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A FORECAST MODEL FOR WATER COOLING IN THE GULF OF BOTHNIA AND LAKE VÄNERN

by Anders Omstedt

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Abstract

A new forecasting model for water cooling in the Gulf of Bothnia and Lake Vänern is presented. The model elements consist of a transient Ekman model, where the turbulent exchange coefficients are calculated with a two-equation model of turbulence, a heat flux package for calculating the net heat loss at the air/sea interface, and geometries based upon area/depth distributions for the Bothnian Bay, the North Bothnian Sea, Lake Vänern/Dalbosjön, and Lake Vänern/Värmlandssjön.

The model system can handle up to five different forecasts of maximum 30 days each simultaneously. It is constructed for easy and rapid interactive handling by letting the forecaster answer questions on a terminal screen.

During the winter navigation period of 1983/84 the model was tested in routine. The results from that test period were most satisfactory, and it is believed that the new forecasting model can serve as a reliable adviser for effective winter navigation planning during coming seasons.

Key words

Gulf of Bothnia, Lake Vänern, Sea surface temperatures, Forecasting model

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1. INTRODUCTION

The winter navigation research at SMHI has during the last few years been concentrated on processes related to water cooling. As one result of this research it has been possible to develop a new operational model for predicting autumn cooling in the Gulf of Bothnia and Lake Vänern. The locations of the different sea areas are given in Figure 1. The purpose of the present report is to describe this model and to give some examples on how it can be used.

Figure 1. Map of the Gulf of Bothnia and Lake Vänern with subbasins.

The main research was started by Sahlberg and Törnevik (1980), when they studied large scale cooling in the Bothnian Bay. In their approach they treated the Bothnian Bay as one constant layer and neglected the importance of vertical temperature variations. However, a method for calculating net heat loss at the air/sea interface was developed and tested with good results.

To get further insight into processes related to autumn cooling, a water temperature measuring system was placed in the Bothnian Bay in October, 1979. The system contained two thermistor chains, type Aanderaa, with 11 thermistors in each. Measurements were made from a depth of 1 m below the sea surface to a depth of 75 m. Data were sampled every 30 minutes and stored on a magnetic tape. The measurements covered 52 days, when the sea surface was cooled from 6 °C to 1.5 °C.

To analyse the measured data, a new mathematical model was developed. Based upon the work by Svensson (1978) a model for the upper layer of the sea was formulated. The model was based upon transient Ekman dynamics with buoyancy effects due to temperature and salinity and with turbulent exchange coefficients calculated with a two-equation model of turbulence.

The mathematical model described the measured data in a most satisfactory way. The results were reported by Omstedt and Sahlberg (1982) and by Omstedt, Sahlberg, and Svensson (1983).

To test the model further, temperature and salinity data were collected at two locations in the Bothnian Sea. The first location in the North Bothnian Sea covered a period of 83 days during the autumn of 1981, when the sea surface temperature was cooled from 9 °C to 0.5 °C. The second location from the South Bothnian Sea covered a period of 80 days during the autumn of 1981, when the sea surface temperature was cooled from 10.5 °C to 1 °C.

The measurements demonstrated considerable changes in the depth of the well mixed surface layer, the importance of both temperature and salinity gradients, and internal waves.

The calculations focused attention on the net heat loss at the sea surface and the mixed layer dynamics. The results were satisfactory and reported by Omstedt (1983), see Appendix B. Horizontal exchange processes, such as advection, were found to have strong influence on the dynamics, particularly in the South Bothnian Sea. Such events illustrate the weakness of a one-dimensional model, which therefore only can be applied to sea areas where advective effects are weak.

Parallel to the winter navigation research, the interest in heat stored in lakes as an energy source has increased in Sweden. Sahlberg (1983) therefore performed a study on how to calculate the heat content in lakes during autumn cooling. Based upon a model similar to the one used in the Gulf of Bothnia, Sahlberg could give a most satisfactory analysis of measured temperature data. The data were taken from Väsman, a lake situated in the central part of Sweden.

The studies mentioned above give confidence in the mathematical model formulation and therefore it seems meaningful to create an operational model system for prediction of water temperatures.

In the next chapter a general description of such a system is given. Then, in Chapter 3, some applications from the winter navigation season of 1983/84 are discussed. Finally, a summary with conclusions is given in Chapter 4.

2. MODEL STRUCTURE

The main idea in the formulation of the model structure was to give the forecaster as much influence on the predictions as possible. This required a system, where the input data rapidly and easily could be given and changed. An interactive data system was therefore constructed, in which the forecaster could answer questions on a data terminal screen, see Figure 2. The forecaster does not need any deeper knowledge of computer programming, instead his meteorological/oceanographical insight and experience can be utilized in an optimal way.

Figure 2. The forecaster gives the input data by answering questions on a terminal screen.
Photo: Gunnar Larsson.

A schematic representation of the model is given in Figure 3. The questions on the terminal screen are shown in Figure 4. The model system can handle up to five different forecasts of maximum 30 days each simultaneously.

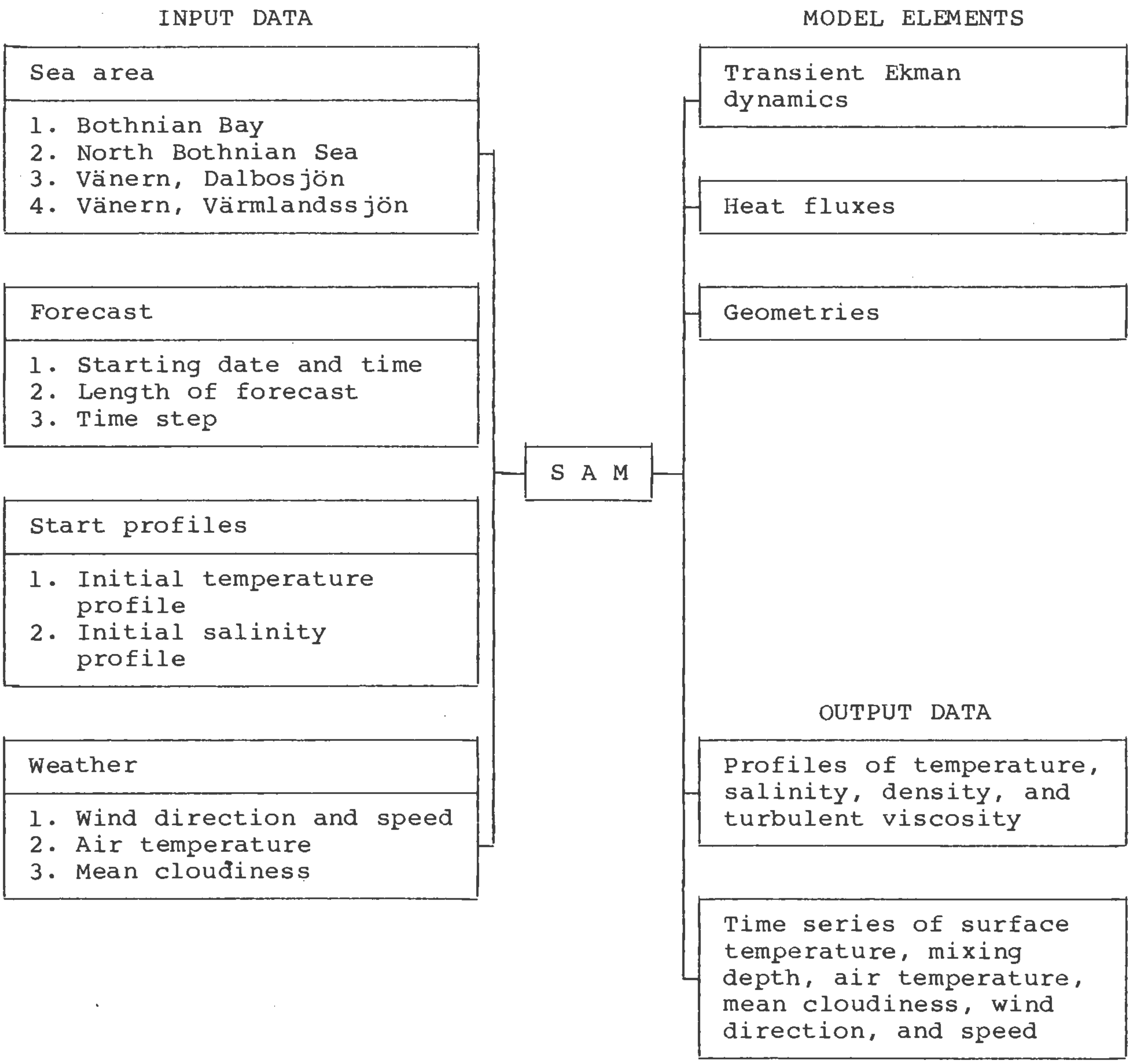

Figure 3. Schematic representation of the SMHI Autumn cooling Model (SAM).

1. Give the required area 1, 2, 3, or 4.
   1 = The Bothnian Bay
   2 = The North Bothnian Sea
   3 = Lake Vänern, Dalbosjön
   4 = Lake Vänern, Värmlandssjön
2. Give the starting time (t_0).
3. Give the forecast period ($n\ \Delta t$).
4. Give the forecast time step (Δt).
5. Give the initial water temperature (T_{sur}, T_{bot}, D3, D4).
6. Give the initial salinity (S_{sur}, S_{bot}, D1, D2).
7. Give the wind direction and speed, air temperature, and cloudiness at time t_0.
8. Give the wind direction and speed, air temperature, and cloudiness at time $t_0 + \Delta t$.
   ....
   ....
   ....
9. Give the wind direction and speed, air temperature, and cloudness at time $t_0 + (n-1)\Delta t$.
10. Would you like to change any data?
11. Would you like to do a new forecast?
12. So long!

Figure 4. Data terminal questions.

The input data to the model are sea area, forecast information, starting profiles, and weather data. The weather data are wind direction and speed, air temperature and mean cloudiness. The starting profiles are water temperature and salinity from the surface to the bottom. In Lake Vänern only water temperatures are given.

The model elements consist of three parts. The first part is a transient Ekman model based on the conservation equation for momentum, heat, and salt.

