Assimilation of non-synoptic observations

LENNART BENGTSSON[1] and NILS GUSTAVSSON, *Swedish Meteorological and Hydrological Institute, Stockholm, Sweden*

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ABSTRACT

A system for continuous data assimilation described recently (Bengtsson & Gustavsson, 1971) has been further developed and tested under more realistic conditions. A balanced barotropic model is used and the integration is performed over an octagon covering the area to the north of 20° N. Comparisons have been made between using data from the actual aerological network and data from a satellite in a polar orbit. The result of the analyses has been studied in different subregions situated in data sparse as well as in data dense areas. The errors of the analysis have also been studied in the wave spectrum domain. Updating is performed using data generated by the model but also by model-independent data. Rather great differences are obtained between the two experiments especially with respect to the ultra-long waves. The more realistic approach gives much larger analysis error. In general the satellite updating yields somewhat better result than the updating from the conventional aerological network especially in the data sparse areas over the oceans. Most of the experiments are performed by a satellite making 200 observations/track, a sidescan capability of 40° and with a RMS-error of 20 m. It is found that the effect of increasing the number of satellite observations from 100 to 200 per orbit is almost negligible. Similarly the effect is small of improving the observations by diminishing the RMS-error below a certain value. An observing system using two satellites 90° out of phase has also been investigated. This is found to imply a substantial improvement. Finally an experiment has been performed using actual SIRS-soundings from NIMBUS IV. With respect to the very small number of soundings at 500 mb, 142 during 48 hours, the result can be regarded as quite satisfactory.

1. Introduction

Conventional meteorological observation systems based on simultaneous, or synoptic observations at regular time intervals are now being planned to be replaced by non-synoptic observation systems. Non-synoptic observations in the form of aircraft reports as well as observations from reconnaissance flights have been available for many years but they have only been of a marginal importance and have never been included in any scheme for objective analysis.

The difficulty of including aircraft reports in a scheme of objective analysis is due to the fact that these reports are distributed over very limited areas in space. The quality of the aircraft reports is also very unsatisfactory (Bengtsson, 1967).

The advent of earth-orbiting weather satellites has made a vast impact on meteorological observation, the most promising being the possibility of receiving the vertical temperature structure through the entire depth of the atmosphere. Since these satellites pass over most of the earth's surface in a 12-hour period the global distribution of temperature will be provided almost continuously in time.

An investigation of the accuracy of the temperature measurement from the satellites has been published by Smith (1971), which shows that the temperature error during clear air conditions in the troposphere is between 1°C and 2.5°C with a minimum value around 500 mb. The error will be greater in the case of clouds and the error is increased by about 50 % when there are middle clouds. It is not very probable that the minimum accuracy will

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be improved very much in the future except for the relatively great errors around the tropopause and in the boundary layer. There will, however, be a substantial improvement in the horizontal resolution which is assumed to increase from more than 100 km to about 30 km and the probability to find cloudless areas will therefore be improved.

In the operational procedure there are two different kinds of retrieval procedures used by NOAA in the processing of SIRS radiance data which are both making use of a dynamical 12-hour forecast in the determination of temperature and water vapor profiles. One of them makes use of a reference level, the other one computes the geopotential by a statistical method, Smith (1970). The derived temperature profiles are those which have a minimum deviation from the forecast in order to satisfy the radiance observations. However, it seems to follow from the numerical retrieval procedure that the computed temperature will not be completely independent of the temperature prediction or any kind of first guess. This may be serious since there is an extensive and systematic interaction between successive analyses and predictions.

Another method for deriving the temperature from the radiation has been presented by Chahine (1968, 1970). Chahine's method is based on an iterative technique which converges to the same result independent of the first guess. It also follows from Chahine's discussion that any temperature variation related to observable variations in the emerging radiance can be reconstructed. There are apparent advantages with an inversion technique that is independent of the prediction. If this is not the case, there will be a correlation between the prediction and the observations that can easily create serious problems in areas where we only have access to data of that kind. A similar situation may easily be developed in conventional systems for numerical weather predictions if the weight of the forecast as a preliminary field for the analysis is made too large in data sparse areas.

