BOREAL ENVIRONMENT RESEARCH 7: 363–369
Helsinki 23 December 2002

ISSN 1239-6095

DIAMIX — an experimental study of diapycnal deepwater mixing in the virtually tideless Baltic Sea

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Stigebrandt, A., Lass, H.-U., Liljebladh, B., Alenius, P., Piechura, J., Hietala, R. & Beszczyńska, A. 2002: DIAMIX — An experimental study of diapycnal deepwater mixing in the virtually tideless Baltic Sea. — *Boreal Env. Res.* 7: 363–369. ISSN 1239-6095

The DIAMIX (DIApycnal MIXing) project aims at investigating wind-driven vertical mixing below the pycnocline. Since tides are exceedingly weak in the Baltic an area east of Gotland was chosen as the study area. Two pilot surveys and two main experiments were conducted between June 1997 and September 2000. The joint effort is motivated to cover as many scales as possible of the distribution of kinetic and potential energy. This paper describes the main features found in the field measurements. Inertial currents, near-inertial waves and internal seiches are the bulk features in the mooring data. Acting against topography these currents may generate strong clockwise and anti-clockwise rotating eddies as well as up- and down-welling which has been observed mainly from ship-borne measurements. From turbulent dissipation measurements the stabilizing effect of the stratification can clearly be seen. Dissipation measurements at the slope indicate a much higher dissipation rate there as compared to the deeper station. All these effects have to be taken into account to add up the power needed to explain the turbulent dissipation and work against buoyancy forces connected to diapycnal mixing in the deepwater as estimated from long-term modeling.

Introduction

The deepwater of the Baltic is contained in deepwater pools. To model the evolution of the vertical stratification in the Baltic on time-scales comparable to or longer than the residence time of water, it is necessary to model the vertical advection and mixing correctly. This is of crucial importance, for e.g. modelling the biogeochemical states of the Baltic because nutrient turnover and benthic nutrient sinks depend strongly on oxygen concentration. Vertical or diapycnal mixing takes place both in the dense bottom currents, carrying new deepwater to the pools, and in the deepwater pools. The magnitude and characteristics of vertical advection depend on both the flow through the entrance straits (the Belts and Öresund) and the vertical mixing.

At the start of DIAMIX, the magnitude of vertical mixing in the deepwater pools had been estimated from observations taken during so-called stagnant periods, i.e. periods lacking inflow of new deepwater, using the budget method, e.g. Matthäus (1990). Vertical mixing in both deepwater pools and dense bottom currents had also been estimated from 20-years-long model simulations using a 1-D ocean model, see Stigebrandt (1987). The vertical diffusivity κ in the deepwater pools seemed to be well described by the following relationship

$$\kappa = \alpha N^{-1} \tag{1}$$

provided the intensity factor α was set to 2×10^{-7} ($m^2 s^{-2}$). N is the buoyancy frequency. However, the contributions from various mechanisms executing the mixing were not known.

The main goal of DIAMIX is to develop improved parameterisations of vertical mixing in deepwater pools based on increased understanding of the physical processes. The strategy to achieve this goal is to first investigate and rank the processes responsible for the mixing. Since tides are exceedingly weak in the Baltic, the mixing processes should ultimately be wind-driven. We will try to describe the paths of wind energy, from the introduction into the surface layer to dissipation in the deepwater. Several processes bringing energy from the surface layer to deepwater were of course known before DIAMIX but their importance in the Baltic were unknown. For instance, the energy transfer from inertial currents, caused by the time-dependent response of the surface layer to changes of the wind stress, to near inertial internal waves beneath the surface layer may be different in the Baltic Sea compared with the ocean. In a shallow bounded sea, like the Baltic, the out-of-phase inertial oscillations below the surface mixed layer, e.g. Krauss (1981), which are compensating the mass transport normal to the shore, are quite intense and can generate inertial waves when oscillating along the gradient of an inclined bottom. Likewise, the energy transfer within the internal wave spectrum due to weak non-linear interaction may be different since the internal wave spectrum in the Baltic can be different from the oceanic (Garrett-Munk) spectrum. Furthermore, the radiation of energy to the deepwater during geostrophic adjustment of mesoscale eddies and of coastal currents due to variations of converging/diverging Ekman transports is so far unknown.

In DIAMIX we intend to estimate the distribution of kinetic and potential energy in an experimental area extending from the shoreline to the maximum depth of a deep basin. In this way, the experiment should cover scales ranging in space from the size of the experimental area and in time from the length of the experiments down to the spatial and temporal scales of molecular dissipation and diapycnal mixing. To cover seasonal variations we have done a summer experiment with a seasonal, essentially thermal stratification in the surface layers, and a winter experiment when the water was almost homogeneous down to the halocline at about 60 m depth.

