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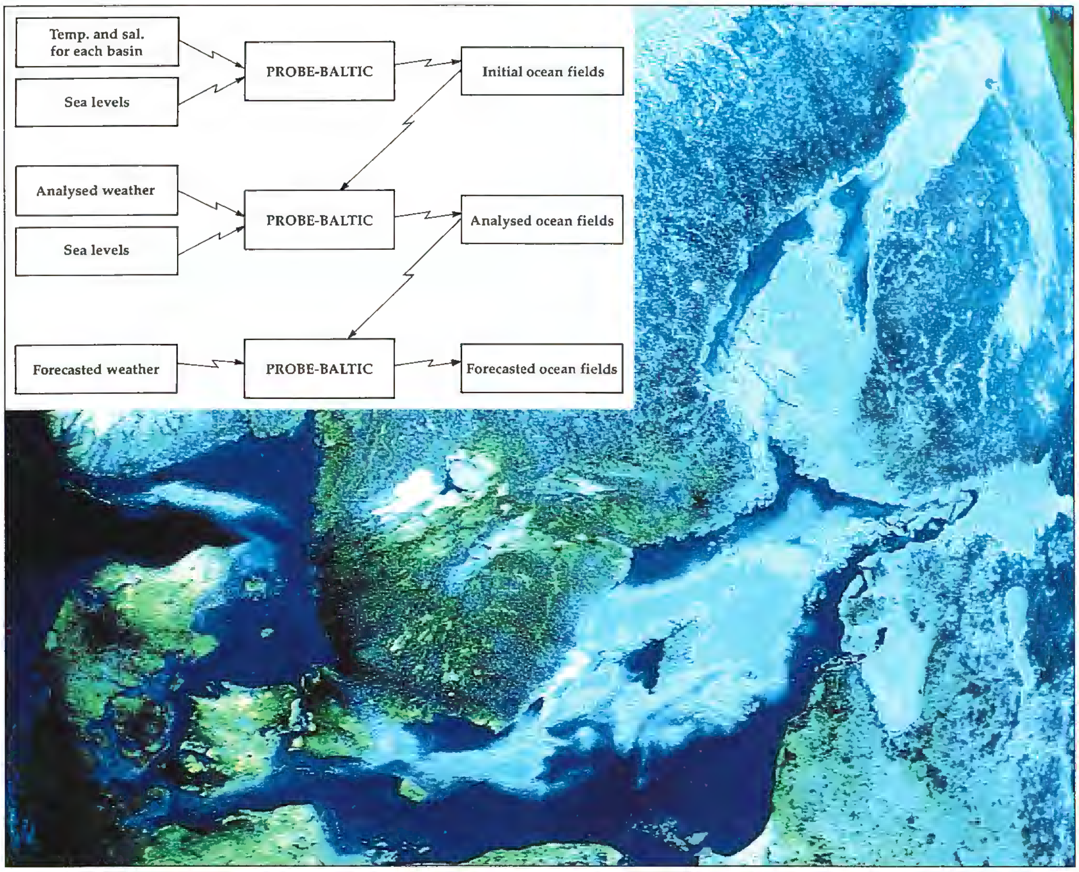

REAL-TIME MODELLING AND FORCASTING OF TEMPERATURES IN THE BALTIC SEA

Anders Omstedt

Front page:

AVHRR image from the NOAA satellite, illustrating the ice extent in March 1987.
Processed by Mats Moberg (SMHI).

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Abstract

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The results from about 8 months of pre-operational tests illustrate that the real-time mode reproduces observed sea surface temperatures quite satisfactorily. However, more efforts must be paid to the obtaining of oceanographic data in real-time. The results from the forecast mode were also satisfactory, but the quality was, of course, dependent on the meteorological forecasts.

Key words

Baltic Sea, modelling, water temperature, sea ice.

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ABSTRACT

A mathematical model for the Baltic Sea has been introduced in an operational system for real-time calculations and forecasts of water temperatures. The model divides the Baltic Sea into 13 sub-basins and treats each sub-basin as a one-dimensional boundary layer with vertical mean velocities based upon in- and outflows from surrounding basins. The operational scheme uses the model in two modes. The first one, the real-time mode, fits the model to meteorological and oceanographical data collected in the recent past. The second one, the forecast mode, starts from the real-time mode, and calculates forecasts on the basis of the ECMWF weather model and statistics.

The results from about 8 months of pre-operational tests, illustrate that the real-time mode reproduces observed sea surface temperatures quite satisfactorily. However, more efforts must be paid to the obtaining of oceanographic data in real-time. The results from the forecast mode were also satisfactory, but the quality was, of course, dependent on the meteorological forecasts.

1. INTRODUCTION

Sea ice is present in the Baltic Sea every year, which causes great problems for the shipping. Due to changing weather from one year to another, the date of freezing may vary considerably. For the planning of shipping and icebreaking service it is therefore of great importance to get reliable information about the water temperature and the ice all around the Swedish coast (Figure 1). The mapping of sea surface temperatures in the Baltic/Skagerrak system started at the Swedish Meteorological and Hydrological Institute (SMHI) on regular basis 1972 (Thompson et al., 1974). Forecast models for surface water cooling in different sub-basins within the Baltic Sea were introduced in the beginning of 1980 (Omstedt, 1984).

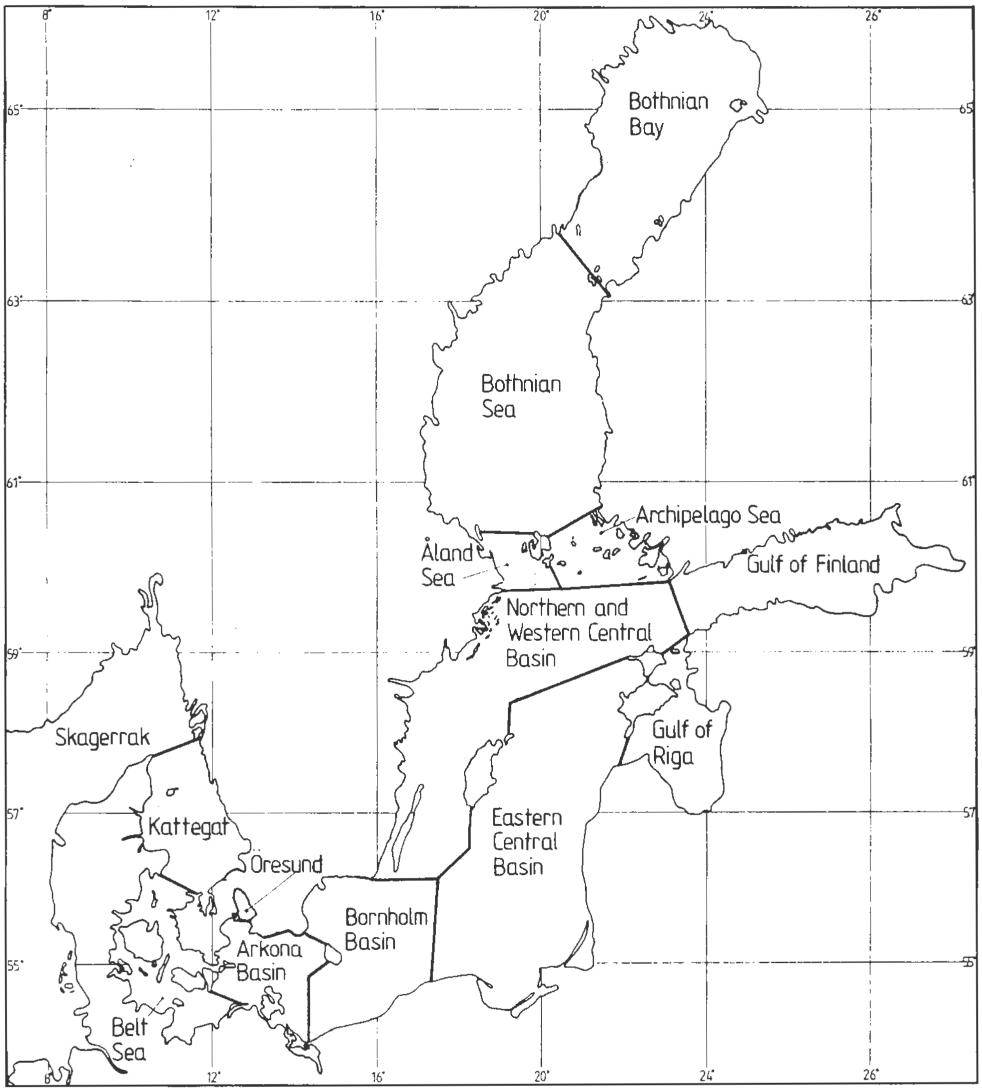


Figure 1. The Baltic/Skagerrak area with sub-basins according to the model by Omstedt (1990).

The forecast models treated different sub-basins as horizontally homogeneous water bodies with variations only in the vertical direction. To extend the forecasting capability to more complicated sea areas, where also advective transports from surrounding basins are important to consider, Omstedt (1987 a) introduced a model for the entrance of the Baltic Sea, in which the Kattegat, the Öresund, the Belt Sea, and the Arkona Basin were treated as four coupled sub-basins. The model was verified during three periods together with forecast tests (Omstedt, 1987 b). Later a model for the whole Baltic Sea (PROBE-BALTIC) was presented by Om-

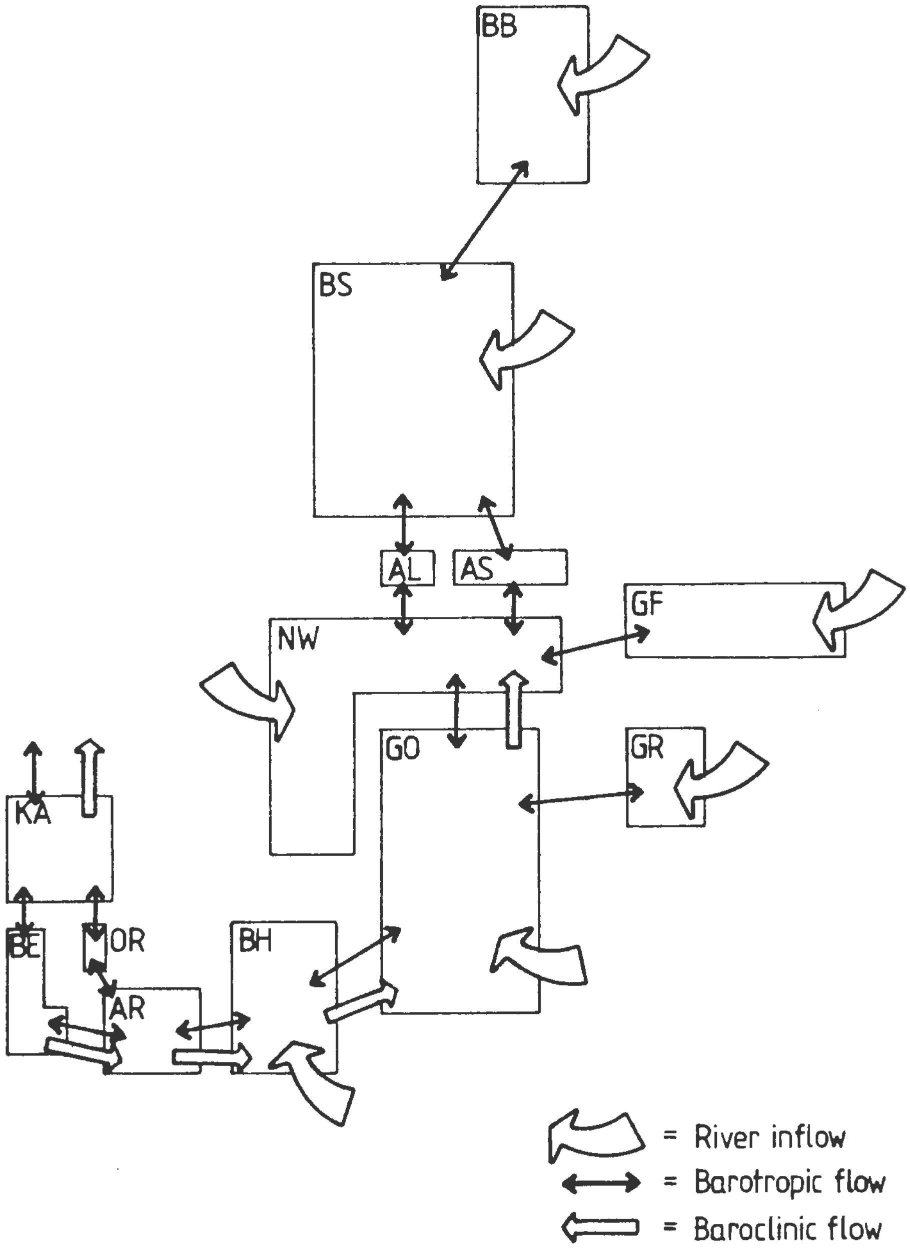


Figure 2. The Baltic Sea represented as 13 sub-basins according to Omstedt (1990). The flows associated with water level variations and estuarine circulation are called barotropic and barocline flows respectively.