To assimilate non-synoptic data by the aid of a model based on the complete equations creates serious problems. Measurements in the real atmosphere are not perfect nor would they fit the normal modes or quasi-geostrophic modes of any approximate model of the atmosphere and as a result spurious gravity waves are generated. Another problem is the systematic errors of the model due to physical and numerical deficiencies.

Some successful experiments have, however, been performed, but in those cases artificial data sets generated by the model itself have been used. Such artificial data belong to the subspace of quasi-geostrophic modes and consequently cannot generate gravity waves. As has been shown by Morel et al. (1971) great differences are obtained if data sets from another model are used for the updating. The same will be valid to a higher degree for real data.

For the time being we will eliminate the problem with spurious gravity waves simply by performing the data assimilation by a quasi-geostrophic model. When the mass field has been established for a given time we may obtain initial data for a primitive model by the solution of the balance equation.

In a recent article by Bengtsson & Gustavsson (1971), hereafter referred to as I, a system for the analysis of non-synoptic data was presented. In that study the experiments were performed by the aid of a quasi-geostrophic barotropic model and the integration domain was a zonal channel circling the globe with the northern and the southern boundaries at 70° N and 30° N latitudes. In the following investigation we have introduced a number of generalisations. Firstly we have performed the computations for a polar-stereographic area covering the area to the north of 20° N and we have also made use of the actual synoptic network as well as correctly computed satellite orbits. Secondly we have simulated cases where the "observational" data have been obtained from actual analyses and thus inconsistent with the model which has been used for the updating. Finally experiments have been undertaken where actual SIRS-soundings have been used.

It is the purpose of this investigation to see if the results obtained in I during idealized conditions are valid also when we perform realistic experiments.

2. The objective analysis

The method of objective analysis has been described in detail in I. Optimum interpolation (Eliassen, 1954; Gandin, 1963) is used to analyse the deviation of the observations from the forecast. It will also be shown that the scheme easily can be modified in such a way that also the space correlation of the observational error can be taken into account. A similar modification was recently proposed by Gandin (1971).

We recall some of the definitions and equations from the derivation of the method. The analysis ψ_{it}^A in gridpoint i at time t is expressed as a linear combination of the forecast ψ_{it}^F and the deviations of the observations from the forecasts $(\psi_{kt}^O - \psi_{kt}^F)$ in the vicinity of the gridpoint: (subscript k refers to the observation)

$$\psi_{it}^A = \psi_{it}^F + \sum_{k=1}^{N} p_k(\psi_{kt}^O - \psi_{kt}^F) \tag{2.1}$$

The weights p_k are determined by minimizing the mean square error of interpolation:

$$E = \overline{(\psi_{it} - \psi_{it}^A)^2}$$
$$= \overline{\left(\psi_{it} - \psi_{it}^F - \sum_{k=1}^{N} p_k(\psi_{kt}^O - \psi_{kt}^F)\right)^2} \tag{2.2}$$

ψ_{it} being the "true" analysis.

A necessary condition for E to have a minimum is that the partial derivatives with respect to the weights p_k must vanish. This condition together with the assumption that the observational errors are independent of the errors of the forecast will give the following system of linear equations for the weights:

$$\sum_{k=1}^{N} (m_{klt} + d_{klt})\, p_k = m_{ilt} \quad (1 = 1, \ldots, N) \tag{2.3}$$

where

$$m_{klt} = \overline{(\psi_{kt} - \psi_{kt}^F)(\psi_{lt} - \psi_{lt}^F)}$$

is the autocovariance function for the forecast error

and $$d_{klt} = \overline{(\psi_{kt} - \psi_{kt}^O)(\psi_{lt} - \psi_{lt}^O)}$$

is the corresponding function for the observational error.

The bar operator denotes ensemble averages. Inserting (2.3) into (2.2) yields an expression for the mean square interpolation error:

$$E = m_{iit} - \sum_{k=1}^{N} m_{ikt}\, p_k \tag{2.4}$$

where

$$m_{iit} = \overline{(\psi_{kt} - \psi_{kt}^F)^2}$$

denotes the variance of the forecast error.