Besides more traditional descriptions of experimental data in terms of e.g. coastal dynamics, mixed layer dynamics, internal waves, dissipation and mixing, an evaluation of the distribution of kinetic and potential energy on all space and time scales down to dissipation scales has been aimed at. This will include the quantification of the transfer of energy between different scales of motion. Knowledge of the meteorological forcing, including buoyancy fluxes through the sea surface is a pre-requisite for the analysis. Finally, parameterisations will be developed for diapycnal mixing as function of e.g. wind speed and air-sea buoyancy fluxes (meteorological forcing), stratification, horizontal and vertical distances to the sea bottom and possibly other important factors yet to be identified.

Field measurements

The chosen area bordering the southeast coast of Gotland was considered appropriate for DIAMIX. Here the bottom slope is typical of the Baltic Proper and the area includes parts of the East Gotland Basin, one of the major Baltic Sea basins. The experimental area is about 30 by 30 nautical miles (Fig. 1).

Two pilot experiments were conducted in the springs of 1997 and 1998 to fine-tune the observational scheme with the given instrumentation. Thereafter, we have conducted the two main experiments, a winter experiment in 1999 and a summer experiment in 2000. All experiments lasted about 2 weeks. Two ships have participated in all the DIAMIX experiments, r/v *Skagerak* (Göteborg University) and r/v *Oceania* (Institute of Oceanology, Polish Academy of Sciences). r/v *Aranda* (Finnish Institute of Marine Research) participated in all except the preliminary experiment in 1998 and r/v *A. v. Humboldt* (Institut für Ostseeforschung Warnemünde) participated in all except the final summer experiment.

To get a description of the actual large-scale fields of density and currents, we made continuous CTD (Conductivity–Temperature–Depth) and ADCP (Acoustic Doppler Current Profiler) measurements along the 30 nautical miles long transects perpendicular to the coast. Vessel-mounted ADCP and vertically undulating vehicles carrying CTDs were used for this. The distance between transects was 3 nautical miles. Each ship was able to cover about four transects a day. Unfortunately, it turned out that the shipborne ADCP measurements have a lot of scatter why it was hard to make quantitative estimates. During the main winter and summer expeditions, r/v *Aranda* was used as a non-anchored platform on a fixed position for hourly CTD casts and hourly bursts (three) of profiles of turbulent dissipation, from the sea surface to near the sea bed (~135 m). A second profiler for microstructure was used in the final summer experiment in the slope region to observe dissipation all the way to the bottom (~80 m) . At the start of each experiment, moorings with current meters (mostly ADCPs) and CT (Conductivity–Temperature) sensors were deployed in the experimental area for studies of the frequency domain.

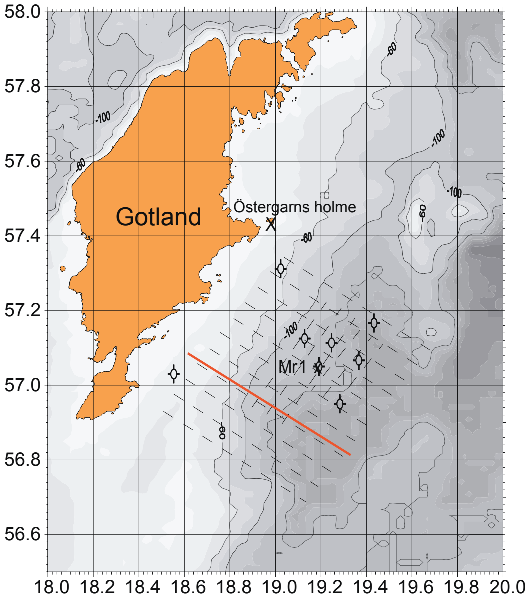

Fig. 1. Map over the DIAMIX survey area. Mr1, (N57.05, E19.2) is the position of the dissipation measurements in September 2000. The symbols are the locations of moorings and the red line shows the section in Fig. 4.

Some results

The halocline was unusually deep (~75 m) during the pilot experiment in 1997. In later experiments the halocline was situated at more normal depths (60 m). During summer one or more strong thermoclines develop which limit vertical exchange. In winter very weak stratification above the perennial halocline may be established by slowly drifting water masses of low salinity.