The equation of state is linear with respect to salinity and quadratic with respect to temperature. Turbulent exchange coefficients are calculated with a two-equation model of turbulence. The mathematical formulation is given in Appendix A.

The second part is heat fluxes based on calculations of net short wave radiation, net long wave radiation, sensible and latent heat. The boundary conditions are further discussed in Appendix A.

The third part is geometries based upon basin areas. The one-dimensional nature of the model takes into account how the horizontal area varies versus depth for each basin. This is of fundamental importance, and the calculations can therefore be looked upon as representing the whole basin in each area. The variation of horizontal area versus depth together with location of each area, given as latitude, define the geometries.

The output data from the model are given as two types of plottings. The first type plots 24-hour mean values of temperature, salinity, density, and turbulent viscosity as vertical profiles, see Figure 5.

The second type plots time series of sea surface temperature, mixing depth, air temperature, mean cloudiness, wind direction and speed, see Figure 6.

In the next chapter some results from the winter navigation season of 1983/84 are discussed. This was the first year in which the model system was tested in routine.

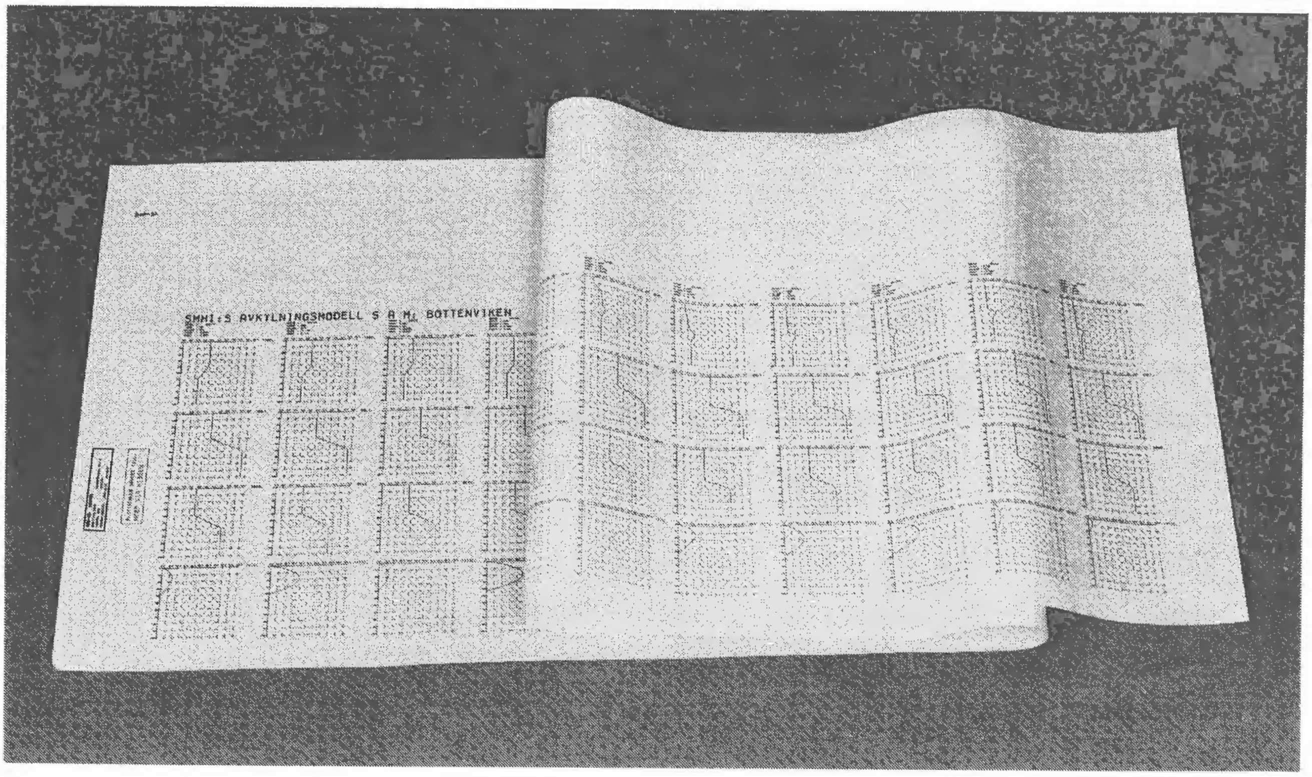

Figure 5. Output data in the form of vertical profiles.
Photo: Gunnar Larsson.

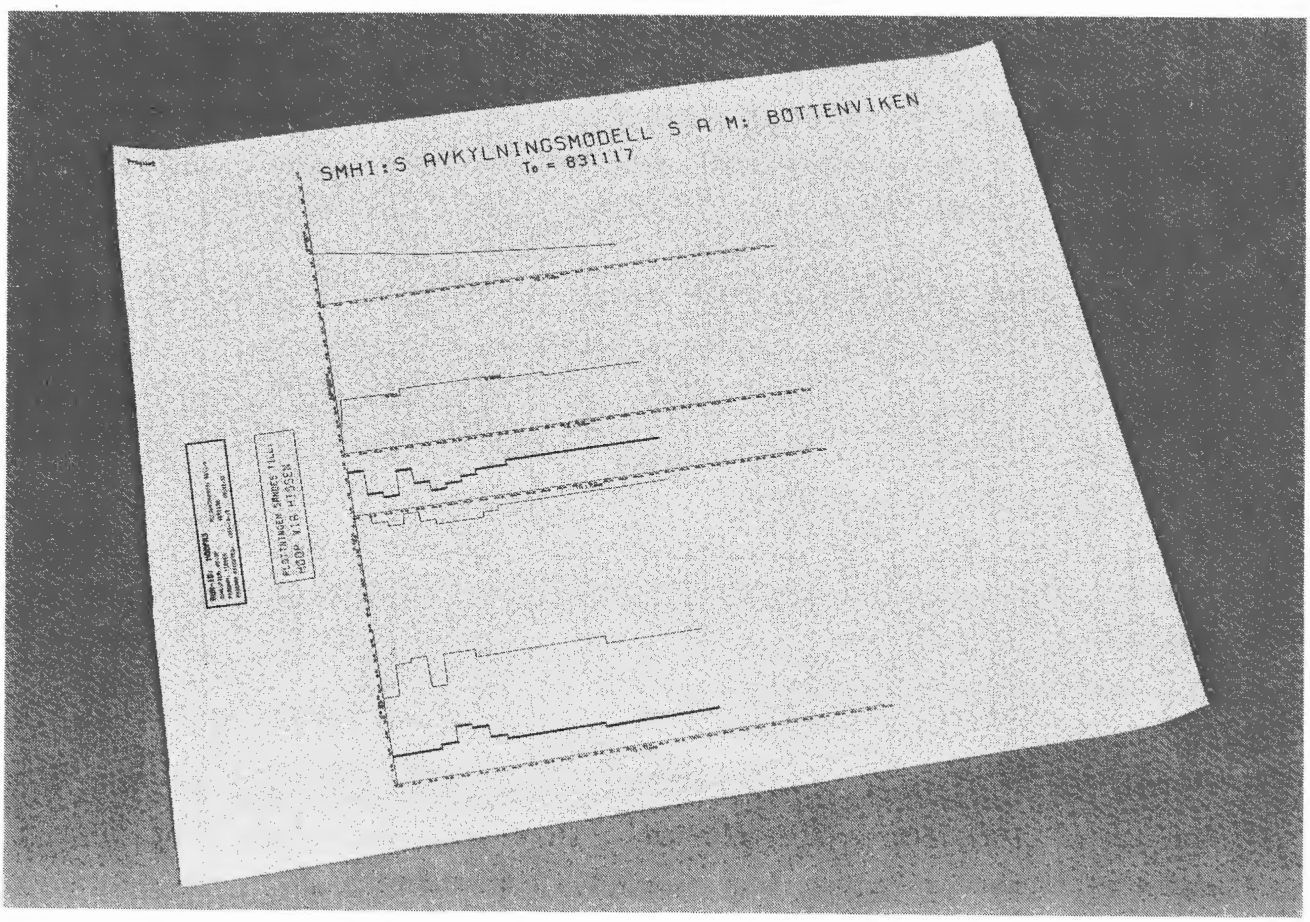

Figure 6. Output data in the form of time series plots.
Photo: Gunnar Larsson.

3. APPLICATIONS

3.1 Introduction

Some applications of the forecast model are given in this chapter. The applications to be presented are the first forecast made for each sea area. As the forecasting system also will serve as a teaching tool, it is believed that in the future the applications will change and the quality increase.