stedt (1990). In this model, which also includes the previous models, the Baltic Sea was divided into 13 sub-basins (Figure 2). The model was verified with data from the severe winter of 1986/87, when ice was observed in all 13 sub-basins. In general the different model applications have given useful information for the planning of the icebreaking service. However, due to the limited number of temperature and salinity data available, necessary for starting up the model, it was concluded that the forecasts needed to be supplemented with updating calculations. These calculations, based on observed weather, wind and sea level data, should then produce the necessary starting values for the forecasts. The purpose of the present work is therefore to present a forecast model for the Baltic Sea, which also includes updating routines.

In Section 2, the basic model ideas are outlined. Then the model structure is presented. In Section 4, applications from 1986/87 and 1989/90 are discussed. Finally, a summary with some conclusions is given in Section 5.

2. MODEL ELEMENTS

The Baltic/Skagerrak system can be regarded as a large estuary, consisting of a sequence of sub-basins. The modelling approach therefore divides the Baltic Sea into different water bodies on the basis of geometrical and oceanographic considerations. In each sub-basin the conservation laws for volume, salt, and heat are considered. As the variations of temperature are often larger in the vertical than in the horizontal direction, one can concentrate on the vertical exchange processes. For the volume calculations this means that the horizontal area versus depth needs to be taken into account. The horizontal areas versus depths for the different sub-basins are illustrated in Appendix A.

The main driving process for sea surface temperatures is the meteorological forcing. Here one has to consider both wind and weather. For the heat loss or gain to the water/air interface, the net heat energy balance needs to be considered. In that balance several different fluxes between water and air are important. They are: the sensible heat flux, which depends on the temperature difference between air and water and the wind velocity; the latent heat flux, which depends on the water vapour density close to the sea surface and in the air and the wind velocity; the short wave radiation, which depends on the amount of clouds, the albedo, the date, the time, and the latitude. The albedo depends on the state of the sea surface, particularly whether there is ice or not.

Primarily it is the temperature that is of interest, but a few more variables need to be mentioned. Salinity is one of these, as it influences several properties of the water. For example, the density of sea water and the freezing temperature are functions of salinity. Also the currents need to be considered. Due to winds, strong vertical current shear is produced in the sea, which generates turbulence (wind mixing). The turbulence influences the effectiveness with which properties of the deeper water are mixed up into the surface layers. As the deeper layers often have other temperatures than the surface water, the wind mixing thus influences the temperatures.

Advective transports, particularly in the entrance of the Baltic Sea, are also considered in the model. In general one can distinguish between transports associated with the water level variations (barotropic flows) and transports associated with the estuarine circulation (baroclinic flows). For the transport associated with water level variations, only the sea level difference between the Kattegat and the central parts of the Baltic Sea is considered.

Two applications of the model are illustrated in Figures 3 and 4.

The first one illustrates measured and calculated data from a sub-basin with weak interaction with surrounding waters. The advective transports are therefore neglected, and only vertical variations are considered. Wind mixing, net heat loss, and restratification are here important response characteristics. The second one illustrates measured and calculated data from a sub-basin with strong interaction with surrounding waters. The advective transports and the upstream properties of salinity and heat are considered as well as vertical variations. The application illustrates that cooling is associated with outflowing brackish water (upstream properties from the Arkona Basin), while events with interrupted cooling are associated with periods of inflowing saline water (upstream properties from the Kattegat). Advection and upstream properties are thus important response characteristics in this sub-basin.

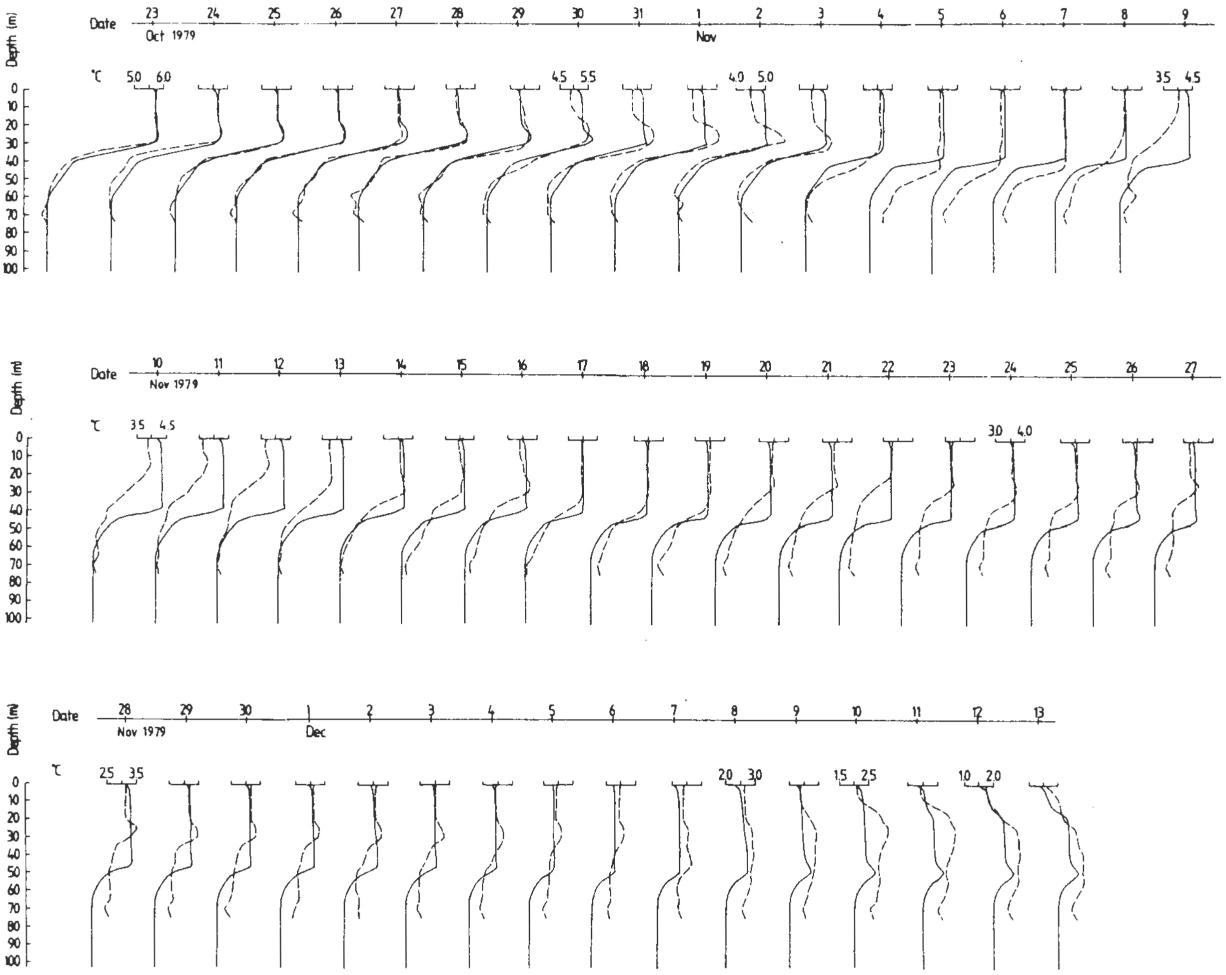


Figure 3. Measured (dashed lines) and calculated (solid lines) profiles from the Bothnian Bay (Omstedt et al., 1983).

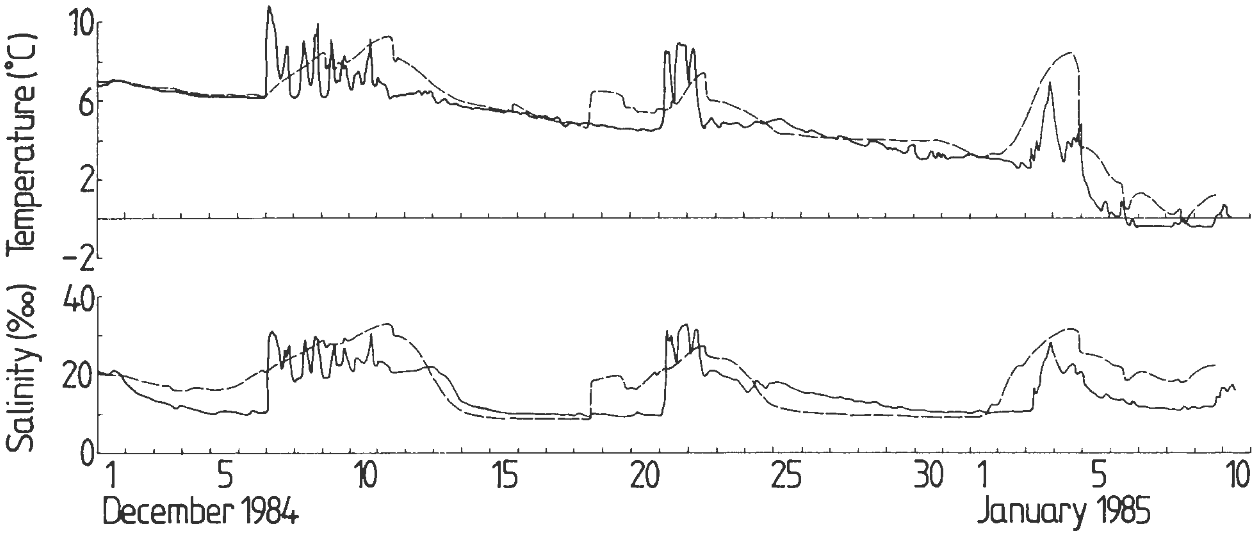


Figure 4. Measured (solid lines) and calculated (dashed lines) temperature and salinity data at 5 meters' depth from the Öresund (Omstedt, 1987 a).