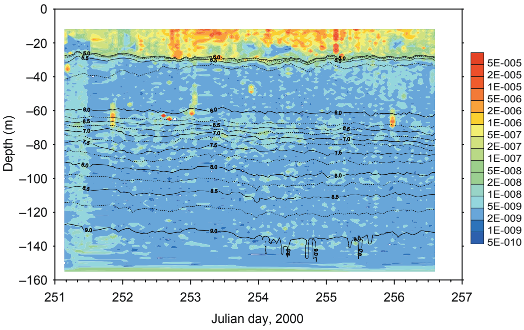

Fig. 2. Log10 of dissipation (W kg^{-1}) from microstructure measurements at Mr1 during the September 2000 survey.

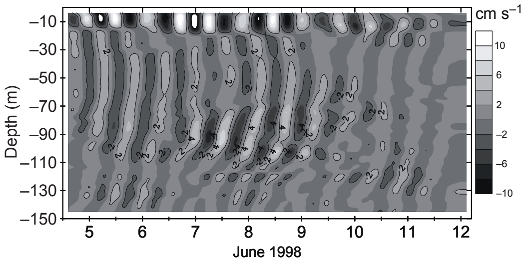

Fig. 3. Filtered east–west velocity component from ADCP measurements at Mr1 in a band 10–20 hours.

Dissipation

Dissipation seems to be governed by two physical regimes. In the surface mixed layer dissipation is most intense and decreases exponentially with depth approximately. Variations of dissipation in the surface layer are correlated with variations of the local wind speed. Dissipation below the surface mixed layer is by far weaker than in the mixed layer and independent of the local wind field. A secondary dissipation maximum was observed within the halocline.

The mean dissipation measured under winter conditions (Lass *et al.* 2001) seems to be less than the dissipation calculated from the diffusivity estimated by tuning long-term model runs against field data. A preliminary analysis of dissipation data from the summer experiment shows that at around the depth of the halocline dissipation was an order of magnitude greater in the slope region than in the open deep sea. Figure 2 shows the dissipation measurements from September 2000 at Mr1. The summer stratification clearly limits the vertical extent of the wind generated turbulence.

Internal waves

The current records from the moorings always showed strong contributions from inertial and super-inertial frequencies. Inertial currents in the surface layers seemed to be generated by the local wind. They were associated with out of phase inertial oscillations in a layer below the surface layer separated by the uppermost pycnocline. Near inertial currents with upward phase propagation were observed in and below the main halocline (cf. Fig. 3).

The energy transfer to deeper layers by internal waves, probably generated by baroclinic wave drag acting on inertial currents in the surface layer, was calculated by Liljebladh and Stigebrandt (2000). They calibrated their model using DIAMIX data and run it thereafter for two years. As an average only about 0.35 mW m^{-2} seems to be radiated into the deepwater by internal waves. This is only about 20%–40% of the power needed for turbulent dissipation and work against the buoyancy forces connected to diapycnal mixing as estimated from long-term modeling. This estimate involves an efficiency factor, the flux Richardsson number Rf. Liljebladh and Stigebrandt (2000) used Rf = 0.06, a number based on estimates from fjord measurements. A much higher number Rf = 0.17 (Osborn 1980) is usually used by the microstructure community. It is well known that geophysical turbulence is highly intermittent and patchy, taking place in a small fraction of both time and space. Estimated values of Rf are possibly not universal but depend on the nature and place of the measurements used. Advective currents are rather weak in this area and shear generated turbulence should be rather small except perhaps along the Gotland slope.

Coastal dynamics

The dynamics at the coast of Gotland changed dramatically during the survey 2000. In the beginning of the experiment there was a pronounced downwelling of surface water at the coast. When the wind turned from northerly to southerly a strong upwelling developed.

Vigorous dynamic activity along the bottoms in response to wind and internal waves was observed, particularly in areas where waters from below the pycnocline enters the slope (Fig. 4). This has been studied in particular by IOPAS.

Eddies in the deepwater

Several eddies were detected during the experiments. Transect data show the presence of an anticyclonic baroclinic eddy in the halocline during the pilot experiment in 1997 (Fig. 5). Hydrographic sections and ship-borne ADCP measurements from r/v *Aranda* gave a consistent picture of an anticyclonic meso-scale eddy in the halocline (Fig. 6). The horizontal scale of this eddy was of the order of 15 nm. The highest velocities in the eddy were about 30 cm^{-1} (Fig. 5) indicating the potential importance of meso-scale eddies for mixing in the area. The eddy propagated slowly, roughly 3 cm s^{-1}, towards southwest along the isobaths.