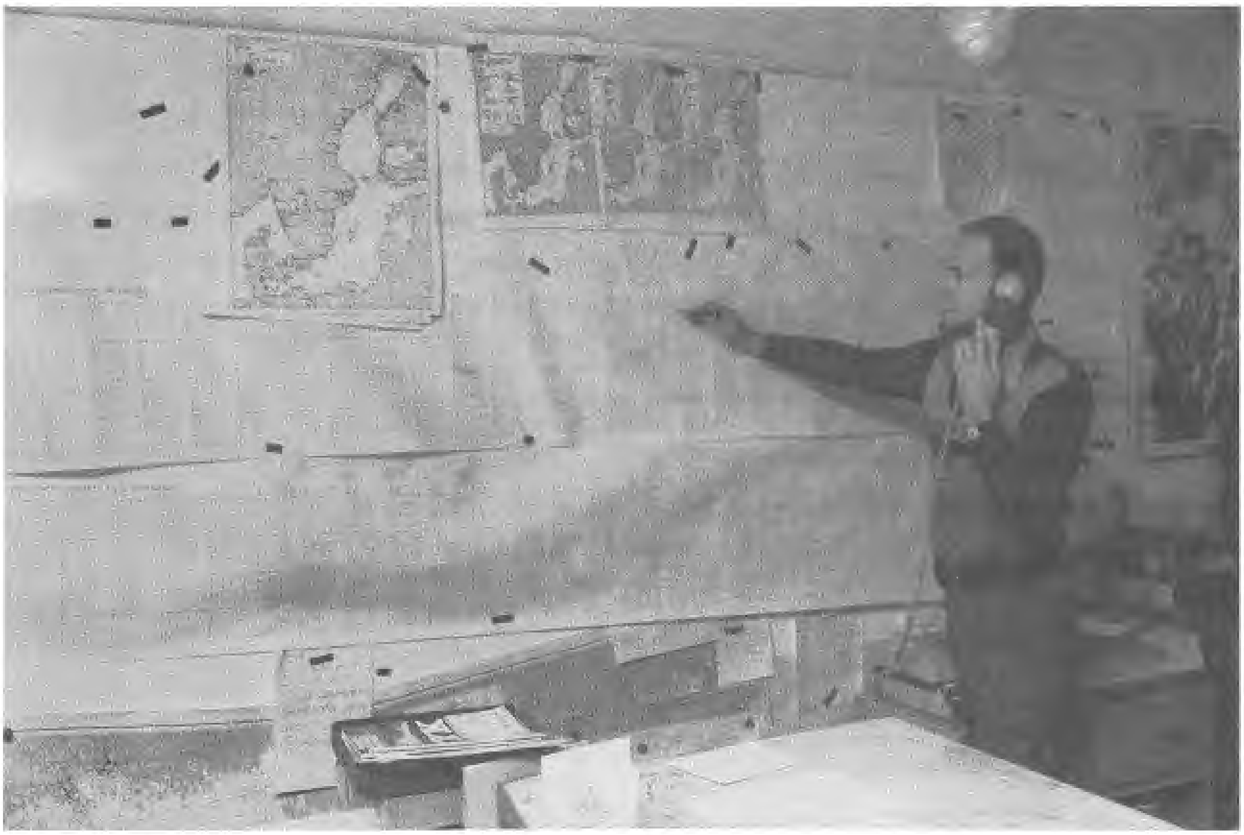

Figure 7. The forecaster provides the Ice-Breaking Service with the latest news.
Photo: Gunnar Larsson.

Mapping and forecasting of different sea parameters are performed daily at SMHI. The Swedish Administration of Shipping and Navigation plan the ice-breaking service in close contact with SMHI, see Figure 7. For this planning, forecasts for up to one month ahead are of great value.

Today weather forecasts beyond five days must rely chiefly on climatology. One may hope that in the future reliable dynamical weather forecasts can be given for up to ten days, but beyond ten days weather forecasts must probably be based upon climatology, even in the foreseeable future.

By forecasting sea surface temperatures, much information beyond ten days can, however, be gained about how soon ice will form. In fact, knowing the starting profiles of temperature and salinity, forecasts based on climatology and expected worst cases can give different possible autumn scenarios and therefore different planning alternatives. This will be illustrated in the next sections.

The importance of measuring the starting profiles of temperature and salinity should be stressed here, as they represent the sea state integrated several months back in time.

3.2 The Bothnian Bay

The very first forecast with the model was a 20-day forecast from November 14, 1983. The input data were given as 24-hour mean values with data taken from the weather forecast during the first five days. After that, climate data were used. The results are given in Figure 8. In that figure also the sea surface temperature forecast based upon analysed weather and measured or estimated sea surface temperatures are plotted. The measured or estimated values are based upon routine mapping of sea surface temperatures in the waters surrounding Sweden, see Thompson, Udin, and Omstedt (1974). From the figure it can be seen that there is a good agreement between the two forecasts. The deviation between the end of November and the beginning of December is due to the weather, which became cold with weak winds during late November, followed by a period of stronger winds in December.

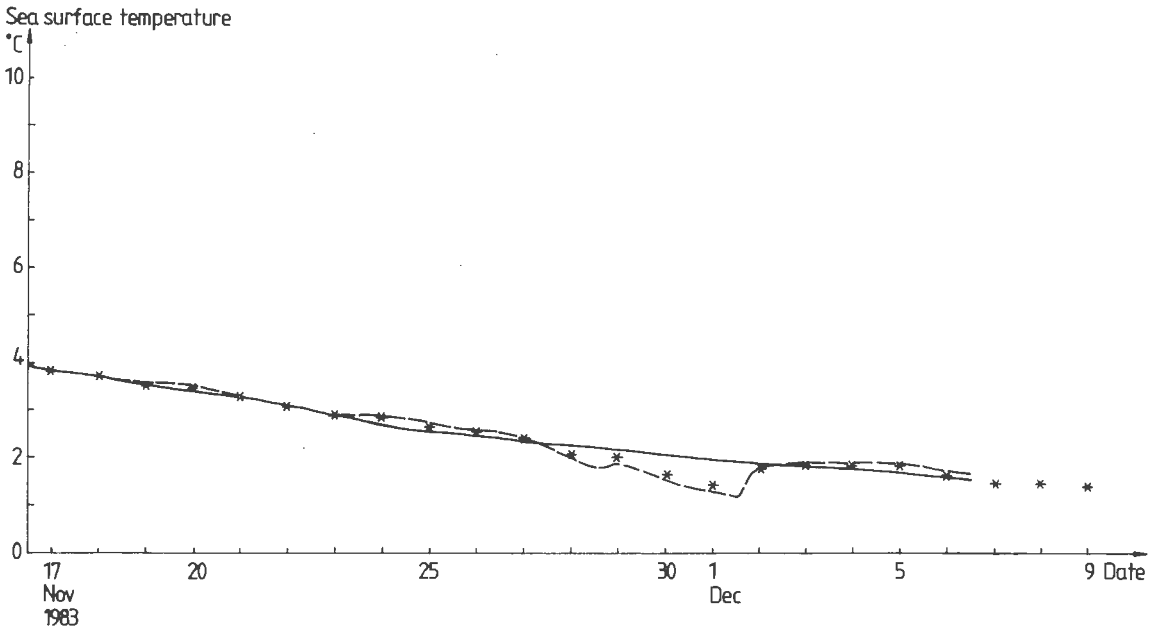

Figure 8. The first forecast for the Bothnian Bay. The fully drawn line represents a sea surface temperature forecast based upon a forecast, classified by normal air temperatures, the dashed line represents a forecast based upon weather analysis, and the stars represent measured or estimated sea surface temperatures.

3.3 The North Bothnian Sea

On January 5, 1984, a 27-day forecast for the North Bothnian Sea was performed. The input data were given as 24-hour mean values, with data taken from the weather forecast for the first five days. For the time beyond that, climate data were used in two different ways. Firstly according to normal air temperatures, secondly according to a weather scenario classified by temperatures below normal. For sea surface temperature forecasts this means weaker winds, colder air temperatures, and less mean cloudiness than normal. The results are given in Figure 9. On the basis of these forecasts one could, in the beginning of January, conclude that, with a normal weather situation, the ice would start to form on January 21. If the weather had become colder, the ice would have started to form on January 14. The weather became, however, milder than it normally is in January, and therefore the ice formation was delayed.

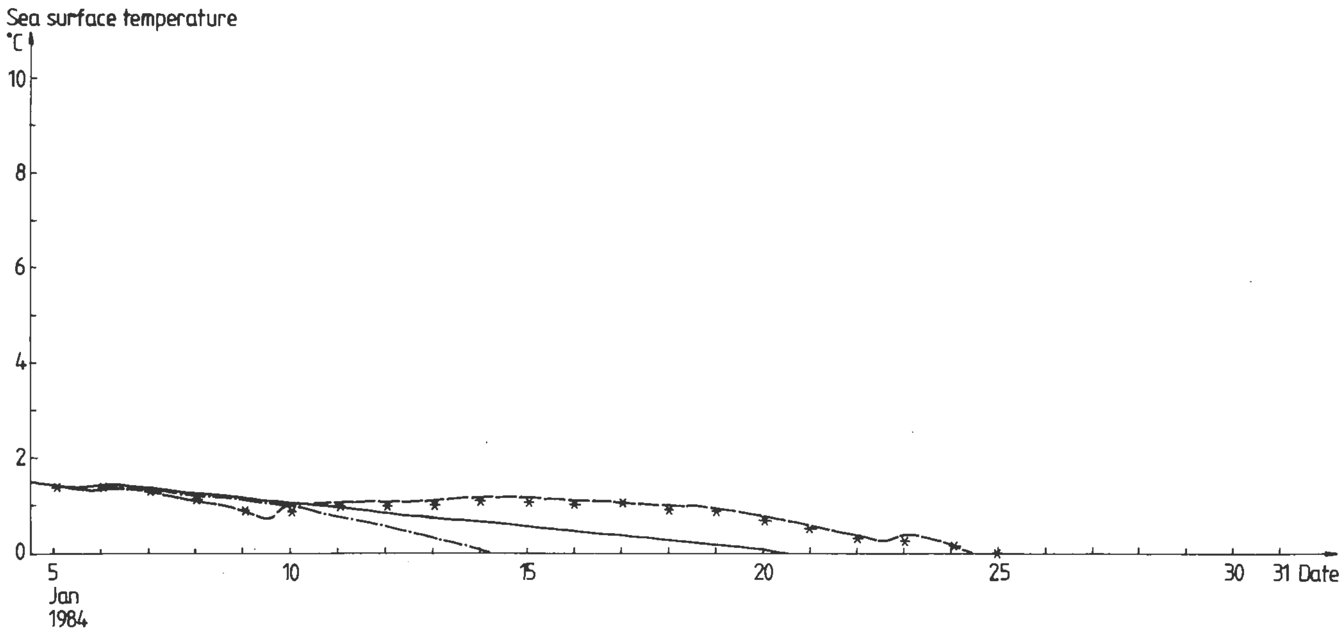

Figure 9. The first forecast for the North Bothnian Sea. The fully drawn line represents calculated sea surface temperatures based upon a forecast, classified by normal air temperatures, the dash-dotted line represents calculations based upon a forecast, classified by air temperatures below normal, the dashed line represents calculations based upon analysed weather, and the stars represent measured or estimated sea surface temperatures.