3. MODEL STRUCTURE

The main effort in the model structure was to optimize all available input data both from the atmosphere and the sea. A real-time scheme was therefore introduced by fitting the ocean model to the data gathered in the recent past. The meteorological data were extracted from a mesoscale model used at SMHI (Andersson et al., 1985). In this model air temperature, humidity and cloudiness were analysed from synoptic weather stations using objective statistical methods. The wind field was calculated using the one-layer primitive equation model described by Danard (1977). For the wind stress and heat loss calculations the analysed meteorological data were extracted from grid points over each sub-basin (see further discussion in Appendix B).

The initial conditions for the ocean model require water level data from the Kattegat and from the central parts of the Baltic Sea, together with salinity and temperature profiles from each sub-basin. The water level data are available from automatic sea level stations, and 24 hours' mean values from Viken and Stockholm were calculated and used. The profile data are not observed frequently enough in space or time to allow automatic inputs. Instead a combination of statistical data and measurements from ship observations was used together with analysed sea surface temperature data. The ship observations were partly from the coast guard and partly from research vessels. These data were then approximated according to Figure 5 and subjectively introduced in the model.

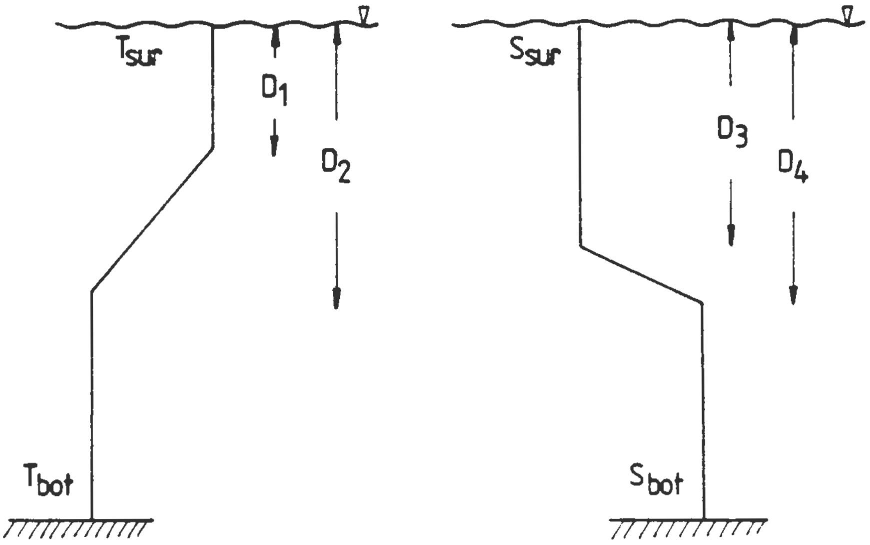


Figure 5. Specification of temperature and salinity profiles.

The model structure is illustrated in Figure 6. In the real-time mode, the starting profiles were calculated and updated with observed forcing data (meteorological and sea level data). In the forecasting mode, meteorological forcing parameters were taken from the European Center for Medium Weather Forecasts (ECMWF). Forecasts of the water level variations were not introduced, and advective transports were neglected in the forecasting mode. In general this is a good approximation except for the entrance of the Baltic Sea.

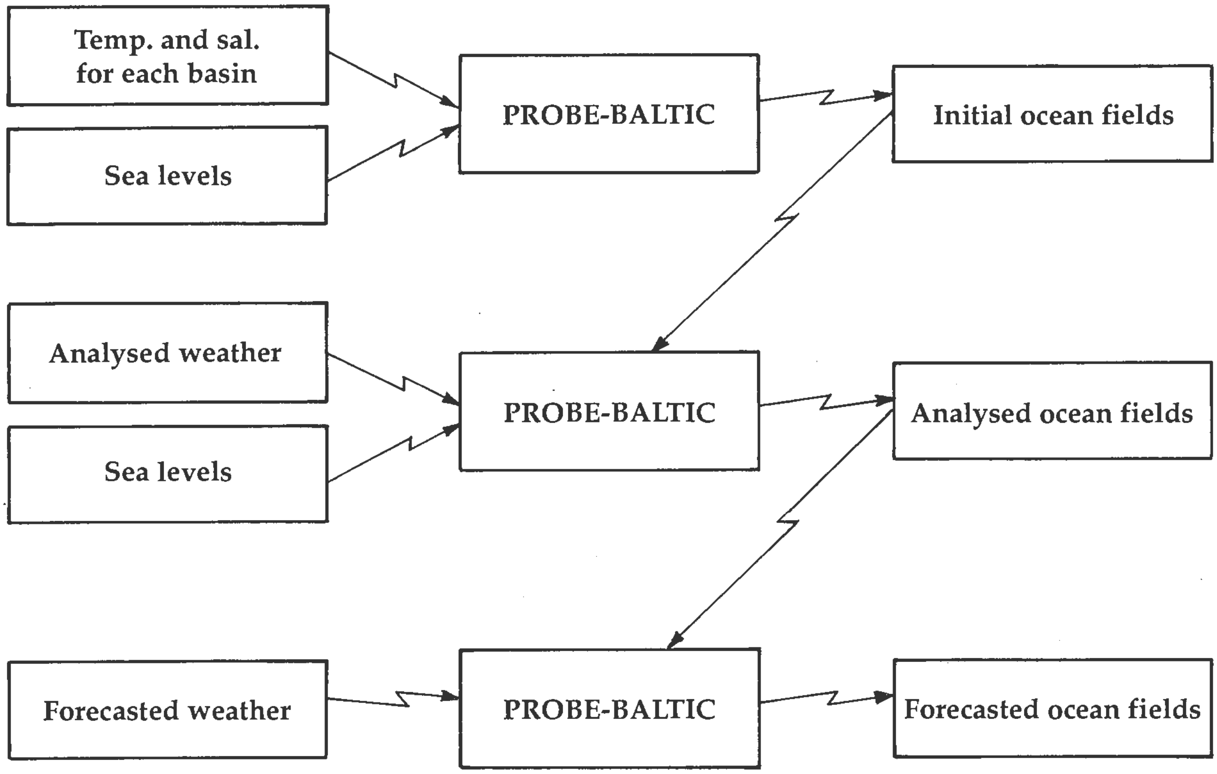
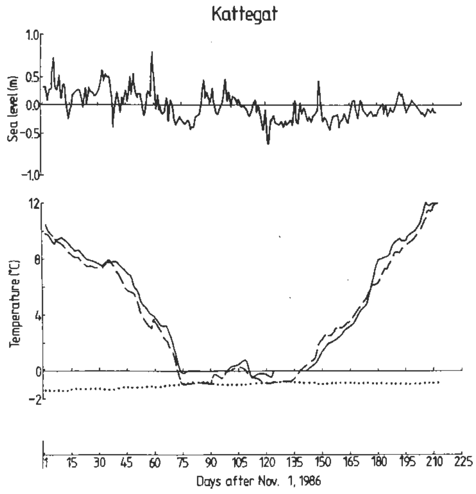


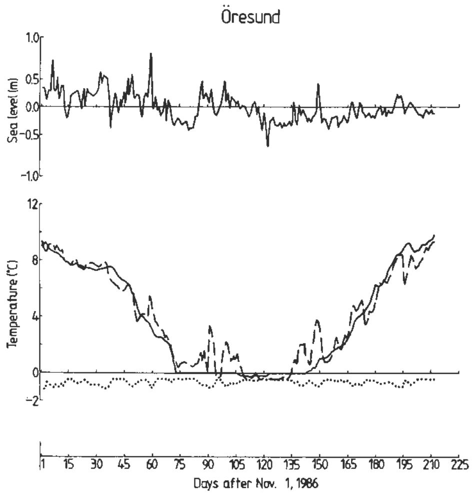
Figure 6. Schematic presentation of the model structure. The calculations of the initial and analysed ocean fields define the real-time mode, while calculations of the forecasted ocean fields define the forecasting mode.

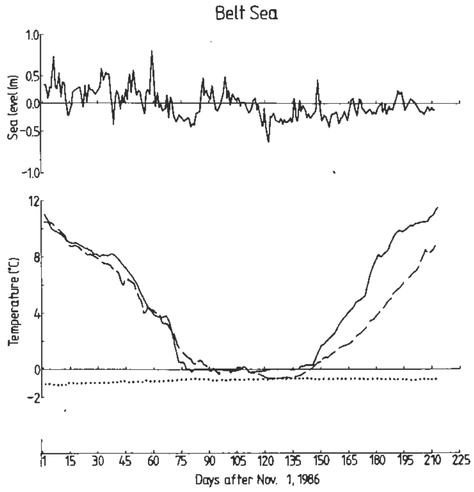
4. APPLICATIONS

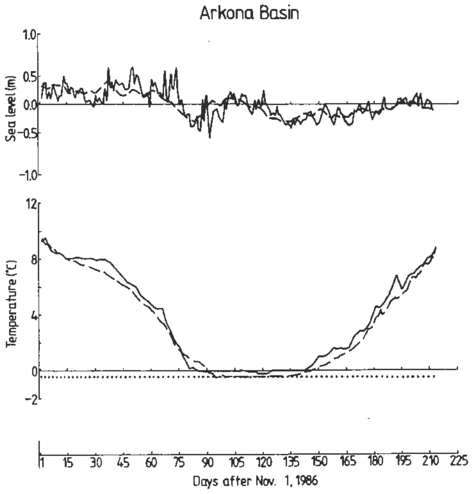
4.1 Introductions

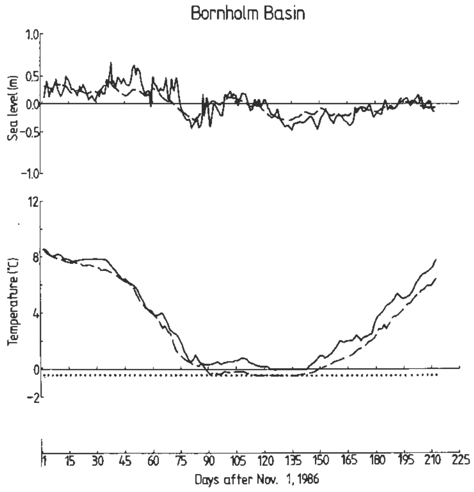
The model was first verified with data from the severe winter of 1986/87 (Figure 7). The study was based upon historical data and was further discussed by Omstedt (1990). The time period considered was from 1 November, 1986, to 31 May, 1987. The meteorological parameters were extracted every 3rd hour from 8 synoptic weather stations. The water level data were taken from Kattegat (Viken) and the central part of the Baltic Sea (Stockholm). Initial temperature and salinity profiles were based upon existing data from the beginning of November. In the model, sea ice was only treated in a rough way. Boundary conditions for an open water surface was applied all through the season, and the water temperatures were put equal

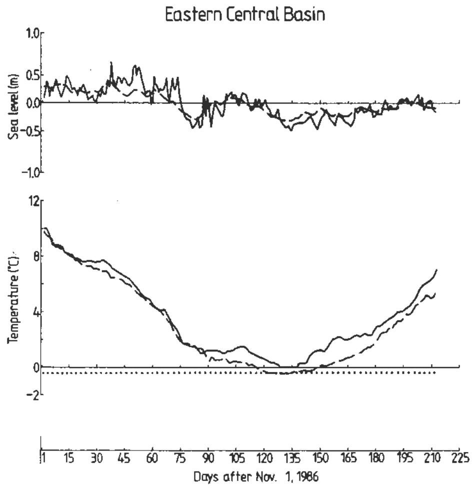












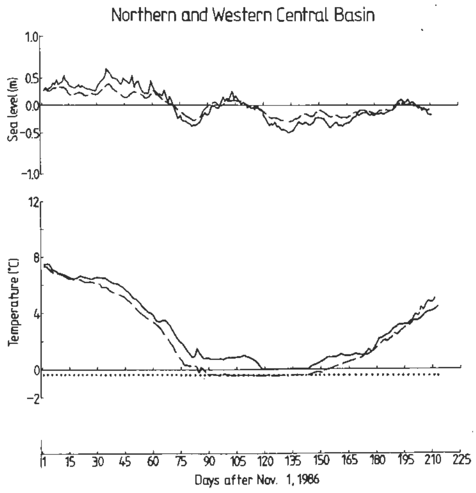


Figure 7.
Observed and calculated sea levels and sea surface temperatures. The observations are noted with full lines, the calculations with dashed lines and the freezing temperature with dotted lines (Omstedt, 1990).