In the winter experiment (1999), several cyclonic baroclinic eddies, characterised by a marked thinning of the pycnocline were observed. They caused vertical displacement of isohaline surfaces by 10–20 m (Fig. 7).

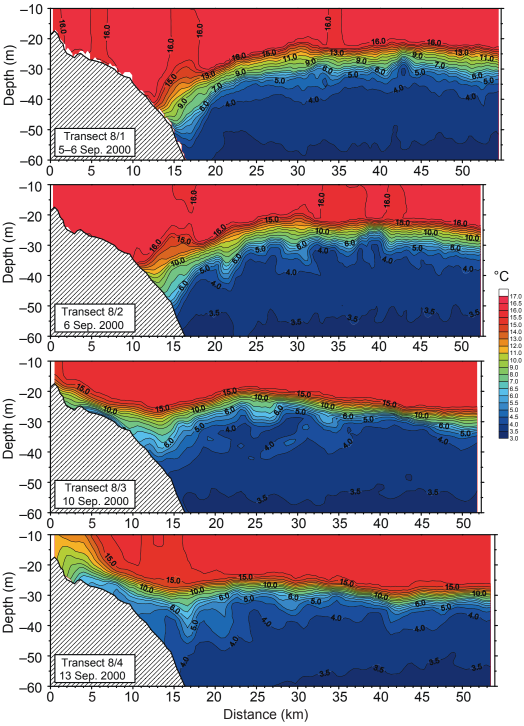

Fig. 4. Changes of temperature distribution in a layer 10–60 m in September 2000 at the transect shown by a red line in Fig 1.

Their horizontal dimension was close to the internal Rossby radius of deformation (~5–10 km). Interestingly, a case with two eddies sharing the same vertical axis but rotating in

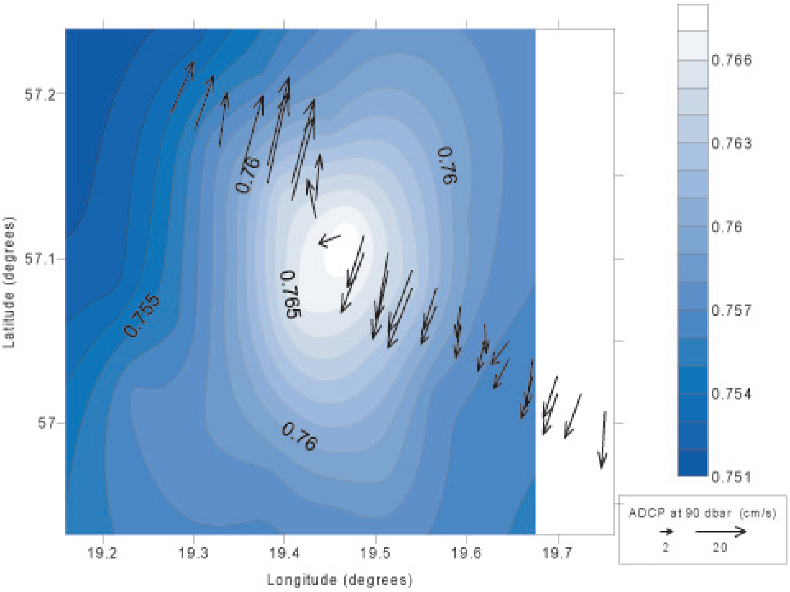

Fig. 5. Dynamic topography (dyn m) in the halocline and ship-borne ADCP current vectors in June 1997.

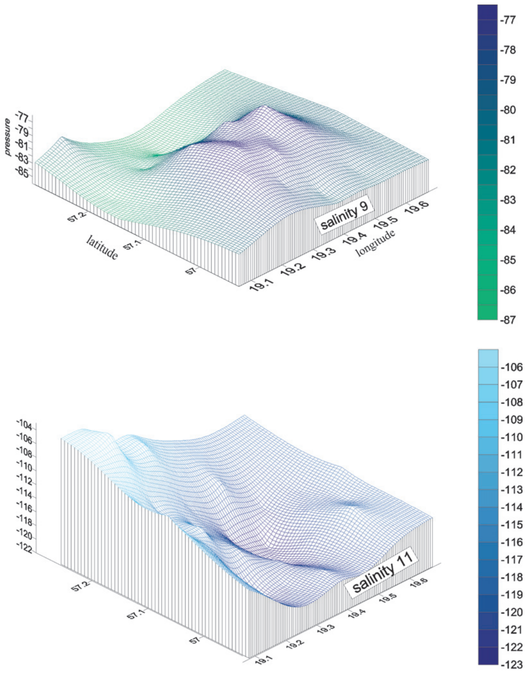

Fig. 6. Depth (m) of isohaline surfaces 9 and 11 (psu) in June 1997.

opposite directions, the upper anticyclonic and the lower cyclonic was observed. These eddies propagated with a speed of a few cm s^{-1} along the isobaths of the Gotland basin towards southwest.

