTD probes in a rosette sampler. The

coast due to the westerly wind forces which had dominated previously. Nitrate, a typical tracer for the Elbe (Brockmann & Eberlein 1986), reached more than 40 µM in the inner German Bight, and was still around 20 µM in the D2 drift area. The shape of the 10 µM nutricline indicated inflow of nitrate-enriched water from the west with the prevailing direction of the coastal current. The first experiment was terminated by onshore wind moving the drifter into shallow areas where navigation with a seagoing vessel was no longer possible; the second experiment was finished when the drifter had left the chemically characterised water mass.

The drifter had a cruciform drag sail with a size of 2 × 3 m (width × height), fixed at 3 m depth to a buoy with a radar reflector. This was a compromise, as all drifters are. During this experiment it was necessary to leave the drifter for some hours and to locate its position from a distance of 3 n.m. Therefore, the buoy had to be large enough to carry a 1.5 m mast with the reflector, in spite of the fact that due to this the drifter was subject to additional driving force from the wind.

To identify advective changes of gradients which would affect process measurements seriously, sampling at the drifter position was supplemented by measurements at 3 stations located 3 n.m. to the south, to the northeast

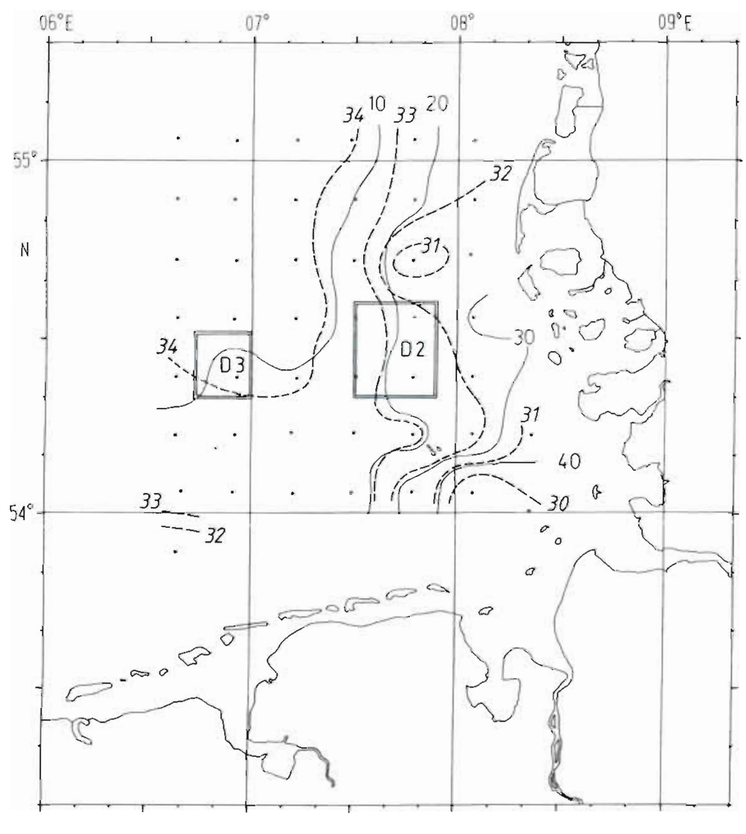

Fig. 3. Isolines of salinity (---, ‰) and nitrate (——, µmol l^{-1}) in the German Bight between April 16 and 21, and drift areas D2 and D3. This series of articles focusses on D3

