BOREAL ENVIRONMENT RESEARCH 2: 337–344 ISSN 1239-6095
Helsinki 14 January 1998

Nutrient intrusions at the entrance to the Gulf of Finland

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Laanemets, J., Kononen, K. & Pavelson, J. 1997. Nutrient intrusions at the entrance to the Gulf of Finland. *Boreal Env. Res.* 2: 337–344. ISSN 1239-6095

The nutrient distribution peculiarities below the seasonal thermocline were analysed on the basis of high vertical resolution (2.5 m) data at the entrance area to the Gulf of Finland. Remarkable increase of nutrient concentration and DIN:DIP and a decrease of temperature on the isopycnals in the onshore direction (towards the Finnish coast) were registered. An intrusive finestructure of the temperature and nutrient fields was observed in the warmer side of thermohaline front, which separates the near-shore and open gulf waters. Nutrient-rich intrusions were cold, with a thickness of 5 to 20 m and the largest horizontal scale of about 5 km. The maximum intensities of intrusions, e.g. for phosphorus and silicate were approximately 0.3 µM and 3 µM, respectively. The generation and isopycnic spreading of intrusions is hypothesized as one link in the chain of overall nutrient transport.

Introduction

Nutrients are the primary limiting factors for autotrophic production in the Baltic Sea during summer, as depicted by the almost undetectable concentrations of dissolved inorganic nitrogen and phosphorus in the euphotic layer after the spring bloom. A remarkable increase in the nutrient concentration takes place within a few metres thick layer coinciding with the lower part of the seasonal thermocline. The meso-scale shear flow below the thermocline and wind induced mixing play an important role in determining the frequency, magnitude and sites of nutrient fluxes into the euphotic layer after the spring bloom (e.g. Kononen *et al.* 1996). As well, some pelagial organisms may avoid nutrient limitation in the euphotic layer by vertical migration downward to the depths of higher nutrient concentrations, for which several alternate mechanisms are known to exist. Therefore, the formation of the horizontal nutrient distribution below the seasonal thermocline is an important factor contributing to the plankton production.

The water masses of the Gulf of Finland are affected by a nitrogen-rich anthropogenic and diffuse loading from the land, having a dissolved inorganic nitrogen to phosphorus ratio (DIN:DIP) close to or even higher than the optimum for primary producers (Suursaar 1992, Pitkänen 1994, Suursaar 1994, Perttilä *et al.* 1995). The northern Baltic Proper water, on the contrary, is affected by denitrification in oxygen-depleted water lay-

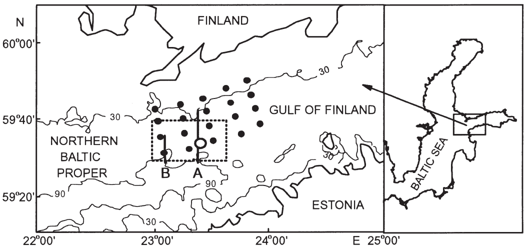


Fig. 1. Schematic map of the entrance area to the Gulf of Finland. Depths are in metres. Filled circles refer to the sampling stations of the pilot survey. The main transect of nutrient sampling (A) and the transect on 29 July (B) are represented by a solid line. Dotted rectangle refers to the area of the meso-scale towed CTD surveys on 27–29 July and 1–2 August. The diurnal anchor station is shown by the open circle.

ers and sediments, thus having a typically lower DIN:DIP (Wulff and Rahm 1988). Therefore, the formation of nutrient distribution at the entrance area to the Gulf of Finland is influenced by the water exchange between the inner gulf and the northern Baltic Proper. The classical basin-wide long-term circulation scheme in the western Gulf of Finland is cyclonic (Palmén 1930). According to that, the outflow of gulf water occurs along the Finnish coast and the northern Baltic Proper water intrudes into the gulf along the Estonian coast. At shorter time scales the current system is often more complicated, while the deviations from the classical scheme are mainly caused by the changes of the wind field (e.g. Elken 1995).

