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NOTE ON THE OCCURRENCE OF DOUBLE-DIFFUSIVE CONVECTION IN THE BALTIC PROPER

by

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1. *Introduction*

Depending upon different molecular diffusivities of heat and salt in sea-water, convection can arise even if the basic density distribution is gravitationally stable. This is due to diffusion, which has a stabilizing effect in thermal convection. It can, however, act in a »double-diffusive» fluid in such a way as to release potential energy stored in one of the two components defining its density and convert it into kinetic energy feeding the convective process. From an oceanographic point of view this is of importance as it provides a means of producing large vertical fluxes of heat and salt by molecular processes only in a fluid that is stably stratified.

Since the birth of the »salt fountain» (STOMMEL *et al.*, 1956), which was given a theoretical foundation by, among others, STERN (1960), WALIN (1964) and VERONIS (1965), double-diffusive convection has matured into a subject with a large variety of applications (for a comprehensive review, see *e.g.* CHEN and JOHNSON 1984).

Basically there are two different types of possible distributions of heat and salt that can give rise to these phenomena. One is the »salt finger» instability, which may occur when warm, salty water lies above colder, less saline water as the diffusivity of heat is substantially larger than that of salt. The salinity distri-

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bution is the destabilizing agent. These fingers were first discovered in the ocean by TAIT and HOWE (1968) beneath the warm salty Mediterranean outflow into the cooler fresher eastern Atlantic. They were later directly observed, by an ingenious optical technique (WILLIAMS, 1975), in the stepped finer structure consisting of well-mixed layers of thickness tenths of meters separated by interfaces with large vertical gradients of salinity and temperature. Recent observations (*cf.* LINDEN, 1978) show that these interfaces, of the thickness several meters, are not of a uniform gradient but consist of a number of nonuniformities on a smaller vertical scale. Salt fingers have been observed restricted to those regions where the vertical gradients of temperature are largest. Their thicknesses are in excellent agreement with predictions based on earlier laboratory experiments by LINDEN (1973). In fact, predictions of the behaviour of salt fingers, based on laboratory investigations, have been surprisingly successful when applied to a usually complex geophysical context.

The other type of instability may occur when both salinity and temperature increase with depth, in which case the temperature now has a destabilizing effect upon the otherwise stable density distribution. The same differences in molecular diffusivity as mentioned above do allow a release of potential energy from the heat distribution even though the mean distribution is hydrostatically stable. This type of instability has been extensively studied in the past (for a short review, see *e.g.* TURNER, 1973, or STERN, 1975). They were first observed in an oceanographical context by NESHYBA, NEAL and DENNER (1971). The applicability of laboratory investigations has been equally successful in this case. Hence HUPPERT and TURNER (1972) have shown that the laboratory results by TURNER (1965) could be applied to a salt-stratified antarctic lake.

Much interest has been focused on the one-dimensional »vertical» effects of double-diffusion but more recent studies have shown that they may represent only one important part of more large-scale, »horizontal», convective processes. STERN (1969) has presented a form of »collective instability», where potential energy from salt fingers feed large-scale wave motion in horizontal layers, which in turn could lead to overturning and intense mixing. Further TURNER and CHEN (1974) and LINDEN (1976) showed that the layers formed by double-diffusion could merge, thus forming more complex density structures than that which the one-dimensional approach may suggest; a phenomenon which hampers their observability in a geophysical context. Despite this fact, a manifold of observations have revealed that double-diffusive convection (as well as salt fingering) plays a crucial role in intrusions and interleaving of different water masses into each other, forming new layers (see *e.g.* TURNER, 1978, who performed a series of laboratory experiments, GORDON, GEORGI & TAYLOR, 1977, and JOYCE, ZENK

& TOOLE, 1978, who dealt with the Antarctic polar front or GREGG, 1975, who studied the interleaving of shelf/slope water into the Pacific outside California). Laboratory experiments by RUDDICK and TURNER (1979) have shown that the formation and propagation of interleaving double-diffusive layers is a self-driven process, sustained by local density anomalies due to quasi-vertical transports across the interfaces. In this way double-diffusive processes (of both types) serve both to produce the layering and to dissipate its energy.

