DEVELOPMENT OF MESO-SCALE ANALYSIS SCHEMES FOR NOWCASTING AND VERY SHORT-RANGE FORECASTING

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Abstract

PROMIS-600 is an experimental work station for nowcasting and very short-range forecasting, which is going to be tested at the Swedish Meteorological and Hydrological Institute. Meso-scale objective analysis schemes are being developed to serve this work station with diagnostic analysis maps and initial data fields for simplified forecast models. These objective analysis schemes have so far been based on the optimum interpolation method. An-isotropic correlation functions have been introduced for the analysis of surface parameters. Land/sea contrasts have been considered in the modelling of these correlation functions. A multi-variate scheme for analysis of vertical profiles, utilizing potential temperature as vertical co-ordinate is being developed.

1. INTRODUCTION

Nowcasting and very short-range weather forecasting are new challenging areas for meteorological research. New observational techniques based on remote-sensing have to be introduced and combined with analysis and forecast methods to form optimized systems for nowcasting and very short-range weather forecasting.

The Swedish Meteorological and Hydrological Institute (SMHI) has started to develop an experimental system (PROMIS-600) for nowcasting and very short-range weather forecasting.

The technical facilities of PROMIS-600 will include two Doppler weather radars, a satellite data reception station, 40 automatic surface stations in a meso-scale network, a lightning location system, computers and data presentation terminals. The geographical distribution of the PROMIS-600 observing system is illustrated in Figure 1.

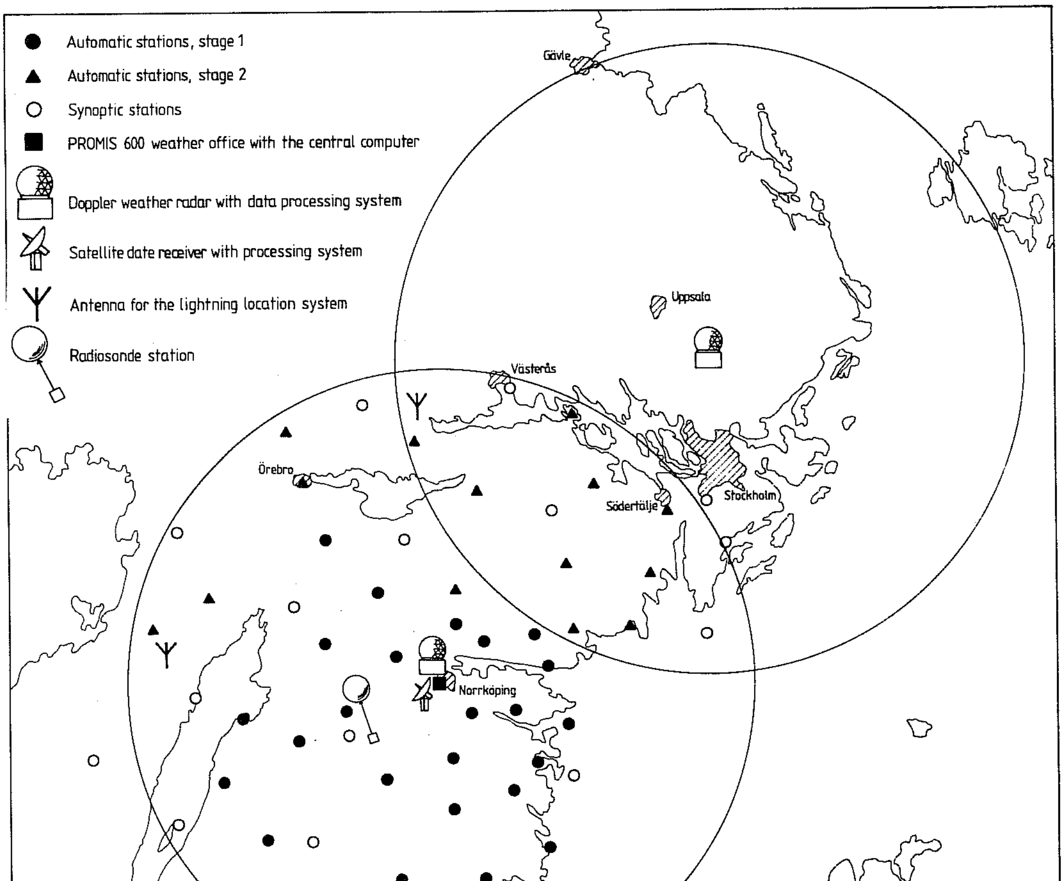
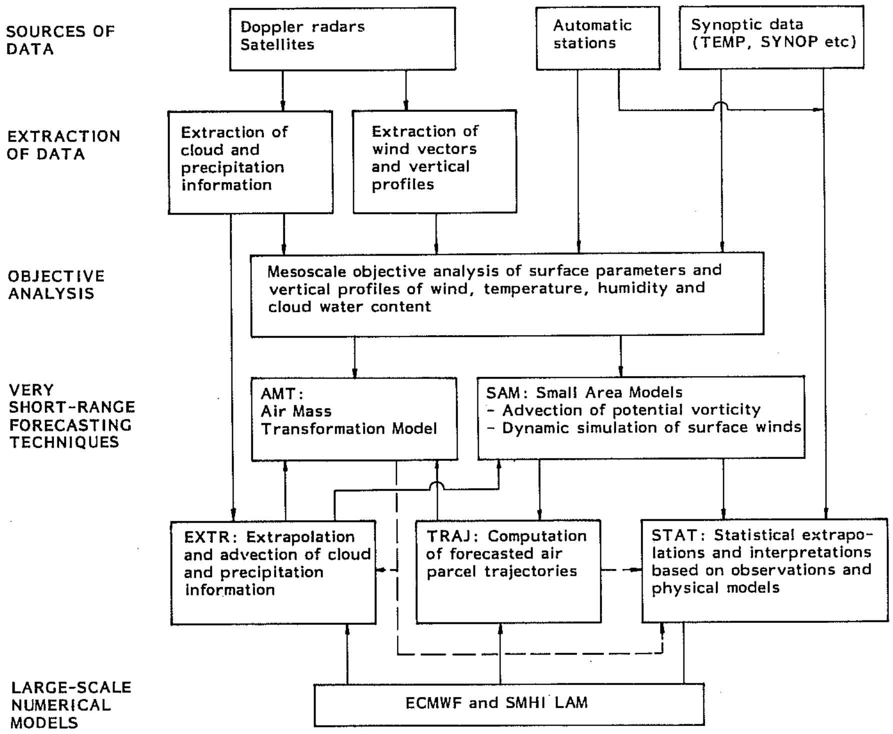


Figure 1 *The PROMIS-600 Observing System.*

Today numerical forecast models have become the main tool for operational preparation of short-range and medium range weather forecasts. Such a universal tool is still not available for operational nowcasting and very short-range weather forecasting (0-12 hours). Meso-scale numerical models exist, but several factors limit the operational application of these models. There are, for example, serious time-delays in the collection of operational upper-air data and existing meso-scale models require too much processing time on available medium-sized computers to make operational application meaningful.

Postponing the application of a general meso-scale model, our plan is to develop a system of simplified and specialized analysis and forecast techniques to be tested in PROMIS-600.



<u>Figure 2</u> *Basic components of the PROMIS-600 very short-range forecasting system.*

The basic components of this system are illustrated in Figure 2 and are briefly described below:

- Cloud, precipitation and surface skin temperature information will be extracted from AVHRR satellite images with the method developed by Liljas (1982).

- Temperature profiles will be retrieved from locally received radiance data (TOVS). A physical temperature profile inversion method is being developed by Svensson (1985).

- Precipitation and wind information will be retrieved from the two Doppler radars.

- Methods for meso-scale objective analysis of meteorological parameters are being developed. This is an important prerequisite for making very short-range weather forecasts with simple methods based on advection and extrapolation, since the initial conditions have to be established with great detail and accuracy.

- Several simplified dynamical and statistical models are being tested for the very short-range forecasts of surface pressure and temperature fields. A simple model based on advection of potential vorticity has been selected for the very short-range forecasting of surface pressure. This model (VAM = Vorticity Advection Model) uses SMHI-LAM predicted lateral boundary values and advective winds. The best advective wind is selected by the aid of an optimization with respect to previous observed pressure changes during the last 6 hours.

- A single level primitive equation model, developed by Danard (1977), will be used to simulate winds in layers close to the ground. This model will be used both as a diagnostic tool in the analysis and for interpretation of forecast fields.

  Experiments with the model have so far given promising results.

- Cloud and precipitation data, extracted from radar and satellite information, will be extrapolated and advected by forecast wind fields (ECMWF, LAM and VAM + wind interpretation).

- A model for computation of 3-dimensional air parcel trajectories from forecast and analysed wind fields has been developed. This model is running operationally on wind forecasts produced by the SMHI-LAM.