The term "thermohaline finestructure" is used to denote inhomogenities on the vertical temperature and salinity profiles. The lower limit of vertical size of inhomogenities is determined by Ozmidov's length scale of largest turbulent fluctuations in the stratified water column (Ozmidov 1965) and upper limit is conditioned by the characteristic vertical scale of features on the mean temperature and salinity profiles. According to that, in the Baltic Sea, the thermohaline finestructure is observed at scales from tens of centimetres to tens of metres in vertical. The horizontal scale of finestructure extends from tens of metres to few tens of kilometres. The finestructure is generated by the internal wave straining and mixing processes of heat and salt: intermittent turbulence, double-diffusion and isopycnic spreading of intrusions. The latter process, associated with intrusion of water masses with different temperature and salinity into one another, is common in the vicinity of thermohaline fronts. It is natural to assume that in the frontal regions with increased across-front nutrient differences the similar finestructure in the nutrient distribution might be observed.

There are references to the observed nutrient intrusions, e.g. in a frontal region of the Southwestern Mediterranean Sea (Raimbault *et al.* 1993). In the Baltic, the relation between meso-scale nutrient structures and physical processes with references also to "smaller scale variations" of nutrients was found out in the beginning of 1980s (Aitsam *et al.* 1984, Hansen 1984). Due to the scarcity of data with a high vertical resolution, the knowledge of the finestructure of nutrient fields is insufficient. On the whole, resolving the finestructure using regular nutrient sampling at standard depths (e.g. monitoring data) is difficult. The aim of the present study is to show the presence of nutrient intrusions in the vicinity of thermohaline front in the case of strong nutrient concentration differences across the front.

The data

Nutrient data were collected in the frame of a multidisciplinary study of the late summer cyanobacterial bloom onboard R/V Aranda (Finnish Institute of Marine Research) on 21 July–3 August 1994. The study area is located in the northern entrance area to the Gulf of Finland (Fig. 1). The depth of the southern part of the study area is about 90 m. The northern part, i.e. the transition to the shallow sea (~ 20 m) near the Finnish coast is relatively steep and characterized by complicated bottom topography.

Observations began with a pilot survey (5 cross-shore transects) on 21–23 July, that covered an area 30 × 50 km (Fig. 1). The survey consisted of 20 biological and nutrient (NO_2, NO_3, PO_4, NH_4 and SiO_4) sampling stations with a vertical sampling interval of 5 m. Nutrients were analysed according to BMEPC (1983). At these and further stations CTD measurements were carried out with NBIS Mark III or SIS PLUS 500 profilers. The pilot survey showed the presence of inversions on nutrient and corresponding temperature vertical profiles at some stations and the occurrence of a remarkable decrease of temperature on isopycnals toward the coast, or thermohaline front located well below the sharper part of the seasonal thermocline. During the following period, daily nutrient samples at 3–5 stations on the main cross-shore transect along 23°23´E (23°06´E on 29 July) were taken (Fig. 1, see also Fig. 8). The vertical sampling interval was chosen 2.5 m in the layer from 15 to 40 m. The locations of sampling stations on the transect were fixed according to the position of the front, determined by the preceding night-time towed CTD survey. On 27–29 July and 1–2 August the meso-scale towed CTD surveys were carried out. A towed undulating system, developed at the Estonian Marine Institute, carrying a NBIS Mark III CTD profiler was used. The depth range of undulation for the towed profiler was 1–60 m, with the horizontal spacing between the subsequent profilings 300–600 m. The additional nutrient samples were collected during the biological diurnal anchor station (sampling interval 3 hours), positioned also on the main transect in the warmer side of the front (Fig. 1).

