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ON AUTUMN COOLING IN THE GULF OF BOTHNIA

by

ANDERS OMSTEDT

SMHI, Box 923,
S–601 19 Norrköping, Sweden

Abstract

Measured and calculated profiles of temperature and salinity are examined from three different sites during autumn cooling in the Gulf of Bothnia. The calculations are based on a transient Ekman model with buoyancy effects due to temperature and salinity in their one-dimensional form and with turbulent exchange coefficients calculated with a kinetic energy-dissipation model of turbulence.

The measurements demonstrate large heat changes due to sea-air interaction and to advection. They also demonstrate considerable changes in the mixed layer depth, the importance of both temperature and salinity gradients in the mixed-layer dynamics, and internal gravity waves.

The calculations focus attention on the influence of vertical exchange processes on the water temperature during the autumn cooling. Most important factors are the net heat loss at the air-sea interface and the dynamics of the mixed layer. The mathematical model describes these and the general development of the data in a satisfactory way.

Horizontal exchange processes, as advection, were found to have a strong influence on the measurements. Such events show the weakness of one-dimensional models.

1. *Introduction*

The purpose of this paper is to present measured and numerically simulated water temperatures in the Gulf of Bothnia (Figure 1) during autumn cooling.

The measurements cover three different time sequencies. The first one from the Bothnian Bay covers a period of 52 days during the autumn 1979, when the sea surface was cooled from 6 °C to 1.5 °C. The second one from the North Bothnian

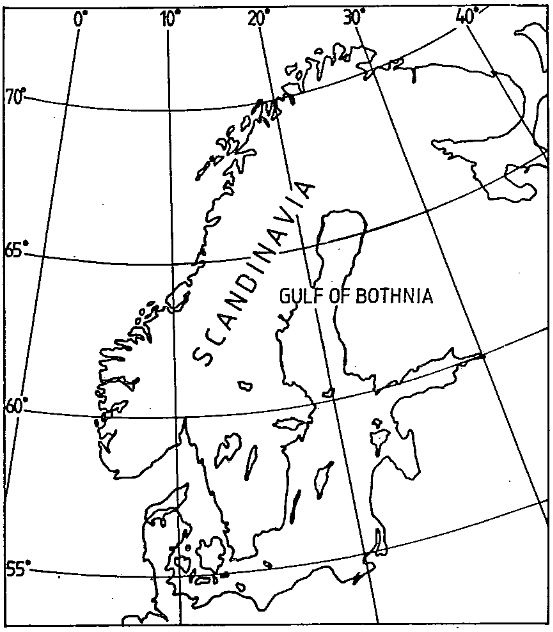

Fig. 1. Map over Scandinavia with surrounding waters.

Sea covers a period of 83 days during the autumn 1981, when the sea surface was cooled from 9 °C to 0.5 °C. The third one from the South Bothnian Sea covers a period of 80 days during the autumn 1981, when the sea surface was cooled from 10.5 °C to 1 °C.

In brackish water, as in the Gulf of Bothnia, autumn cooling brings about some special features regarding the mixing processes. Cooling brackish water with a temperature above the temperature of maximum density, $T_{\rho m}$, will cause an unstable stratification with respect to temperature, while cooling below, $T_{\rho m}$, will have a stabilizing effect. The temperature of maximum density is mainly influenced by salinity, and decreases when salinity increases. In the Gulf of Bothnia this temperature varies around 3 °C due to different salinities. All three measurement systems therefore recorded temperatures well above and well below the temperature of maximum density.

When calculating changes in the sea surface layer due to different meteorological conditions, several kinds of models have been used. In general a one-dimensional approach is taken, as temperature and salinity often varies more along the vertical axis than the horizontal ones.

A discussion of one-dimensional models for the upper ocean is made by NIILER and KRAUS (1977). In oceanographic literature there is a debate about how to represent turbulence. Some argue that integral models are preferable, because they give more direct physical insight, TURNER (1981).

In this paper, however, a so salled closure model of turbulence, with one equatio for the turbulent kinetic energy and another for the dissipation of turbulent kinetic energy, is used. This kind of model has been tested for many different problems with success, and consequently the strength of this approach is due to its generality

A full description of the model used is given by OMSTEDT *et al.* (1983), and the reader is referred to that paper for details about the assumptions.

A general description of the problem is given in next chapter. Chapter 3 deals with the meteorological and hydrographical data. The calculated and measured temperatures and salinities are discussed in chapter 4. The main conclusions of the work presented, may be found in chapter 5 together with a short summary.

2. *The problem*

The Gulf of Bothnia is the northern extension of the Baltic. Climatically it is situated in the northern part of the westerlies. The weather is influenced by the meandering polar front and the disturbances on it, which can cause strong winds during late autumn.

From an oceanographic point of view, the Gulf of Bothnia can be considered as an estuary, consisting of two main basins: the Bothnian Bay and the Bothnian Sea. The Bothnian Sea is divided into the North and the South Bothnian Sea. This convention will also be applied in the following chapters. The depth distributions in the North and South Bothnian Sea are, however, quite different. The North Bothnian Sea is characterized by one main basin. The South Bothnian Sea is characterized by shallow westerly and southeasterly areas and a deeper channel.

The low salinities in the Gulf of Bothnia are due to a positive water balance (*i.e.* precipitation and runoff exceed evaporation) and a relatively shallow sill. A typical residence time for the water in the Gulf is between two and four years. A typical time scale for the autumn cooling in the Gulf is some months. The renewal of the water is therefore a slower process compared with the autumn cooling. This implies that the autumn cooling in the Gulf is mainly due to meteorological conditions above the basin areas.

The heat exchange between the sea surface and the atmosphere is due to heat and radiation fluxes. The short wave radiation is of minor importance during autumn, but net long wave radiation, fluxes of sensible and latent heat, and precipitation particularly as snow have to be considered. The changes in water temperatures are also due to the hydrographic response because of meteorological forcing. During autumn cooling, horizontal temperature gradients are created close to the coast. In the main basins horizontal temperature gradients are less pronounced.

The internal hydrographic response in a system like the Gulf can be expected to be barotropic in the basin regions and baroclinic in the coastal regions, WALIN (1972). This means that temperature and salinity surfaces are mainly horizontal in the basins, which implies that a one-dimensional approach can be taken as a first step to the problem of autumn cooling.

The sea surface layer response due to meteorological forcing is also effected by turbulent mixing. Turbulent mixing in the sea surface layer is particularly influenced by the stability of the sea water, by the current shear and by the breaking waves.