- A one-dimensional air-mass transformation model is being developed in co-operation with the Swedish Defence Research Institute. This is a one-dimensional boundary layer model, including hydrological cycle and surface energy balance calculation, which will be advected along air parcel trajectories in the boundary layer. Preliminary experiments (Karlsson, 1984) have shown that models of this kind are able to predict fog and stratus clouds.

It should be stressed that all the listed analysis and forecast methods are not applicable in all types of weather situations. It will be the task of the forecasters to select which methods are to be used for the various weather situations. Therefore, all the forecast methods will be linked together in an interactive system supported by a flexible system for graphical output.

Requirements for objectively analysed meteorological fields in PROMIS-600 are based on the need of initial data for the simplified models, together with the need of diagnostic analysis maps to support the manual forecasting.

These requirements can be summarized as follows.

(A) Meso β-scale (20-200 km according to Orlanski) analysis fields covering a geographical area considered as the influence area for very short-range forecasting (3-12 hours) in the Norrköping region. An analysis grid consisting of 41x40 gridpoints with a horisontal resolution of 0.2^ox0.2^o has been designed for this analysis task (Figure 3).

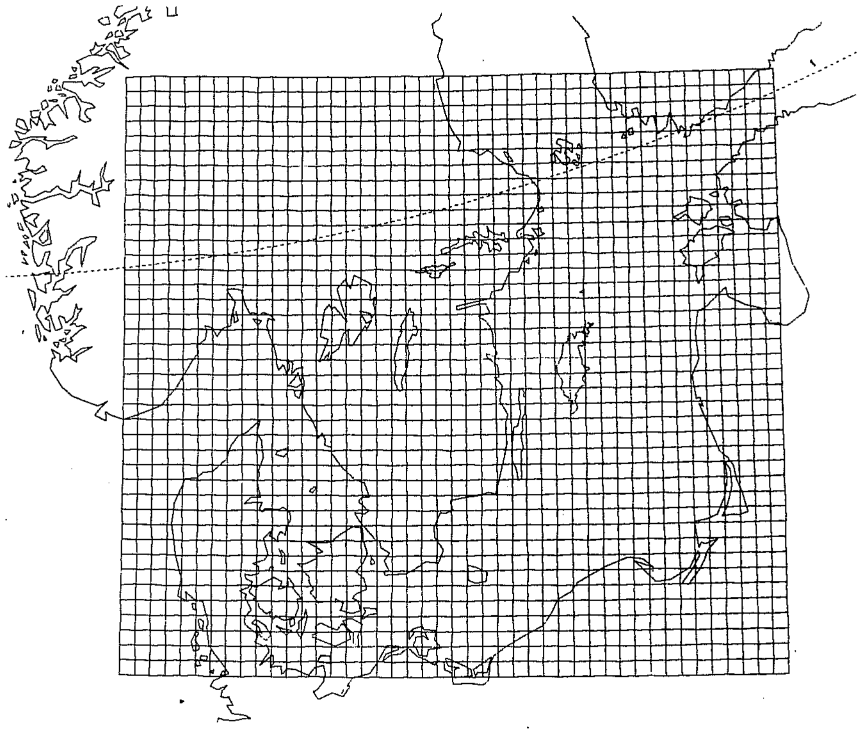


Figure 3 *Horisontal grid for the PROMIS-600 meso-β-scale objective analysis*
$\Delta lat = \Delta long = 0.2^o$.

The following parameters are to be analysed over this area:

- Sea-level pressure, temperature at the 2-meter level, humidity at the 2-meter level and wind at the 10-meter level.
- Cloudiness parameters - as a starting point, cloud amount at three levels will be analysed.
- Snow depth.
- Sea-surface temperature and sea-ice coverage.
- Precipitation amount (every 12th hour) and precipitation intensity (every 3rd hour).
- Temperature, humidity and wind at a few vertical levels in the lower troposphere.

Most of these parameters will be analysed with a temporal resolution of 3 hours.

(B) Analyses of detailed vertical profiles of temperature, humidity, wind and cloud water content are required at all starting-points for the air-mass transformation model.

(C) Meso γ-scale (2-20 km according to Orlanski) analysis fields over the regional PROMIS-600 forecast area are required for nowcasting purposes. Data from the automatic stations and from the Doppler radars are the major data sources. Sea-level pressure, 2-meter temperature, 2-meter humidity, 10-meter winds and precipitation are to be analysed. An accurate analysis of the divergent part of the wind field is of utmost importance for the nowcasting task.

2. MESO-SCALE OBJECTIVE ANALYSIS OF SURFACE PARAMETERS FOR PROMIS-600

Considering that meso-scale objective analysis is a new area for meteorological research and with regard to the time-table of PROMIS-600, it was necessary to choose a pragmatic approach to the problem of meso-scale objective analysis for PROMIS-600. The operational SMHI-LAM objective analysis system was converted to a meso-scale objective analysis scheme by introduction of necessary modifictions. The operational LAM analysis system is based on 3-dimensional uni-variate statistical interpolation of forecast errors. Gaussian isotropic correlation functions in the horizontal are used for the geopotential and humidity analyses, and non-divergent wind component correlation functions are derived by representing the stream function forecast error correlations also by Gaussian isotropic functions. A variational technique is used to adjust the wind and geopotential analysis increments towards geostrophic balance.

As regards meso-β-scale analysis of surface parameters for PROMIS-600, the following two main modifications were introduced into the LAM analysis system:

(1) Operational experience and theoretical considerations have indicated poor spectral properties of the Gaussian correlation function with regard to meso-scale variations. Therefore, the Gaussian correlation function was replaced by a modified first order Bessel function of the second kind.

(2) Most operational objective analysis schemes, utilized for synoptic and larger-scale analyses, assume isotropy of parameters to be analysed with respect to horizontal auto-correlations. This assumption is less valid for meso-scale circulation systems and especially for those parameters which are depending on the characteristics of the earth's surface.

> Thus, anisotropic correlation functions have been introduced for analysis of some surface parameters. So far, land/sea contrasts have been considered in the modelling of these anisotropic correlation functions.

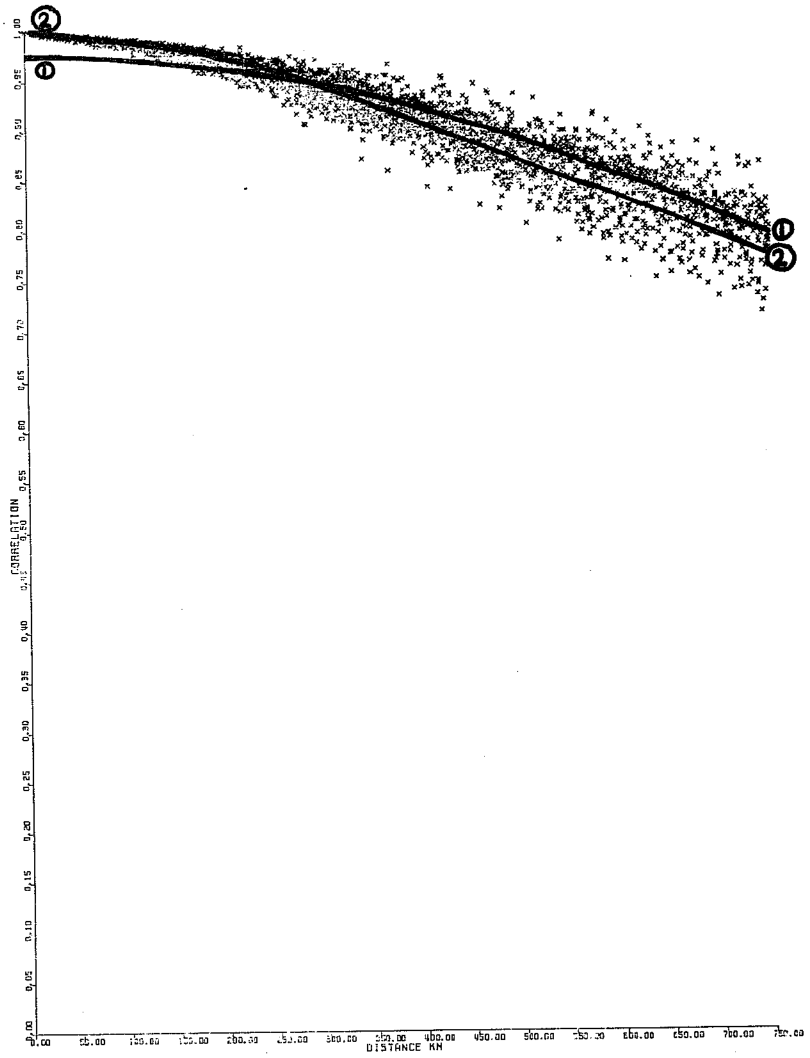
Details of the analysis schemes for the various surface parameters are described in the following.

Another general assumption of synoptic-scale objective analysis schemes is that the statistical structure models do not have any case-to-case variations. Also this assumption has to be relaxed for a proper analysis of meso-scale structures, since many meso-scale circulation systems have strong relation to the type of large-scale circulation (e g by separation into weather regimes). This concept of flow-dependent objective analysis has, so far, not been introduced into the PROMIS-600 meso-scale objective analysis system.