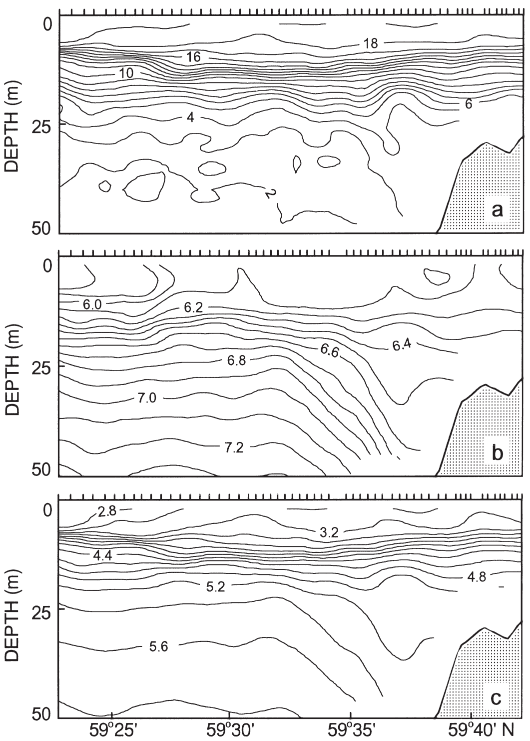


Fig. 2. Vertical distributions of temperature (a), salinity (b) and density anomaly (c) on the main transect along 23°23´E on 26 July. Contour intervals are 1 °C, 0.1 psu and 0.1 kg m^{-3} respectively. Ticks on the upper bound of each panel refer to the positions of towed CTD descent.

Results

Large scale background

Weak wind (2–6 m s^{-1}) of variable direction prevailed during the observation period, except two stronger NW–N wind events with speed up to 10 m s^{-1}. Nevertheless, these stronger winds of 5–6 hours duration were not sufficient to generate any upwelling in the Finnish coastal zone (data not shown). Also, the influence of wind induced mixing onto the nutrient vertical distribution below thermocline is highly unlikely.

The characteristic vertical distributions of temperature, salinity and density anomaly on the transect of the sampling stations are presented in Fig. 2. The sloping isopycnals point to the dynamically active frontal zone in the near-coast region. The maps of temperature on the 5.3 kg m^{-3} density anomaly surface of the two areal towed CTD surveys show the enhanced isopycnic temperature gradients, i.e. increased thermoclinicity, in the frontal zone below the thermocline (Fig. 3). The front separates the open gulf and near-shore waters with clearly different T–S characteristics in the interval of the density anomaly of 5.0–5.7 kg m^{-3} (Fig. 4). The near-shore water above the bottom slope is colder (with the cross-front isopycnic temperature differences up to ~ 2.5 °C) and slightly less saline. The mean width of the front was about 5 km. The front is characterized by meanders and moderate changes of its position and width. For the period of the second survey, the front had decayed to the east from the main transect (Fig. 3b).

The cross-shore nutrient distributions on the transect are also presented on the isopycnal of 5.3 kg m^{-3} to link them to the observed thermoclinicity (Fig. 5). For calculation of the nutrient concentration values onto the fixed isopycnal, the linear interpolation was used. The nutrient distributions before the decay of the front revealed the clear tendency of an increase of nutrient concentrations in the onshore direction, while the main changes occur in the frontal zone. An increase of DIN:DIP in the near-coast stations was observed as well.

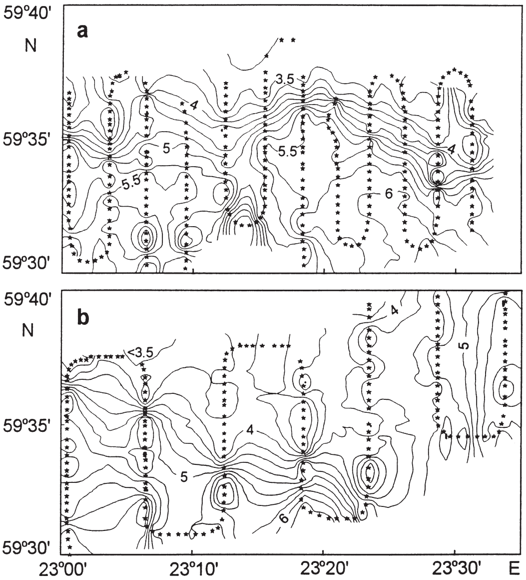


Fig. 3. Maps of temperature on the 5.3 kg m^{-3} density anomaly surface on 27–29 July (a) and 1–2 August (b). Contour interval is 0.25 °C. Stars indicate the positions of the towed CTD descent.