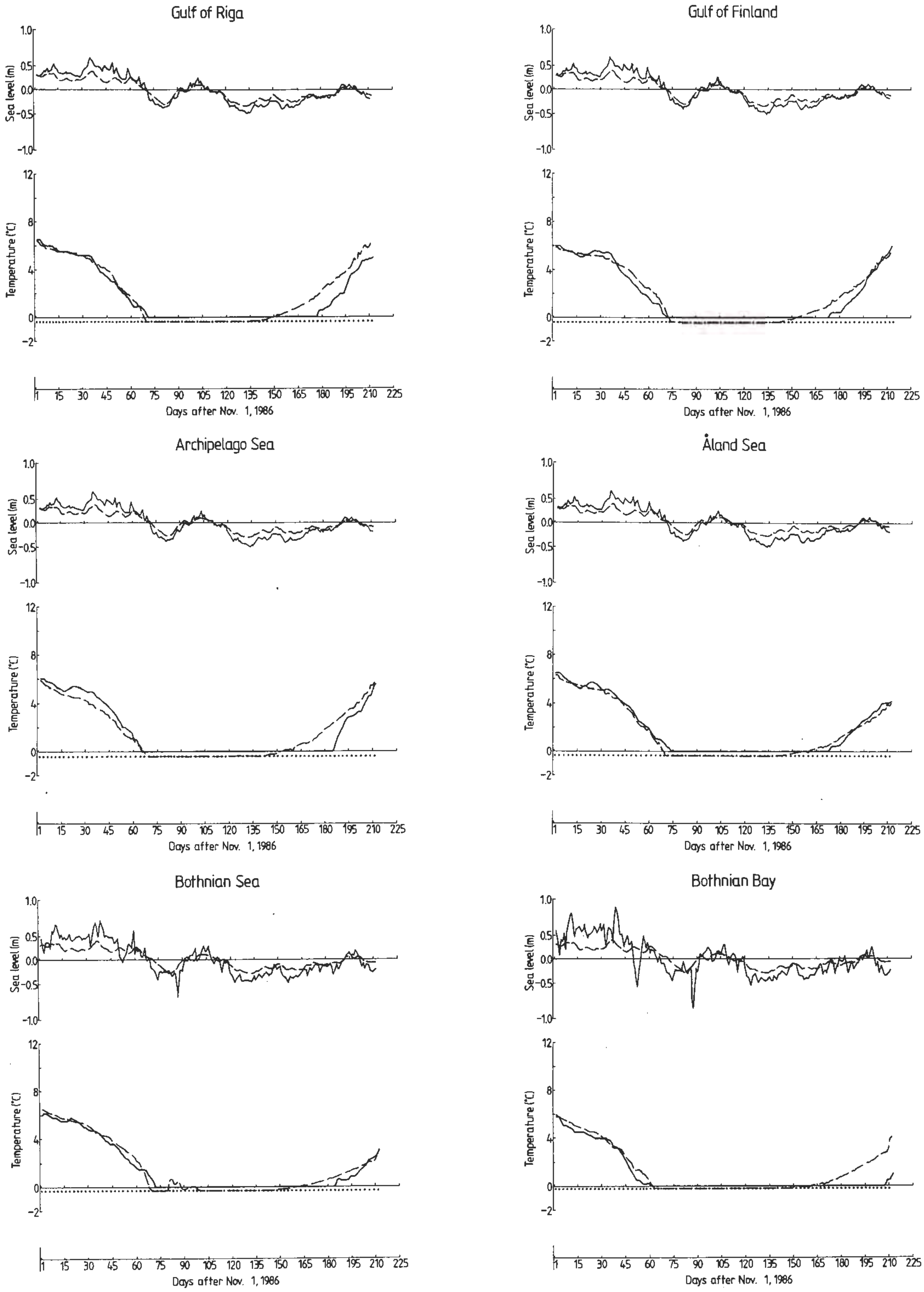


Figure 7, cont.

to the freezing point when they were below freezing. From Figure 7 one can notice that reasonably good results were achieved except during spring, when sea ice delayed the warming in some sub-basins.

4.2 Real-time model scheme

The real-time model scheme was started in a pre-operational test in late June, 1989. The meteorological parameters were automatically extracted from the mesoscale model at SMHI. Also sea level data from Kattegat (Viken) and the Baltic Sea (Stockholm) were extracted in real-time. The initial temperature and salinity profiles for June, 1989, were based upon existing data and estimates. New data on temperature and salinity were also added to the model on different occasions during the calculation. The quality of the meteorological parameters calculated in the mesoscale meteorological model is examined in Appendix B. In general there was a good agreement between calculated and observed temperatures. The wind velocities were more scattered, as well as the total amount of clouds.

Observed and calculated sea surface temperatures for the different sub-basins are given in Figure 8. The main deviations between calculated and observed data were partly due to some errors in the analysed wind field and partly to missing temperature and salinity data. Also problems with the computer (delay in data extractions) caused some errors in the calculations. The small amount of temperature and salinity profiles available influenced the results, particularly when estimating the deep water properties. For example, the temperature drastically decreased in the Bothnian Bay in late July. The reason was an error in the analysed wind field, giving very high winds. The wind mixed the whole basin completely, and as the deep water temperatures were lower, the surface water temperature decreased. After the summer vacation this error was observed and new data were subjectively introduced in August. However, the deep water temperatures were overestimated and new data had to be introduced on two other occasions - in the beginning of September and in the beginning of November - when temperature and salinity data from R/V Argos were available.

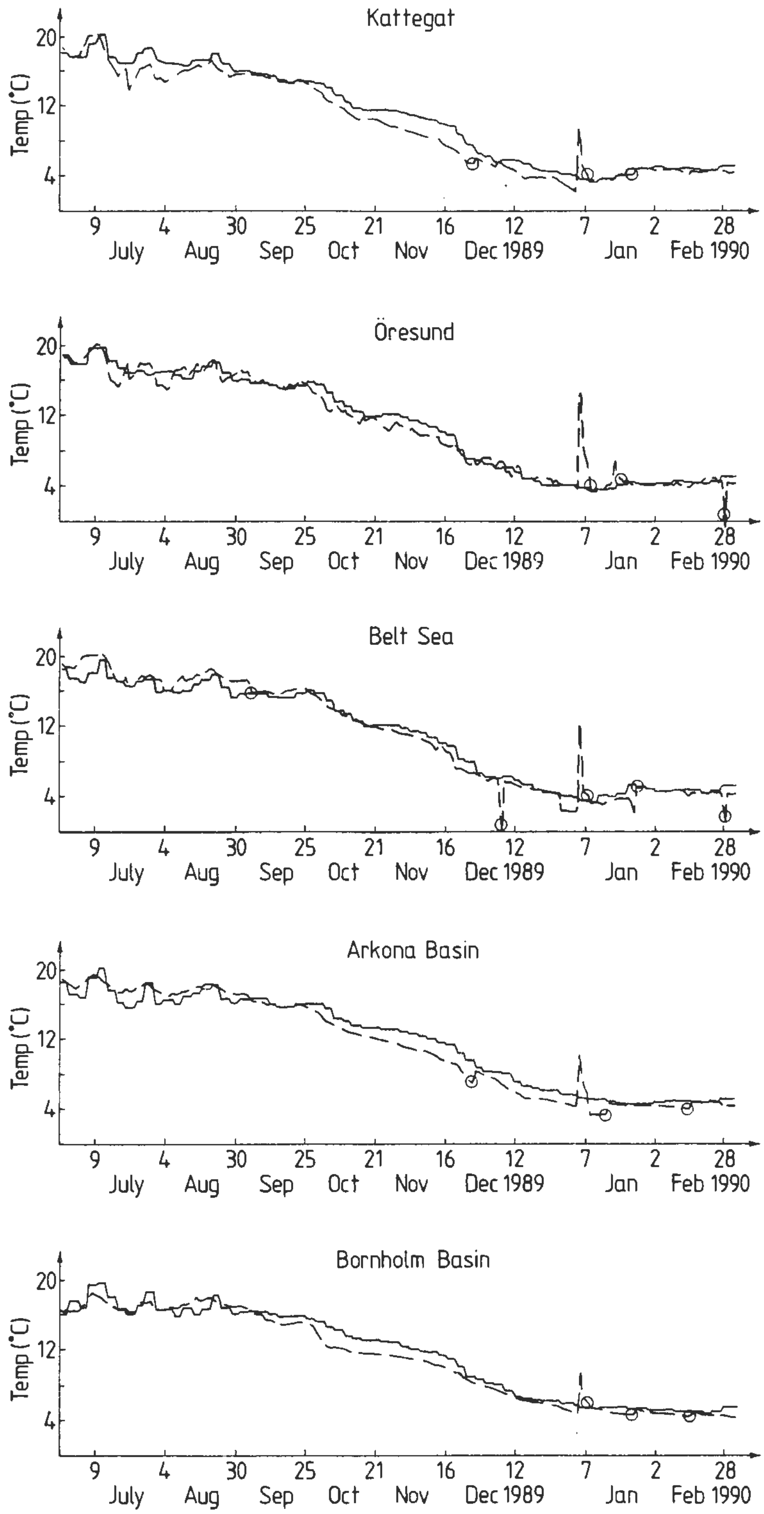


Figure 8. Observed (solid lines) and calculated (dashed lines) sea surface temperatures. The circles indicate when new temperature and salinity data were added to the model.