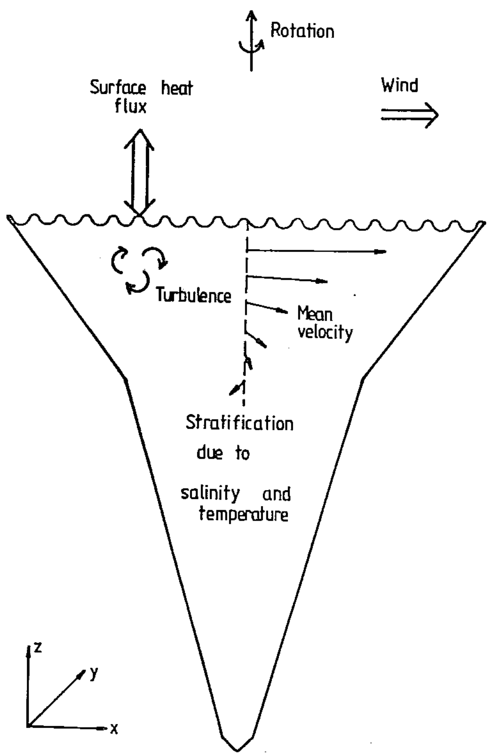

Fig. 2. Schematic representation of the one-dimensional model approach.

During cooling of a water mass with a temperature above the temperature of maximum density, the surface water becomes hydrostatically unstable with respect to temperature. Convection deepens the mixed layer, and the cooling rate decreases. After reaching the temperature of maximum density, the density profile is solely due to the salinity profile. Further cooling causes stable stratification with respect to temperature, and the turbulence is reduced.

Wind driven currents set the scene for the turbulent mixing due to vertical shear. From the classical observations by GUSTAVSSON and KULLENBERG (1936), rediscussed by KULLENBERG (1981), it is known that time dependent Ekman dynamics is a characteristic feature in the Baltic. This can also be expected in the Gulf of Bothnia, see for example UUSITALO (1980).

Turbulence due to breaking waves increases the mixing in a relatively thin surface layer, which has a thickness comparable with the amplitude of the breaking waves, KITAIGORODSKI (1979).

The considerations indicate that several vertical exchange mechanisms are present during the autumn cooling, and a one-dimensional analysis may be suitable for the Gulf of Bothnia, if the basins are treated separately. The one-dimensional analysis has to consider time dependent Ekman dynamics, stratification effects around the temperature of maximum density and the exchange of heat and momentum between atmosphere and sea.

A schematic representation of the problem is given in figure 2. Section 4 will serve as a quantitative test of the applicability to this approach.

3. *The data*

3.1 Meteorological data

The wind stress, heat and radiation fluxes were calculated on the basis of weather data extracted from synoptic weather stations around the Gulf of Bothnia. Areal mean values for the Bothnian Bay, the North Bothnian Sea, and the South Bothnian Sea were calculated separately, see figure 3–6. The weather data were extracted for every third hour in the Bothnian Bay case and for every sixth hour in the Bothnian Sea cases.

The geostrophic winds were calculated from extracted air-pressure data in a 150 km grid above the Gulf, reduced by a constant factor of 0.75 and turned 17° to the left in accordance with JOFFRE (1982).

In the stress calculation a quandratic law, with a drag coefficient slightly increasing with wind speed, was used according to GARRATT (1977).

The surface air temperatures were taken as mean values between extracted areal

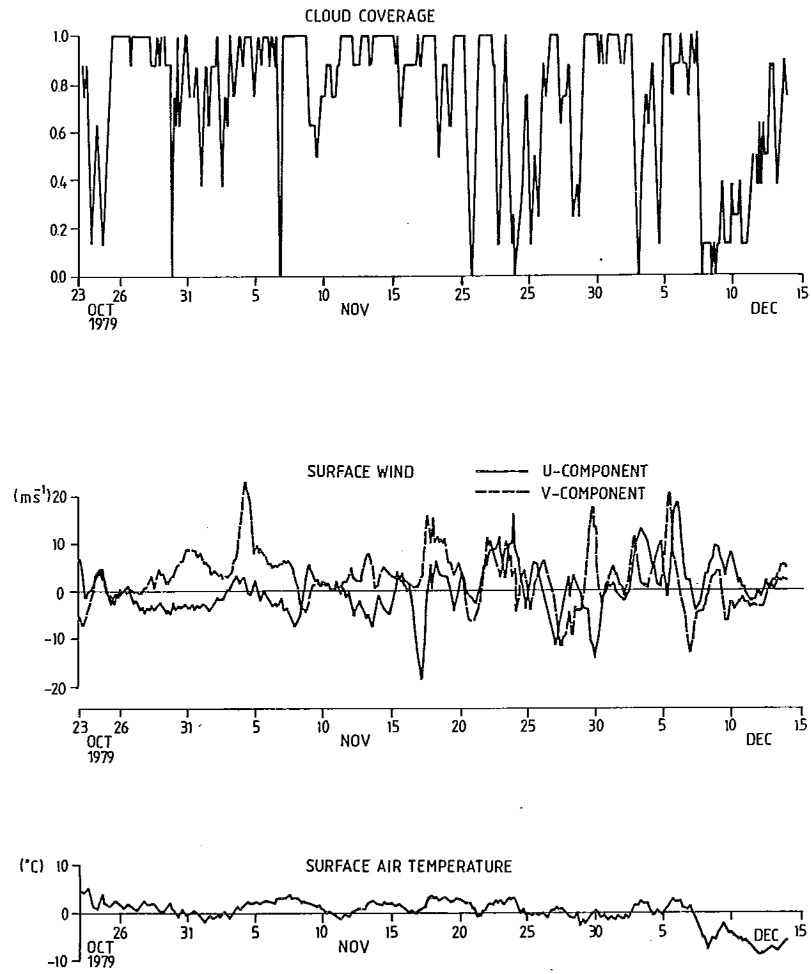

Fig. 3. Meteorological areal mean data for Bothnian Bay.

mean air temperatures and calculated sea surface water temperatures in each region.

The heat flux due to precipitation, F_p, was only treated in the Bothnian Sea cases. The heat flux was calculated according to

$$F_p = \begin{cases} \rho_w C_p W_p (T_A - T_W) & \text{when } T_A > 0 \\ \rho_w L W_p & \text{when } T_A \leqslant 0 \end{cases}$$