2.1 Analysis of sea-level pressure

Sea-level pressure is presently being analysed by a uni-variate statistical interpolation scheme with a first guess analysis field taken as a LAM short-range forecast (3, 6 or 9 hours). Transformation to the high-resolution grid of this first guess is done by bi-cubic interpolation.

At the time when this analysis scheme was designed, no quality controlled observed-minus-forecasted sea-level pressure data were available for computation of horizontal correlation functions. Therefore, manual tuning and comparison with observed-minus-climatological correlations were used to construct the analysis correlation functions. Following Balgovind et al (1983), a modified first order Bessel function of the second kind was used to represent the distance dependence of the correlations. This type of correlation function provides a better representation of the small-scale part of the forecast error correlation than a Gaussian function does (see Figure 4).



<u>Figure 4</u> *Spatial correlations of observed-minus-climatological sea-level pressures based on 5 years of Swedish SYNOP reports, April-September, 12 GMT only. Distance-dependent correlation functions obtained by least-square fit:*
(1) Gaussian function.
(2) First order Bessel function of the second kind.

Manual comparisons also favoured objective analyses based on this Bessel-type correlation function in comparison with analyses based on the Gaussian correlation function.

Recently the ECMWF statistical data files with quality-controlled observed-minus-forecasted sea-level pressure data were used to re-evaluate the horizontal correlation functions. The first thing noticed was the significant anisotropy of the forecast error correlations in the vicinity of the Scandinavian mountain chain (Figure 5).

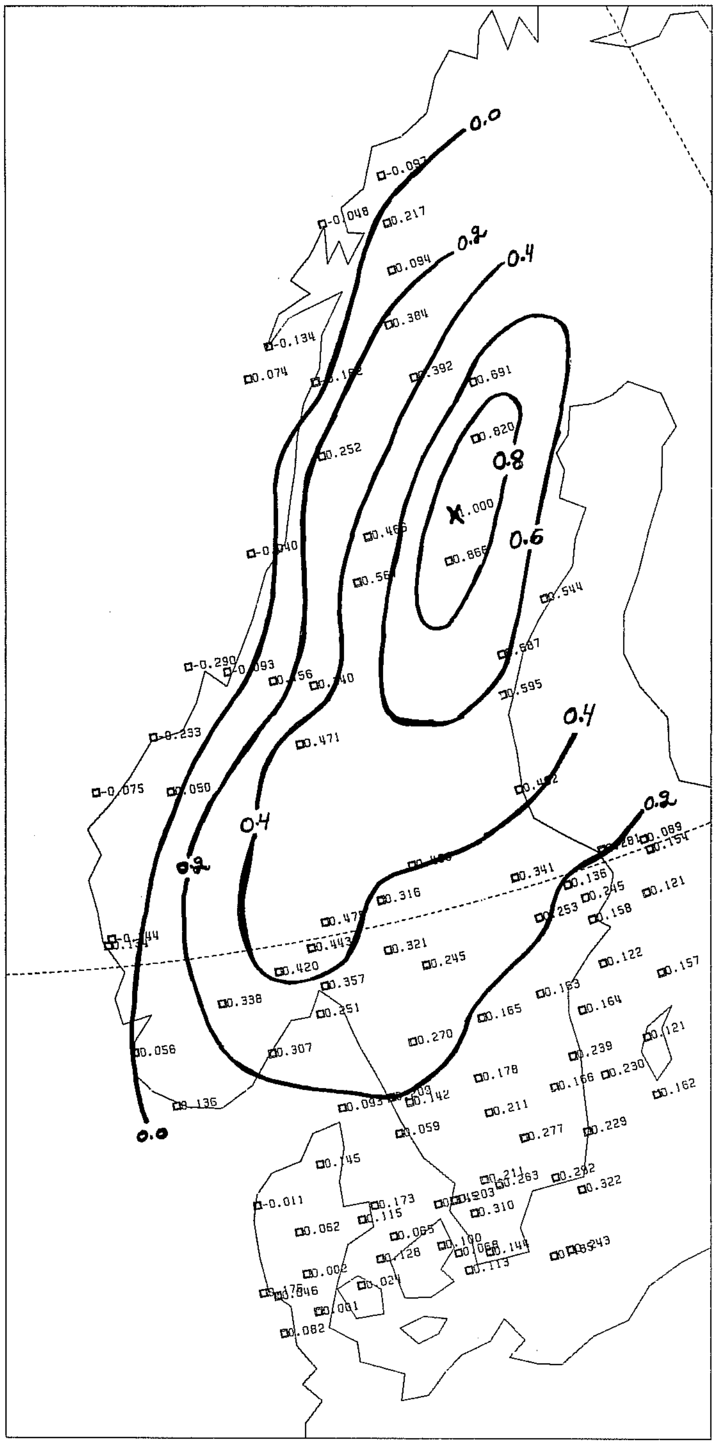


Figure 5 *Spatial correlations of ECMWF 6 hour sea-level pressure forecast errors, Dec 83 - Feb 84, 12 GMT only. Reference station indicated by x.*

No attempt has yet been made to model this anisotropy. Instead, an area less influenced by topographic effects was selected for determination of a covariance model. In this case, isotropy appears to be a relevant assumption (Figures 6 and 7) though the scatter is significant.

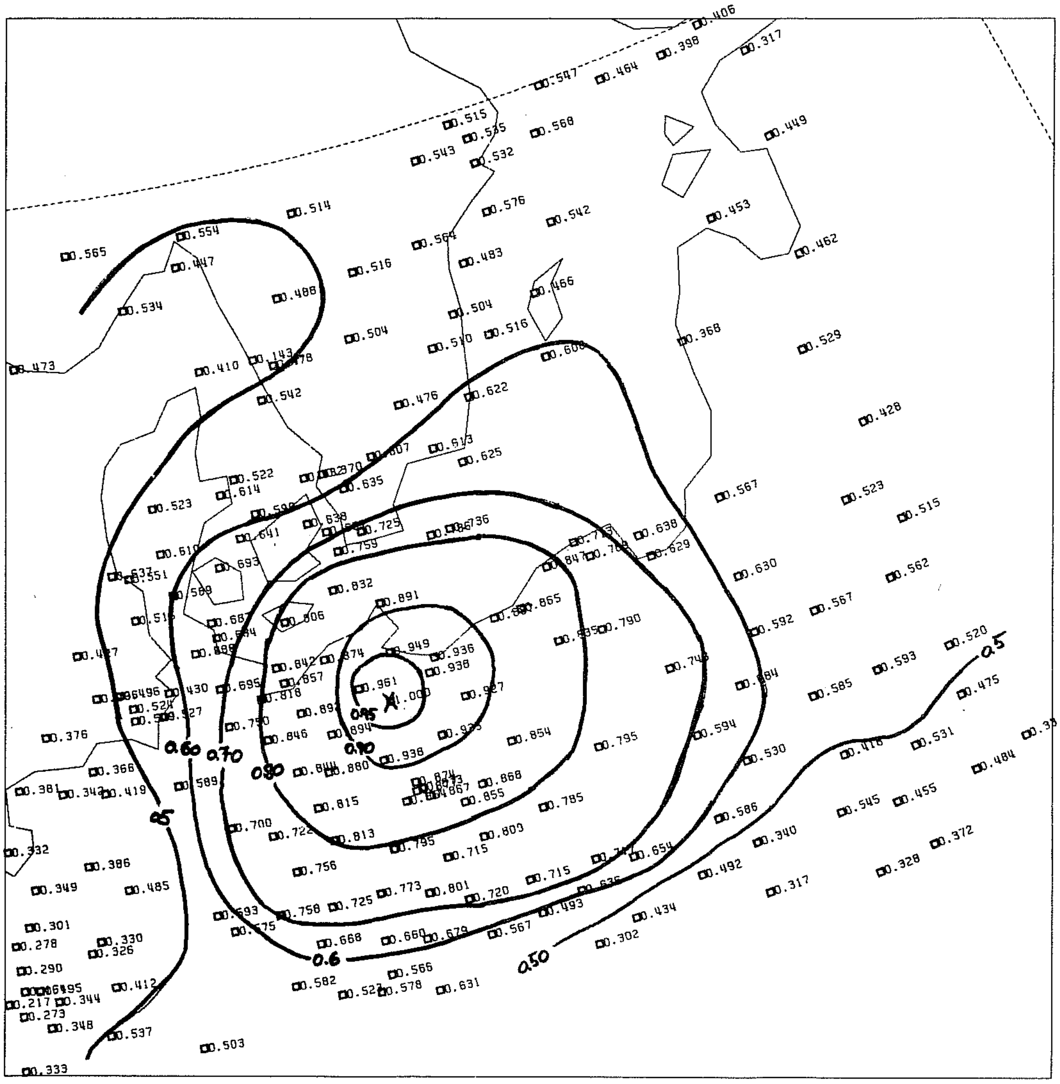


Figure 6 *Spatial correlations of ECMWF 6 hour sea-level pressure forecast errors, Dec 83 - Feb 84, 12 GMT only. Reference station indicated by x.*