The variance m_{iit} is continuously updated during the analysis-forecast. The expression (2.4) is used to compute the new variance estimate after the analysis is performed. The variance is assumed to grow linearly in time from zero to a maximal value $m_{ii\,\max}$ during a timeperiod T.

Thus

$$m_{ii(t+\Delta t)} = m_{iit} + \frac{\Delta t}{T} m_{ii\,\max}$$

Assuming the auto correlation function $\mu_{klt} = m_{klt}/\sqrt{m_{kkt}\, m_{llt}}$ to be independent of time $(\mu_{klt} = \mu_{kl})$ the autocovariance function can be written

$$m_{klt} = \sqrt{m_{kkt}\, m_{llt}}\, \mu_{kl} \tag{2.5}$$

The relevance of this assumption was discussed in I.

We also introduce

$$\sigma_{kt}^2 = \overline{(\psi_{kt}^O - \psi_{kt})^2}$$

being the variance of the observation error, and

$$\tau_{klt} = \frac{d_{klt}}{\sigma_{kt}\, \sigma_{lt}}$$

which is the autocorrelation function for the observation error.

Assuming τ_{klt} to be independent of time $(\tau_{klt} = \tau_{kl})$ the system (2.3) can be written:

$$\sum_{k=1}^{N} (\sqrt{m_{kkt}\, m_{llt}}\, \mu_{kl} + \sigma_{kt}\, \sigma_{lt}\, \tau_{kl})\, p_k = m_{ilt} \tag{2.6}$$

One may well expect that the existence of large scale cloud systems will influence the emitted radiance in a systematic way and that therefore the derived temperatures from the satellite will have errors which are correlated on a scale similar or less than the scale of the correlation of the forecast error. If we assume τ_{kl} to be equal to μ_{kl} it is found that this yields a very small increase of the error unless we have a dense network and a small variance of the forecast error. This will not be the case in this study where we are using a relatively crude model in our simulation experiments.

The system (2.6) is used in the computations, but we have assumed that τ_{kl} only take the values $0(=kl)$ or $1(k=l)$.

One of the problems using optimum interpolation is the occasional ill-conditioning of the system (2.6) resulting in very large values in the solution for the weights. Even for relatively small observation errors this can cause very serious errors in the analysis. One way of treating this ill-conditioning has been described by (Krüger, 1970).

The ill-conditioning is likely to occur when the observations are closely situated. To avoid this an averaging of closely situated observations is performed. The analysis area is divided into subareas of equal size and a mean observation is constructed by averaging the observed values and coordinates. The error of this mean observation includes an interpolation error.

The variance of this error can be computed from the valid autocorrelation function. For middle tropospheric heights it turns out that an averaging over distances up to about 400 km will result in an error smaller than the observation error. Further, if uncorrelated, the observation error will be reduced.

This averaging procedure counteracts the ill-conditioning but it does not in all cases guarantee that it will not occur. For safety a test for ill-conditioning is performed after the solution of the system. If the value of any weight is larger than a given tolerance the system is considered ill-conditioned and a further averaging is performed between the two observations within the system that are closest together. The reduced system is solved and if necessary reduced again.

Since, in some of our experiments, we have used real data, transmitted over the telecommunication lines, it was necessary to include an additional control in the system, which was also performed by optimum interpolation. For every observation an interpolated value is computed from the observations in the vicinity of the observation point. The observation is rejected if the difference between the observed and the interpolated values is greater than a tolerance which is proportional to the square-root of the mean-square interpolation error (2.4).

3. The numerical model

Similarly to the experiment described in I we have used also here the quasi-geostrophic barotropic model for the updating. In order to improve the prediction of the very long waves a correction term has been added. The barotropic equation then reads:

$$\frac{\partial}{\partial t}(\nabla^2 \psi) - q\frac{\partial \psi}{\partial t} - J(\nabla^2 \psi + f; \psi) = 0 \qquad (3.1)$$

J is here the Jacobian operator and f the Coriolis parameter. According to practice in routine numerical forecasting $q = 0.75 \times 10^{-12}$ m^{-2}.