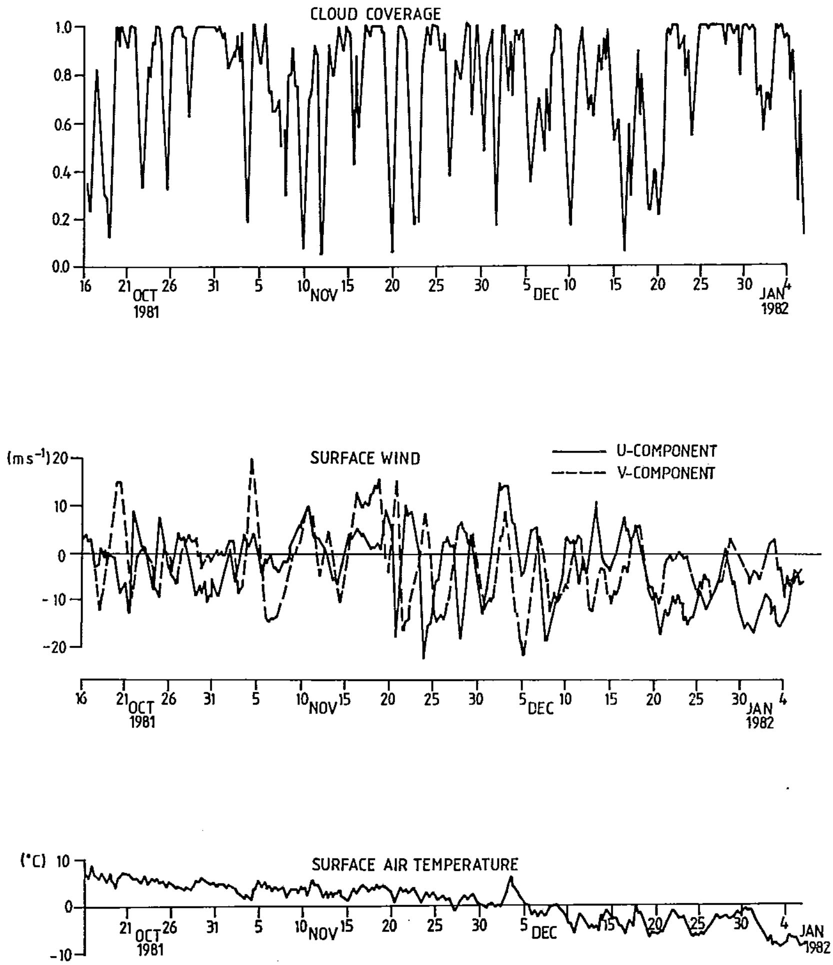

Fig. 4. Meteorological areal mean data for North Bothnian Sea.

where ρ_w is surface water density, C_p specific heat of water, W_p precipitation speed, T_A air temperature, T_W surface water temperature, and L latent heat of ice.

Together with areal mean cloud coverage values, heat and radiation fluxes were calculated according to bulk formulas. For further details see OMSTEDT *et al.* (1983).

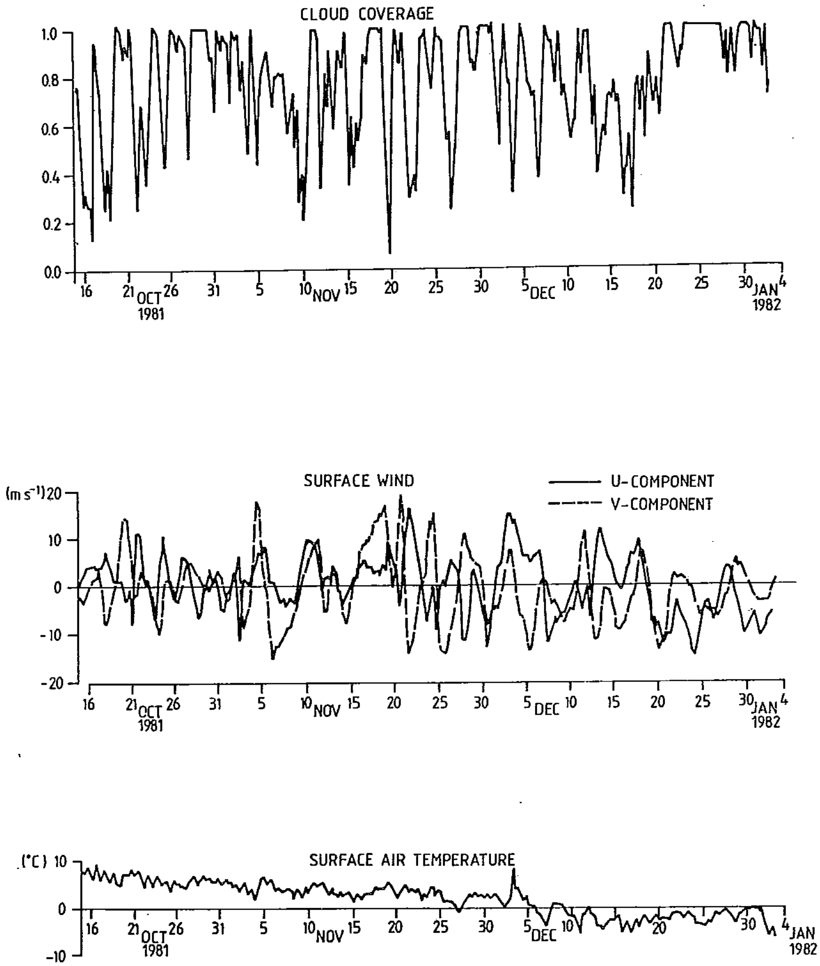

Fig. 5. Meteorological areal mean data for South Bothnian Sea.

3.2 Hydrographic data

The hydrographic data consist of temperature data and some salinity profiles. In the Bothnian Bay a water temperature measuring system was placed in autumn 1979, figure 7. The system contained 2 thermistor chains, type Aanderaa, with 11 thermistors in each chain. Measurements were made from a depth of 1 metre

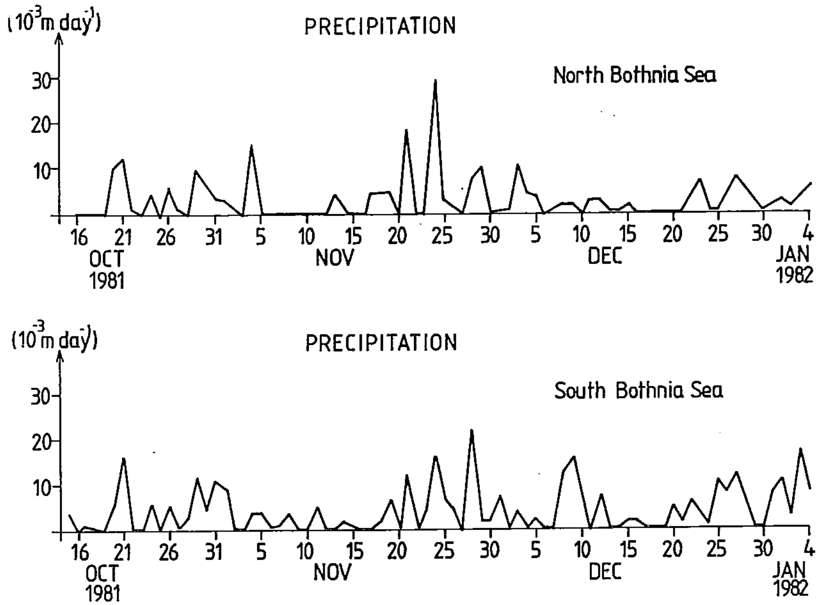

Fig. 6. Areal mean precipitation for North (upper curve) and South (lower curve) Bothnian Sea.

below the sea surface to a depth of 75 metres. Data were sampled every 30 minutes and stored on a magnetic tape.

In the autumn 1981 two water temperature systems were placed in the Bothnian Sea, one in the northern part and another in the southern part. The measurement systems were of the same type as those in the Bothnian Bay, but measurements were made down to 88 metres and sampled just every hour. The relative accuracy of the data is better than 0.05 °C.

During the Bothnian Sea periods, some salinity profiles were also taken from different vessels passing the areas, figure 8.

To gain a first insight into processes present during autumn cooling in the Gulf of Bothnia, spectral analysed water temperature data are presented. Normalized energy spectrums for temperatures at different depth are shown in figures 9 to 11. The dashed lines at short time periods are due to the uncertainty in the spectral analyses, when reaching periods close to the sampling interval. The vertical lines in the figures represent 80 (%) confidence interval according to chi-square test, KINSMAN (1965).