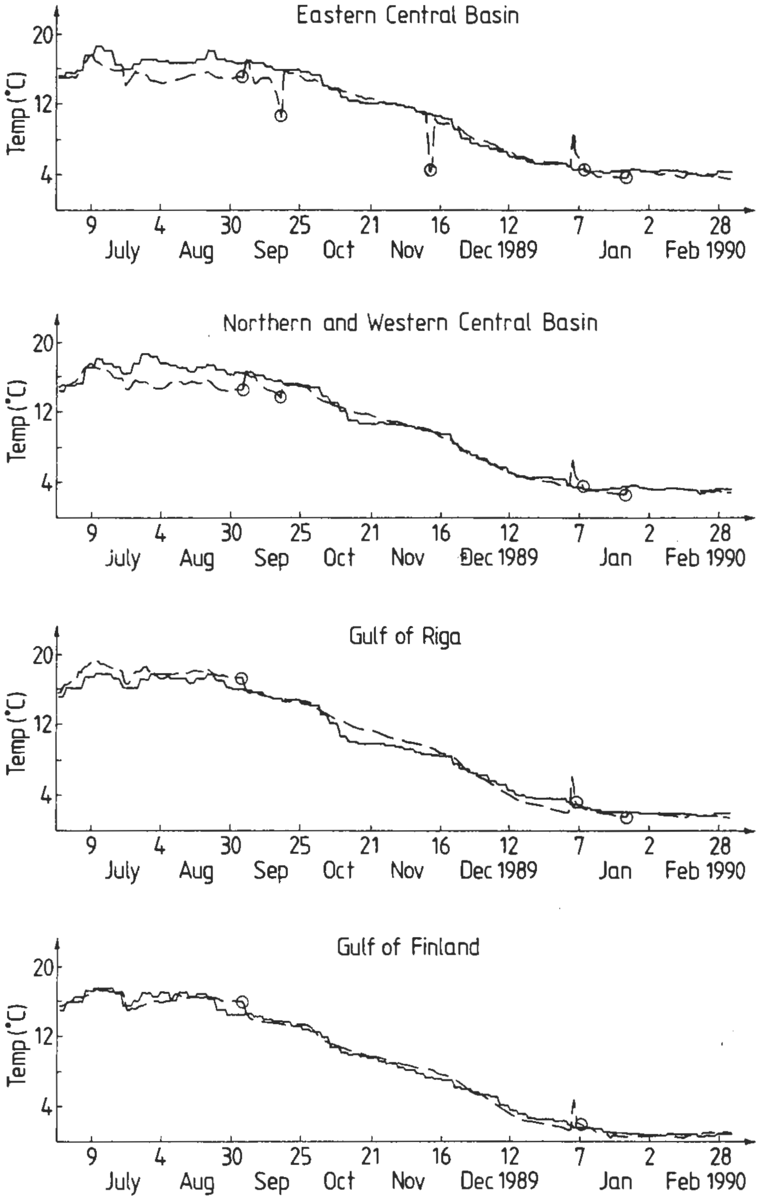


Figure 8, cont.

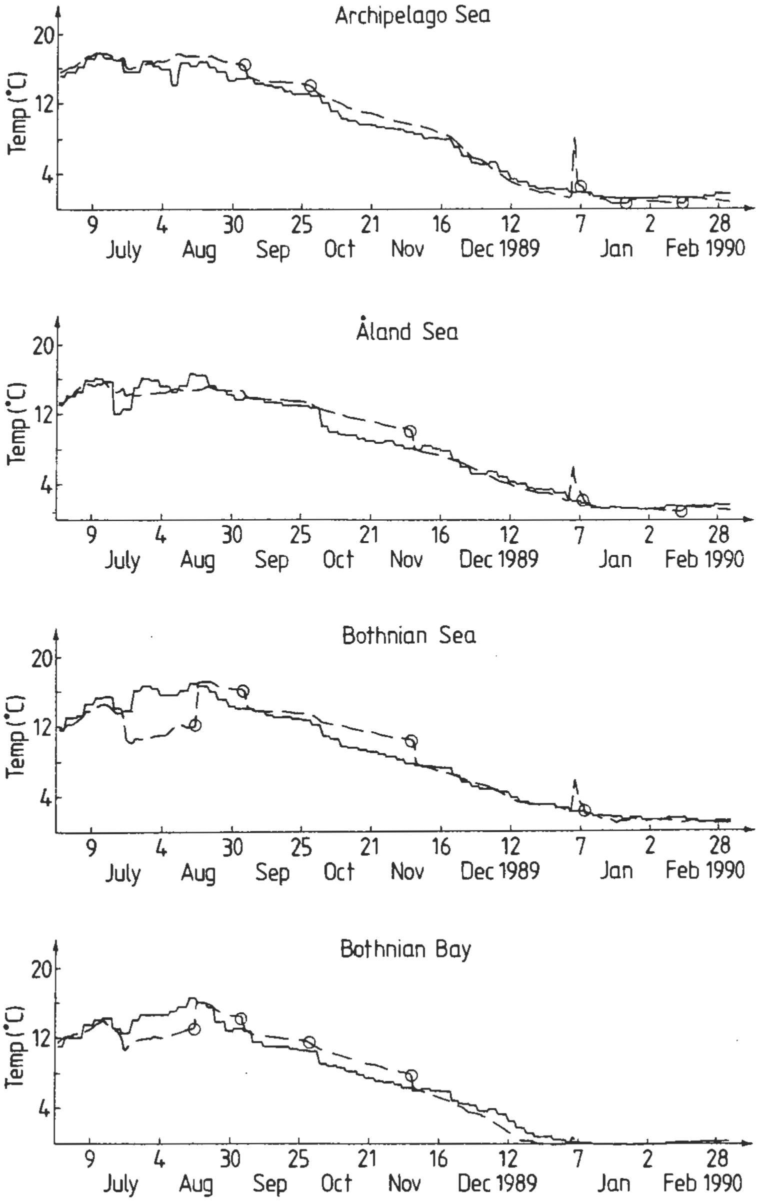


Figure 8, cont.

The results illustrate that the real-time calculations can quite satisfactorily reproduce observed sea surface temperatures. More efforts must, however, be paid to the obtaining of oceanographic data in real-time. If profile data once a month for each sub-basin could be collected in real-time, much better results could probably be achieved.

4.3 Forecasting

The purpose of the real-time scheme discussed in the previous section was to fit the ocean model to data gathered in the recent past and to calculate initial values for the forecasts. During the winter of 1989/90 several forecasts were made. These were 10-day forecasts using forcing parameters from ECMWF and partly longer forecasts using ECMWF data together with climatology. The 10-day forecasts were automatically started early in the morning, and the results were available at 8 o'clock each morning. For the longer forecasts, climatologic data were manually added before each forecast. In these cases only a single sub-basin was considered at each time. One example of the forecast output is given in Figure 9.

```
                                   P R O B E   B A L T I C
                                   FORECASTED FORCING FIELDS
DATE :    900118   KL 24

SUB-BASIN                T-SUR     T-BOT    D1        D2           S-SUR     S-BOT     D3        D4

KATTEGAT   (KA)           2.87      7.73    10.85     18.59        17.83     33.17     10.85     18.59
ORESUND    (OR)           3.07      6.08    19.95     22.70        25.74     32.50     19.95     22.70
BELTEN     (BE)           3.11      7.42    20.56     23.59        20.83     32.80     20.56     23.59
ARKONA     (AR)           3.04      7.09    29.74     34.32         8.48     15.14     29.74     34.32

BORNH-BAS  (BH)           4.94      6.57    47.25     70.43         7.87     16.94     47.25     70.43
GOTL-BAS   (GO)           4.04      5.93    62.33     72.13         6.98     11.68     62.33     72.13
NW-BAS     (NW)           2.82      4.92    62.33     72.13         6.55      9.92     62.33     72.13
GULF-RIG   (GR)           2.02      2.09    18.84     44.18         6.51      6.51     18.84     44.18

GULF-FIN   (GF)           1.04      5.87    40.71     62.01         6.03      7.47     40.71     62.01
ARCH-SEA   (AS)           0.90      3.36    44.80     50.85         7.02      7.93     44.80     50.85
ÅLAND-SEA  (AL)           1.46      2.97    45.31     62.33         6.40     10.99     45.31     62.33
BOTHN.SEA  (BS)           1.55      2.97    57.99     78.36         6.01      7.00     57.99     78.36

BOTHN.BAY  (BB)          -0.20      1.98    47.83     64.91         3.41      4.39     47.83     64.91
```

Figure 9. An output example from a 7 day forecast, where the temperature and salinity data are specified according to Figure 5.

5. SUMMARY AND RECOMMENDATIONS

A mathematical model for the Baltic Sea has been introduced in an operational system for real-time calculations and forecasts of water temperatures. The model divides the Baltic Sea into 13 sub-basins and treats each sub-basin as a horizontally homogeneous water body. The operational scheme uses the model in two modes. The first one, the real-time mode, fits the model to meteorological and oceanographical data collected in the recent past. The second one, the forecast mode, starts from the real-time mode, and calculates forecasts based upon the ECMWF weather model and statistics.

The experience from about 8 months of pre-operational tests illustrates that the real-time mode reproduces observed sea surface temperatures quite satisfactorily. The results from the forecasts were also satisfactory, but the quality was, of course, dependent on the meteorological forecasts.

The calculations were made on a VAX 8600 computer, which required about one minute CPU-time for each simulated day. This means that the total CPU-time for about 8 months of real-time calculations were 3 hours. The corresponding time for one person to update the model and check the results was 25 hours.

The calculations were made during pre-operational conditions and should become better when more ocean data are used. Some recommendations for the future use of the model would be:

- The calculations should be controlled some times each week.
- The model should be checked and, if necessary, updated whenever new temperature and salinity profile data are available.
- More efforts should be paid to the obtaining of salinity and temperature profile data in real time.

ACKNOWLEDGEMENTS

This work is a part of a Swedish-Finnish Winter Navigation Programme and has been financed by the Swedish National Maritime Administration. I would particularly like to thank Jan Stenberg for his interest and support during the work. Several colleagues at SMHI have also supported the work. Special thanks are given to Jan-Erik Lundquist for analysing the temperature data, to Barry Broman, Catarina Sundström, Håkan Palmén and Jan Szaron for supporting me with salinity and temperature data, and to Jörgen Sahlberg, Claes Larsson and Esbjörn Olsson for help with programming. Also the drawing by Ann-Margreth Holst and the printing by Vera Kuylenstierna are gratefully acknowledged.

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Appendix A

SUB-BASIN CHARACTERISTICS

The horizontal area versus depth for each sub-basin is illustrated below. The area - depth distributions are calculated according to the depth data base at SMHI.