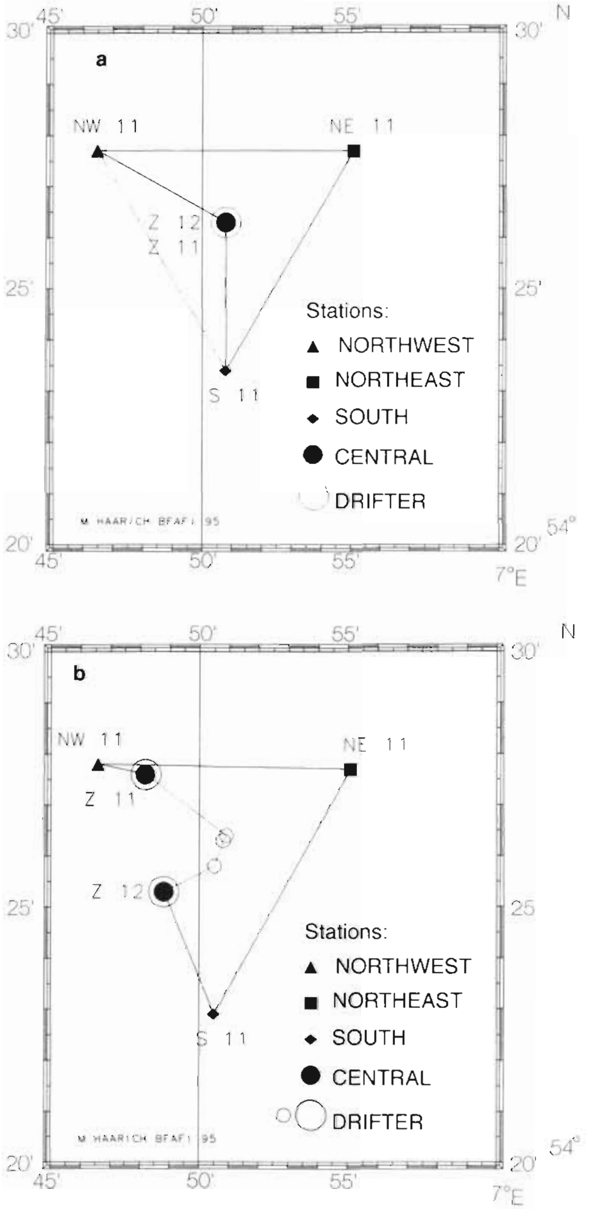

Fig. 4. Arrangement of central and surrounding drift stations in relation to the (a) drifting field and (b) geographic positions during the third drift experiment. Example of sampling positions (11 and 12): (a) Lagrangian, (b) Eulerian

analysis of the pelagic ecosystem was based on measurements of nutrients, dissolved and particulate organic and inorganic material, chlorophyll and phyto- and zooplankton. Contaminants were sampled at depths selected from the standard program, using special samplers (Freimann et al. 1983, Gaul & Ziebarth 1983). Particulate material, collected in a drifting sediment trap attached to the drifter, was also analysed for contaminants.

Due to the fact that the analyses of trace contaminants consume much more time than measurements of other ecosystem components, samples for the estimation of trace metals and pesticides were only collected at the central drift position. By measuring the basic ecosystem components at all stations it was possible to relate advective shifts in the surrounding area to changes at the central position and also to consider these effects in the interpretation of contaminant data.

As can be deduced from the nitrate measurements during the drift experiment, the central station during Drift 2 was located in an east-west gradient of the river plume because the concentrations were higher about 2.6 n.m. eastward and lower westward, whereas there were no differences at the southern station (Fig. 6). During Drift 3, outside of the main river plume, there were no or only small but variable, mainly south-north