A polar-stereographic projection has been used and the integration has been performed over a regular octagon covering the area to the north of 20° N (see Fig. 1).

The grid length of 300 km at 60° N has been used and the time-step in the integration was 30 minutes.

4. Simulation of observational updating

The simulation experiments have been performed in a similar way to those described in I, but we have also tried to simulate the satellite updating in a more realistic manner. As can be seen from Fig. 1 the computations of the satellite tracks are performed in the same way as for satellites in polar orbits. The basic purpose has been to compare the properties of the actual synoptic network with an observational system based on SIRS-soundings from satellites in polar orbits.

4.1. *The use of normals*

As a consequence of the very sparse network in some areas especially over the Pacific the analysis error can be very large (see Fig. 2). A successive updating every 12th hour can therefore create serious problems if we only are using running predictions and observations. The reason for this is that there are isolated areas that will never be updated by any new information. The prediction error will thus

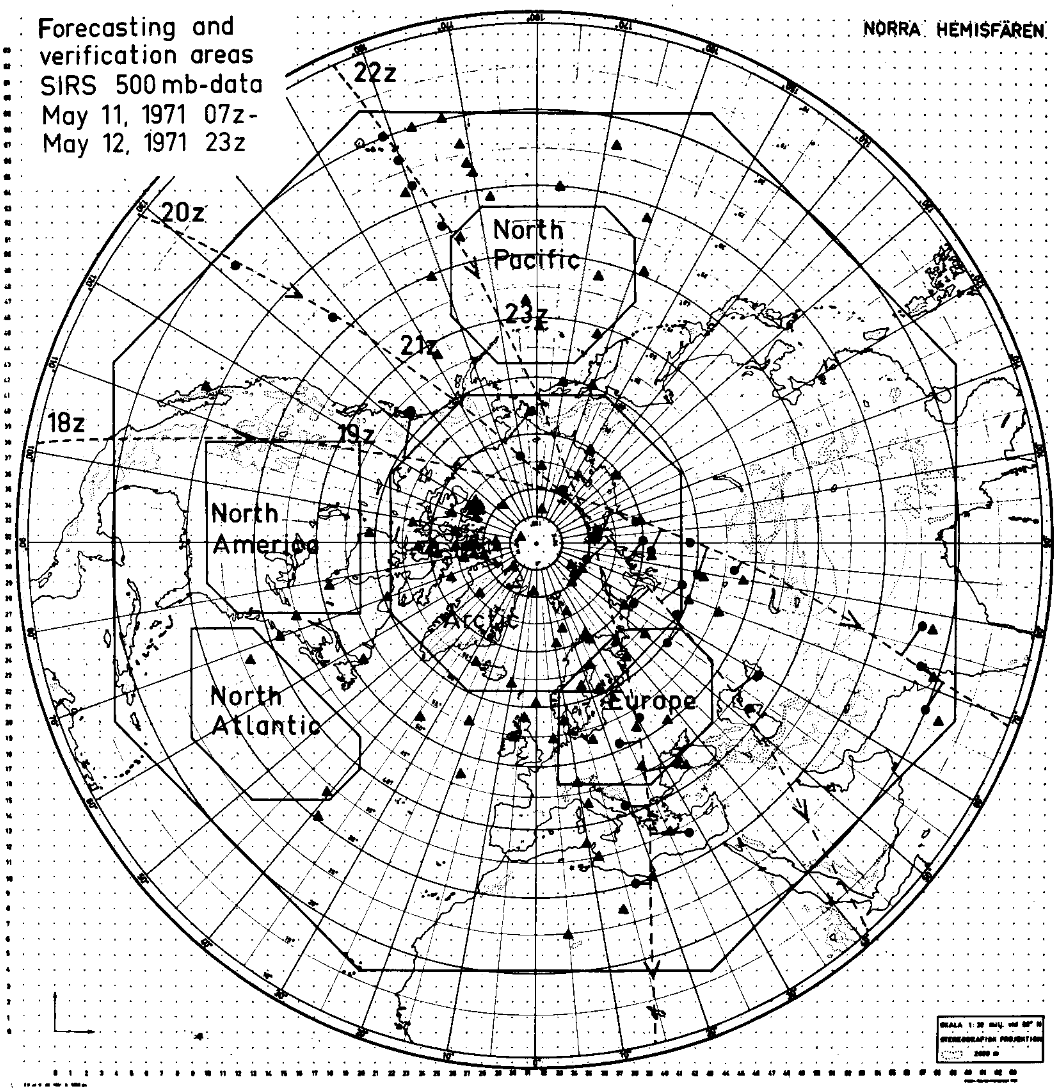

Fig. 1. Forecasting area and 5 different verification areas. Satellite tracks and distribution of 500 mb observations from Nimbus IV for the interval May 11, 1971 07z–May 12, 1971 23z. Observations for the interval May 12, 1971 18z–May 12, 1971 23z, which are associated by the indicated tracks, are indicated by ●, the other observations by ▲.

grow continuously and after a number of days the whole area will be influenced as can be seen from the full curve in Fig. 2. One way to eliminate this is to combine the forecast field with the monthly mean field, each time the updating is performed.

The dashed and the dotted curves in Fig. 2 show the results when we have used the monthly normal field in this way. The dotted curve corresponds to the case, in which the variance of the forecast error is constant in time and the dashed curve shows the results of the variance of the forecast error if the variance of the forecast error is assumed to vary according to the description in section 2. When updating from the synoptic network has been performed we have therefore used a combination of analyses of the deviation from the monthly field and analyses of the deviation from the forecast.