The normalized energy spectrums illustrate two main features. Firstly the

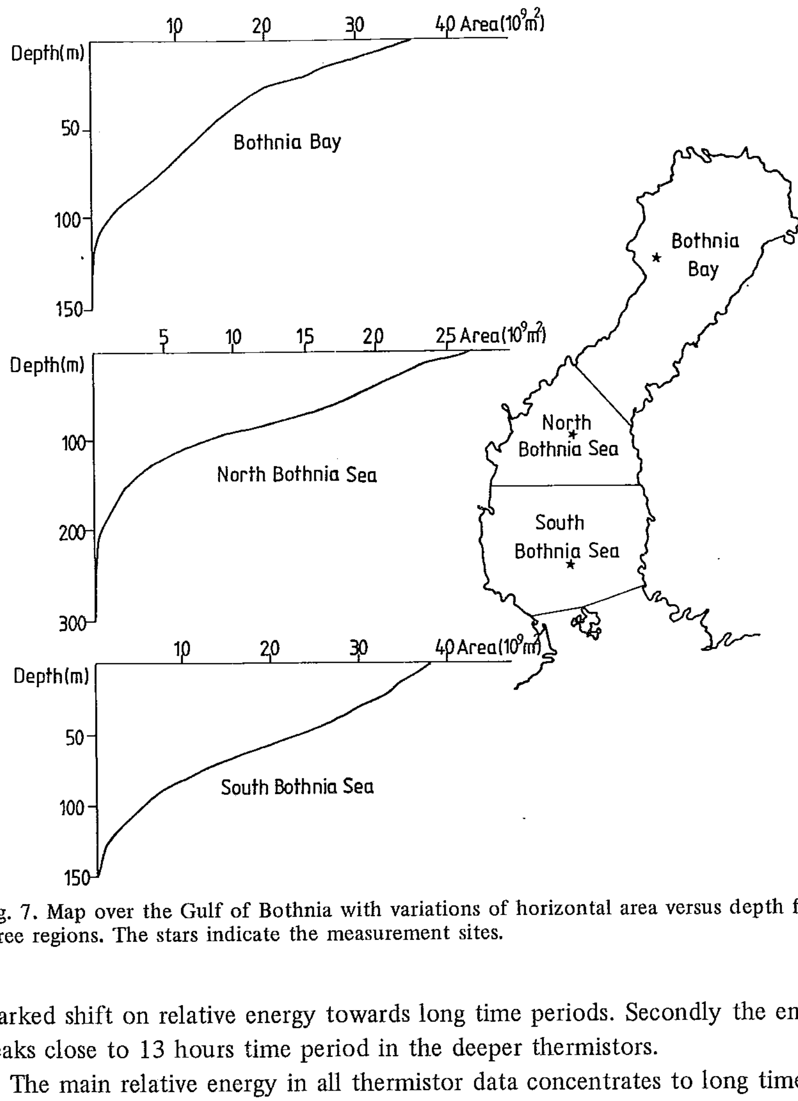

Fig. 7. Map over the Gulf of Bothnia with variations of horizontal area versus depth for the three regions. The stars indicate the measurement sites.

marked shift on relative energy towards long time periods. Secondly the energy peaks close to 13 hours time period in the deeper thermistors.

The main relative energy in all thermistor data concentrates to long time periods, particularly in the surface layer. This indicates that the main processes during autumn cooling are due to meteorological forcing on time scales larger than 24 hours.

In the deeper layers the relative energy also concentrates on time periods close to but less than 13 hours. The inertial periods at the three different sites are slightly larger than 13 hours. This implies that sub-inertial gravity waves are present in the data – a feature which is typical for open sea conditions.

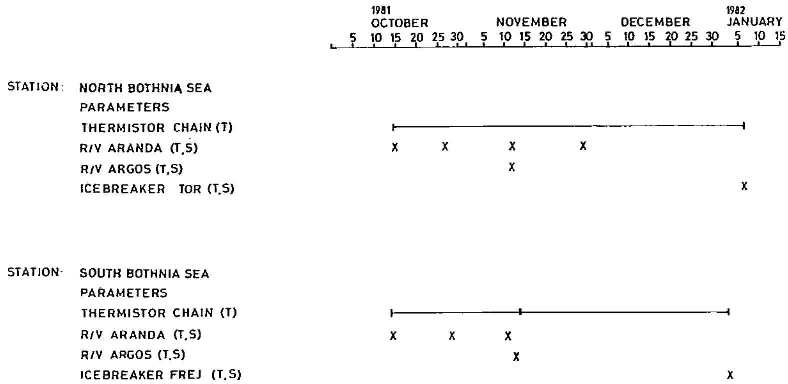

Fig. 8. Measurement periods and parameters for North and South Bothnian Sea.

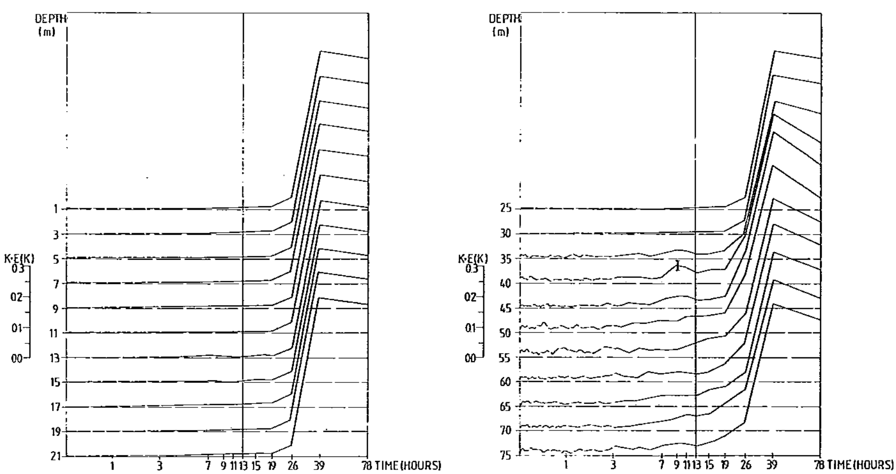

Fig. 9. Normalized energy spectrums for different depths based upon Bothnian Bay temperature data. The vertical line at the 40 m depth represent a 80 (%) confidence interval.

The sub-inertial oscillations are most pronounced in the South Bothnian Sea. The data also show a shift of relative energy towards shorter time periods at deeper layers in the South Bothnian Sea. This has probably no dynamical significance, as the relative importance of measurement noice increases at time periods close to the sampling interval.