3.4 Lake Vänern/Dalbosjön

On November 22, 1983, a 24-day forecast for the western part of Vänern was performed. The input data were given as 24-hour mean values with data taken from the weather forecast for the first five days. For the time beyond that, two weather scenarios were chosen. Firstly according to normal air temperatures, secondly according to air temperatures below normal. The results are given in Figure 10. On the basis of the sea surface temperature forecasts one could, on November 22, conclude that even if the weather should become much colder than normal, ice would not form until after December 15. From the figure one can see that the actual weather was close to normal. The rapid sea surface cooling rate after December 6, for the case of cold weather, is due to the fact that the temperature of maximum density, which is 4 ^{O}C for fresh water, has been passed, and restratification starts, giving a shallow thermocline.

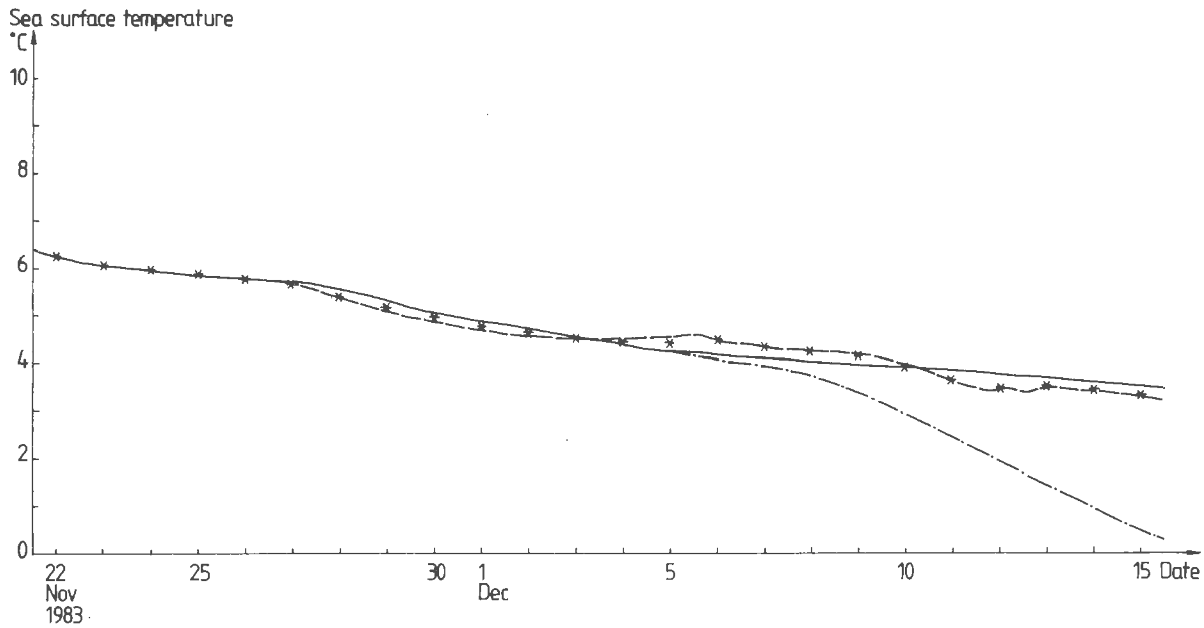

Figure 10. The first forecast for Lake Vänern/Dalbosjön. The different symbols are explained in the text under Figure 9.

3.5 Lake Vänern/Värmlandssjön

On November 22, 1983, a 24-day forecast was also performed for the eastern part of Vänern. The input data were given as 24-hour mean values, and they were exactly the same as those used for Dalbosjön. The results are given in Figure 11. In the same way as with Dalbosjön one could, on November 22, conclude that there was no ice risk before December 15. From Figure 11 one can also see that there is only a slight difference between the forecasts based upon normal and below normal temperatures. This is due to the fact that the water temperatures in the two cases have not reached the temperature of maximum density, and the water has thus to be cooled from the surface to the bottom.

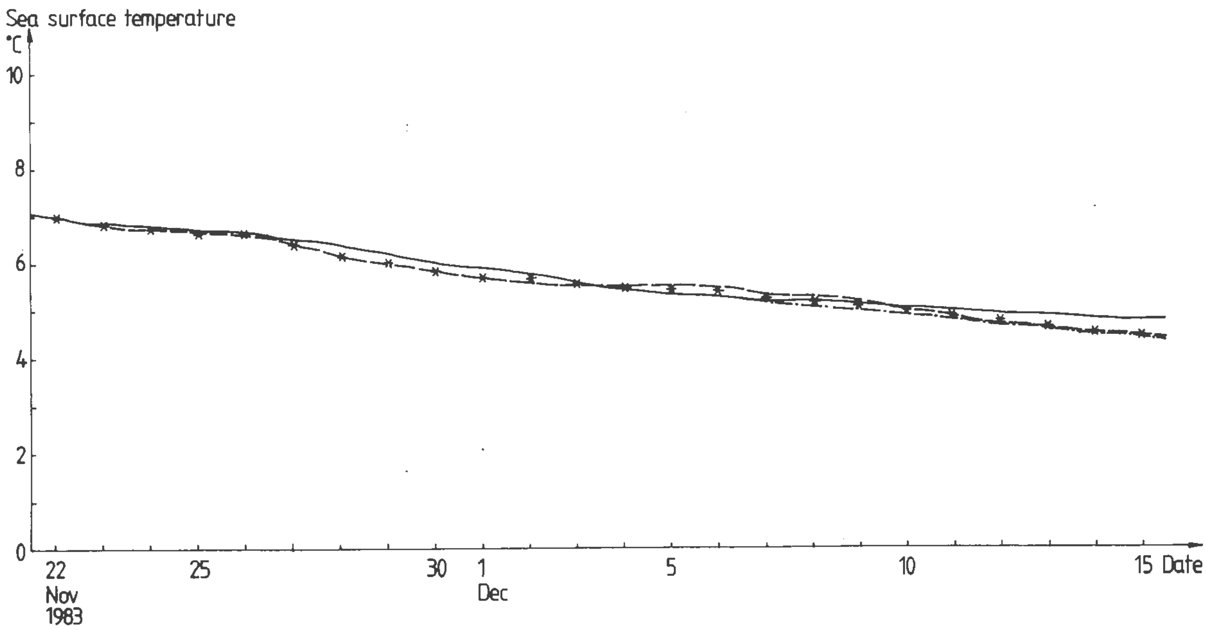

Figure 11. The first forecast for Lake Vänern/Värmlandssjön. The different symbols are explained in the text under Figure 9.

4. SUMMARY AND CONCLUSIONS

The purpose of this report has been to present a new forecasting model for water cooling in the Gulf of Bothnia and Lake Vänern.

During the winter navigation season of 1983/84 the model has been tested in routine. Some of the forecasts from this test period are also discussed in the report.

The model elements consist of three parts:

- Firstly, a transient Ekman model with turbulent exchange coefficients calculated with a two-equation model of turbulence.

- Secondly, a heat flux package, calculating the net heat flux through the air/sea interface.

- Thirdly, geometries based upon area/depth distributions for the Bothnian Bay, the North Bothnian Sea, Lake Vänern/ /Dalbosjön, and Lake Vänern/Värmlandssjön.

The input data are based on starting profiles of salinity and temperature, forecasting information, and weather data. The weather data required are wind speed and direction, air temperature and mean cloudiness.

The output data are given both as profile data and time series.

The model is constructed for easy and rapid handling by letting the forecaster answer questions on a terminal screen. The model system can handle up to five different forecasts of maximum 30 days each simultaneously.

The results from the test period are most satisfactory. It is therefore believed that this new forecasting model can serve as a reliable guide for effective winter navigation planning during coming seasons.

ACKNOWLEDGEMENTS

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Several colleagues at SMHI have also contributed during the work. In this report I would especially like to thank Bernt Samuelsson and Svante Andersson. Bernt Samuelsson contributed by writing the data terminal program, and Svante Andersson by testing the model during the winter navigation season of 1983/84. Their and all other colleagues' work is gratefully acknowledged.

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APPENDIX A:

Model equations and constants

Basic assumptions:

The model will restrict its attention to horizontally homogeneous flows, which means that terms containing gradients in the horizontal plane are neglected. It will further be assumed that there is no mean vertical velocity. The turbulent mixing processes are assumed to be described by turbulent exchange coefficients. The short wave radiation is treated as a surface flux of heat, and the rotation of the earth is described by the Coriolis' parameter.

Mean flow equations:

$$\frac{\partial}{\partial t}(\rho C_p T) = \frac{\partial}{\partial z}\left(\frac{\nu_T}{\sigma_T}\frac{\partial}{\partial z}(\rho C_p T)\right)$$

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\nu_T}{\sigma_S}\frac{\partial S}{\partial z}\right)$$

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial z}\left(\nu_T\frac{\partial U}{\partial z}\right) + fV$$

$$\frac{\partial V}{\partial t} = \frac{\partial}{\partial z}\left(\nu_T\frac{\partial V}{\partial z}\right) - fU$$

$$\rho = \rho_0(1 - \alpha(T - T_{\rho M})^2 + \beta S)$$

where z is the vertical space coordinate, positive upwards, t time coordinate, f Coriolis' parameter, U and V mean velocities in horizontal direction, T mean temperature, S mean salinity, C_p specific heat of water, ρ water density, ρ_0 reference density, α and β constants, $T_{\rho M}$ temperature of maximum density, σ_T and σ_S Prandtl/Schmidt numbers, and ν_T turbulent kinematic viscosity.

Turbulence equations:

$$\frac{\partial k}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\nu_T}{\sigma_k}\frac{\partial k}{\partial z}\right) + \nu_T\left(\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right) + \frac{g}{\rho}\nu_T\frac{\partial \rho}{\partial z} - \varepsilon$$

$$\frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\nu_T}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial z}\right) + C_{1\varepsilon}\nu_T\frac{\varepsilon}{k}\left(\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right) + C_{3\varepsilon}\frac{g}{\rho}\frac{\varepsilon}{k}\nu_T\frac{\partial \rho}{\partial z} - C_{2\varepsilon}\frac{\varepsilon^2}{k}$$

$$\nu_T = C_\mu\frac{k^2}{\varepsilon}$$

where k is the turbulent kinetic energy, ε dissipation rate of k, g constant of gravity, C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ constants used in the turbulence equations, and σ_k, σ_ε Prandtl/Schmidt numbers.