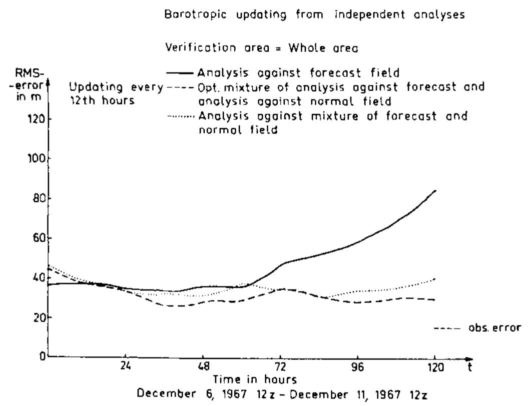

Fig. 2. Time variation for the RMS-error of the analysis for three different kinds of successive analyses every 12th hour using observations from the synoptic network. Full line indicates analysis of the deviations from current forecasts. Dashed and dotted lines show mixtures of analyses of the deviations from the current forecasts and deviations from the monthly field. See text for further information.

4.2. *Experiments with simulated and real data*

A necessary condition for an efficient system for the assimilation of non-synoptic observations is a model that can give accurate short-range predictions. So far most of the data assimilation experiments have been performed by simulated model-dependent data, i.e. the model has generated its own data. This can be regarded as equivalent to experiments performed by a *perfect* model using real data.

Some experiments have shown (Morel, 1971) that updating with model-dependent data differs considerably from updating using data inconsistent with the current model. If the updating is performed with a primitive model using a neutral or a very small damping time-integration scheme even numerical instability may occur. In order to investigate to what extent the deficiencies in the model are influencing the error in the analysis we have performed the updating experiment both with observations generated by the barotropic model and observations generated from successive independent 500 mb analyses (NMC, Washington).

A 5-day barotropic forecast was first computed from an initial state taken from the 500 mb flow of the 6th of December 1967 12 GMT. This was a situation characterized by a highly baroclinic state. The error growth in the barotropic model was therefore very fast and the error variance approached that of climatology after 48 hours. In our first experiment a 5-day period of forecasts was generated. This solution was then regarded as a reference forecast, assuming that this time sequence represented the true 500 mb flow. Synthetic "synoptic observations" were then generated for every 12th hour at locations corresponding to the actual network of aerological stations. A random observation error with a normal distribution was then added to the observations. The statistical mean of the error was zero and the standard deviation 15 m.