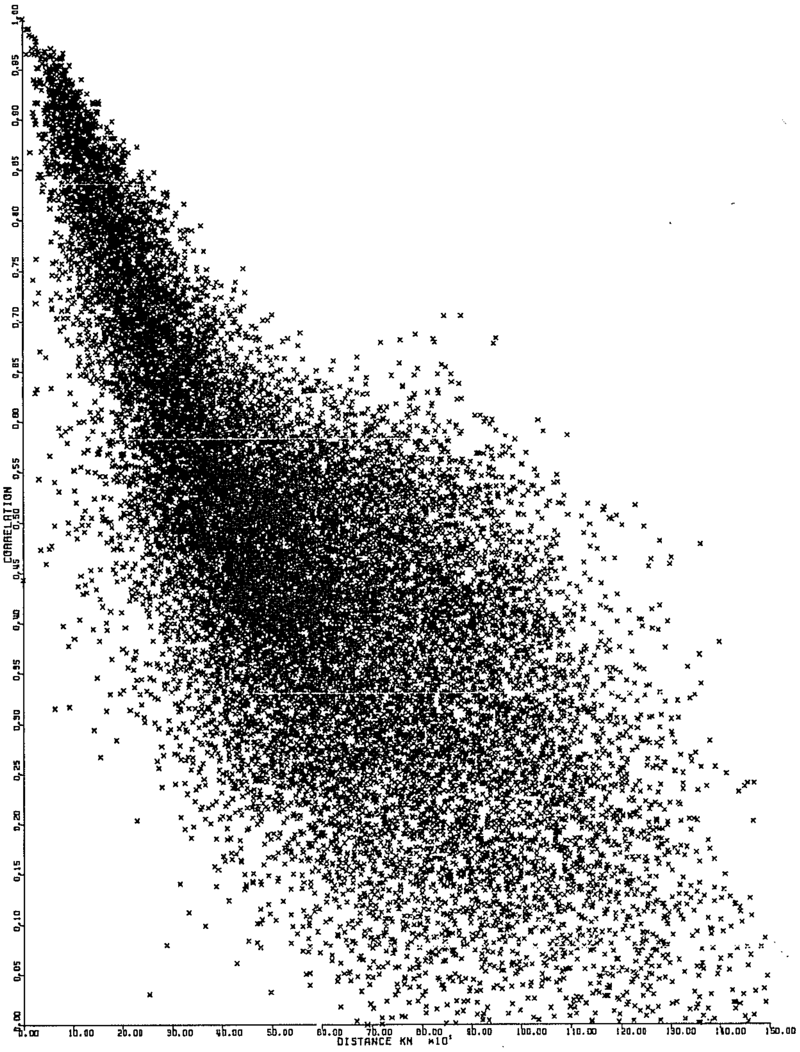


Figure 7 *Spatial correlations of ECMWF 6 hour sea-level pressure forecast errors plotted as functions of distance. Area indicated in Figure 6, Dec 83 - Feb 84, 12 GMT only.*

If modified first order Bessel-functions of the second kind were fitted to the distance-averaged empirical correlations, the fitting coefficients turned out to be in good agreement with those selected manually for operational use (Figure 8).

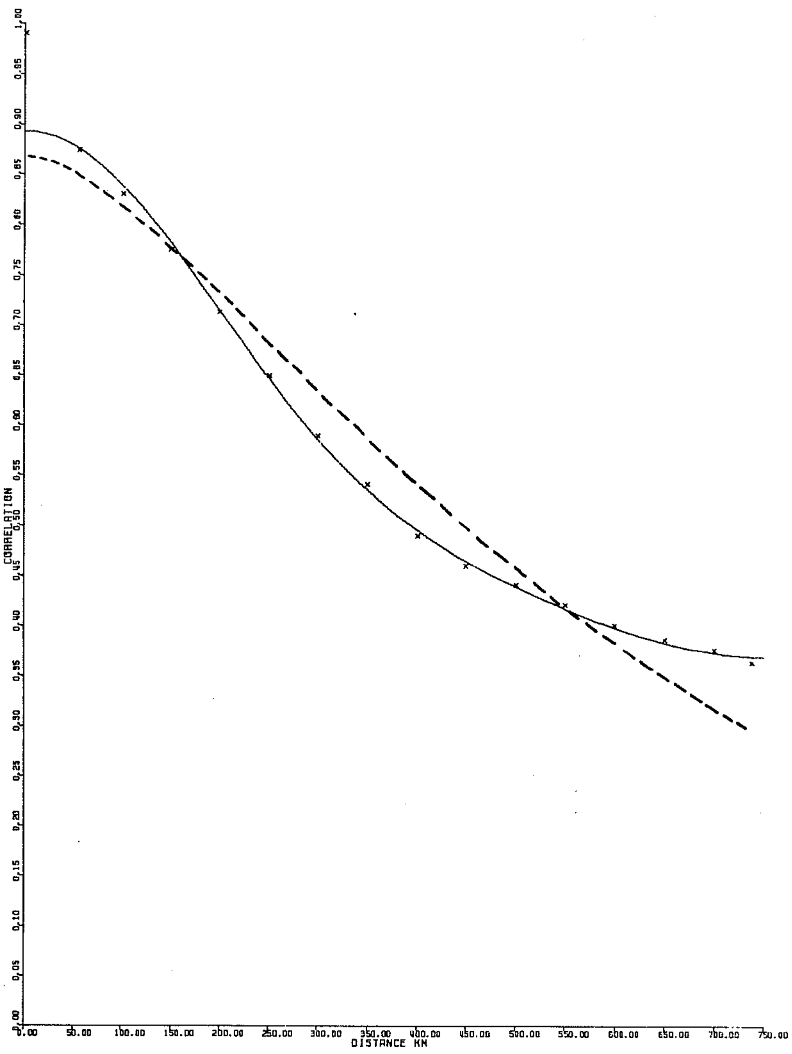


Figure 8 *Spatial correlations of ECMWF 6 hour sea-level pressure forecast errors averaged in separation distance classes. Area indicated in Figure 6, Dec 83 - Feb 84, 12 GMT only. Distance-dependent correlation functions obtained by least-square fit:*

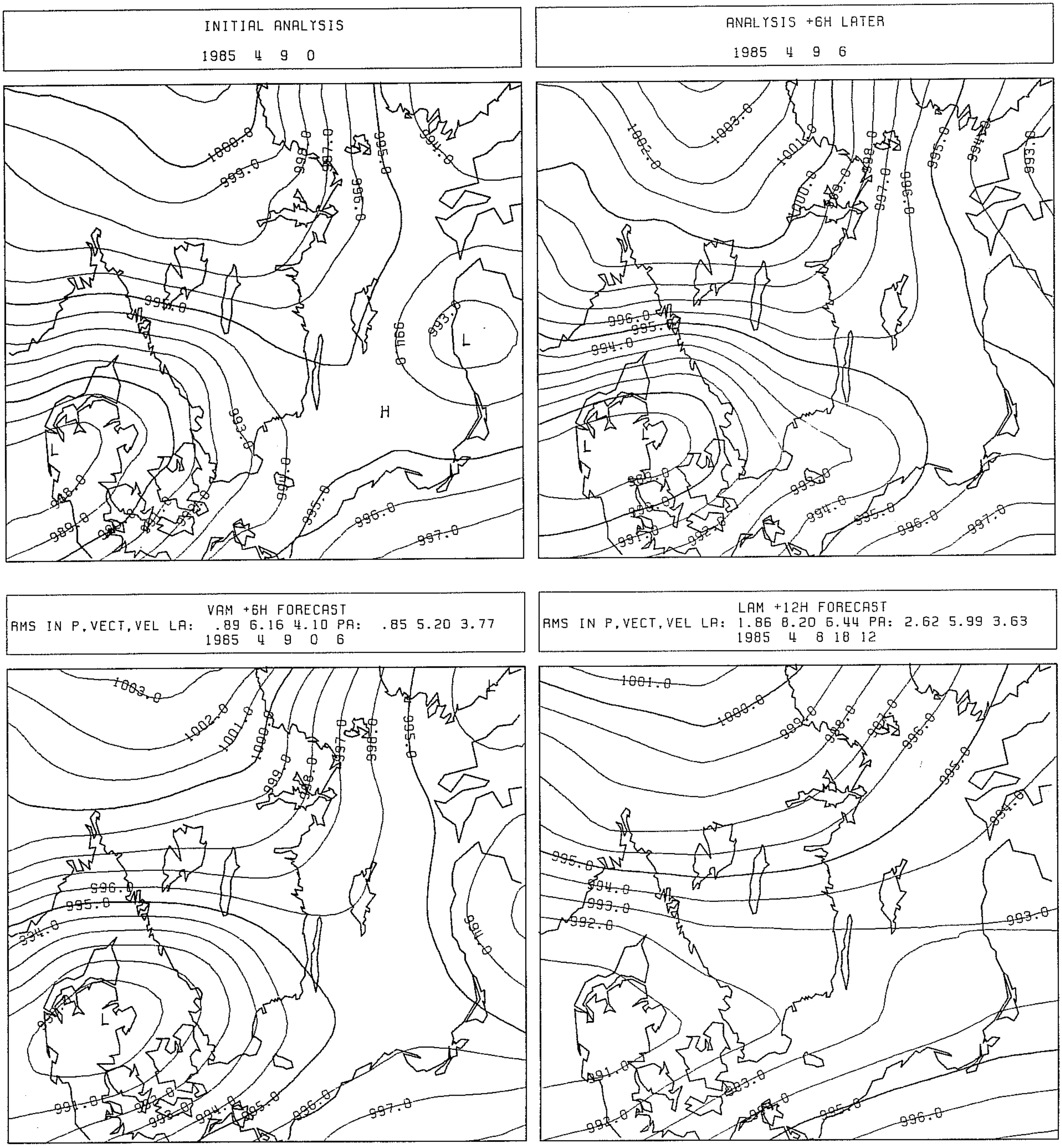
– – – – – – First order Bessel-function of second kind.