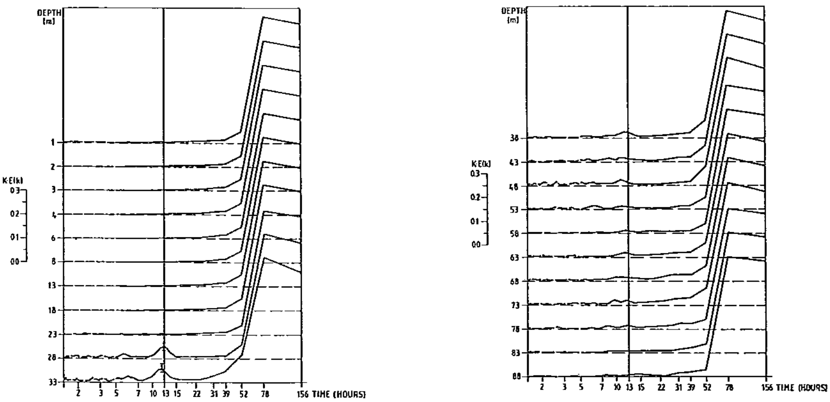

Fig. 10. Normalized energy spectrum for different depths based upon North Bothnian Sea temperature data. The vertical lines represent 80 (%) confidence intervals.

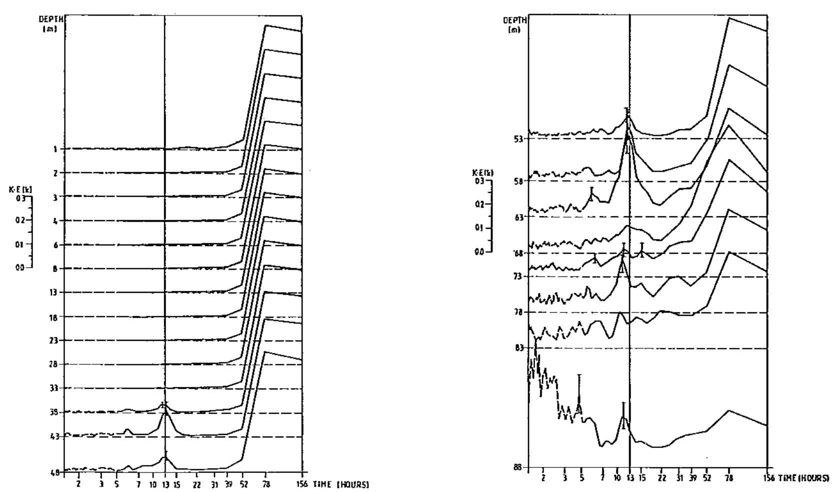

Fig. 11. Normalized energy spectrum for different depth based upon South Bothnian Sea temperature data. The vertical lines represent 80 (%) confidence intervals.

The following chapters mainly concentrate on temperature changes in the well mixed sea surface layer, where almost all relative energy is, at time periods, larger than 24 hours. The calculations and measurements are therefore taken as 24 hour mean values.

4. *Calculations*

4.1 General remarks

In this chapter the measured profiles are compared with the calculated profiles, according to the model presented by Omstedt *et al.* (1983). The mathematical model is based on time dependent Ekman dynamics with buoyancy effects due to temperature and salinity. It also considers the change of sign in buoyancy flux at the temperature of maximum density. Turbulence due to breaking waves has, however, not been treated in the model.

Two slight modifications have been made in the calculations according to this paper compared with Omstedt *et al.* (1983). Firstly, the precipitation is taken into account, which influences both the net heat balance and the salinity flux condition at the air-water interface. Secondly the drag coefficient in the stress calculations is wind dependent. The modifications have, however, just slight effects on the result.

In all calculations, the variations of horizontal area versus depth are according to the Bothnian Bay, the North Bothnian Sea and the South Bothnian Sea, see figure 7. When judging the performance of the calculations one ought to have in mind that just initial profiles in temperature and salinity are used, and also the uncertainty in the meteorological input data.

After these general remarks on the calculations the three hydrographic areas are discussed separately in the following chapters.

4.2 Bothnian Bay

In this chapter the results from the Bothnian Bay period will be presented. Computed and measured sea surface temperatures are compared in figure 12. The sea surface temperature is defined as the temperature at one metre's depth. The computed sea surface temperatures fall well on the measured ones.

In figure 13 the calculated and measured total heat contents are plotted. It can be seen that the changes in total heat loss by surface heat fluxes, calculated total heat contents, do not exactly correspond to the actual change in the measured total heat contents during the period studied. Particularly the measured total heat contents change rapidly during some days at the beginning of November. Advective transports in the sea are the most probably explanation for this discrepancy.

In Omstedt *et al.* (1983) the measured and the calculated data are further discussed. The analyse demonstrates clearly the importance of both temperature

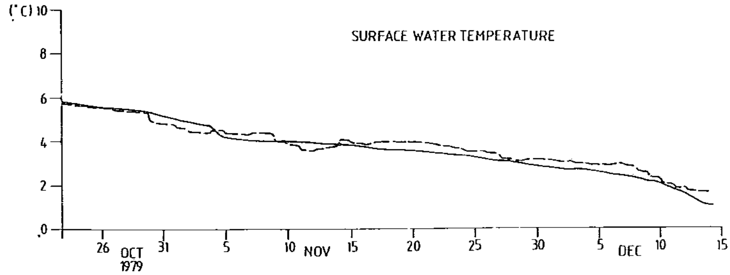

Fig. 12. Measured (dashed line) and calculated (fully drawn line) sea surface temperatures for the Bothnian Bay case.

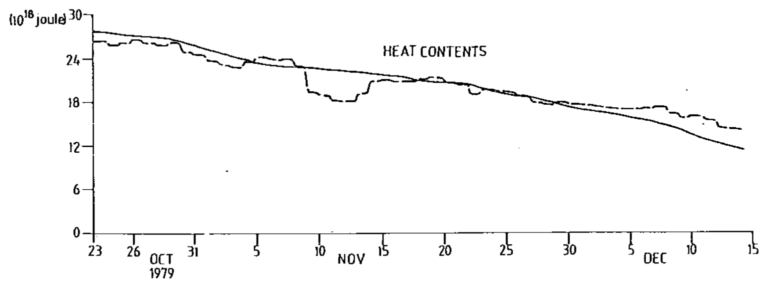

Fig. 13. Measured (dashed line) and calculated (fully drawn line) total heat contents for the Bothnian Bay case.

and salinity gradients in the mixed layer dynamics. Also advection, not represented in the mathematical model, was found to influence the temperature profiles. However, the main features during the autumn cooling in the Bothnian Bay were well calculated by the model.

4.3 North Bothnian Sea

The measured and the numerically simulated sea surface temperatures for the North Bothnian Sea period are compared in figure 14. In the light of all uncertainties, the agreement obtained after 83 days of time integration is most satisfactory.

The calculations were performed both with and without considering the precipitation. Figure 14 illustrates that precipitation only contributed to the cooling in the end of the period, when precipitation was in the form of snow.

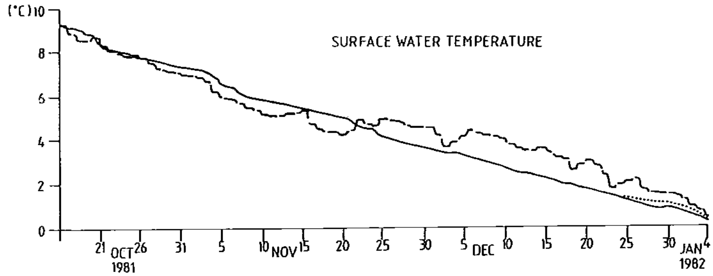

Fig. 14. Measured (dashed line), calculated without considering precipitation (dotted line) and calculated with considering precipitation (fully drawn line) sea surface temperatures for the North Bothnian Sea case.