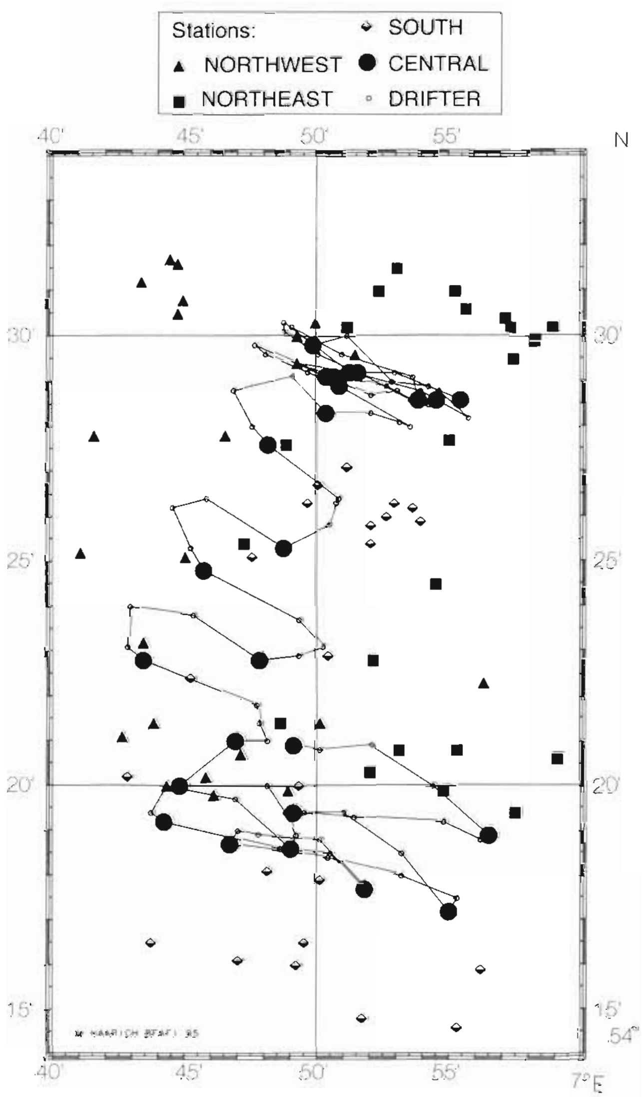

Fig. 5. Locations of central and supplementary drift stations during Drift 3. Line shows the (Eulerian) position of the central drift section

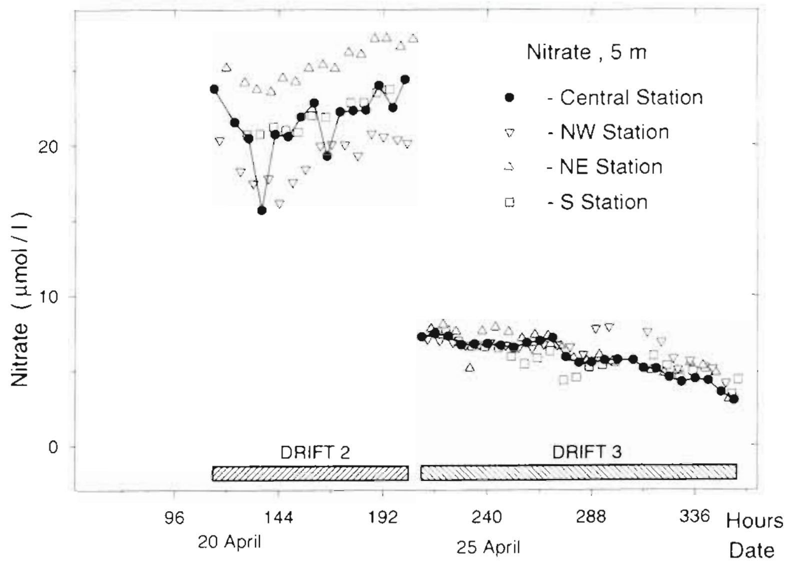

Fig. 6. Development of nitrate concentration in the drift field during Drift 2 and Drift 3

for the different drifting positions were significantly positive, indicating the advection of nitrate-richer water from the west into this area (Fig. 8).

This fact made it difficult to calculate production processes from concentration changes. Indeed, the decrease of nitrate during Drift 3 was significantly correlated with a salinity increase, which was a clear signal that the drifter had moved into a different water mass. Model studies showed the change of water masses as well (König & Schrum 1977, this volume). However, after this shift, the ratio of nitrate to salinity still showed a decrease during Drift 3, indicating net consumption in the course of primary production in the area (Fig. 7). The primary production could be estimated from the differences in salinity-correlated and measured nitrate of 0.23 µM d^{-1} (0.7 µM over 3 d, April 26 to 29) (Raabe et al. 1997). This biological nitrate consumption could already be deduced from the diurnal variation of the nitrate concentrations itself (Fig. 6): during daytime the strongest decrease occurred, whereas at night a small increase indicated a permanent nitrification of remineralised ammonium. Therefore, primary production calculated from nutrient decrease will give a rough net estimate.

nitrate gradients in the neighbourhood of the central drift station.