The purpose of the present work is to investigate some of the conditions necessary for the occurrence of double-diffusive phenomena in the deeper parts of the Baltic proper and their distribution therein. This is achieved by utilizing existing hydrographic data obtained during regular monitoring programs in the Baltic. The spatio-temporal resolution will of course be poor due to the standard depth convention adopted, but reliable CTD-data are sparse from the area, thus motivating this approach. Despite the limited conclusions that may be drawn from this work, the investigation may still be of some value in that it focus the interest on certain aspects of the complicated system that governs the deep-water circulation and renewal of the Baltic. Of special interest is the question of how the deep water from the Bornholm Basin enters and mixes with the corresponding deep water of the Baltic proper.

2. *Baltic deep water*

In the deep water of the Baltic proper, both temperature and salinity increase with depth, as can be seen in the composite TS-plot, Fig. 1a. A necessary condition for the occurrence of double-diffusive convection in this area is thus fulfilled. The TS-data shown in the figure are from a series of hydrographic stations along a »transect» from the Bornholm Basin (BY5) via the Eastern Gotland Basin (BY15) and the Northern Central Basin (BY29) up to the Landsort Deep (BY31). (For a geographical orientation of the various stations, see Fig. 1b). The different plots are based on data obtained from routine surveys made by the Fishery Board of Sweden during the period 1957–1982 and reported to ICES. The characteristic TS-curve of the Baltic proper is caused by the inflowing deep water from the Kattegatt, which is generally both warm and saline. Due to entrainment of cold, less saline water from the lower part of the brackish surface layer, which is assumed to occur when the inflowing water enters the Baltic proper (see *e.g.* PEDERSEN, 1977), the deep water of the latter attains its characteristic TS-properties. This process, as well as mixing, which may occur at the sloping bottom (see *e.g.* LINDEN and WEBER, 1977), probably causes horizontal interleaving by different water masses

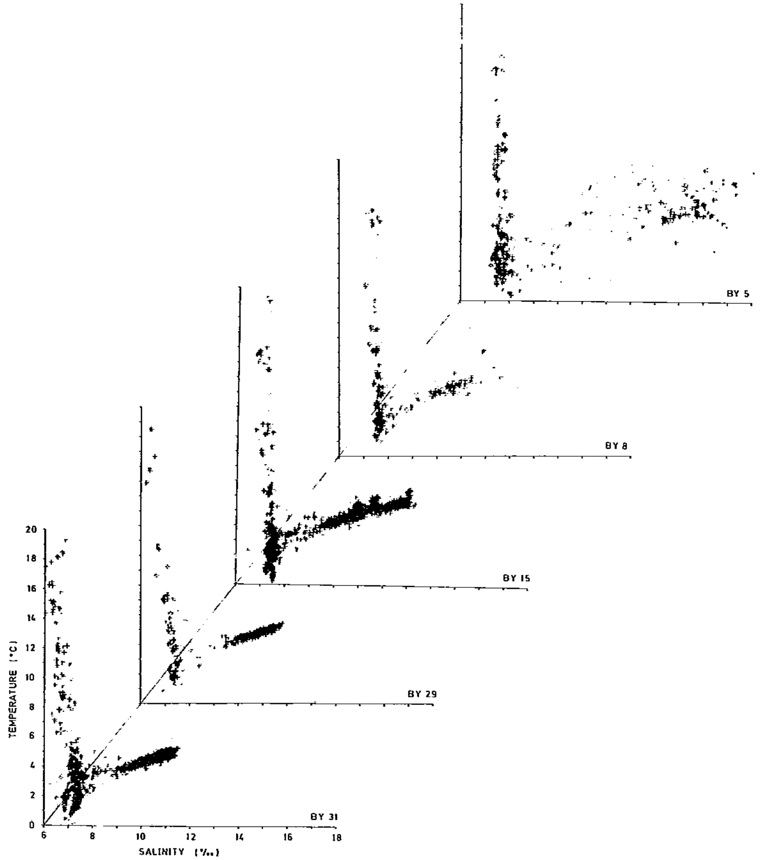

Fig. 1. a) Quasi-perspective presentation of TS-curves from selected series of hydrographic stations in the Baltic proper. Labels define the specific stations.