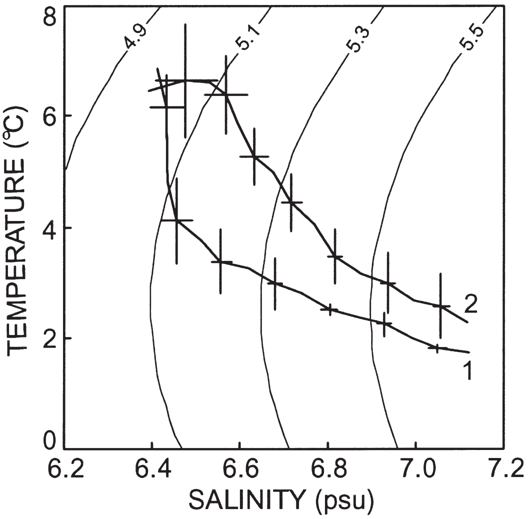


Fig. 4. Averaged T–S curves over the period of 23–30 July on the main transect. 1: open Gulf of Finland (59°30´N), and 2: coastal slope (59°38´N) waters. Vertical bars indicate the r.m.s. deviation of temperature and horizontal bars the r.m.s. deviation of salinity.

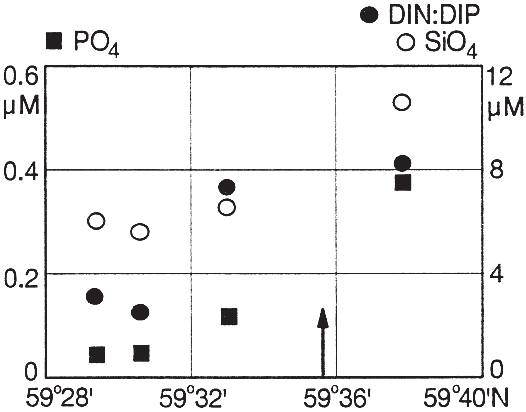


Fig. 5. Distributions of PO_4, SiO_4 (in µM) and DIN:DIP on the isopycnal of 5.3 kg m^{-3} along the main transect on 28 July. Arrow indicates the position of the front.

Finestructure of thermohaline and nutrient fields

The presence of inversions on temperature and salinity profiles is usually characteristic to the intrusive thermohaline finestructure. The inversions appear as local maxima and minima on the vertical profiles thus reflecting intrusions of waters with different properties. In the Baltic Sea, in the layer below the thermocline, the inversions on salinity profiles are practically not observed due to the low salinity and temperature values and relatively strong salinity stratification. The observed temperature varies close to the maximum density temperature, therefore its contribution to the density is small. For example, salinity changes of up to 0.05 psu (dependent on the background temperature) are sufficient to compensate the temperature deviation of 1 °C. Thus, only the temperature and nutrient profiles were compared to clarify accordance of inversions on both of them. In the water column, due to the various bio-chemical processes, the nutrients behave quite differently as compared to salt or heat. The most important processes transforming nutrients between particulate, dissolved and gaseous phases take place in the trophogenic layer or in the anoxic-oxic transitions. Since the present analysis is restricted to a layer below the trophogenic layer and far from anoxic-oxic boundaries, the nutrients are