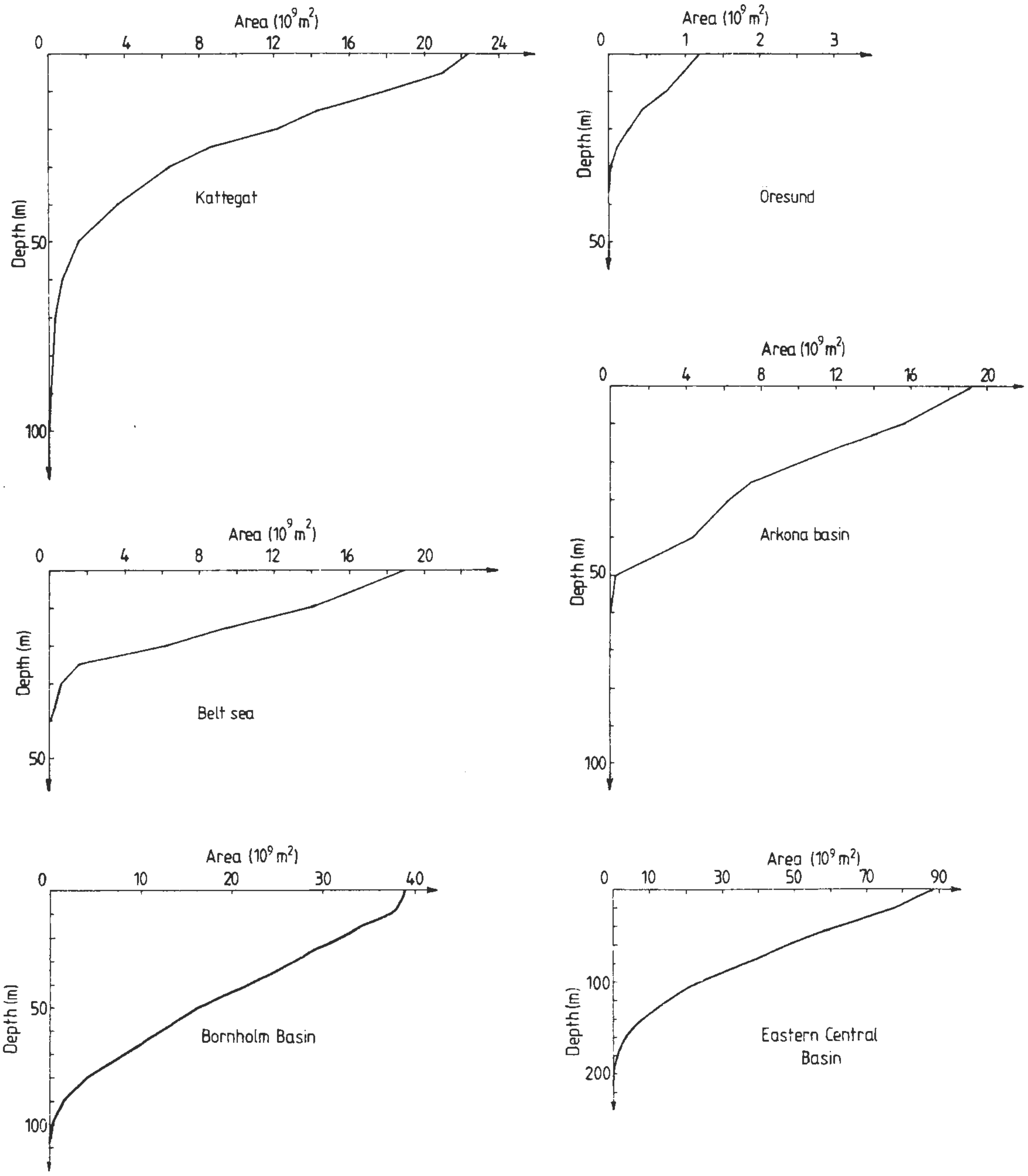


Figure A 1. The horizontal area versus depth for each sub-basin.

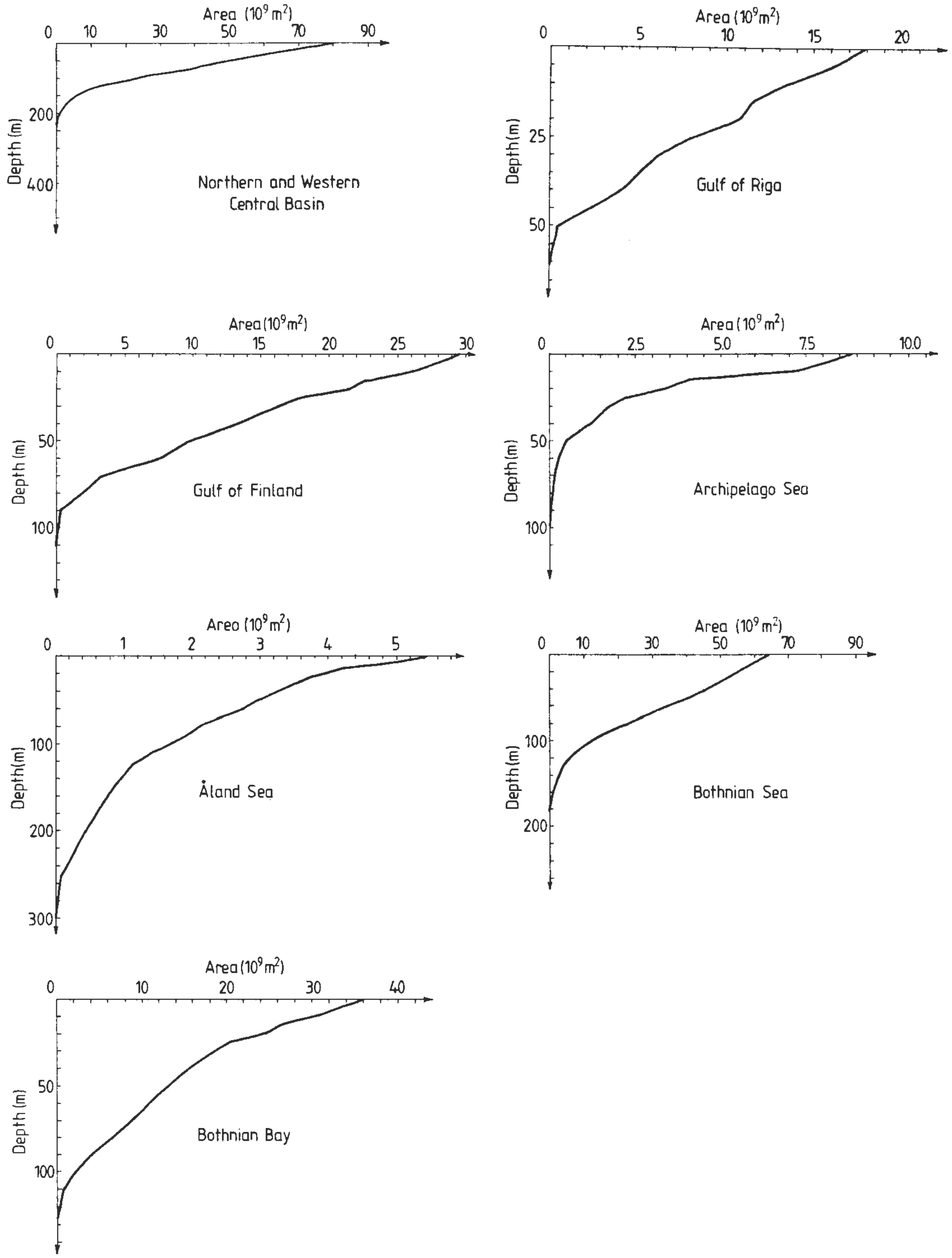


Figure A 1, cont.

Appendix B

VERIFICATION STUDY
OF THE ANALYSED METEOROLOGICAL PARAMETERS

The heat flux calculations require information about air temperature, wind, total amount of clouds and relative humidity. The data should represent the weather situation above each sub-basin. Weather services around the world have long operational experience in using observed data to draw conclusions about the spatial distribution of these parameters. The parameters are usually represented in networks of grid points and the method to interpolate the data in space and time is called data assimilation. At SMHI a high resolution meso scale analysis model is in operational use (Andersson et al., 1986). The model applies data assimilation to interpolate available meteorological data. The grid is illustrated in Figure B 1.

The quality of the meteorological parameters calculated from this model is analysed by comparing calculated and observed data from some different synoptic weather stations. The comparison is presented in Figure B 2, and the positions of the different weather stations are indicated in Figure B 1. Some statistical information is also given in Table B 1.

Table B 1. Statistics based upon 3 hour-values during the period 1st September, 1989, to 28th February, 1990.

Station	Mean wind ratio	Mean temperature difference
Kullen	0.93	0.33
Sandhammaren	0.88	0.31
Hoburgen	1.11	0.33
Gotska Sandön	0.90	- 0.01
Hölick	1.01	0.07
Bjuröklubb	0.80	- 0.04

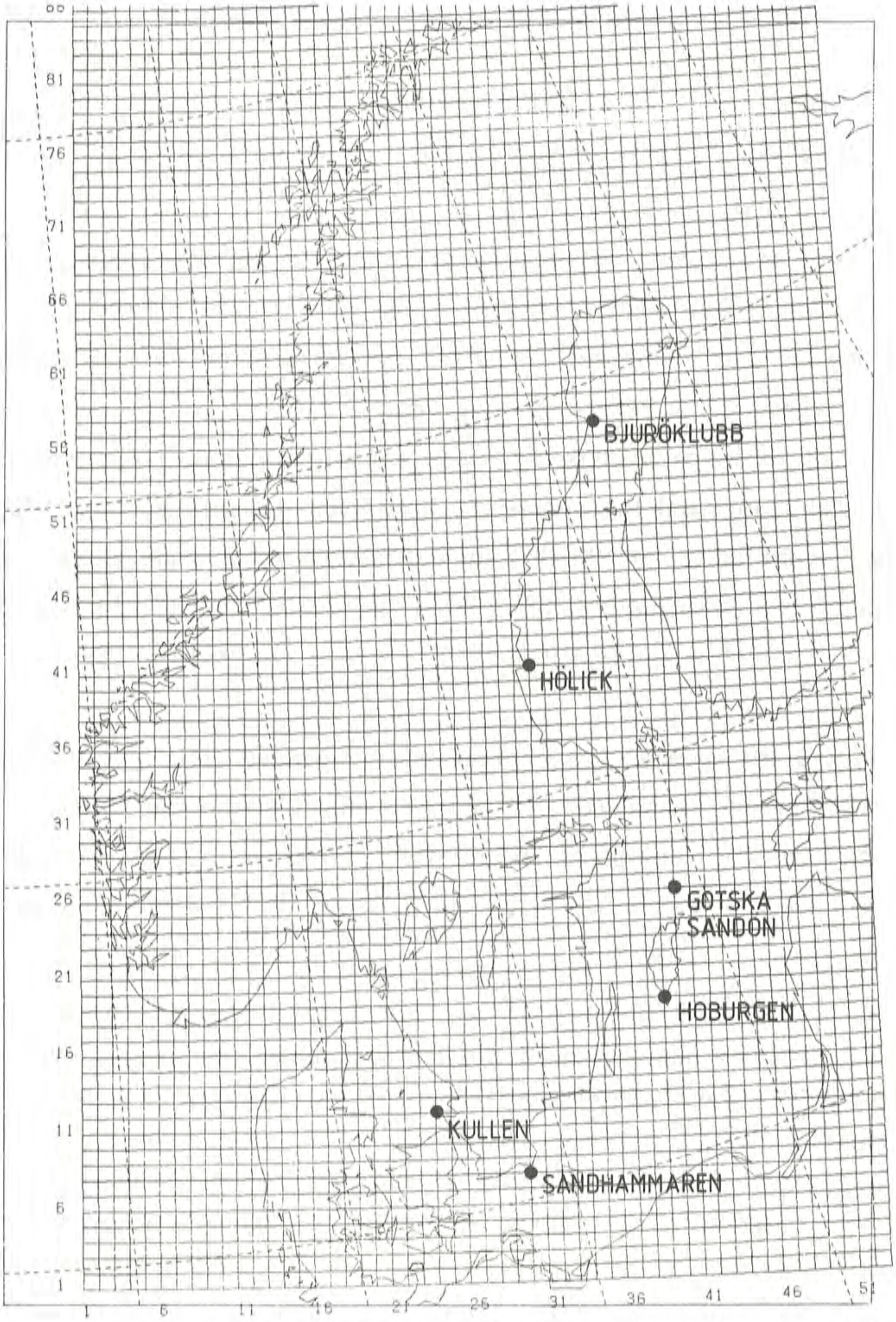
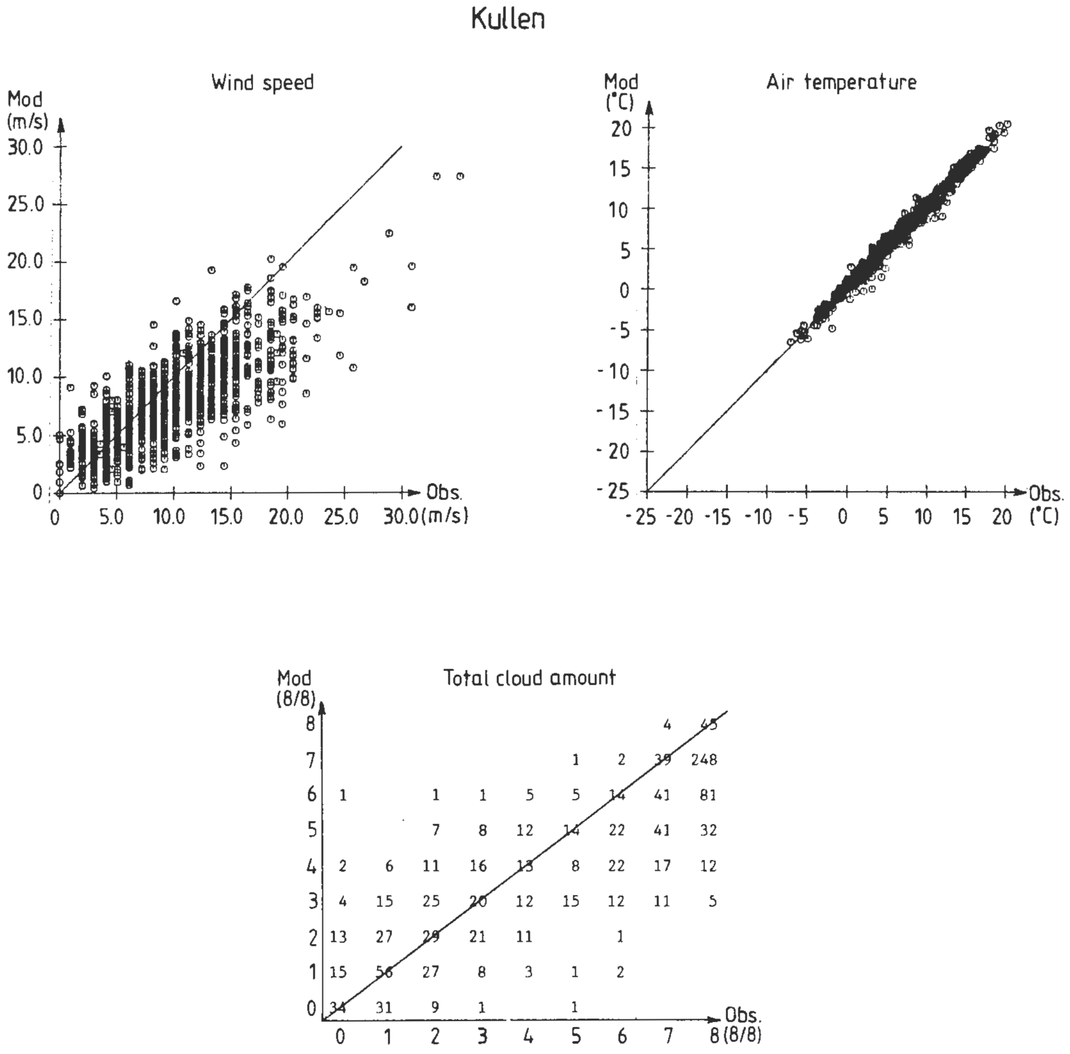