———— Series of 4 terms of zero order Bessel functions of first kind.

It was found, however, that a series of 4 terms of zero order Bessel functions of the first kind gave a much better representation of the empirical correlations. These correlation functions have not yet been tested for analysis.

Data selection and data rejection by quality control turned out to be crucial problems for the meso-scale analysis of sea-level pressure.

One of the main reasons for both of these problems is the relative sparseness of observations over the Baltic Sea. The data selection algorithm is presently local, with individual selection of observations to influence each gridpoint. When the set of selected sea-level pressure data, mainly from coastal and island stations, was gradually altered in the middle of the Baltic, discontinuities in the meso-scale pressure analyses were created. To resolve this problem temporarily, it was necessary to increase the number of influencing observations and to force one observation from each 45^{o}-sector around the gridpoints to enter the analysis computations. It seems obvious that a box data selection algorithm should be preferable for meso-scale sea-level pressure analysis. The PROMIS-600 sea-level pressure analyses have so far been utilized in two applications: for the dynamical simulation of surface winds and for very short-range forecasting of sea-level pressure fields by a method based on advection of potential vorticity. Both applications have indicated promising results. Results from the dynamic wind simulations are dicussed below. An example of sea-level pressure forecast by means of vorticity advection is given in Figure 9. Compare the details of this sea-level pressure forecast with the corresponding LAM sea-level pressure forecast. LAM advective winds and lateral boundaries are used in the advection of vorticity. However, the best advective wind is chosen by an optimization with respect to observed pressure changes during 6 hours in advance of the initial forecast time.



INITIAL ANALYSIS
1985 4 9 0

ANALYSIS +6H LATER
1985 4 9 6

VAM +6H FORECAST
RMS IN P,VECT,VEL LA: .89 6.16 4.10 PA: .85 5.20 3.77
1985 4 9 0 6

LAM +12H FORECAST
RMS IN P,VECT,VEL LA: 1.86 8.20 6.44 PA: 2.62 5.99 3.63
1985 4 8 18 12

Figure 9 A 6-hour sea-level pressure forecast with a simple vorticity advection model (VAM) and corresponding verification. For comparison the operational available LAM 12 hour forecast is also depicted.

2.2 Analysis of surface temperature and humidity

The spatial variability of surface temperature and humidity is to a large extent related to regional and local factors. (In the following 'surface temperature and humidity' are used for the values of these parameters at the 2 meter level). This property is reflected in empirical spatial correlations of these parameters.

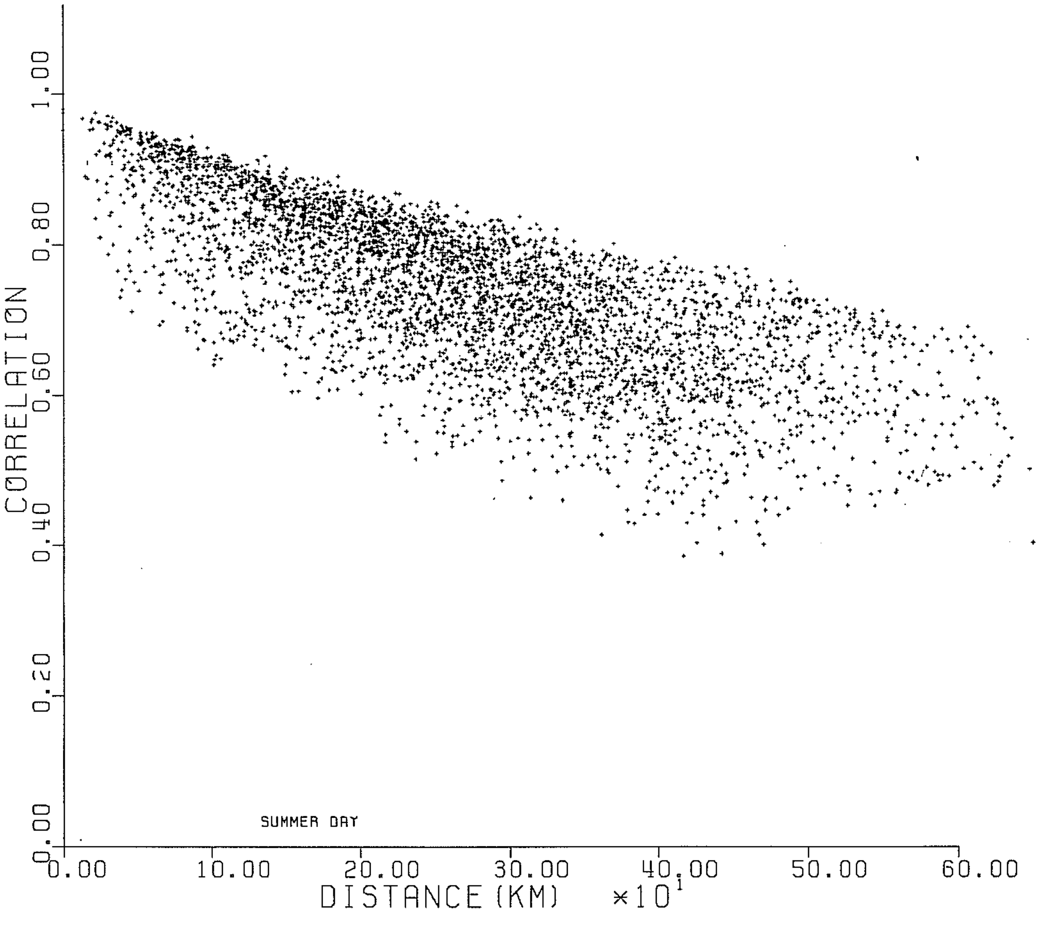


Figure 10 *Spatial correlations of observed-minus-climatological 2 meter temperatures, 5 years of Swedish SYNOP-data, June-August, 12 GMT only.*

Figure 10 shows horizontal correlations of observed-minus-climatological values of surface temperature computed from 5 years of Swedish SYNOP-data taken from the summer seasons (June-August) and 12 GMT only. The scatter of these correlations as functions of distance is great and very small correlation values occur already for small distance separations.

Horizontal plots of individual correlations corresponding to one fixed reference station show that the land/sea contrast is a dominant factor influencing this anisotropy (Figure 11).

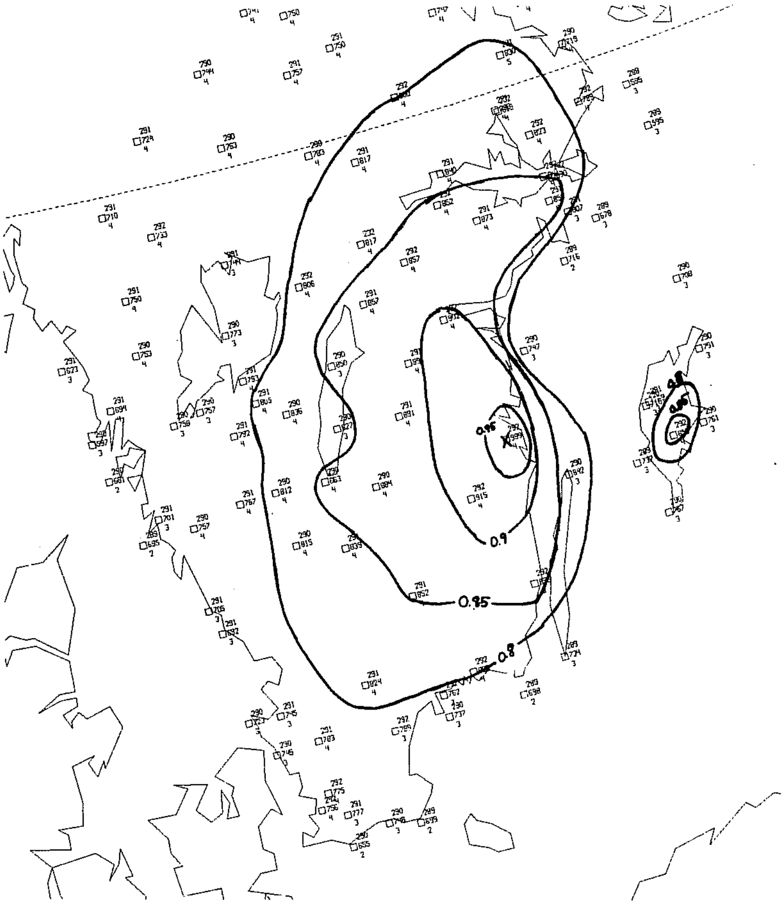


Figure 11 *Spatial correlations of observed-minus-climatological 2 meter temperatures, 5 years of Swedish SYNOP-data, June-August, 12 GMT only. Reference station indicated by x.*

This is also clearly illustrated by the eigen-vector of the empirical covariance matrix corresponding to the largest eigen-value (first empirical orthogonal function, Figure 12).