(see *e.g.* TURNER, 1978), something which thus can occur throughout the Baltic. As a consequence of the above, intrusion effects can be expected, with individual flows bounded above and below by the two types of double-diffusive instabilities.

In order to get an overview of the hydrographic conditions for a few different stations in the Baltic, it is convenient to calculate the density ratio $R\rho$,

$$R\rho = (\beta/\alpha)\ \partial S/\partial T$$

Here $\partial S/\partial T$ measures the salinity gradient with respect to temperature for an arbitrary level z. The expansion coefficients α and β are defined in the usual way:

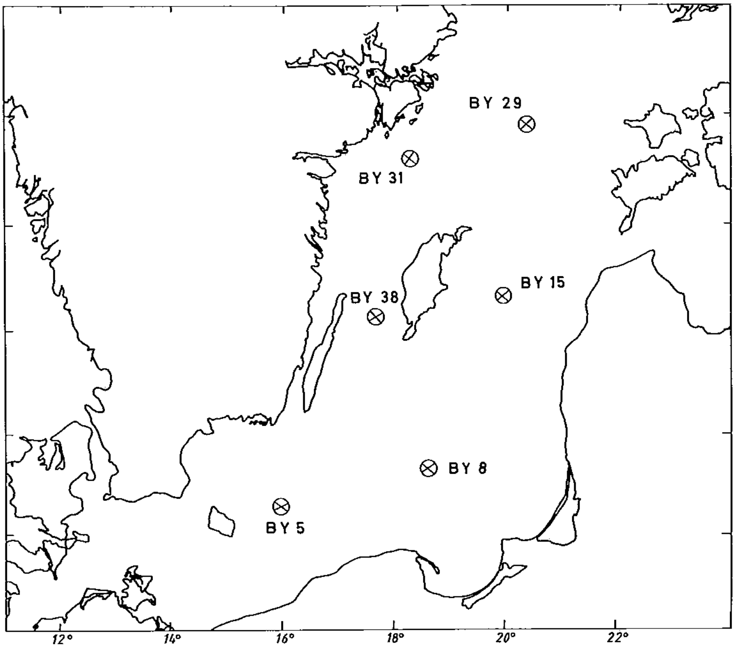

Fig. 1. b) Schematic map of the location of the different hydrographic stations.

$$\alpha = -\rho^{-1} \partial\rho/\partial T$$

$$\beta = \rho^{-1} \partial\rho/\partial S$$

where the density ρ is calculated from the equation of state presented by GILL (1982). The effects of pressure are neglected due to the shallowness of the regions investigated. Chebyshev polynomials of low (third) order were fitted by the least squares method to the TS-profiles determined from the data mentioned above. A lower limit on the salinity of 8 ppt was adopted, as the interest is focused on the properties of the deep water. The $\partial S/\partial T$ gradient was then calculated from the polynomials mentioned above. The resulting $R\rho$-values from the Baltic proper, though excluding BY5 (the Bornholm Deep), are, throughout their domain of existence in the TS-space, both homomorphic with and almost collapse on each other, see Fig. 2. This is not surprising as the corresponding TS-curves are also similar to each other (see also Fig. 1a). The $R\rho$-values determined at BY5 are presented in the graph for a comparison. The density ratio is well below 40 for the salinity above 10 ppt, and with a minimum of about 27 at 12 ppt (see *e.g.*