Boundary conditions:

Boundary conditions for the mean flow equations at the surface are specified according to:

$$\left(\frac{\nu_T}{\sigma_T}\frac{\partial}{\partial z}(\rho C_\rho T)\right) = Q_N(t)$$

$$\left(\frac{\nu_T}{\sigma_S}\frac{\partial S}{\partial z}\right) = S_{sur}(P(t) - E(t)) = 0$$

$$\left(\nu_T\frac{\partial U}{\partial z}\right) = -\tau_x(t)\,\rho_0^{-1}$$

$$\left(\nu_T\frac{\partial V}{\partial z}\right) = -\tau_y(t)\,\rho_0^{-1}$$

where $Q_N(t)$ is the net heat flux, S_{sur} surface salinity, P(t) precipitation, E(t) evaporation, $\tau_x(t)$ and $\tau_y(t)$ wind stresses.

Due to z positive upwards, the fluxes are treated as positive in z-direction. The surface flux condition for salinity is set to zero in the model, but the above formulation was used by Omstedt (1983) in the study of autumn cooling in the Gulf of Bothnia.

The surface heat budget equation is:

$$Q_N(t) = Q_S + Q_L + Q_C + Q_E$$

where Q_S is the net short wave radiation, Q_L net long wave radiation, Q_C sensible heat flux, and Q_E latent heat flux. For further details, see Omstedt and Sahlberg (1982).

In the stress calculation a quadratic law with a drag coefficient slightly increasing with wind speed is used according to Garratt (1977).

The temperature for maximum density is taken to be a function of salinity only. If pressure effects are neglected, the formula becomes:

$$T_{\rho M} = 3.982 - 0.2229\ S_{sur}$$

according to Caldwell (1978).

Boundary conditions for the turbulence equations at the surface are specified according to:

$$k = \tau_w (\rho_0 \sqrt{C}_\mu)^{-1}$$

$$\varepsilon = C_\mu^{\ 3/4}\ k^{3/2}\ (\kappa \Delta Z_s)$$

where τ_w is the stress in the water, κ von Karman's constant, and ΔZ_s is half the cell size at the sea surface.
At the lower boundary a zero-flux condition is used for all variables besides momentum, were a zero velocity condition is used.

Constants:

Constants used in the model are according to Table 1.

Table 1. Model constants.

Constant	Value	Unit
C_μ = Constant in the turbulence model	0.09	-
$C_{1\varepsilon}$ = Constant in the turbulence model	1.44	-
$C_{2\varepsilon}$ = Constant in the turbulence model	1.92	-
$C_{3\varepsilon}$ = Constant in the turbulence model	0.8	-
σ_k = Prandtl/Schmidt number	1.4	-
σ_ε = Prandtl/Schmidt number	1.3	-
σ_T = Prandtl/Schmidt number	1.0	-
σ_S = Prandtl/Schmidt number	1.0	-
α = Constant in the equation of state	$5.57\ 10^{-6}$	$(^\circ C)^{-2}$
β = Constant in the equation of state	$8.13\ 10^{-4}$	$(^0/_{00})^{-1}$
ρ_0 = Reference density	$1.0\ 10^3$	$kg\ m^{-3}$
C_p = Specific heat of water	$4.217\ 10^3$	$J\ (kg\ ^\circ C)^{-1}$
f = Coriolis' parameter	$1.3\ 10^{-4}$	s^{-1}

APPENDIX B

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ON AUTUMN COOLING IN THE GULF OF BOTHNIA

by

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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 equation 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

B 4

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.

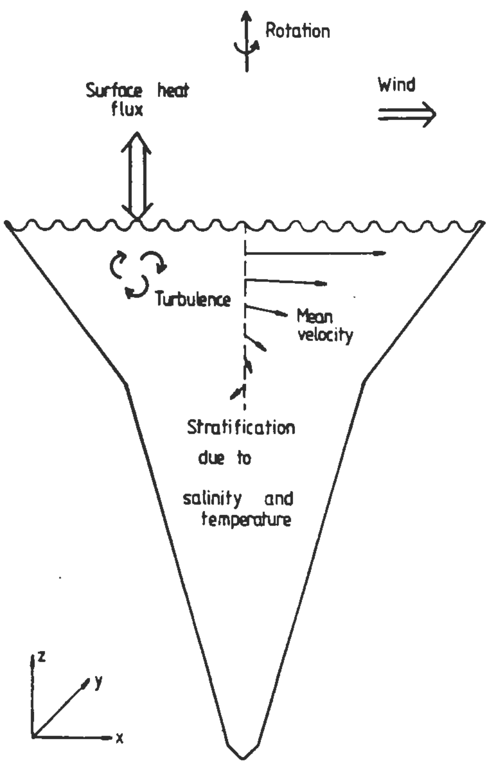

Fig. 2. Schematic representation of the one-dimensional model approach.

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

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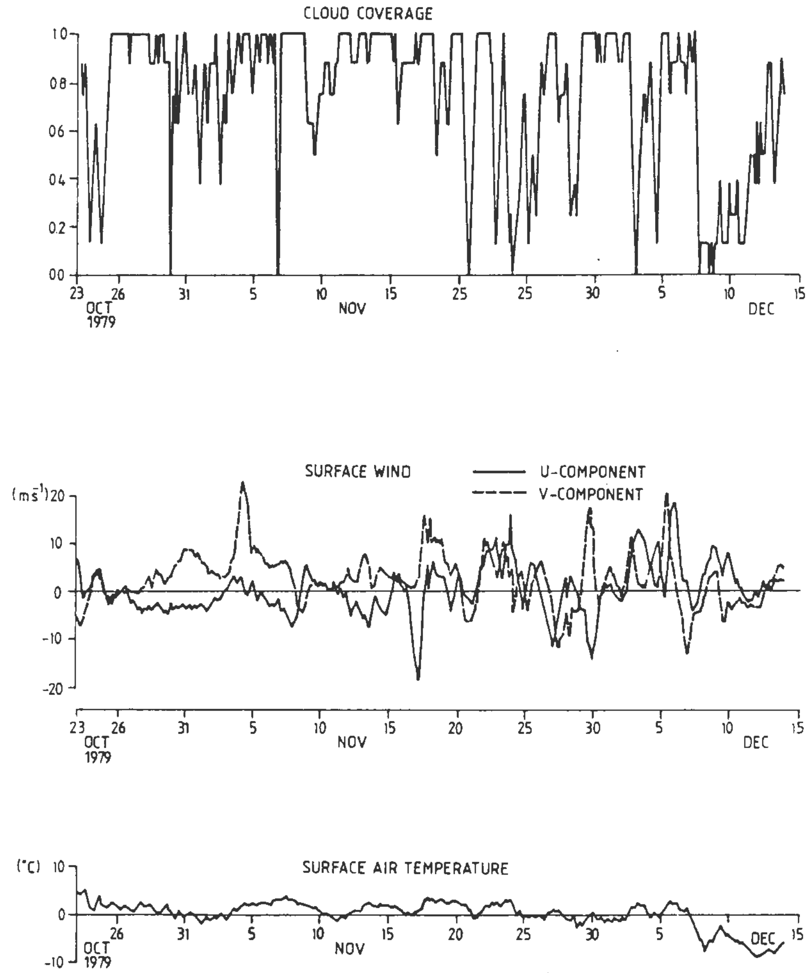

Fig. 3. Meteorological areal mean data for Bothnian Bay.

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

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

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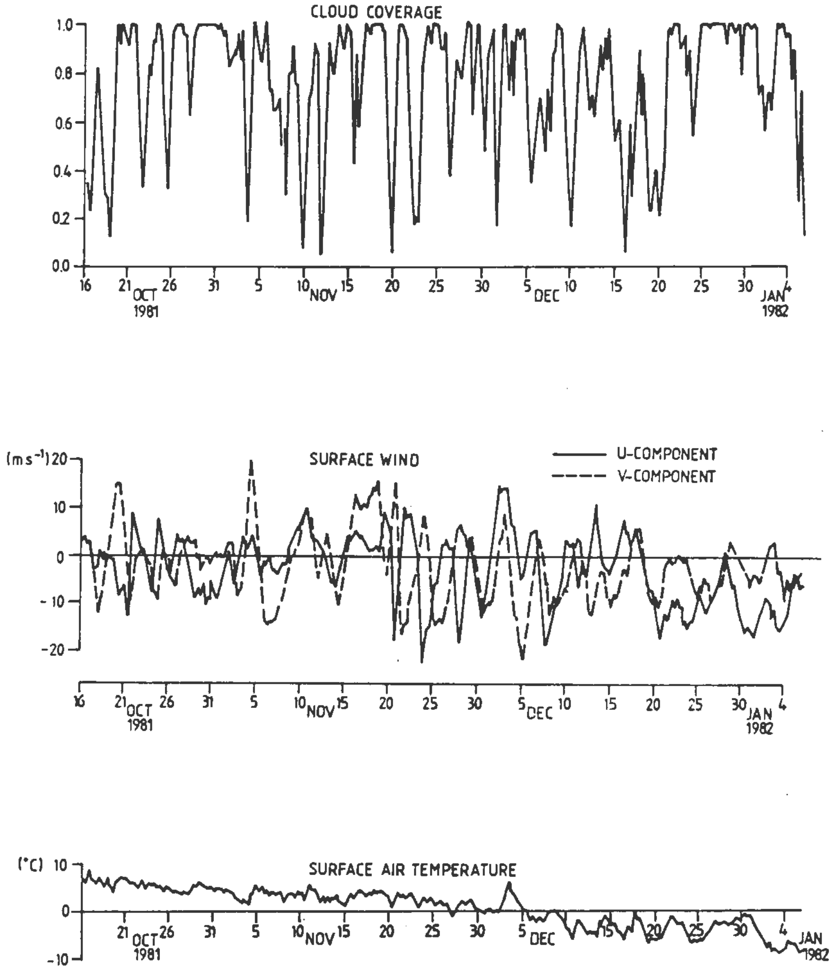

Fig. 4. Meteorological areal mean data for North Bothnian Sea.

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).