Figure B 1. The grid used in the present meso scale weather model.

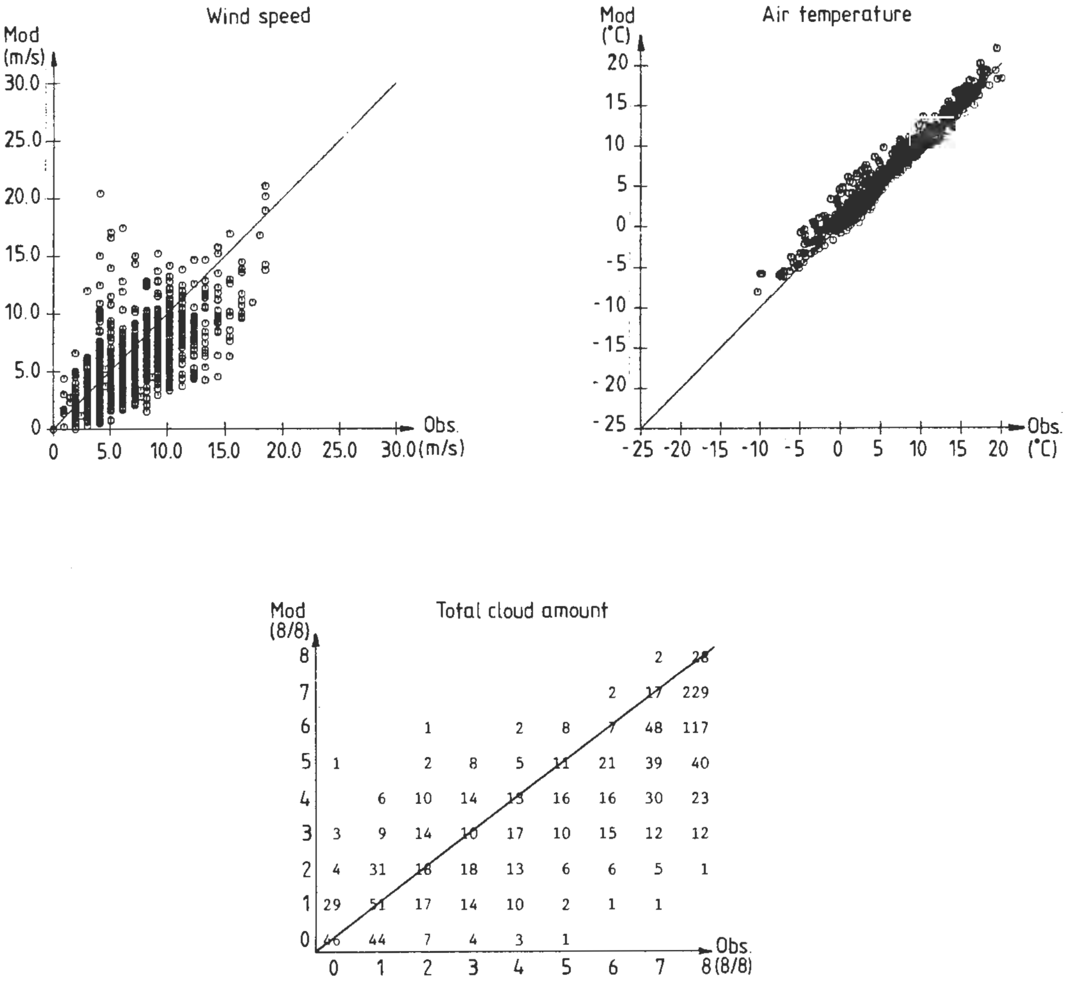
From the comparison between observed and calculated data one can notice that the air temperatures are well simulated. The wind velocities are rather scattered with model calculations slightly lower than observations. This is partly due to the fact that the synoptic weather stations are measuring at higher levels compared to the reference level used in the calculations, which is 10 meters above the sea surface. The mean wind ratio values in Table 1 seem reasonable and could probably also be used as a good guess how the synoptic winds should be reduced down to 10 meters. The total cloud amounts are more scattered and in general the calculations underestimate the cloud amounts.



Mod (8/8) \ Obs. (8/8)	0	1	2	3	4	5	6	7	8
8								4	45
7						1	2	39	248
6	1		1	1	5	5	14	41	81
5			7	8	12	14	22	41	32
4	2	6	11	16	13	8	22	17	12
3	4	15	25	20	12	15	12	11	5
2	13	27	29	21	11		1		
1	15	56	27	8	3	1	2		
0	34	31	9	1		1			

Figure B 2. Comparison between modelled (Mod) and observed (Obs) meteorological data from the time period 1st September, 1989, to 28th February, 1990.

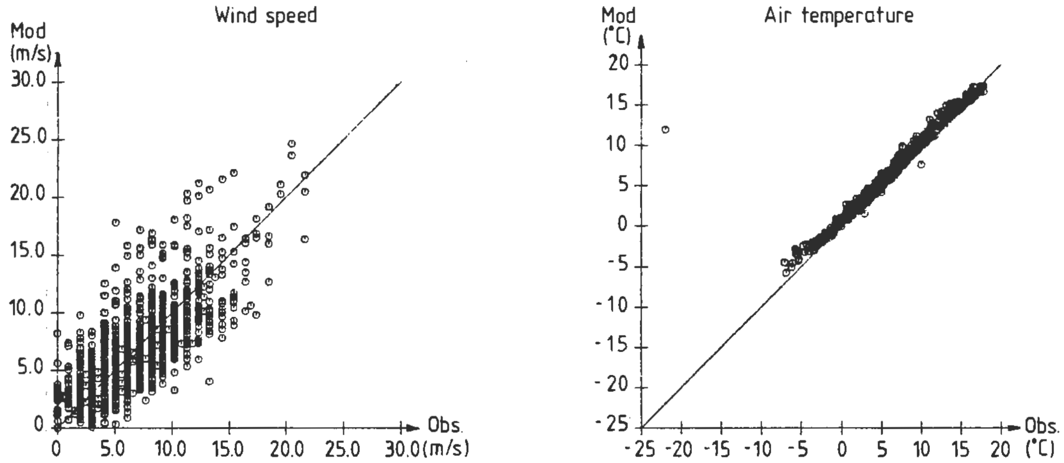
Sandhammaren

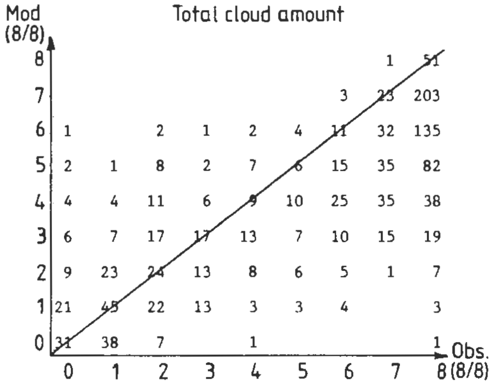


Mod (8/8) \ Obs. (8/8)	0	1	2	3	4	5	6	7	8
8								2	28
7							2	17	229
6			1		2	8	7	48	117
5	1		2	8	5	11	21	39	40
4		6	10	14	13	16	16	30	23
3	3	9	14	10	17	10	15	12	12
2	4	31	18	18	13	6	6	5	1
1	29	51	17	14	10	2	1	1	
0	46	44	7	4	3	1			

Figure B 2, cont.