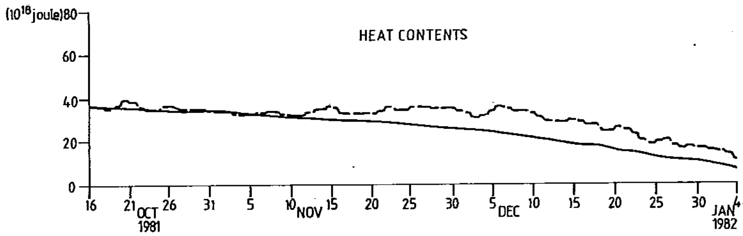

Fig. 15. Measured (dashed line) and calculated (fully drawn line) total heat contents for the North Bothnian Sea case.

In figure 15 the calculated and measured total heat contents are plotted. The two curves diverge from the middle of November to the beginning of December. The measured total heat contents indicate advections, bringing heat into the system, which almost balances the net heat loss to the atmosphere during that period.

In figure 16 details on measured and calculated temperature profiles are given for nine different occacions during the cooling period. Also calculated salinities, densities, and dynamical eddy viscosities are plotted in the figure. The measured temperature profiles show a slight increase in deeper layers, which is not calculated by the model. Restrification, after temperature has passed the temperature of maximum density (2.6 °C), is less pronounced compared with the Bothnian Bay period due to higher winds.

Measured and calculated salinities are shown in figure 17. The mixed layer depth increases considerably during the period, which seems to be well calculated by the model. There are, however, differences in the absolute values. The meas-

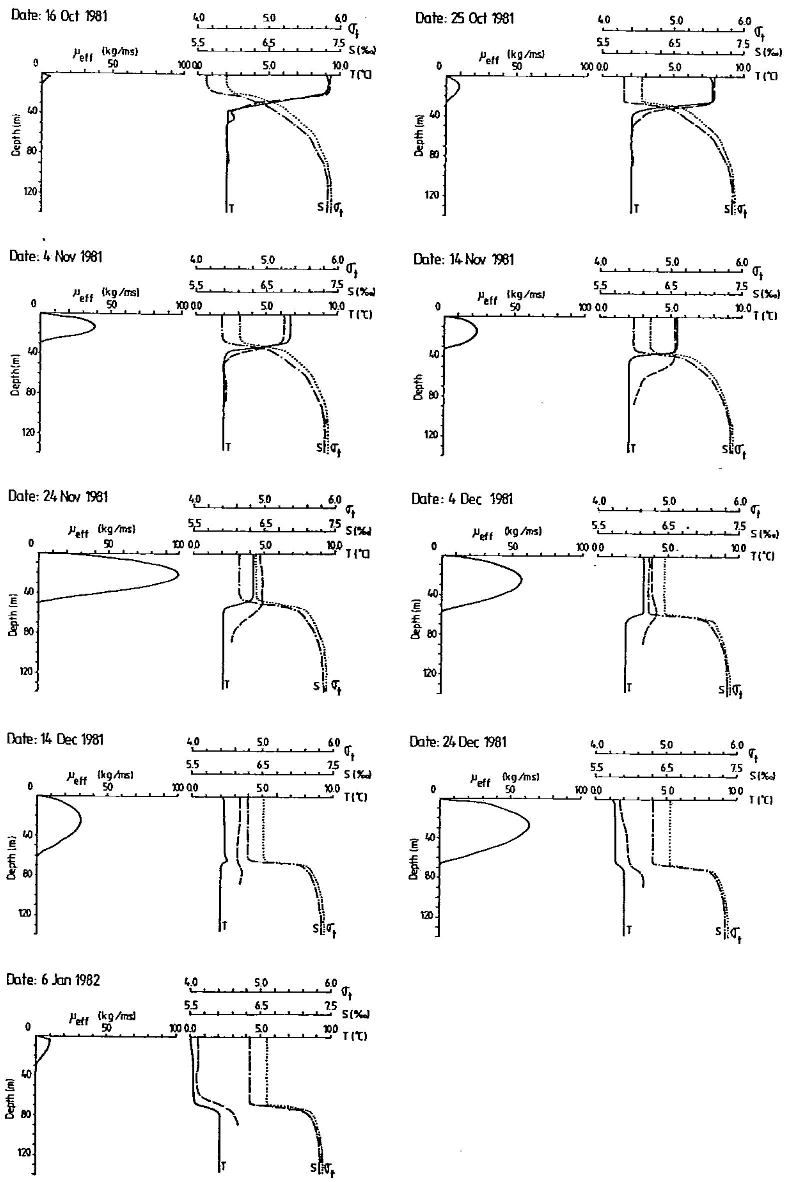

Fig. 16. Model calculations of dynamical eddy viscosity (μ_{eff}), temperature (T), salinity (S) and density (σ_t) from nine occasions during the cooling period in the North Bothnian Sea. The dashed lines are observed temperature profiles. All data are 24 hour averages.

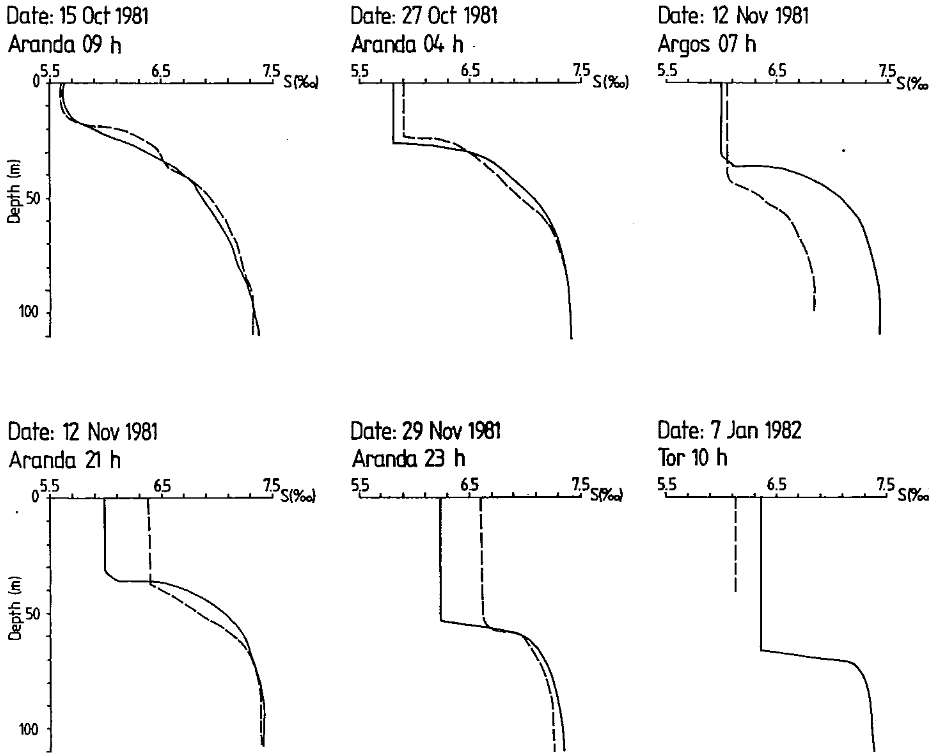

Fig. 17. Measured (dashed lines) and calculated (fully drawn lines) salinities. All calculated data are 24 hour averages. Measured data are taken at specific times given in hours in the head of each figure.

ured salinities in the mixed layer exceed the calculated ones until late November, after that time the calculated salinities exceed the measured ones. The discrepancy between calculated and measured salinities further support that advection is present.