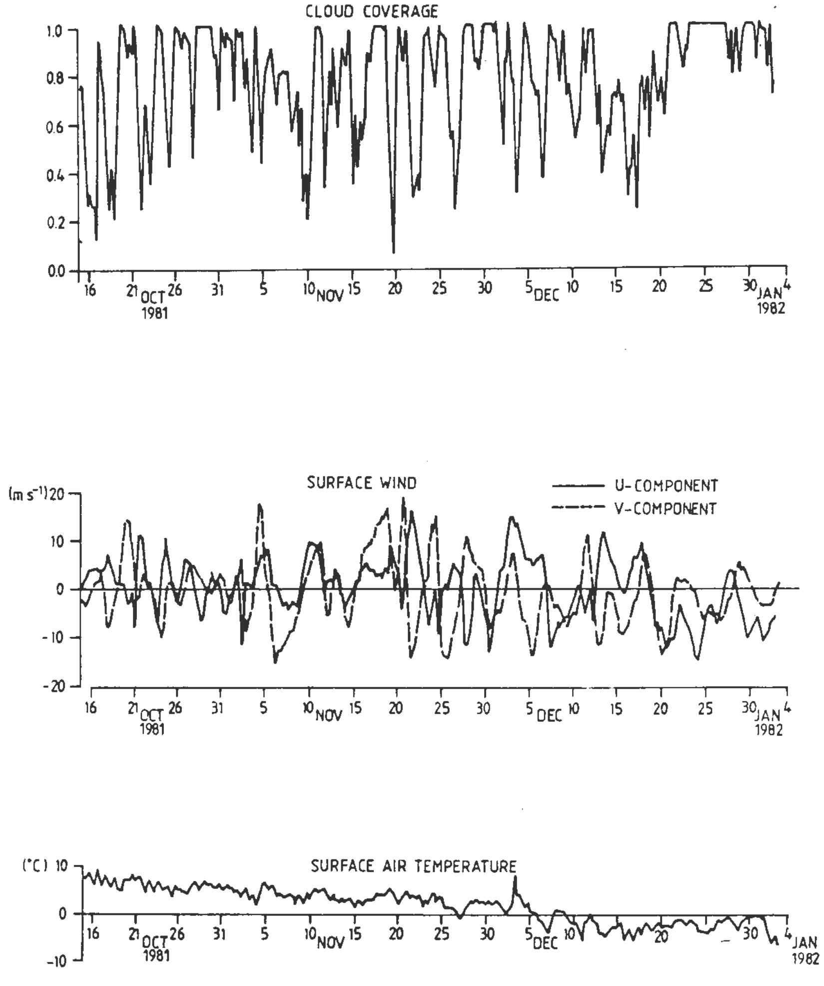

Fig. 5. Meteorological areal mean data for South Bothnian Sea.

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

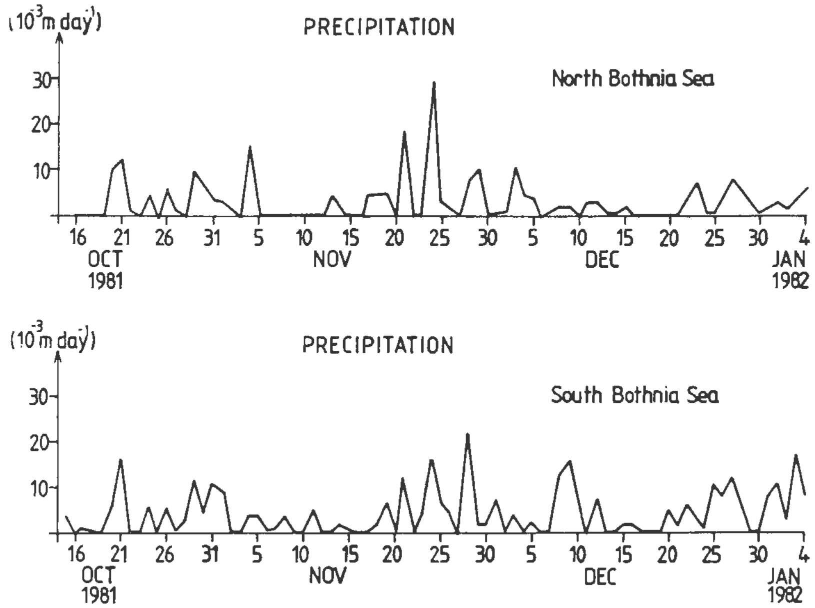

Fig. 6. Areal mean precipitation for North (upper curve) and South (lower curve) Bothnian Sea.

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

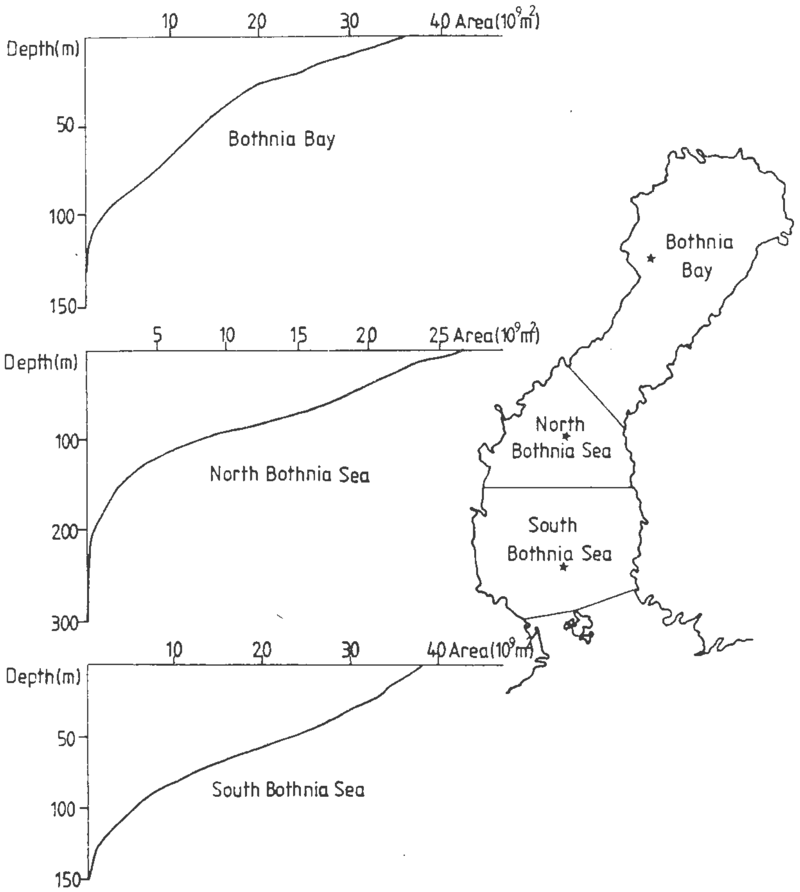

Fig. 7. Map over the Gulf of Bothnia with variations of horizontal area versus depth for the three regions. The stars indicate the measurement sites.

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.

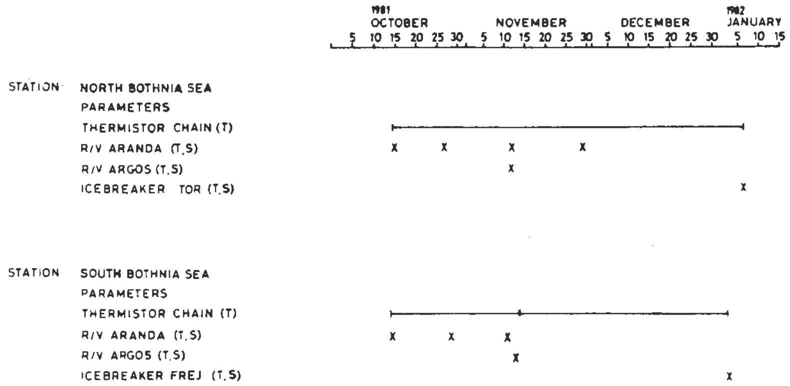

Fig. 8. Measurement periods and parameters for North and South Bothnian Sea.

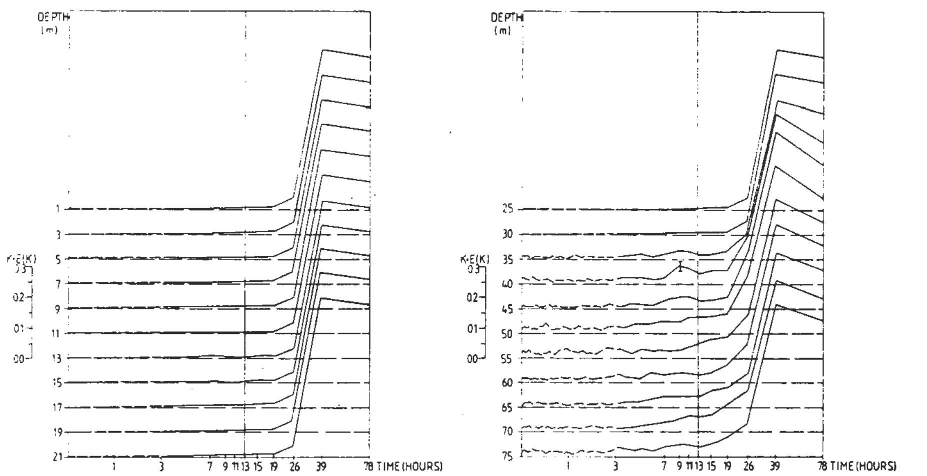

Fig. 9. Normalized energy spectrums for different depths based upon Bothnian Bay temperature data. The vertical line at the 40 m depth represent a 80 (%) confidence interval.

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.

B 12

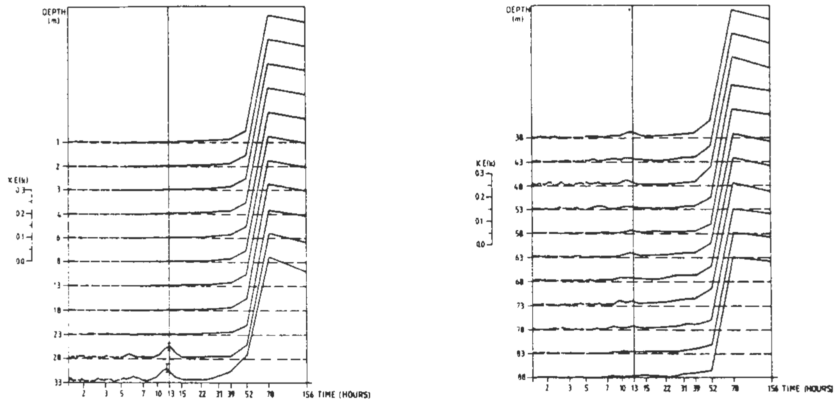

Fig. 10. Normalized energy spectrum for different depths based upon North Bothnian Sea temperature data. The vertical lines represent 80 (%) confidence intervals.