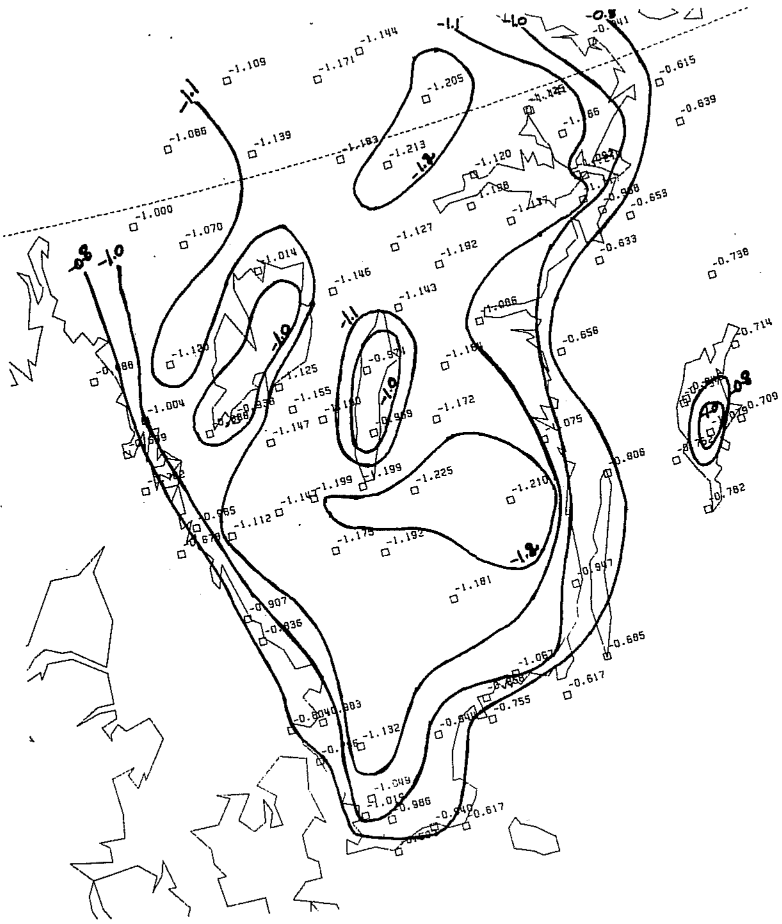


Figure 12 *First empirical orthogonal function of the spatial covariance matrix of 2 meter observed-minus-climatological temperatures. 5 years of Swedish SYNOP-data, June-August, 12 GMT only.*

It is evident, that it is necessary to consider the land/sea contrasts when covariance models for analysis of surface temperature are to be constructed. A preliminary model for the spatial covariance of surface temperature, which takes the land/sea contrasts into account, was constructed by the aid of a manual classification of SYNOP stations and gridpoints. The following classification scheme was used:

Class number	Description
1	inland
2	near coast
3	coast
4	inland lake
5	sea

Examples of this classification of stations and gridpoints are given in Figure 13.

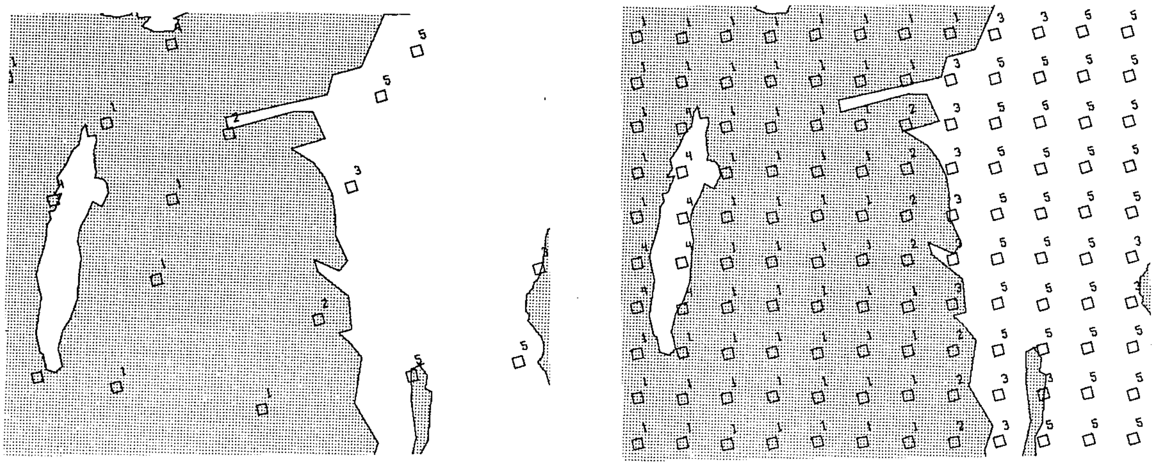


Figure 13 *Classification of surface stations (left) and gridpoints (right) in relation to inland lakes and sea (examples)*
1=inland; 2=near coast; 3=coast; 4=inland lake; 5=sea.

The result of a stratification of all the empirical correlation values according to the classification of the station pairs, followed by an averaging in separation distance classes is illustrated in Figure 14.

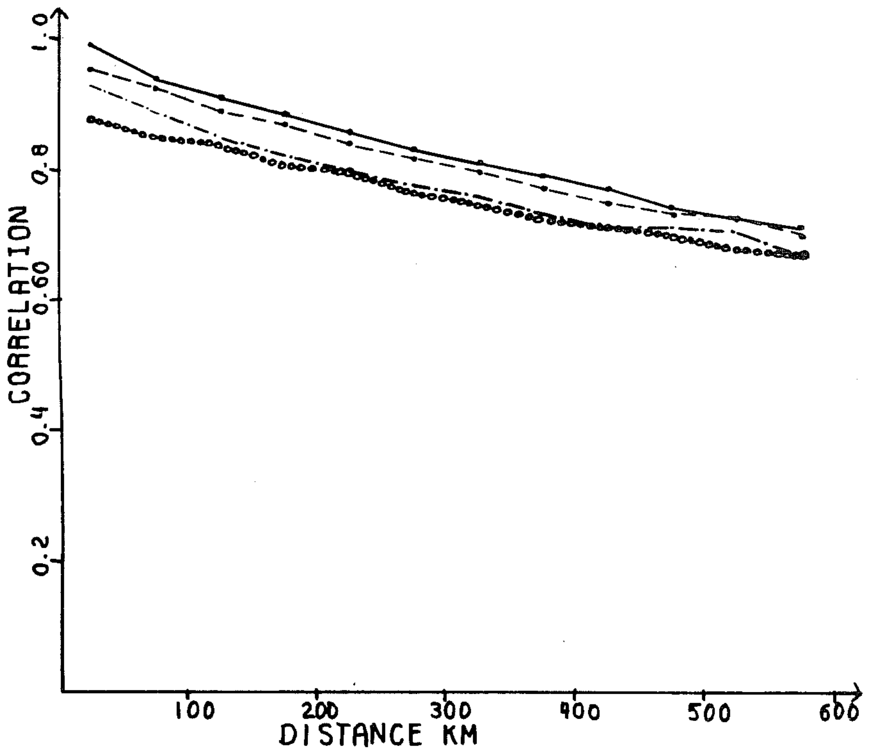


Figure 14 *Spatial correlations of observed-minus-climatological 2 meter temperatures stratified according to distance and classification of station pairs. 5 years of Swedish SYNOP-data, June-August, 12 GMT only.*

————————	*Inland/Inland*	----------	*Inland/Near coast*
-.-.-.-.-.	*Inland/Coast*	oooooooooo	*Inland/Sea*

Correlation functions for surface temperature have so far only been studied for observed-minus-climatological values. A short-range LAM forecast field is used as first guess field for the present, operational meso-scale analysis scheme. Coastlines as well as topography of both grids are taken into account when interpolating this first guess field from the LAM grid to the meso-scale grid. It seems likely, however, that land/sea effects on the spatial covariances of forecast errors will be similar to those of the observed-minus-climatological values. Therefore, the operational meso-scale analysis of surface temperature utilizes a spatial correlation function of the following type:

$$\mu(i,j) = \alpha(\text{class}_i, \text{class}_j) \cdot \beta(r_{ij})$$

where class_i and class_j are the class number values of the two positions (see above) and

r_{ij} is the distance between the two positions

The following correlation table $\alpha(\text{class}_i, \text{class}_j)$ was manually selected and tuned by the aid of analysis experiments.