However, looking at the nitrate gradients during Drift 3 in more detail, significant deviations up to 2 µM could be registered within the drift field (Fig. 6). The drifter was initially in an area with dominant north-south gradients and moved on April 26 into water masses with west-east nitrate gradients, with higher values in the west (for details see Raabe et al. 1977, this volume). This was in contrast to the main nitrate gradients in the German Bight, which were dominated by the Elbe discharge and, therefore, significantly negatively correlated with salinity. The same correlations

As shown in Fig. 6, the differences in nitrate between the drift positions were mainly less than 1 µM but sometimes reached more than 2 µM. The salinity gradients did not vary in the same way, resulting especially during the second half of Drift 3 in a stronger deviation of the nitrate/salinity ratio between the western and the

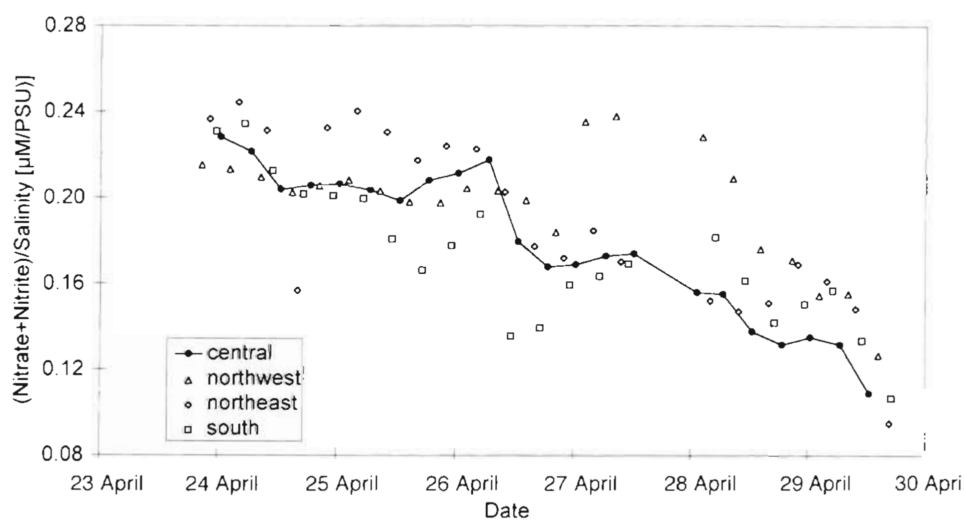

Fig. 7 Nitrate+nitrite salinity ratio at 5 m depth during Drift 3 (April 1991) at the central position and 3 surrounding stations 3 n.m. away

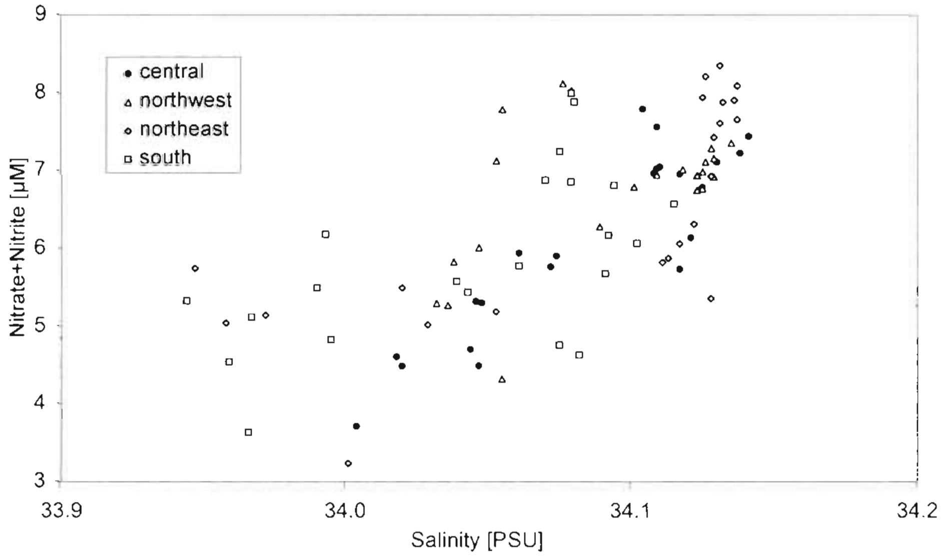

Fig. 8. Nitrate concentrations in relation to salinity at the 4 stations of Drift 3

other stations, indicating that the western stations were affected by processes other than simple advection, probably mixing with water originating from the Elbe plume (Fig. 7). The explanation can only be found by monitoring these gradients at a larger scale than that of the measurements in the station grid (see below).