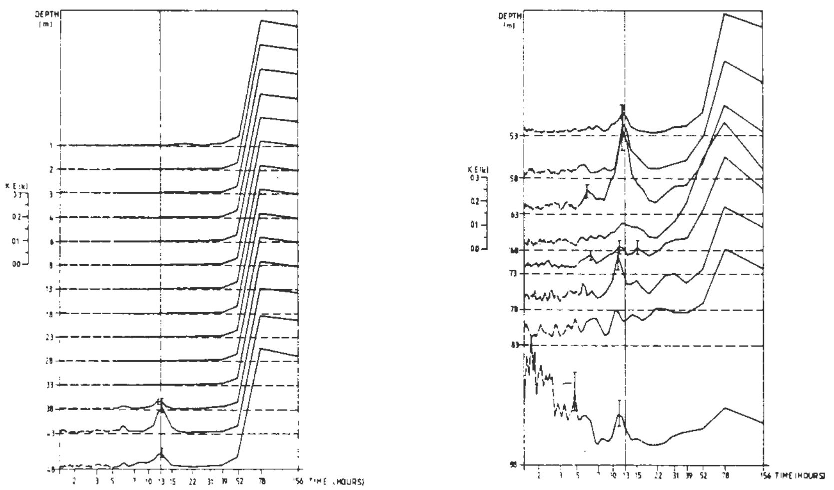

Fig. 11. Normalized energy spectrum for different depth based upon South Bothnian Sea temperature data. The vertical lines represent 80 (%) confidence intervals.

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

B 14

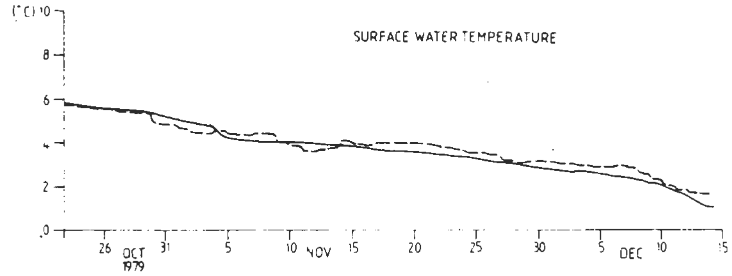

Fig. 12. Measured (dashed line) and calculated (fully drawn line) sea surface temperatures for the Bothnian Bay case.

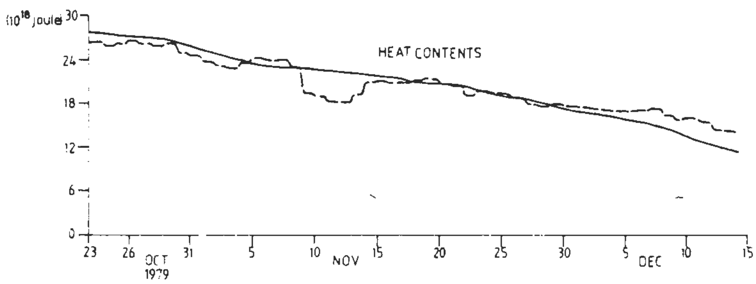

Fig. 13. Measured (dashed line) and calculated (fully drawn line) total heat contents for the Bothnian Bay case.

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.

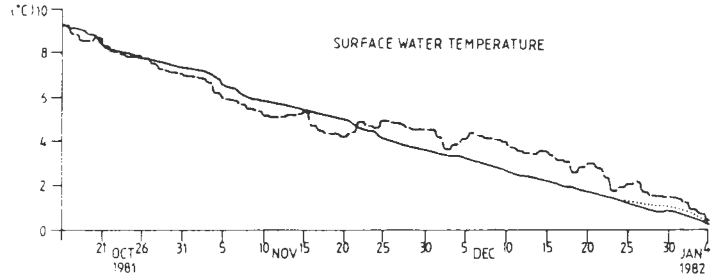

Fig. 14. Measured (dashed line), calculated without considering precipitation (dotted line) and calculated with considering precipitation (fully drawn line) sea surface temperatures for the North Bothnian Sea case.

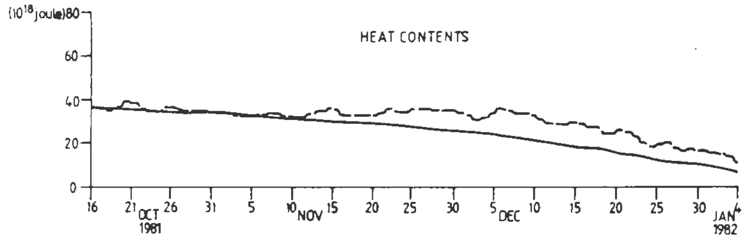

Fig. 15. Measured (dashed line) and calculated (fully drawn line) total heat contents for the North Bothnian Sea case.

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-

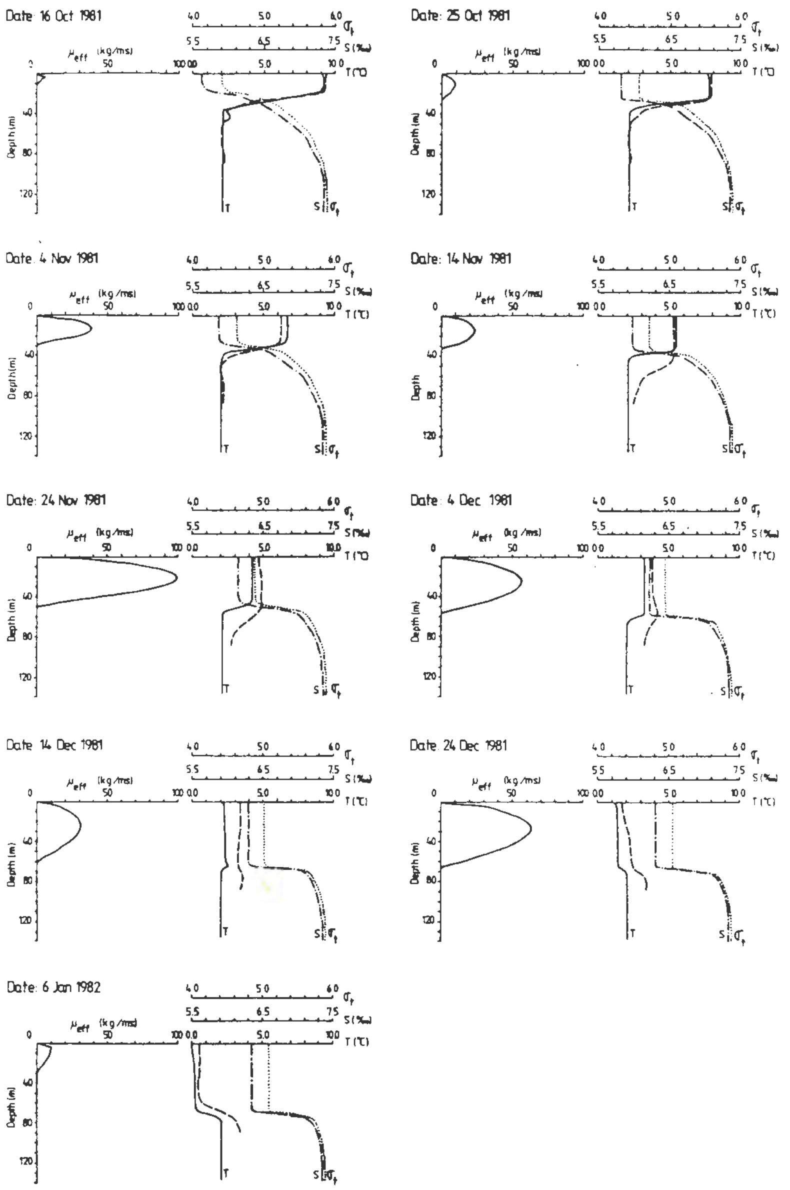

Fig. 16. Model calculations of dynamical eddy viscosity (μ_{eff}), temperature (T), salinity (S) and density (σ_t) from nine occasions during the cooling period in the North Bothnian Sea. The dashed lines are observed temperature profiles. All data are 24 hour averages.

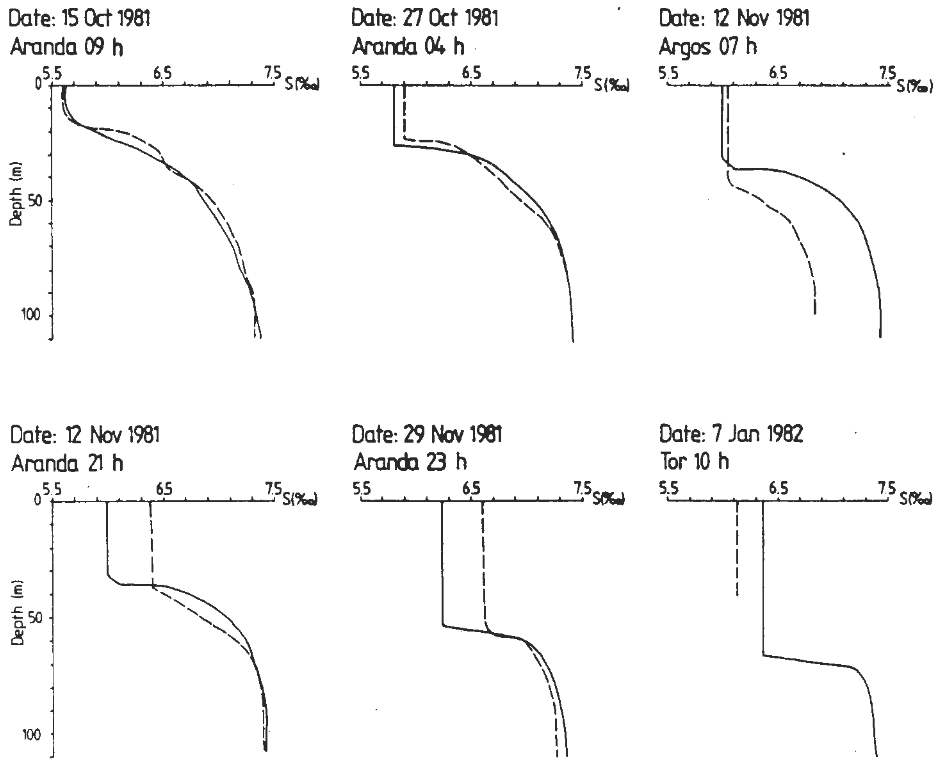

Fig. 17. Measured (dashed lines) and calculated (fully drawn lines) salinities. All calculated data are 24 hour averages. Measured data are taken at specific times given in hours in the head of each figure.