	Class				
	1 Inland	2 Near coast	3 Coast	4 Inland lake	5 Sea
1 Inland	1.0	0.95	0.88	0.88	0.80
2 Near coast		1.0	0.95	0.95	0.88
3 Coast			1.0	0.95	0.95
4 Inland lake				1.0	0.95
5 Sea					1.0

A first order Bessel-function of second kind is used to represent the distance-dependence:

$$\beta(r_{ij}) = \alpha r \cdot K_1(\alpha r)$$

with $\alpha = 2 \cdot 10^{-6}$ and distance r in meters. Objective analyses of surface temperature based on this correlation function seem to represent the meso-scale variations reasonably well.

Certain problems have been noted, for example:

- Covariance modelling of the land/sea effect should preferably be flow-dependent by taking the surface wind direction into account.
- Covariance modelling of night-time temperature should depend on the existence of clouds.

An example of a meso-scale temperature analysis is given in Figure 15.

Surface humidity is analysed by the aid of a similar correlation function model. Evaluation of real forecast error covariances for surface temperature and humidity is needed in order to construct more objective covariance models.

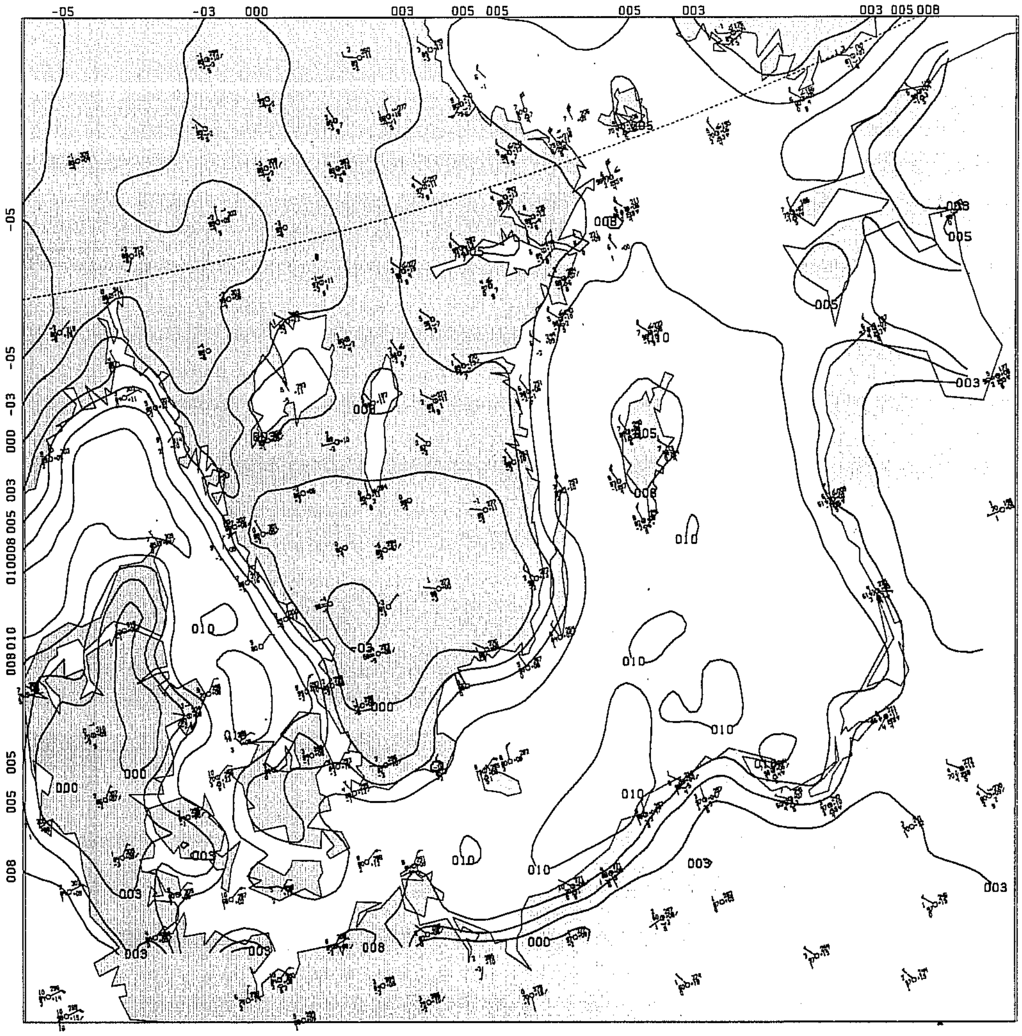


Figure 15 *Meso-scale objective analysis of 2 meter temperature, 10 January, 1983, 00 GMT.*

2.3 Analysis of sea-surface temperature and ice-coverage

Sea-surface temperatures and the variation of sea-ice in the Baltic are factors of great importance for the short-range forecast of air-mass transformations over the Baltic. Therefore, a simple semi-automatic scheme for analysis of sea-surface temperatures and for manual updating of an ice-coverage field has been introduced. Sea-surface temperature spot values are inserted by the marine forecasters and these values are analysed by a successive correction scheme.

A first guess field is obtained from the observations by a least square fit to a linear function depending on latitude, longitude and sea-depth.

2.4 Dynamic simulation of surface winds

From preliminary experiments it became evident that a meso-scale surface wind analysis cannot be based on synoptic wind observations exclusively. This is partly due to the small number of high quality wind observations that exist, and also to the fact that many of the observations represent a micro-scale rather than a meso-scale wind field.

Another limiting factor is the present analysis scheme which assumes non-divergence of wind forecast errors, an assumption which is less valid in layers close to the ground.

For the time being, we are therefore obtaining surface wind fields by dynamic simulation. We are using the one-layer primitive equation model, described by Danard (1977), in a slightly modified form. Starting with surface pressure, surface temperature and vertical stability analyses, a parameterization of the surface fluxes of heat and momentum and with an introduction of a meso-scale topography, the model is run for a number of time steps towards a quasi-stationary state. It is not clear, however, whether such a balance always exists or not. Verification against high quality wind observations has shown that the model can give valuable guidance about the wind field. An example of a wind simulation, obtained in the meso-scale grid with horizontal resolution $0.2^{\circ} \times 0.2^{\circ}$, is given in Figure 16.