As the long time mean circulation in the Bothnian Sea is counter-clockwise, it is tempting to interpretend the discrepancy as due to advection coming from south with higher salinities and higher temperatures. The last salinity profile and the total heat contents, however, indicate that the advection reversed in the beginning of December, bringing less saline water to the measuring system.

The results illustrate that the vertical exchanges during autumn cooling are first order processes, and that a one-dimensional approach can be successful, even if advection is present.

4.4 South Bothnian Sea

The measured and calculated sea surface temperatures for the South Bothnian Sea period are shown in figure 18. The two curves diverge rapidly at the beginning of the period and do not converge during the whole period. The discrepancy after 80 days of time integration is more than 2 °C.

This is further explored in figure 19, where calculated and measured total heat contents are plotted. The measured total heat contents show a more rapid decrease, particularly at the beginning of the period, than one could expect considering the heat fluxes between the air-water interface. Advection is again the most probable explanation.

In figure 20 the measured temperature profiles are compared with the calculated profiles at nine different occasions. The mixed layer temperatures are badly calculated. The mixing depth, however, seems more accurate. In the deeper layer one can also notice a slight increase in measured temperatures. After cooling has passed

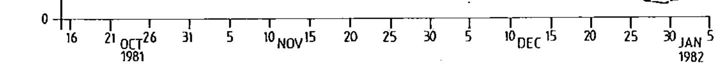

Fig. 18. Measured (dashed line), calculated without considering precipitation (dotted line) and calculated with considering precipitation (fully drawn line) sea surface temperatures for the South Bothnian Sea case.

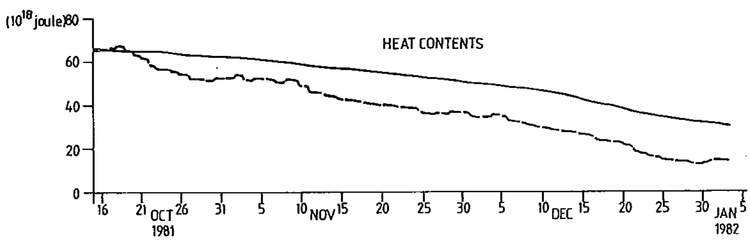

Fig. 19. Measured (dashed line) and calculated (fully drawn line) total heat contents for the South Bothnian Sea case.

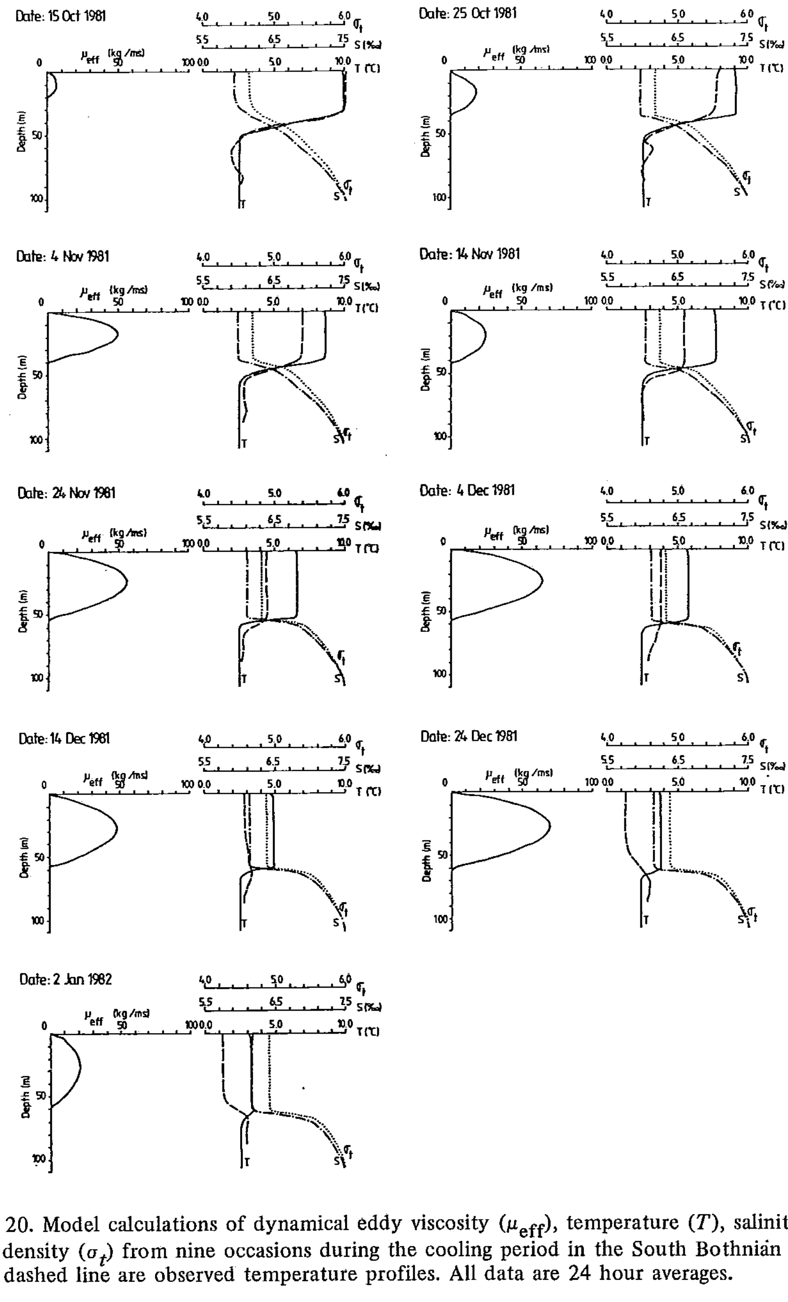

Fig. 20. Model calculations of dynamical eddy viscosity (μ_{eff}), temperature (T), salinity (S) and density (σ_t) from nine occasions during the cooling period in the South Bothnian Sea. The dashed line are observed temperature profiles. All data are 24 hour averages.