Station grid surveys. The movement of water masses e.g. of different salinity, caused by local wind stress and long distance advection, could best be documented by monitoring a station grid covering large parts of the German Bight. By these measurements the extent of the Elbe river plume, the density stratification as well as occasional upwelling events connected with the formation of frontal systems could also be identified. By repeated surveys of the complete station grid surrounding the local drift experiments, advective shifts of gradients as well as roughly estimated net conversion processes could be monitored.

The nesting strategy with regard to analyses of ecosystem components and contaminants was also followed in sampling the station grid. During the first grid survey, 2 ships operated parallel to each other, allowing synoptic sampling of contaminants and ecosystem components. Effects of phase transfer on the distribution of contaminants could be deduced from the development of the ecosystem, as monitored on 4 repeated surveys, in addition to the continued parallel measurements at the central drift station.

The net turnover and advection of gradients can be roughly estimated from the repeated grid sampling (Fig. 9). In the western part of the river plume, in which Drift Area 2 was located (between Stns 25, 26, 17, and 18; see Figs. 1 & 3), a nitrate increase was observed, due to prevailing easterly winds (Fig. 2) spreading the river plume westward. The short period of westerly winds around April 21 and 22 during the second grid survey (Fig. 2) was well reflected in an intermediate nitrate decrease at Stns 30, 29, 28, 27, and 17. The nitrate increase during Drift 2 (April 20 to 23) occurred during westerly winds, which moved the drifter more towards the center of the nitrate-rich river plume.

Outside the plume, there was a general nitrate decrease, with the exception of some stations (60, 61, 34, 33, 22, 21) in the area of the Elbe valley, probably due to upwelling processes. Here, nitrate-rich water flowed into the German Bight due to upwelling during easterly winds. This is also an explanation for the nitrate increase during Drift 3 (between Stns 20 and 23) at the northwesterly drift station on April 27–28 following a period of increasing easterly winds (Fig. 2). Indeed, the highest nitrate concentrations were measured at Stn 21, compared to the surrounding grid stations (Fig. 10). The comparison between grid and drift station (only the central station is presented) showed that there was good agreement for the data sets and that trends and deviations at the drift stations could be explained by advection in the surrounding area. On the other hand, the nitrate consumption observed during Drift 3 could be assumed to be representative for a larger area surrounding the river plume. This process could not be deduced from the nitrate gradients in the outer river plume, but it can be assumed to occur there as well (Morris et al. 1995).

By combining the different data sets it will be possible to identify both the net turnover and advective movements of gradients in space and time.

Moorings. In order to study the effects of tidal action, wind stress, and residual currents over a longer period