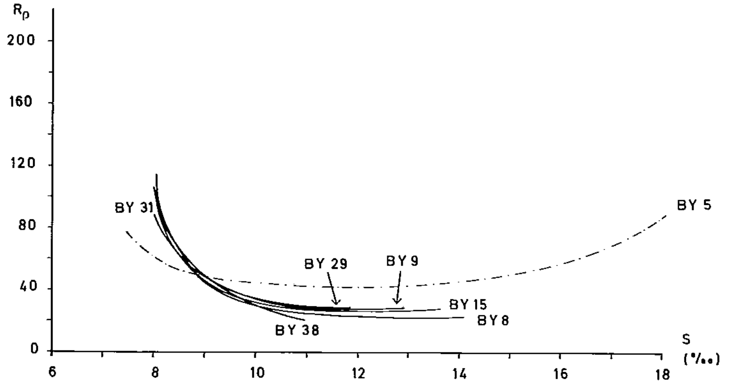

Fig. 2. The calculated $R\rho$-values vs. salinity for some hydrographic stations in the Baltic proper (solid line). The corresponding curve from the Bornholm Basin (dash-dotted line) is also shown.

BY9 in Fig. 2), though BY38 (west of Gotland) is monotonically decreasing. The steep increase in $R\rho$ and, in fact, its singular behaviour for salinity values close to 8 ppt, is essentially caused by the associated low temperatures and the quadratic behaviour of the equation of state in this TS-region (as α changes sign at the point of maximum density).

Not surprisingly, these values are well above those reported for observed instabilities, as they are calculated on the averaged TS-profiles from 25 years of monitoring at rather few depths and, further, they are smoothed by the low order of polynomials used. However, the relatively low $R\rho$-values obtained throughout most parts of the salinity range indicate regions potentially feasible for double-diffusive processes. Recent laboratory experiments by Howard and Krishnamurti (1984) have revealed that values of $R\rho$ as high as 16 may occur as end results of double-diffusive convection. They have studied subcritical finite amplitude convection, *i.e.* convection in such a parameter regime as, according to linear theory, the fluid is stably stratified, but, due to finite perturbations, it may still become unstable. (In fact, they report convection at such low Rayleigh numbers as approximately 10 % of the critical Rayleigh number determined by the linear theory, while both the thermal and the saline Nusselt numbers are well above unity). They further suggest that the high $R\rho$-values observed in the terminal state of their experiments would also be frequent in those regions of the oceans where the necessary conditions for a double-diffusive convection to occur are fulfilled. Estimates performed by the authors, based on the mean hydrographic state in the western Mediterranean, seem to corroborate their hypothesis. The results, obtained from the Baltic proper, also fit well into this picture.

3. *A case study*

The low vertical resolution of the data used, coupled to the averaging process, prevented a study of finer details. However, CTD-data from the Gotland Deep (BY15) are derived from a routine cruise on the R/V »ARGOS» in January 1984, by the Fishery Board of Sweden (H. Palmén priv.comm.). The CTD-data are sampled 3–5 times per meter. Though the »absolute» instrumental errors are considerable (± .03 ppt and ± .06 °C) the »relative» errors in consecutive samplings are substantially smaller, enabling a study of »finer structures» on a vertical scale of a few meters. Vertical profiles of salinity and temperature are presented for salinity values larger than 8 ppt in Fig. 3.

Our primary interest is in one of the »structures» observed at a depth of 140–160 m (bounded by the two vertical lines in Fig. 3). As is evident in Fig. 4, several small layers with a neutral or slightly negative stability exist. The one at 11.9 ppt is the most pronounced, with a vertical thickness of 4–5 m. The corresponding TS-curve, Fig. 5, exhibits a complete loop at this level, indicating an intrusion of water with characteristic TS-properties different from the ambient water. (The interval of interest is bounded by thin solid lines in Fig. 4 and 5).