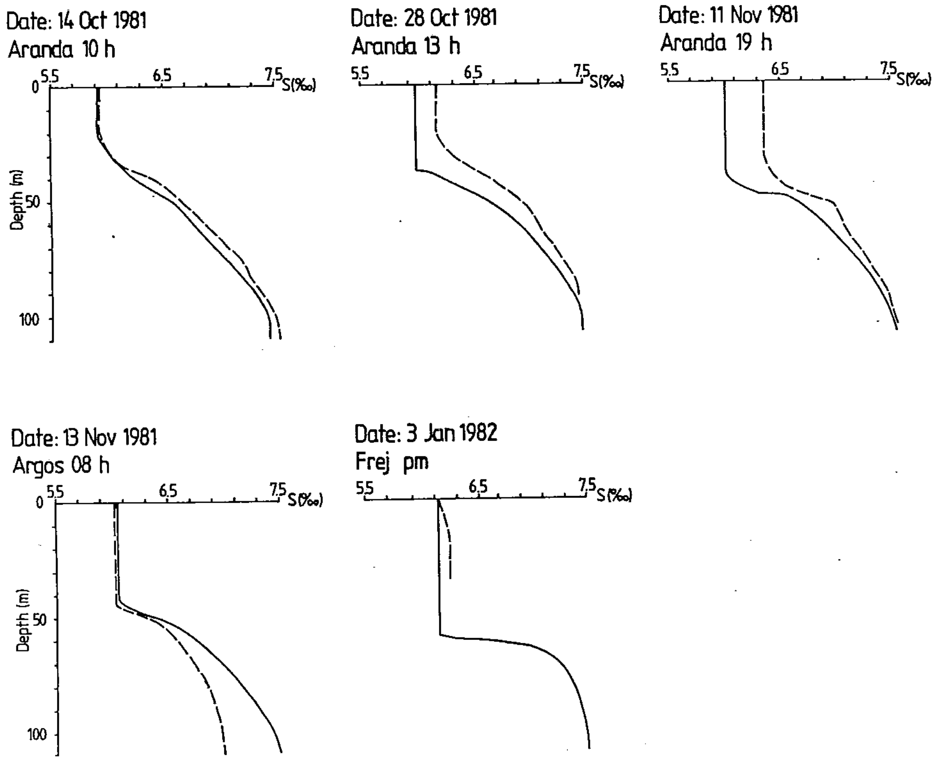

Fig. 21. Measured (dashed lines) and calculated (fully drawn lines) salinities for the South Bothnian Sea case. All calculated data are 24 hour averages. Measured data are taken at specific times given in hours in the head of each figure.

the temperature of maximum density (2.6 °C), restratification can start. The restratification is, however, weak due to rather high winds.

The measured and calculated salinity profiles are plotted in figure 21. At the beginning of the period the measured salinities indicate advection with saltier waters coming into the system, but later on less saline water enters. The mixing depth increases considerably during the period, which seems to be well calculated by the model.

The advection at the beginning of the period therefore brings less heat but higher salinities compared with the calculated ones. In the middle of the period advection seems to change. With the long time mean circulation in mind, it is tempting to interpretend the discrepancy, particularly at the beginning of the period, as due to advection of cold and saline water coming from shallow areas

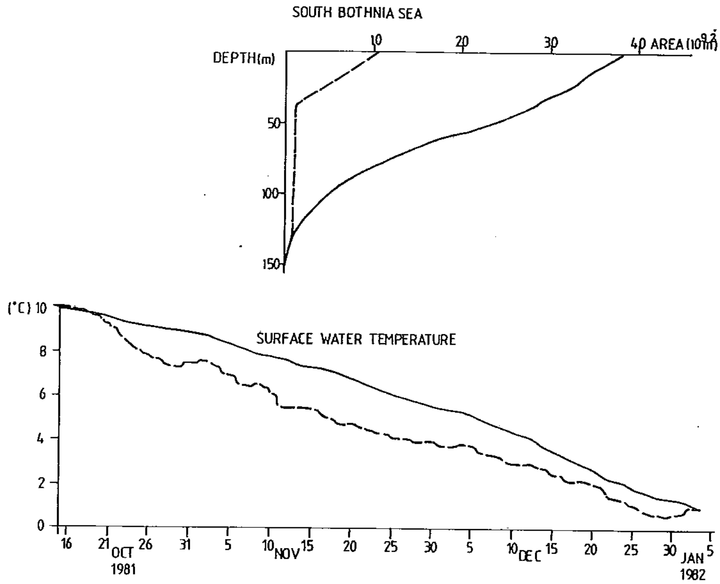

Fig. 22. Recalculated (fully drawn line) and measured (dashed line) sea surface temperatures for the South Bothnian Sea case. The variations of horizontal areas versus depth represent the observed distribution according to the South Bothnian Bay (fully drawn line) and the distribution used in the recalculation (dashed line).

south of the area.

The depth distribution in the South Bothnian Sea is more complex compared with that of the other two areas. As it was pointed out in chapter 2, the South Bothnian Sea is characterized by shallow westerly and southeasterly areas and a deeper channel.

The spectral analyses discussed in chapter 3.2 also illustrated a more pronounced shift towards sub-inertial oscillation in the South Bothnian Sea. This may be due to the facts that this area has a more complicated depth distribution compared with the other two locations and is situated more close to the sill depth. Therefore it seems misleading to represent the South Bothnian Sea with just one basin, as autumn cooling proceeds much faster in the shallow areas than in the deeper channel area. In figure 22 recalculated and measured sea surface temperatures are drawn. The recalculation was based upon the same input data as earlier, but now the areal distribution with depth mainly represents the shallow coastal areas in the South Bothnian Sea. The agreement obtained after 80 days of time integration is more satisfactory. The calculations therefore indicate that the measuring system in the South Bothnian Bay was influenced by waters advected from the coastal areas.

5. *Summary and conclusions*

The purpose of this paper is to present measured and calculated water temperatures from the Gulf of Bothnia during the autumn cooling.

The water temperatures were measured in the Bothnian Bay during 52 days, in the North Bothnian Sea during 83 days, and in the South Bothnian Sea during 80 days. Some salinity profiles were also measured. All three measurement systems recorded temperatures well above and well below the temperature of maximum density. The measured data are compared with calculated ones, obtained by a mathematical model. The mathematical model is based on transient Ekman dynamics with buoyancy effects due to temperature and salinity. It also consider the changes of sign in buoyancy flux at the temperature of maximum density. The heat and radiation fluxes are calculated from bulk formulas with weather data extracted from synoptic weather stations. Turbulent exchange coefficients are calculated with a two-equation model of turbulence. The approach is just one-dimensional, and therefore the three measurement systems are represented by the variation of horizontal area versus depth for the surrounding waters.

The calculations focused attention on the influence of vertical exchange processes on the water temperature during autumn cooling. Most important factors are the heat loss at the air-sea interface and the dynamics of the mixed layer.

The measured temperature and salinity profiles clearly demonstrate the importance of both temperature and salinity gradients in the mixed layer dynamics. Considerable changes in the mixed layer depth were observed and calculated in all three measurement periods.

In the light of all uncertainties in the meteorological and hydrological data and of the restriction that just vertical exchange processes were calculated, the results are satisfactory.

Horizontal exchange processes, as advection, were found to have a strong influence on the measured temperatures. Such events show the weakness of one-dimensional models, which, of course, cannot handle advection. However, the results support the one-dimensional model approach as a first step when studying autumn cooling in the Gulf of Bothnia.

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