Also a non-synoptic observational set was computed. These observations were assumed to consist of SIRS-soundings. In order to simulate in a very crude way the influence from small scale cloud systems they have been generated at random along the orbital track. The width of the area where the observations have been distributed has been chosen to be somewhat more than 2 000 km. This corresponds roughly to the performance of NIMBUS IV which has a sidescan capability of almost 40° (see Fig. 1).

In the basic experiments 200 observations have been generated per track (according to personal communications with NOAA Satellite Center this is likely to be the case already from the summer of 1972).

This yields about 1 000 observations a day distributed over the forecast area. A random error has also in this case been added to the observations with a standard deviation of 20 m. This is an error which is representative for cloudless areas or areas only covered with low clouds (Smith, 1971).

The analysis error has been studied over the whole area as well as over 5 different subregions (see Fig. 1). Two of these regions have been placed in areas where we have a relatively dense aerological network. Two other regions have been placed in data sparse areas over the oceans. The fifth covers the area to the north of 60°N. Due to the form of the satellite tracks (see Fig. 1) this area will have a satisfactory coverage by the satellite soundings. Fig. 3 yields the result for synoptic updating (dashed lines) and satellite updating (full lines). Everywhere, except over areas where we have a good observational network, Europe and North America (not shown here), the satellite observations will give a more accurate analysis than the observations from the aerological network.

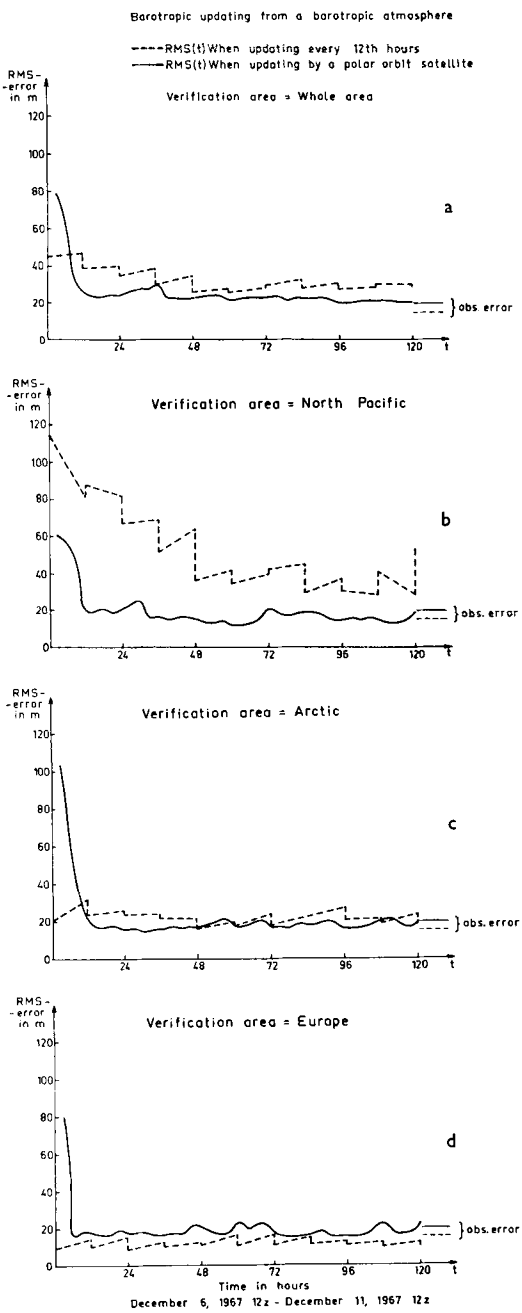

Fig. 3. Barotropic updating from a barotropic atmosphere. Time variation of the analysis error for synoptic (dashed line) and non-synoptic (full line) updating. December 6, 1967 12z – December 11, 1967 12z. Verification is performed for (*a*) whole area (*b*) North Pacific, (*c*) Arctic, and (*d*) Europe. The verification areas are shown in Fig. 1.