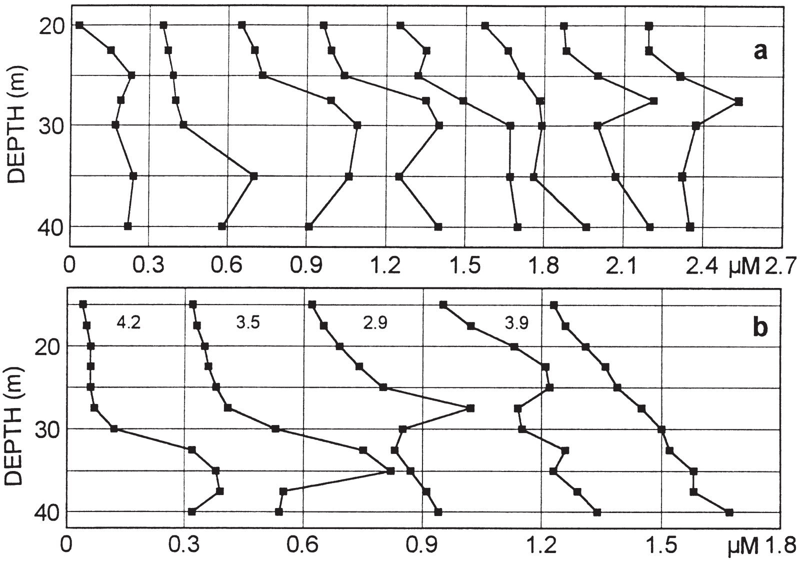


Fig. 6. Vertical profiles of PO_4 (in µM) in the anchor station on 25 July (a) and in the stations along the transect along 23°06´E on 29 July (b). The sampling interval in the anchor station is 3 hours. Numbers between the profiles on the lower panel indicate the distance between the stations in km. Profiles are offset by 0.3 µM.

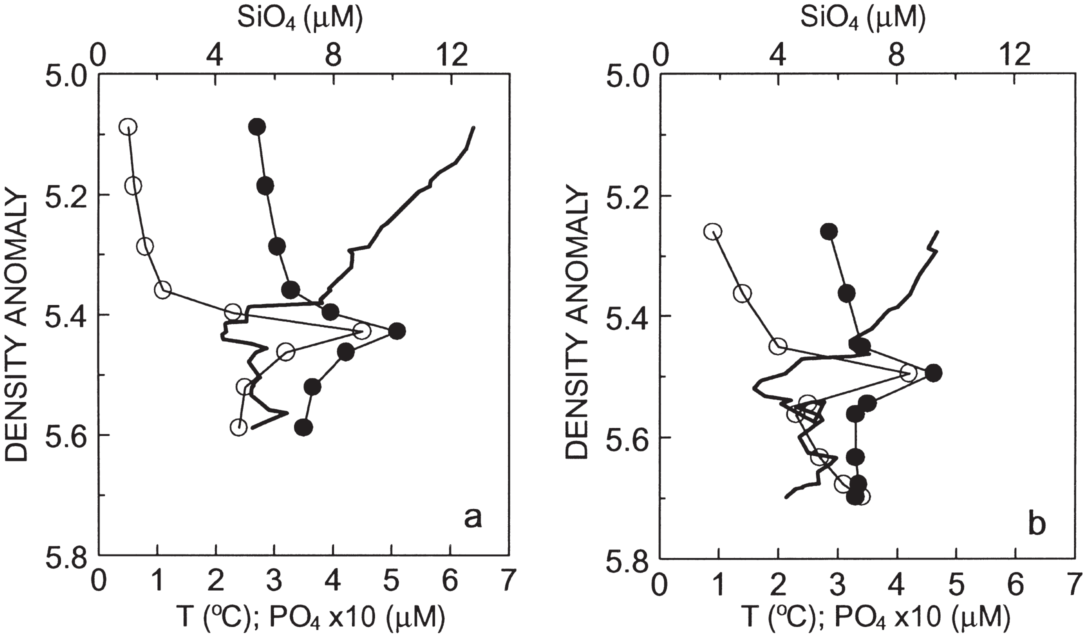
considered as passive tracers and the changes in the nutrient distribution are mainly due to the physical impact at the time scale of a week.