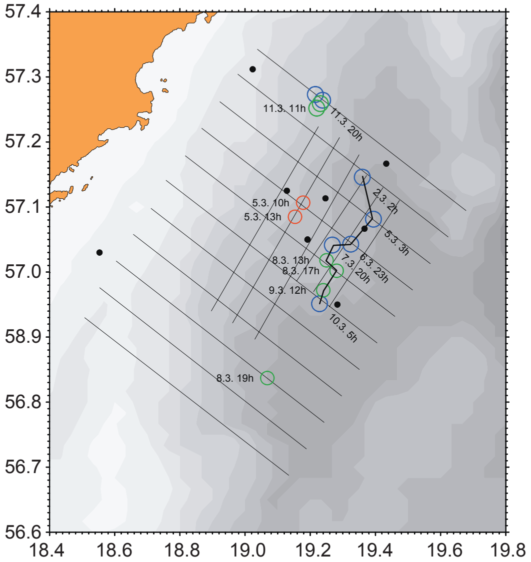

Fig. 8. Circles show the approximate position and path of the observed eddies in March 1999

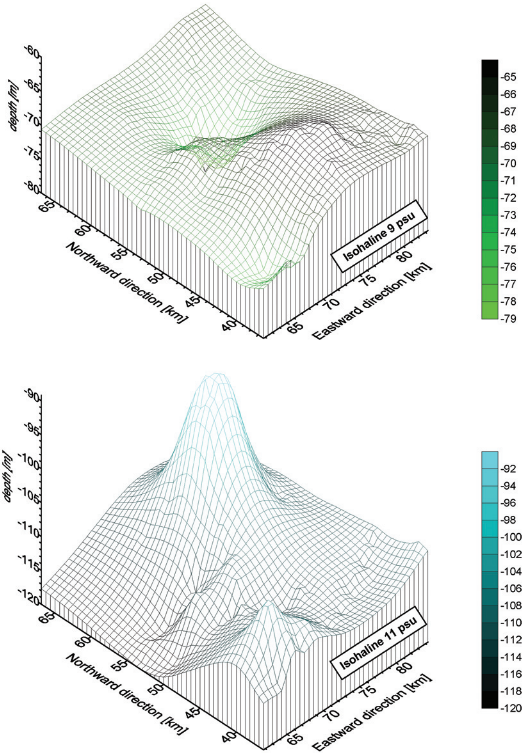

Fig. 7. Depth (m) of isohaline surfaces 9 and 11 (psu) in March 1999.

One particularly stable anticyclonic eddy was observed during 9 days, moving with an average speed close to 5 cm s^{-1} (Fig. 8). Dissipation increased when eddies were present at the site of the dissipation measurements. However, it is not yet clear whether the contribution by eddies to deepwater mixing is of significant importance.

Discussion

DIAMIX has acted as a primer for focused research on mixing processes in the Baltic. In this work, analysis of historical data and modelling have been important. The budget method was carefully applied to data obtained under stagnant conditions in the Baltic proper by Axell (1998). His results basically confirm the validity of Eq. 1 for the East Gotland Basin but with a relatively large seasonal variation of α, with maximum in winter and minimum in summer in pace with the wind over the Baltic. Furthermore, he also found that α is a factor of ten greater in the narrow Landsort Deep rather close to the Swedish coast. Later, Axell (2001) developed a mixing parameterisation that explicitly included the forcing by wind. He tested this formulation using an 1-D ocean model and found that the N-dependence suggested in Eq. 1 actually is the one that best fits data. Each of the topics briefly described in above will be described fully in papers under completion.

The DIAMIX data sets will also be quite useful for testing ocean circulation models with respect to, e.g. meso-scale dynamics including coastal dynamics. Circulation models are instrumental for the interpretation of motions on larger spatial scales in the experiment.

Acknowledgements: Participation of the Göteborg University in DIAMIX was supported by grants from the Swedish Natural Science Research Council (NFR) to Anders Stigebrandt. Institut für Ostseeforschung Warnemünde was supported by the German Federal Ministry of Research and Education under grant number 03F0231A. We thank Prof. Pentti Mälkki (Finnish Institute of Marine Research) for continuous support to the project.

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Received 23 January 2002, accepted 5 October 2002