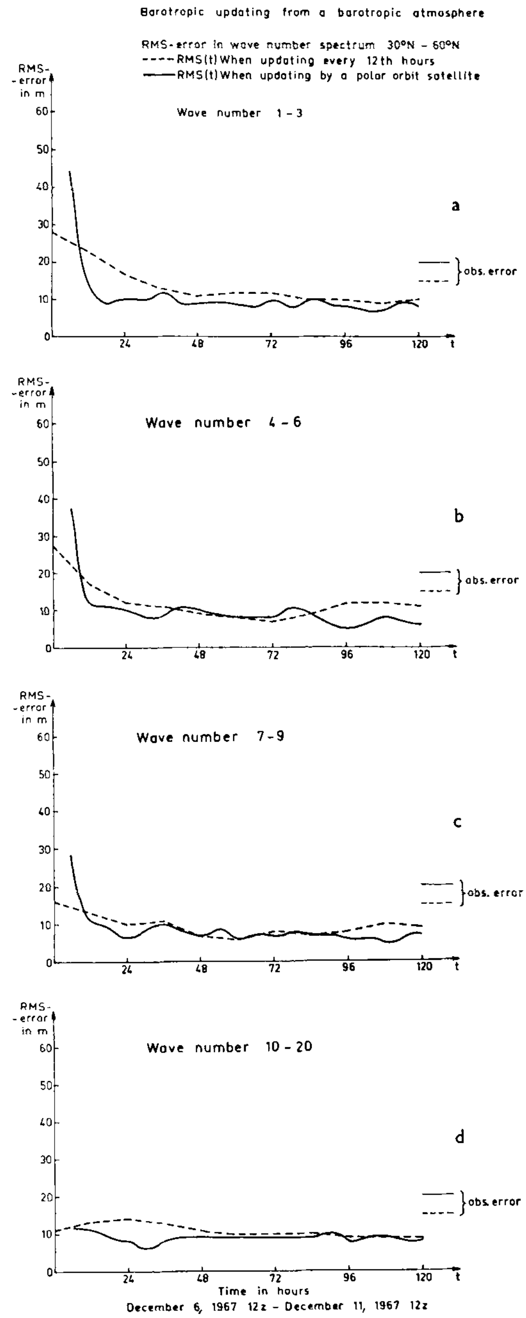

Fig. 4. Same experiments as in Fig. 3. Time variation of the analysis error in 4 different spectral regions 30° N – 60° N for synoptic (dashed line) and non-synoptic (full line) updating (*a*) Wave number 1–3, (*b*) wave number 4–6, (*c*) wave number 7–9, and (*d*) wave number 10–20.