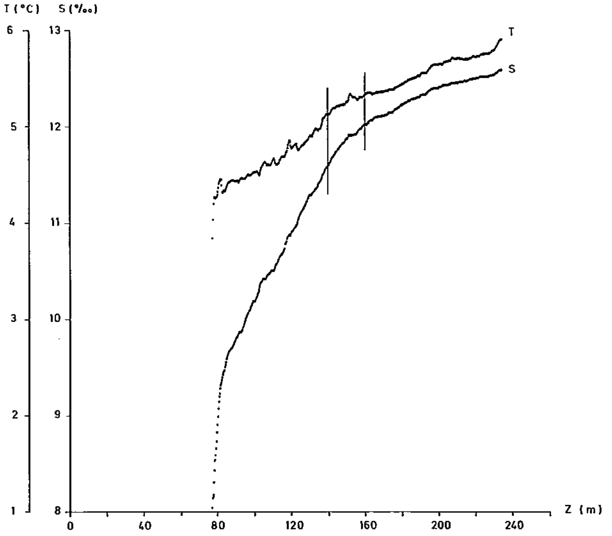

Fig. 3. Profile taken at BY15 in January 1984. Temperature (T) and salinity (S) vs. depth (z) are shown for salinity values above 8 ppt. The two vertical solid lines indicate the region of interest in this work.

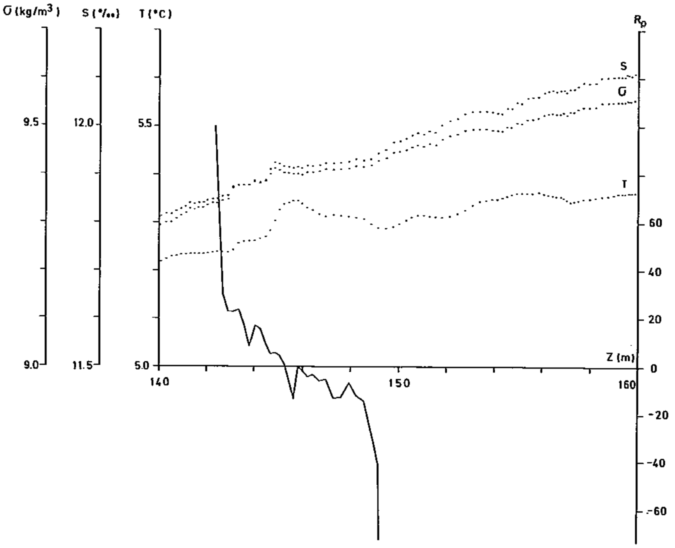

Fig. 4. Section of the profile taken at BY15 together with the calculated density values (σ). $R\rho$-values calculated at the interval of interest are also presented.

Note that our choice of interval is rather arbitrary, as several loops are discernible at a closer examination of the complete TS-curve.

This type of intrusion may be associated with double-diffusion above it and salt fingering below it, as has been reported by several authors, see *e.g.* GREGG (1975) or TURNER (1978). The actual loop formation has been discussed by POSMENTIER and HOUGHTON (1978), who showed that the distinct loops frequent in TS-curves can be caused by an interleaving between warm salty water and cooler fresher water. Double-diffusive mixing is the mechanism responsible for this behaviour. Thus the observed features above clearly indicate the existence of such a mixing process in the Baltic (especially as several loops are found in the CTD-record analysed above).

The characteristic vertical length scale of double-diffusive intrusions has been discussed by RUDDICK and TURNER (1979). They found that the thickness could be expressed as

$$\Delta H = \beta \Delta S (\rho^{-1} \partial\rho/\partial z)^{-1}$$

which in our case (with $\beta \approx 8\ 10^{-4}\ {}^{\circ}\mathrm{C}^{-1}$, $\Delta S \approx 4\ 10^{-2}$ ppt and $\rho^{-1}\partial\rho/\partial z \approx 1.5\ 10^{-5}\ \mathrm{m}^{-1}$) becomes $\Delta H \approx 2$ m. This should be compared with the typical length-