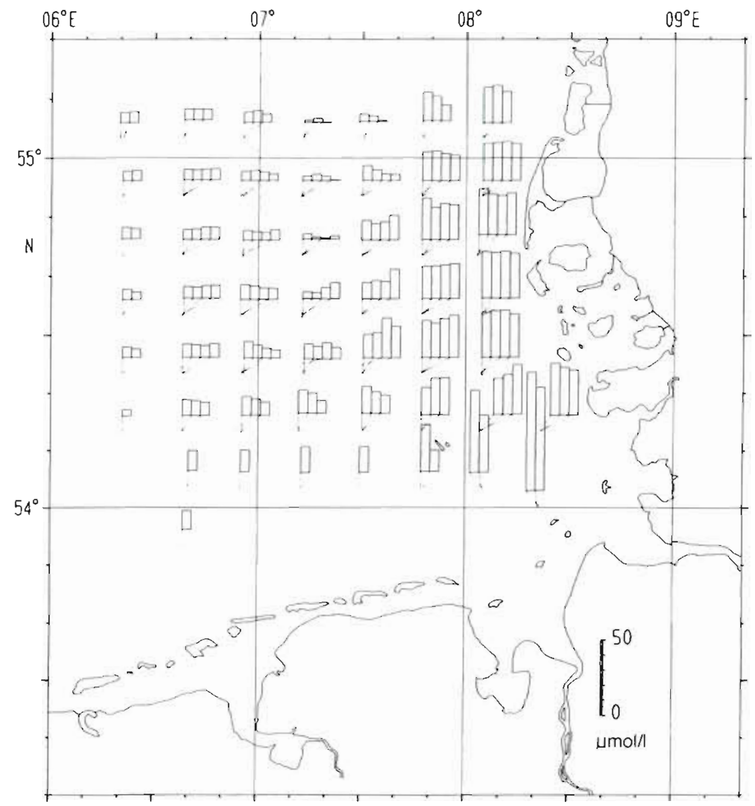

Fig. 9. Surface nitrate concentrations (µmol l^{-1}) measured during the station grid surveys in the German Bight. The bars represent from left to right the succeeding measurements between April 4 and 30 (Survey 1. April 16–20; Survey 2: April 21–24; Survey 3: April 24–27; Survey 4: April 27–30). The northern and southern legs were only sampled at the beginning of the experiment. Sampling in the western leg was supplemented during the last 2 surveys

the frequently changing tidal signals. These data are supplementary for the interpretation of measurements in the drift areas and on the station grid, and they were primarily used for validation of hydrodynamic modelling.

The first moored systems were already working on April 15, registering a storm on April 16 and 17 with a significant increase in turbidity near the bottom (Becker et al. 1992). This event mixed the water column completely and caused the observed high concentrations of ammonium and phosphate released from the sediment at the beginning of the grid measurements (Brockmann et al. 1992). The turbidity measurements indicated a permanent offshore transport of suspended matter by tidal action, which was included in transport models (Beddig et al. 1997).

The measured tidal currents gave a first estimate of water mass transport for identifying the deviation of the drifter course from the originally defined water mass. The progressive vector diagram from a current meter moored in 10 m depth, 22 n.m. northwest of Helgoland near Drift Area 2, gave the same direction, extension and tidal ellipse dimensions as the observed drifter course between April 20 and 24 (Becker et al. 1992). This provided a basis for hydrodynamic models to simulate the drifter's course relative to the currents.

of time, 6 moorings were deployed. Since they were launched before the start of the main ship-based investigations, the state of the Bight preceding the experiment and affecting its initial conditions could be monitored as well. The moorings were located around the presumed area of spreading of the Elbe river plume. For logistical and safety reasons, the moorings were checked regularly by a third vessel, thus providing intercalibration measurements and prevention of damages by the fishery. For this reason, it was not possible to moor hydrodynamic systems over great distances and, therefore, no instruments were anchored in the western part of the German Bight.

The probe systems provided information on local shifts in salinity, temperature and turbidity gradients, including

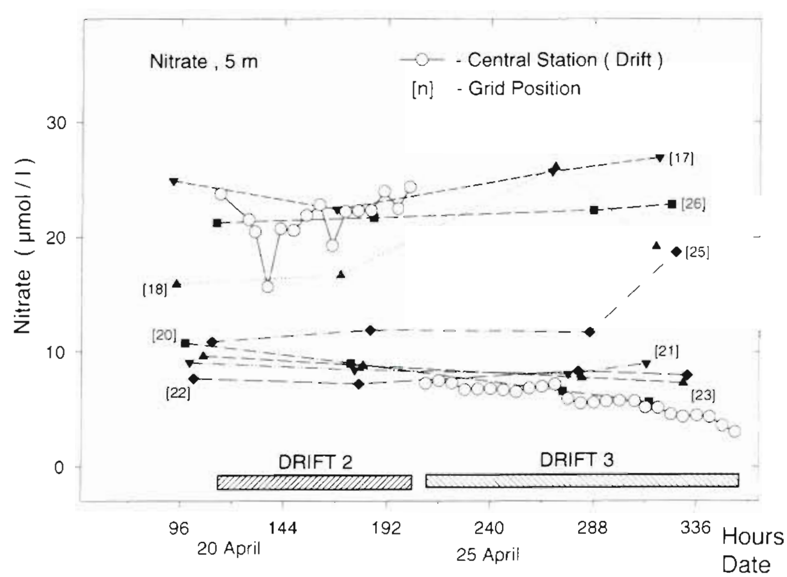

Fig. 10. Nitrate concentrations at the central drift position and at the adjacent grid stations

INTEGRATION WITH MODELLING

Scaling. The experimental time scale includes (1) large-scale meteorological observations and transport modelling, including the distant field of the Northwest European shelf, for obtaining boundary conditions in the German Bight, (2) mesoscale resolution for grid sampling, mooring distances and meteorological sampling stations surrounding the Bight, and (3) small-scale drift experiments within a few n.m., including high-resolution vertical profiles in the water column.