Well developed intrusive structures on the nutrient profiles were found out at many stations in the vicinity of the thermohaline front. The vertical profiles of phosphorus at the anchor station and at the stations along the cross-shore transect, illustrating the vertical as well as horizontal variability of fine scale nutrient field, are presented in Fig. 6. The similar vertical structures were also observed on the profiles of all other analysed nutrients. At the open gulf and near-shore stations the intrusive structures were absent or less pronounced. To quantify the intensity of intrusive layering, the difference between the successive extremes on the nutrient profile was used. For example, the maximum difference estimates for phosphorus was 0.3 µM and for silicate 3 µM. The thickness of intrusions varied from 5 m, i.e. only one sample was taken from the intrusion, to roughly 20 m. The intrusion patterns of nutrient and thermohaline fields were linked in the frame of density as vertical coordinate. Using the density instead of the depth enables to follow the same intrusions at different stations. Examples in Fig. 7 reveal that the water layers with increased concentration of nutrients coincide with cold thermohaline intrusions and layers with low nutrient contents coincide with warm intrusions. The distances between successive sampling stations were too large for adequate estimation of the horizontal scale of intrusions. Only in two cases the nutrient intrusions, which lay in the same density anomaly interval at the neighbouring stations, were found (one of them is presented in Figs. 6b and 7ab). The distances between these stations, 3 and 3.5 km, give the estimate of the horizontal scale of the largest intrusions about 5 km.

The spatio-temporal map of temperature on the 5.3 kg m^{-3} density anomaly surface along the transect of sampling displays the changes of the position of the thermohaline front as well as its decay on 30 July (Fig. 8). Cold and nutrient-rich intrusions were observed only on the warm side of the front, reflecting mixing across the thermohaline front. After the decay of the front, the nutrient-rich intrusions were found mainly in the periphery of a smaller and colder water mass. This water mass, advecting through the sampling transect for about three days, obviously originated from near-shore waters.

4. Discussion

The following items of evidence in the distribution of nutrient and hydrographic fields below the



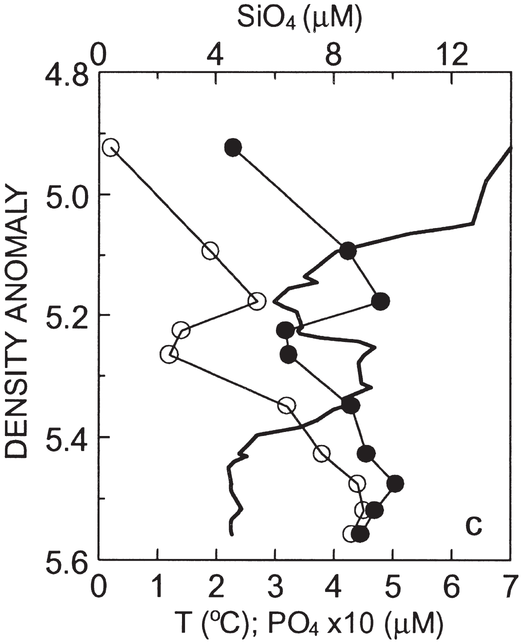


Fig. 7. Profiles of temperature (bold line), PO_4 (circles) and SiO_4 (filled circles) for different stations. The vertical coordinate is density anomaly. (a) and (b) show the same cold nutrient rich intrusion at the neighbouring stations. PO_4 profiles correspond to the second and third profiles on Fig. 6b. Note the advantage of the use of density as vertical coordinate in determining isopycnically spreading intrusion. (c) demonstrates the presence of a pair of cold and warm intrusions with high and low nutrient content, correspondingly.

thermocline were revealed: (1) near-shore and open gulf water masses have clearly different T–S and nutrient properties and are separated by a front and (2) intensive intrusive finestructure appeared in both the thermohaline and nutrient fields in the warmer side of the front. The complexity and instability of coastal processes is well reflected in the rapid decay of the thermohaline front in the eastern part of the study area (Figs. 3 and 8). This process is also accompanied with an intensive finestructure. The near-shore nutrient-rich water mass at the entrance area was likely to have been originated from the inner Gulf of Finland (outflow along the Finnish coast), rather than as a result of local mixing above the bottom slope. That is supported by the geostrophic estimation of velocity from the density field as well as by current meter data (P. Alenius, unpubl.).