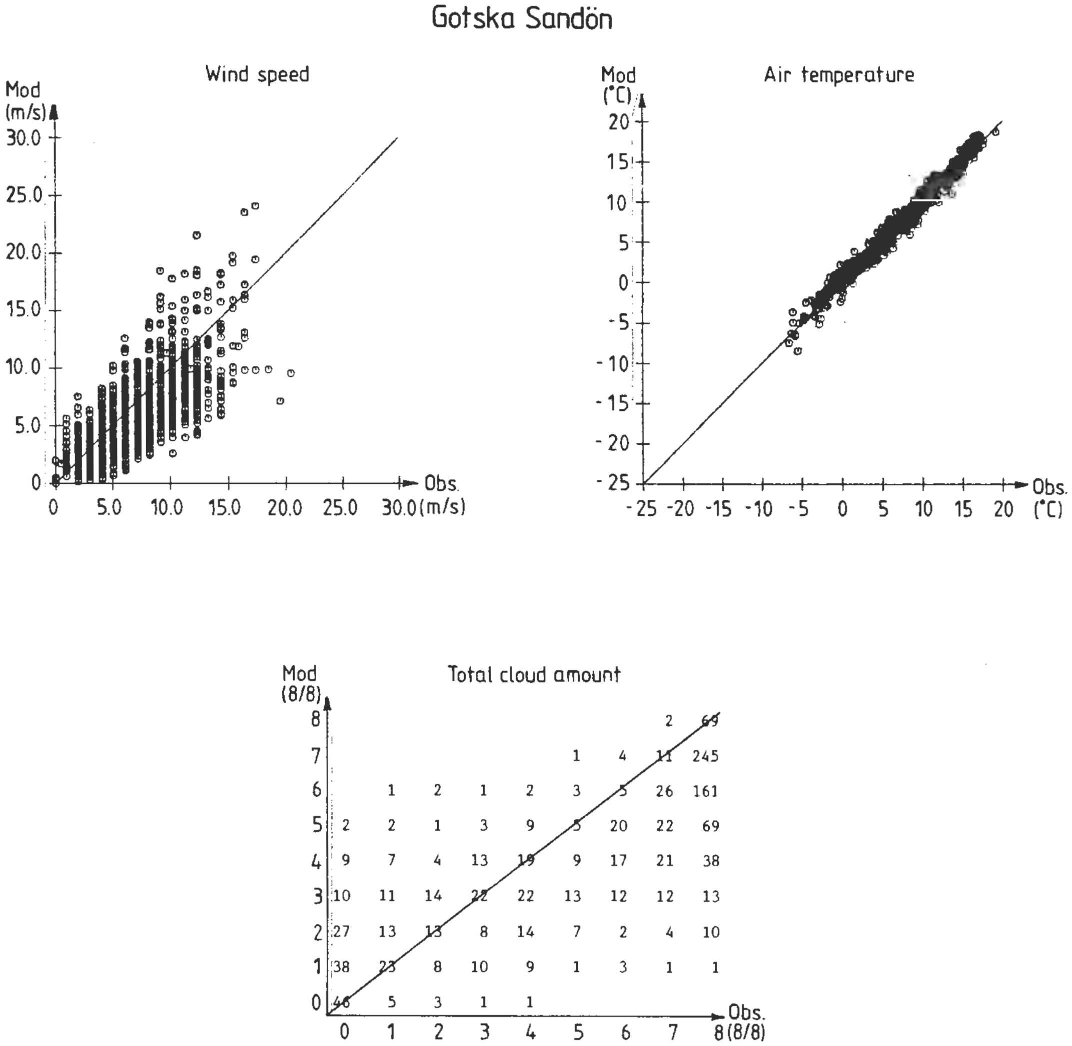
Hoburgen





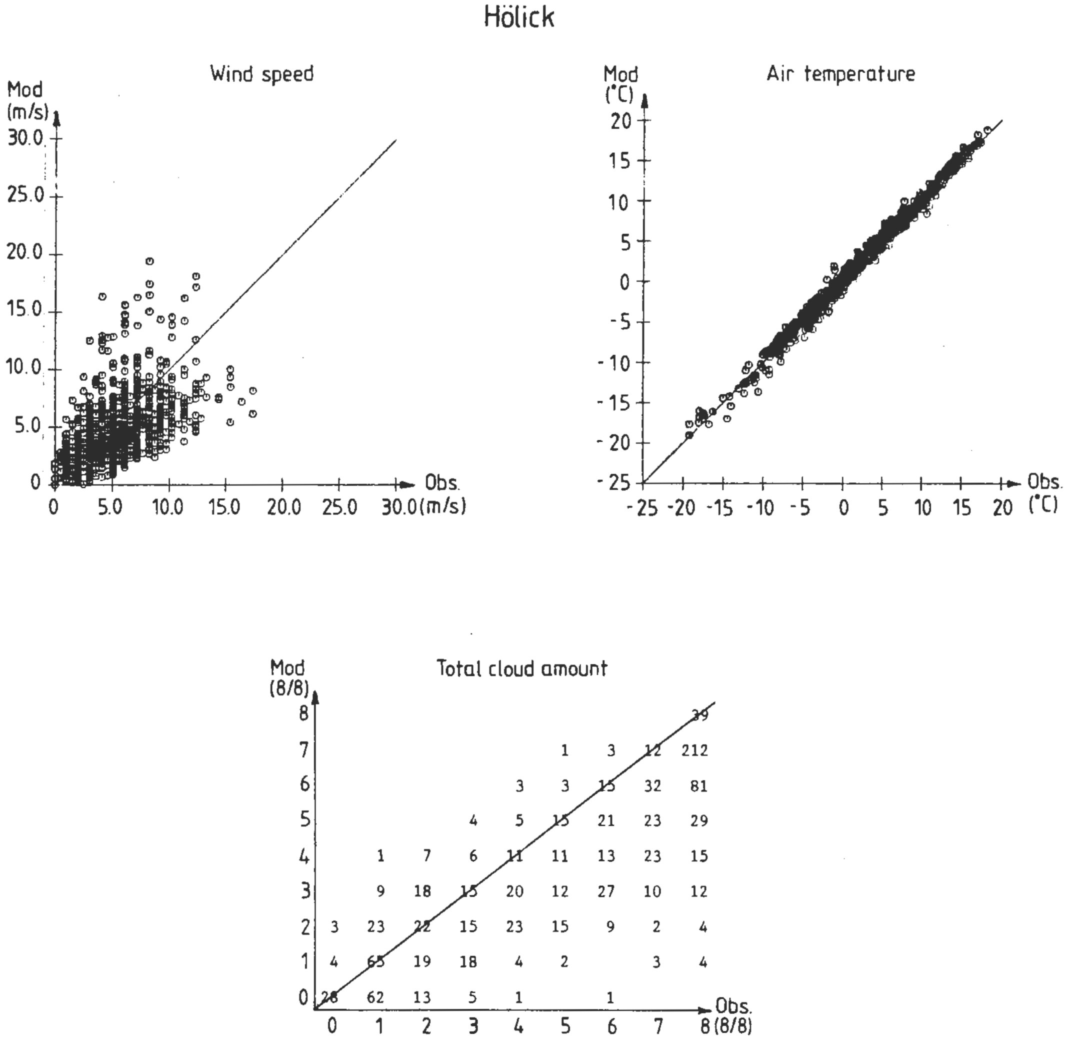
Mod (8/8) \ Obs. (8/8)	0	1	2	3	4	5	6	7	8
8								1	51
7							3	23	203
6	1		2	1	2	4	11	32	135
5	2	1	8	2	7	6	15	35	82
4	4	4	11	6	9	10	25	35	38
3	6	7	17	17	13	7	10	15	19
2	9	23	24	13	8	6	5	1	7
1	21	45	22	13	3	3	4		3
0	31	38	7		1				1

Figure B 2, cont.



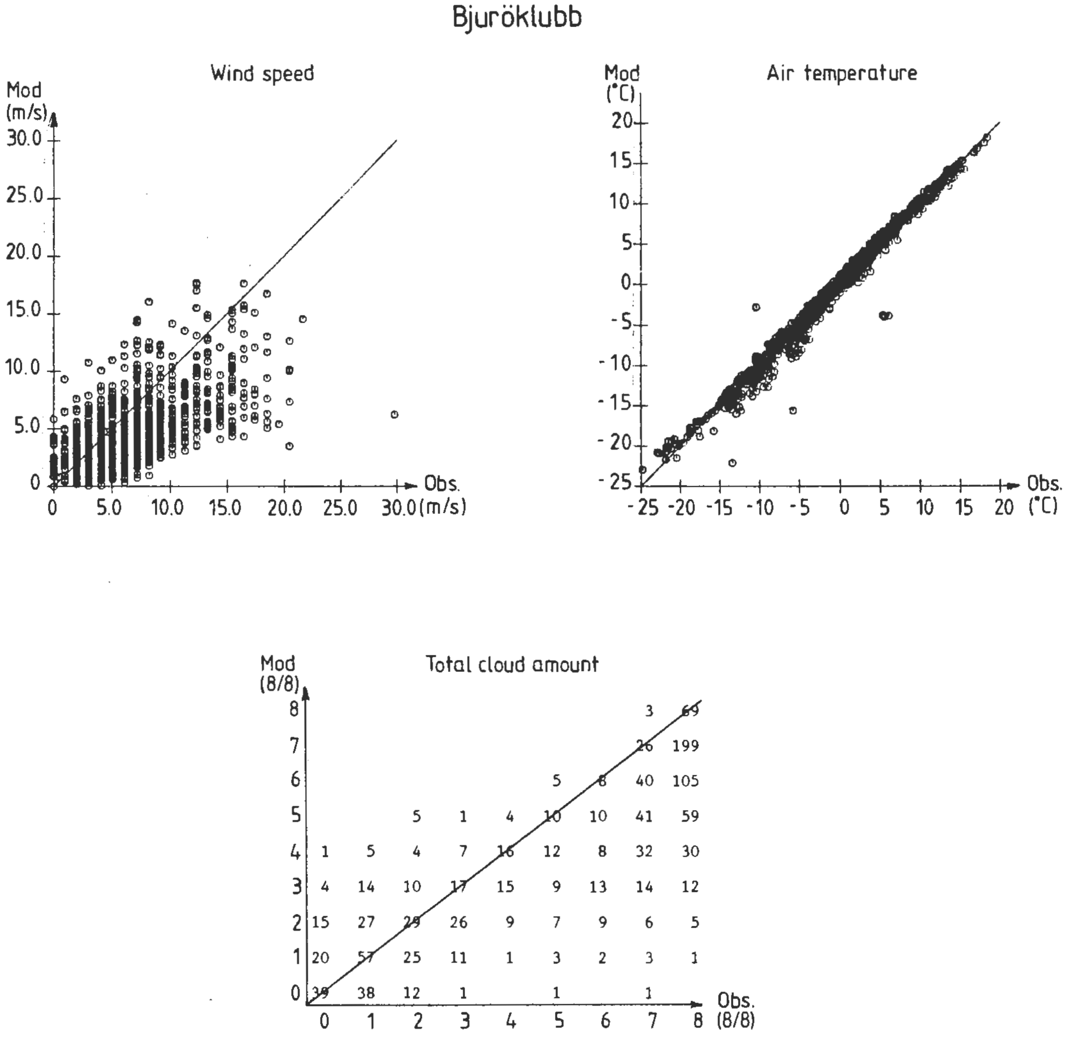
	0	1	2	3	4	5	6	7	8
8								2	69
7						1	4	11	245
6		1	2	1	2	3	5	26	161
5	2	2	1	3	9	5	20	22	69
4	9	7	4	13	19	9	17	21	38
3	10	11	14	22	22	13	12	12	13
2	27	13	13	8	14	7	2	4	10
1	38	23	8	10	9	1	3	1	1
0	46	5	3	1	1				

Figure B 2, cont.



Mod (8/8) \ Obs. (8/8)	0	1	2	3	4	5	6	7	8
8									39
7						1	3	12	212
6					3	3	15	32	81
5				4	5	15	21	23	29
4		1	7	6	11	11	13	23	15
3		9	18	15	20	12	27	10	12
2	3	23	22	15	23	15	9	2	4
1	4	65	19	18	4	2		3	4
0	28	62	13	5	1		1		

Figure B 2, cont.



Mod (8/8) \ Obs. (8/8)	0	1	2	3	4	5	6	7	8
8								3	69
7								26	199
6						5	8	40	105
5			5	1	4	10	10	41	59
4	1	5	4	7	16	12	8	32	30
3	4	14	10	17	15	9	13	14	12
2	15	27	29	26	9	7	9	6	5
1	20	57	25	11	1	3	2	3	1
0	39	38	12	1		1		1	

Figure B 2, cont.

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