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

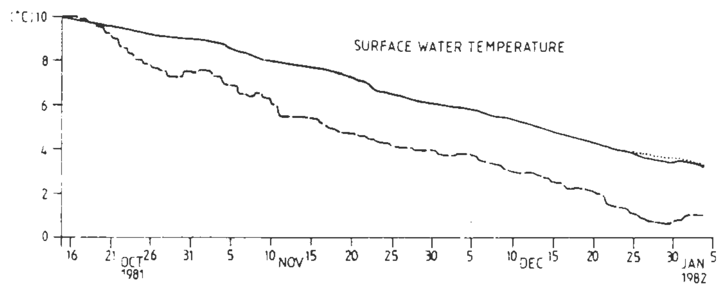

Fig. 18. Measured (dashed line), calculated without considering precipitation (dotted line) and calculated with considering precipitation (fully drawn line) sea surface temperatures for the South Bothnian Sea case.

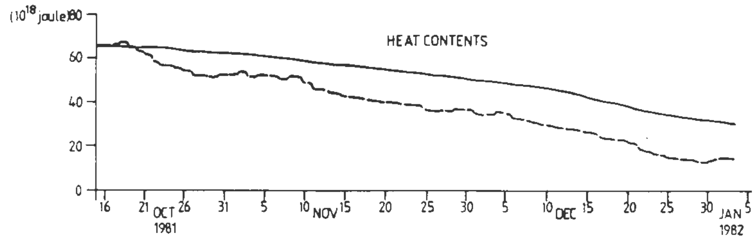

Fig. 19. Measured (dashed line) and calculated (fully drawn line) total heat contents for the South Bothnian Sea case.

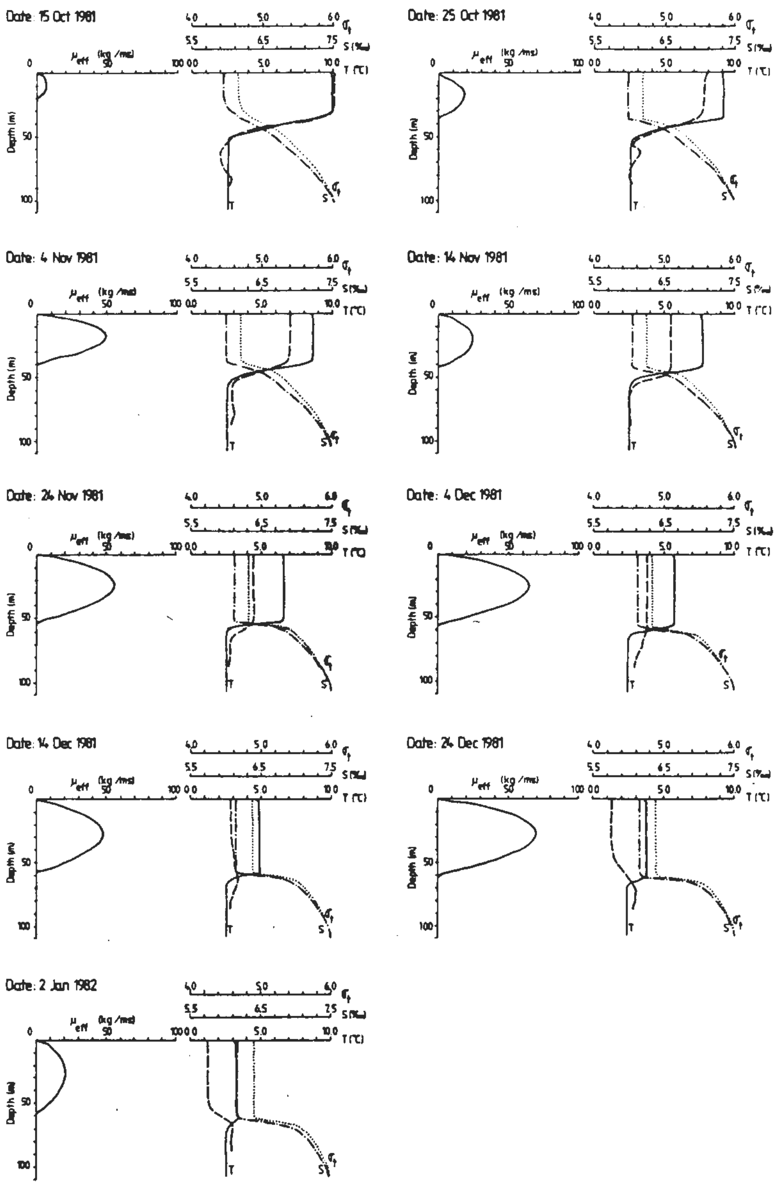

Fig. 20. Model calculations of dynamical eddy viscosity (μ_{eff}), temperature (T), salinity (S) and density (σ_t) from nine occasions during the cooling period in the South Bothnian Sea. The dashed line are observed temperature profiles. All data are 24 hour averages.

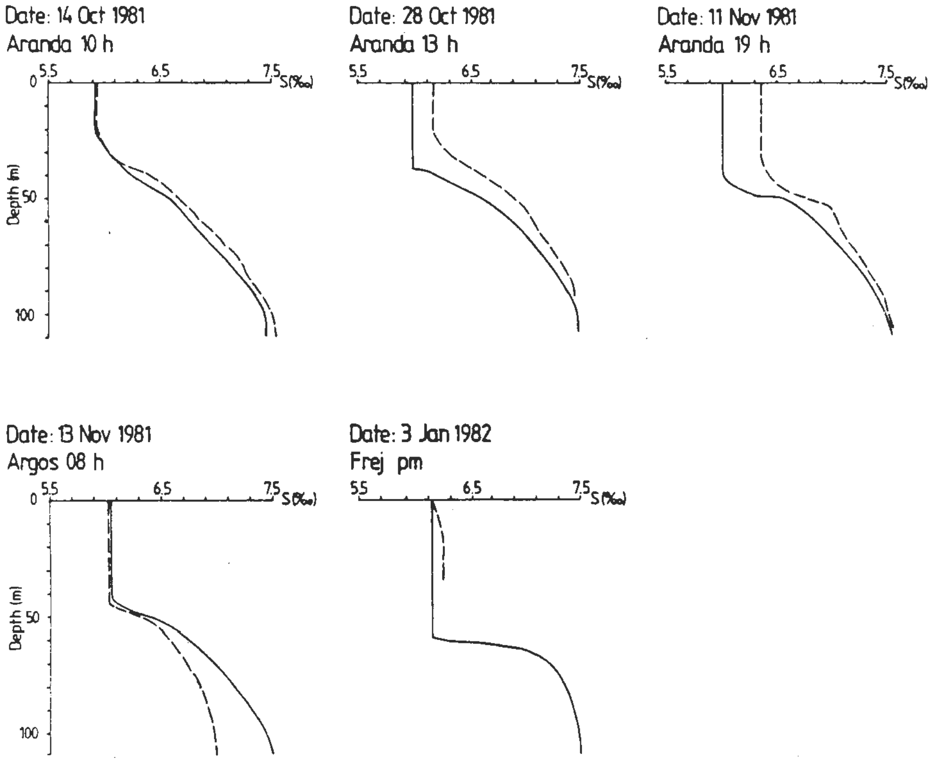

Fig. 21. Measured (dashed lines) and calculated (fully drawn lines) salinities for the South Bothnian Sea case. All calculated data are 24 hour averages. Measured data are taken at specific times given in hours in the head of each figure.

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

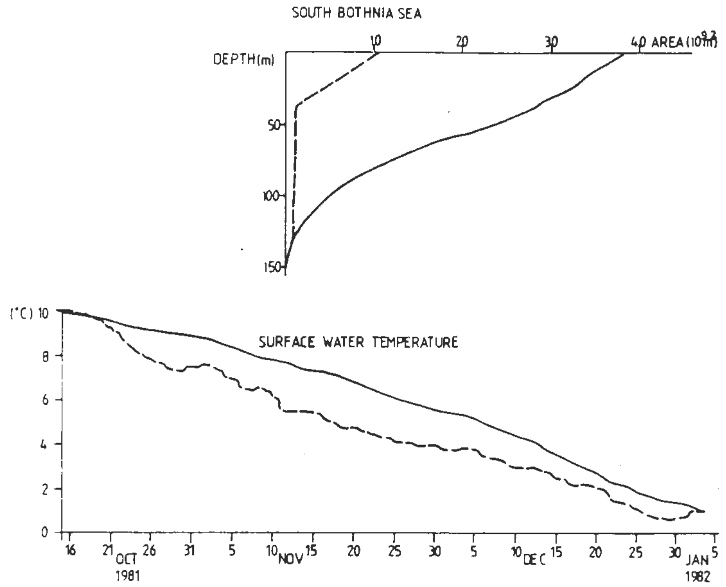

Fig. 22. Recalculated (fully drawn line) and measured (dashed line) sea surface temperatures for the South Bothnian Sea case. The variations of horizontal areas versus depth represent the observed distribution according to the South Bothnian Bay (fully drawn line) and the distribution used in the recalculation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