Dynamical activity of the frontal zone is characterised by the baroclinicity i.e. by the slope of isopycnic surfaces relative to isobaric surfaces. In the purely baroclinic frontal zone, where the isopycnic, isothermic and isohaline surfaces are parallel, the intrusions are not observed. The enhanced thermoclinicity and low baroclinicity are expected as preconditions for the intrusion generation in the frontal zone (e.g. Fedorov and Meshchanov 1989). Both preconditions for intrusion formation are fulfilled in the present case.

The downward inclined isopycnals in the onshore direction (Fig. 2c) and the strong isopycnic temperature gradients (Fig. 3) point to a baroclinic frontal zone with increased thermoclinicity. At the same time the baroclinicity was about 5 times smaller in the warmer side of the front compared to the cold side.

The isopycnic spreading of the nutrient-rich intrusions afar the frontal region increases the variability of the nutrient field in the Gulf of Finland, as well as in the northern Baltic Proper. Small-scale turbulence, which by nature is a vertical transport, diffuses the generated fine scale variability. The possible splitting of intrusions, frequently mentioned in the studies of thermohaline finestructure (Gargett 1976, Gregg 1980), increases the surface contact area for turbulence and so accelerates the mixing process.

To summarize, the observations demonstrate that the frontal zone intrusions transport nutrients from the coastal zone to the open gulf. The flow diagram for cascades of energy links different scale physical processes from atmospheric forcing to dissipation of turbulent kinetic energy by molecular viscosity (Woods 1980). The fine-scale physical processes causing the heat and salt mixing, constitute one level of the cascade. The circulation, carrying the inner gulf water out along the coast, creates thermohaline front accompanied by the enhanced cross-shore isopycnic nutrient concentration gradients at the entrance area. The intrusions, generated in the frontal zone as well as those accompanied by the decayed front, further spread isopycnically and diffuse under the influence of the small-scale turbulence. Thus, the nutrient intrusions are expected to be as a possible link in the chain of the overall nutrient transport.

Also, it is worth to point out that the fine-scale variability of a nutrient field increases the "noise" level in the monitoring time series, especially in the coastal region. Therefore, the analysis of nutrient data together with the physical background will improve the quality of estimates of the long-term trends of the sea environment.

Acknowledgements: We thank the captain and crew of R/V Aranda for their assistance in the field measurements. We are grateful to A. Pastarus for his preparation and management of the towed CTD-system on the cruise. Maija Hälvä, Jaana Huovinen and Pirjo Tikkanen are acknowledged for performing the nutrient analyses. This work was financially supported by the Maj and Tor Nessling Foundation.

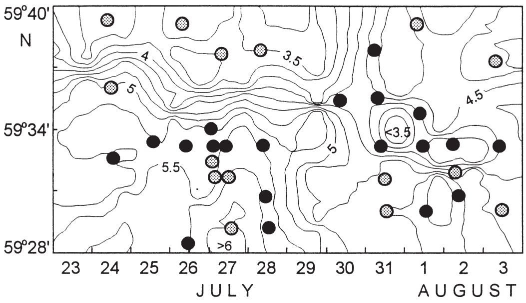


Fig. 8. Spatio-temporal map of temperature on the 5.3 kg m^{-3} density anomaly surface along the main transect from 23 July to 3 August. Filled circles indicate the stations with nutrient intrusions and shaded circles the stations without intrusions. The difference between successive extremes on the PO_4 profile, larger than 0.05 µM, was used as a criteria for the intrusion.

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Received 18 November 1996, accepted 21 May 1997