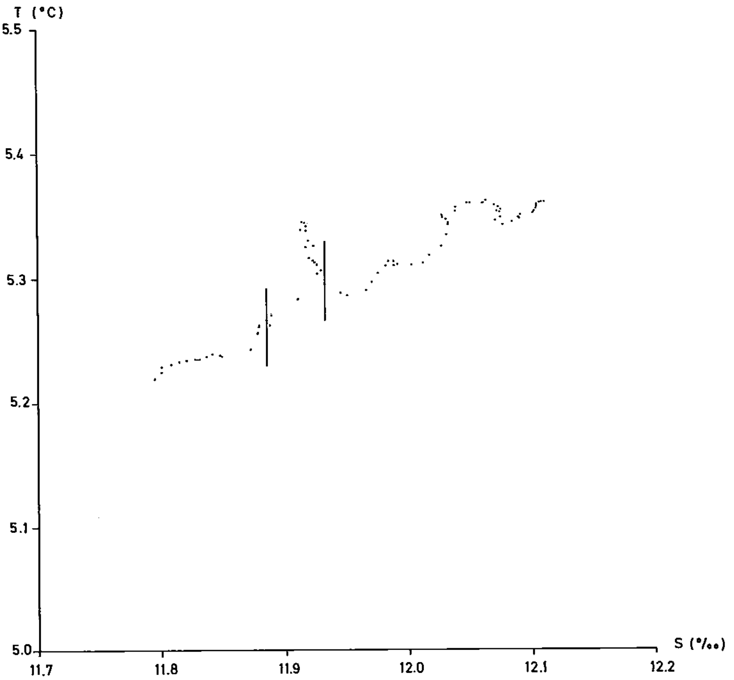

Fig. 5. TS-diagram for the 140–160 m interval discussed in this work.

scale found in Fig. 4 of roughly 4 m. The agreement is surprisingly good, especially if the uncertainties of the various estimates are considered.

In order to illustrate the changing conditions within our interval, $R\rho$ is estimated by a »sliding mean value» over approximately one meter (5 concecutive samplings). The singular behaviour at the end of the interval considered depends on local extrema in the temperature distribution. Of interest is the decrease in $R\rho$ over the interval and the change of sign in the lower, presumably »finger» interface. Note that one characteristic feature of double-diffusive intrusion, with sharp gradients in the »diffusive» interface above the more or less homogeneous layer and weak gradients in the »finger» interface below, is also discernible in the graph, Fig. 4. The reader should, however, not forget the difficulties associated with interpreting sparse field data in this way.

4. *Conclusions*

The present study, though tentative in many ways, shows that the conditions are probably appropriate for double diffusion in the deeper parts of the Baltic. The intrusion discussed in section 3 and the double-diffusive processes coupled to it suggests a new mechanism for the renewal of the Baltic deep water. The incoming water may interleave with the existing water masses and mix by double-diffusive processes (as described by *e.g.* TURNER, 1978). Such a renewal has been observed in some fjords, especially during spring, when analogous hydrographic conditions may occur (FARMER and FREELAND, 1983). Even estimates of significantly larger »eddy diffusivities» of heat than of salt have been obtained (FARMER and FREELAND, 1983).

The horizontal extent of the individual intrusion layers is unknown. Even the nature and geographical location of the actual mixing between the different deep water masses are unknown. Does it occur *e.g.* during the inflow through the Stolpe Channel, immediately after the inflowing water enters the Eastern Gotland Basin or does the inflowing water progress northward along the eastern boundary of the basin simultaneously with the production of intrusive layers, thus extending the »mixing zone» to cover the major part of the basin? According to recent investigations by PERKIN and LEWIS (1984) regarding how the Atlantic water in the West Spitzbergen Current enters the Arctic Basin, the latter concept is favoured. Thus a manifold of questions are raised that need to be considered, but if successfully answered, they would substantially improve our knowledge about the deep water circulation and renewal in the Baltic proper.

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