The more expensive sampling and analyses of contaminants were nested within this program, and the interpretation was based on transport models and on the development of the marine ecosystem, whose compenents were measured at a higher resolution.

Hydrodynamic models. Hydrodynamic models were used within this measurement strategy to calculate the boundary conditions for the investigations in the German Bight, such as the existence of large scale recirculation west of Helgoland coupled with local upwelling (König & Schrum 1997).

Also the course of the drifter was recalculated using a hydrodynamic model based on hydrographic measurements and wind field data, resulting in estimates of daily differences between the drifter track and the calculated trajectory of water mass transport. This difference was largest on April 26 and 27 (König & Schrum 1997). The event which caused this was responsible for the observed maximum gradients within the drift field on April 27 and 28 (Figs. 6 & 7). It could be shown that wind effects on the drifter were responsible for these deviations, reaching a maximum of 10 n.m. during Drift 3.

Due to the easterly winds, strong vertical deviations were calculated for the currents in the glacial Elbe valley, which had to be considered when extrapolating changes in the upper layer. Indeed, the observed diurnally modulated thermohaline stratification increased during the drift experiments and caused significant vertical gradients of all measured components.

Atmospheric forcing and atmosphere/ocean interaction. The atmospheric situation, the measurements performed and the models applied are described by Schrum et al. (1997, this volume) in detail. The atmospheric forcing was calculated on a 42×42 km^2 grid at 3 h intervals from routine measurements provided by the German Weather Service. Wind stress and surface pressure were analysed from these data according to Luthardt (1987) for the whole North Sea.

Besides physical data, the transport and deposition of contaminants emitted at the adjacent coasts were also studied. The substances considered include lead from power plants and traffic as well as nitrogenous compounds from these sources and from agriculture. Backward trajectories were calculated to estimate areas of emission and to obtain more information on the history of the probed air masses (Schlünzen et al. 1997).

The atmospheric input was calculated by a combination of measurements and model results. Aerosols and rain samples were collected onboard the drifting ship and at 4 other sites (Fig. 1) to get an idea of the regional lead distribution. The lead concentrations were measured to obtain ambient air concentrations and, when multiplied by the amount of rain, wet deposition. A high-resolution mesoscale model (Schlünzen 1991) was applied to calculate wind and temperature as well as hourly deposition fields for the German Bight area and deposition velocities in the drift area (Schlünzen et al. 1997). The model was initialized with radiosonde data taken during the experiment (see Schrum et al. 1997). The model-calculated deposition velocities were multiplied by measured concentrations to give the dry deposition. Summed with wet deposition values derived from the measured rain samples, the atmospheric input into the ocean was estimated for the drift area. The input data are needed for studies of the lead dynamics in the drift area (Schlünzen et al. 1997).

CONCLUSIONS

The behaviour of the drifter was important for interpreting the data. The slip of the drifter should be reduced in future experiments either by enlargement of the drag sail or reduction of the floating construction. The vertical diversity of current directions will always limit any tracing of water masses by drifters to a defined water layer and a period of a few days.

Improvements in obtaining process-related data could be achieved by operating with more moorings, more analyses within the drifting field, etc., but also by use of continuous measurements of appropriate chemical and biological parameters by analytical profiling robot systems. In particular, biological and chemical process studies in the water column could be conducted with drifting mesocosms, but this would require another research vessel and calm wind conditions (Brockmann 1992).

Sedimentation and resuspension control transport and vertical geochemical gradients. These processes could be followed during PRISMA only by sampling a drifting sediment trap every few days and by analyses of moored turbidity meters. More effective sediment traps and resuspension/sedimentation experiments, like those of Creutzberg & Postma (1979), would provide data on the actual local behaviour of suspended matter and its interaction with the sediment. Due to the frequent interactions with the sediment in shallow areas like the German Bight, supplementary analyses

of the sediment surface, including incubation experiments to estimate exchange processes, should be involved in the future.

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