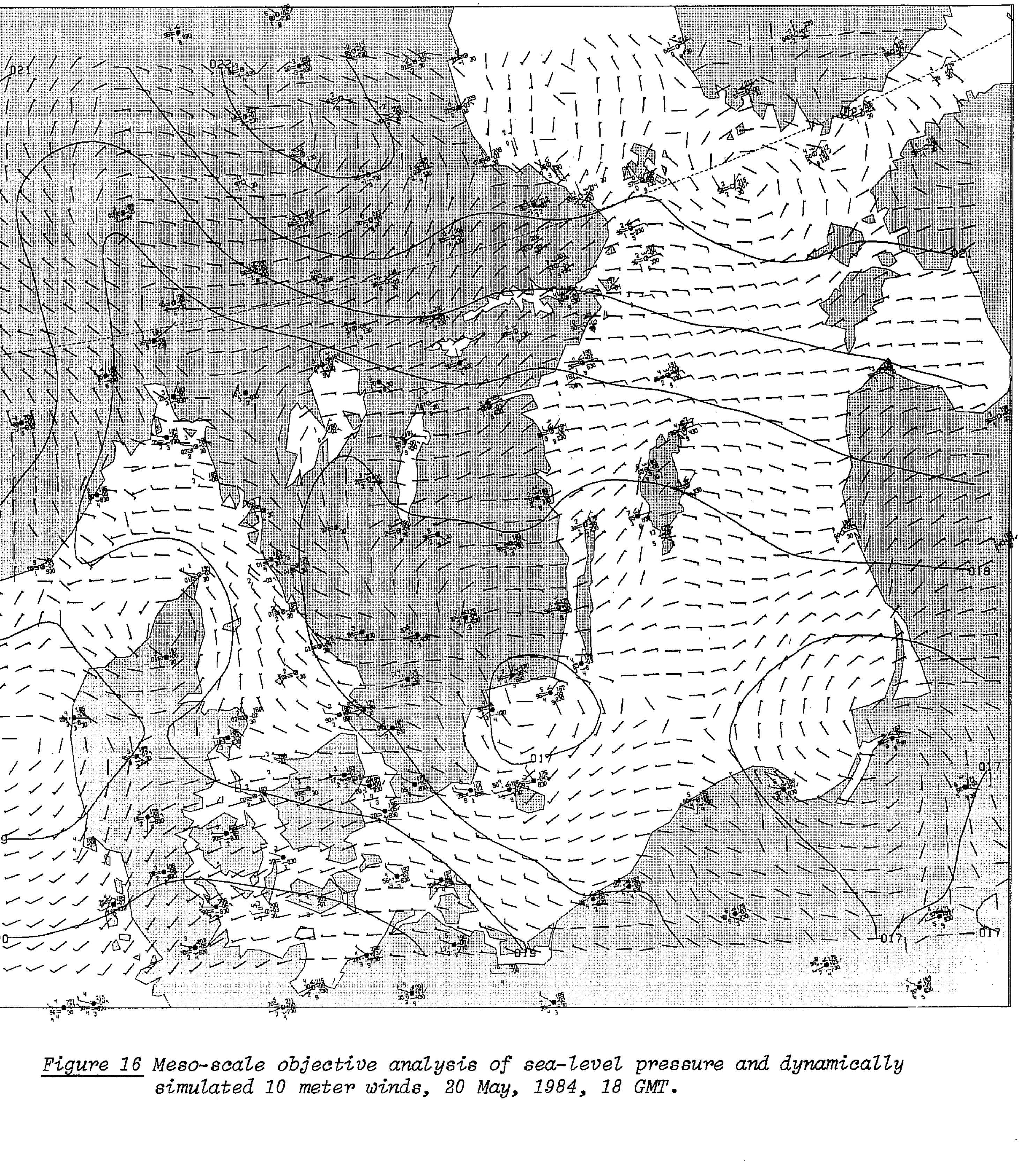


Figure 16 Meso-scale objective analysis of sea-level pressure and dynamically simulated 10 meter winds, 20 May, 1984, 18 GMT.

Verification of simulated wind speeds against observed wind speeds over the Island of Gotska Sandön in the middle of the Baltic (59'N 19°E) is given in Figure 17. Since this island is rather isolated from other land areas, the agreement between observed and simulated wind speeds is mainly an indication that the analyses of sea-level pressure gradients and vertical stability are of reasonable quality though the station density is rather poor in this part of the Baltic.

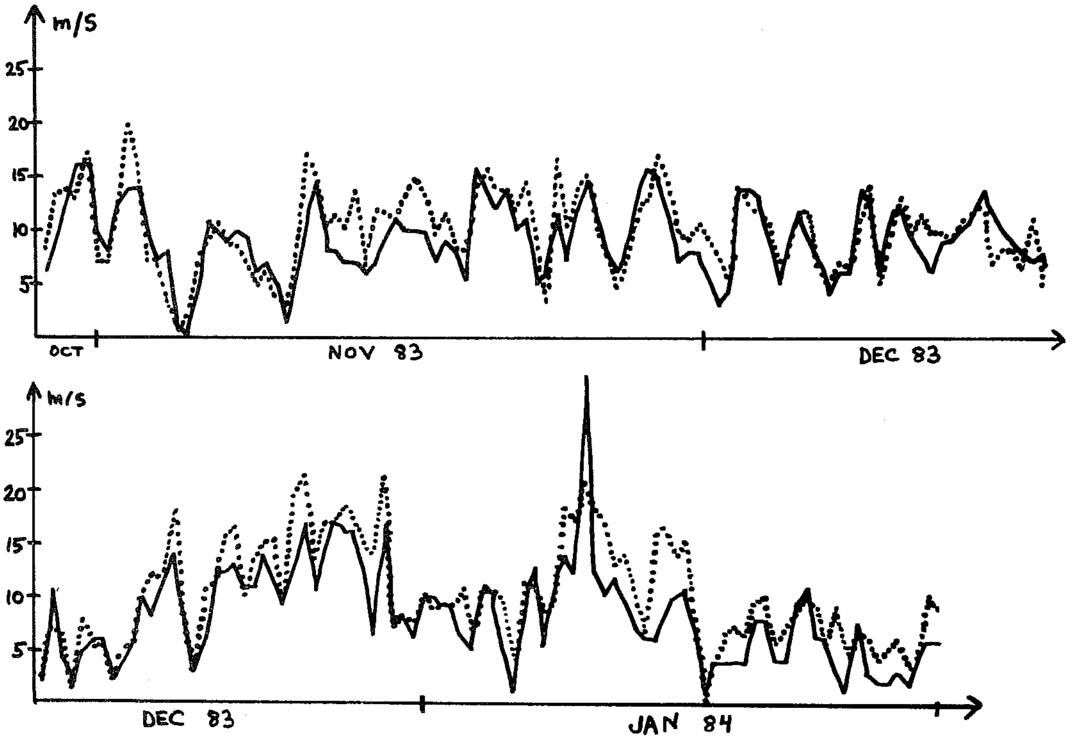


Figure 17 *Observed and dynamically simulated wind speeds at the Island of Gotska Sandön.*
Period: Oct 29 1983 - Jan 31 1984.
———————— *Observed wind speed.*
·········· *Simulated wind speed.*
RMS-difference = 1.9 m/s.

2.5 Analysis of cloud and precipitation parameters

Accurate analysis and short-range forecasting of cloud and precipitation parameters are of importance both for production of direct output to the forecasters and for production of initial data as well as physical forcing data to the forecast models.

As an example, the air-mass transformation model needs information about the cloud coverage and the state of the ground for a proper simulation of the surface energy balance including radiational effects.

Development of analysis methods for cloud parameters is carried out by two approaches, both of which we hope to be able to combine into one cloud parameter analysis system:

(1) Extraction of cloud parameters from satellite image data by multi-spectral classification and texture analysis techniques.

(2) Spatial interpolation of cloud parameters from conventional surface station reports.

A first version of an optimum interpolation scheme for analysis of the coverage of low, middle-high and high clouds has been developed and tested. The quality of the resulting analysis fields seems reasonable. Covariance models and quality control algorithms for cloud parameters are being developed. As regards analysis methods for precipitation parameters (rain- and snowfall intensity, accumulated precipitation and snow-depth), the development work is also carried out along several approaches. The intention is to combine these approaches into a co-ordinated precipitation analysis scheme:

(1) Determination of precipitation intensity values and accumulated precipitation values from radar reflectivity data and automatic surface station data.

(2) Determination of precipitation intensity from satellite image data by multi-spectral classification and texture analysis techniques.

(3) Objective analysis of precipitation parameters from synoptic station data.

Preliminary tests with an optimum interpolation scheme for analysis of precipitation intensity from synoptic surface station data have indicated results of reasonable quality. Message code values for temperature and present weather (ww) are utilized to infer precipitation intensity and type of precipitation (rain or snow).

3. ANALYSIS OF VERTICAL PROFILES

Detailed vertical profiles of temperature, wind, humidity and, if possible, cloud water content have to be analysed for the initialization of the Air-Mass Transformation (AMT) model to be tested during PROMIS-600. In addition, detailed vertical cross-sections are needed as diagnostic tools to support the manual forecasting and nowcasting work.

In order to utilize the excellent vertical resolution of radiosonde data we have decided to use potential temperature as vertical co-ordinate for the analysis of profiles. A multi-variate statistical interpolation scheme for analysis of Montgomery potential and wind on isentropic surfaces has been developed. SMHI LAM and/or ECMWF short-range forecast fields are utilized for the construction of first guess profiles. The ECMWF statistical files with quality-controlled observed-minus-forecasted radiosonde data are used to develop a co-variance model for forecast errors on isentropic surfaces.

The AMT-model also requires properly initialized boundary layer profiles of wind, temperature and humidity. The sensitivity of the AMT-model forecast quality to details in these initial boundary layer profiles is not clear and needs to be tested.

We have considered various approaches for the boundary layer analysis and initialization. Presently, we have started to test the following approach for data assimilation and forecasting with the AMT-model.

(A) Analyse vertical profiles of temperature, wind and humidity for time t_1 at the starting point of a trajectory ending at time t_3 in the forecasting area.

(B) Run the AMT-model along the trajectory from time t_1 until time t_2 ($t_1<t_2<t_3$) while inserting all available surface data along this trajectory. If possible, surface layer theory will be used to extrapolate surface data through the lowest few hundred meters of the boundary layer.

(C) Re-analyse vertical profiles in the free atmosphere for time t_2 at the appropriate position along the trajectory and merge the forecasted and analysed profiles.

(D) Run the AMT-model prognostically from time t_2 until time t_3 along the trajectory.

4. SUMMARY

Basic ideas and some early results of a system for meso-scale objective analysis to support nowcasting and very short-range forecasting have been presented. The results indicate an ability of the analysis system to recover meso-scale features. Development work will continue until and during the pre-operational testing of PROMIS-600 in 1986-1988.

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