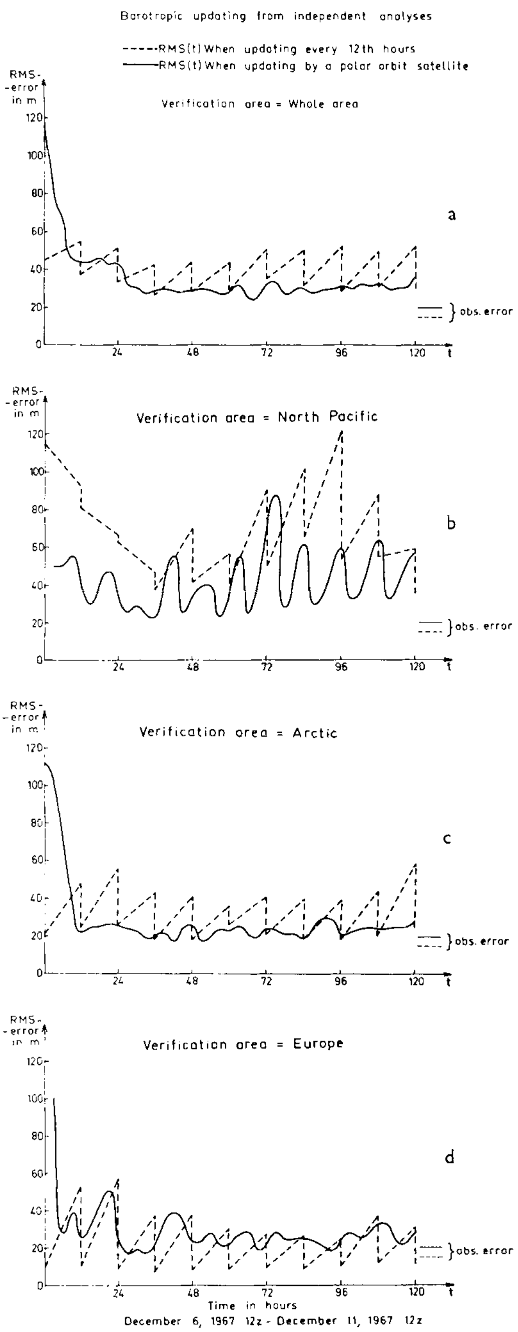

Fig. 5. The same as Fig. 3 but barotropic updating from an independent analysis.

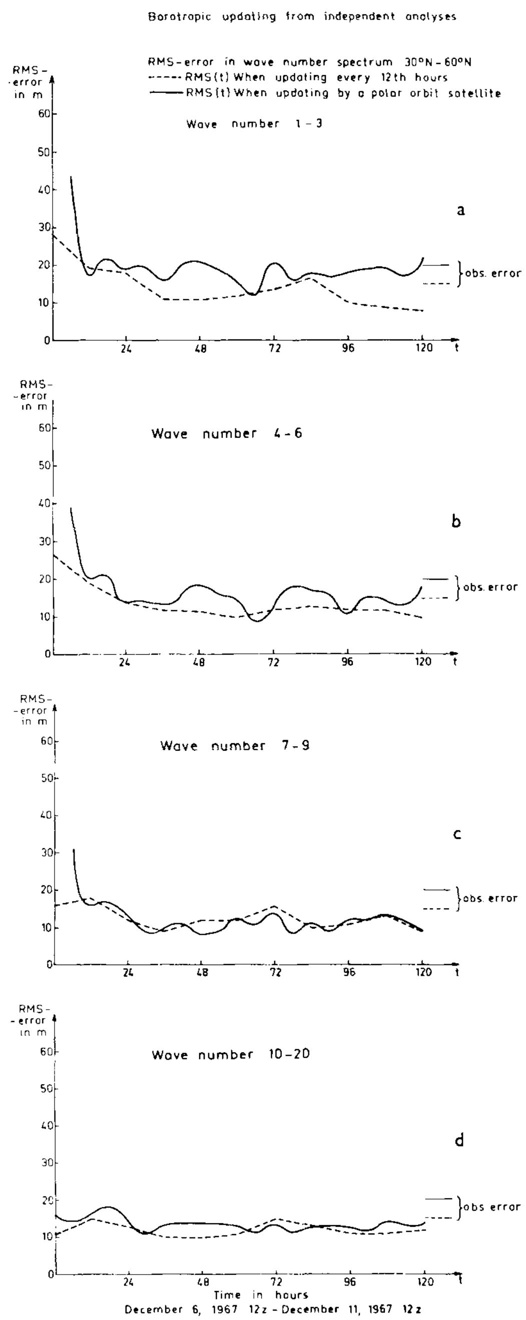

Fig. 6. The same as Fig. 4 but barotropic updating from an independent analysis.

We have performed a harmonic analysis of the analysis error between 30° N and 60° N and the error has been separated into different spectral intervals. As can be seen from Fig. 4 the error is about the same for all spectral intervals. It also follows that the analysis based on satellite observations is better for almost all wave numbers, especially for the ultra-long waves.

In the second experiment the updating was performed with model-independent observations. These observations have been extracted from the regular 500 mb analyses from NMC in Washington. A continuous set of data for the simulation of the satellite soundings was obtained by a parabolic interpolation in time from the NMC-analyses which were available every 12th hour. As can be seen from Fig. 5 the analysis error is much larger in this case and the benefit of the satellite system is not so obvious as in the earlier experiment. The verification over the Pacific indicates a very rapid increase in the error when the satellite moves away from the area. As was mentioned earlier the chosen situation was characterized by strong baroclinic developments especially over the Pacific.

Another reason for the rapid error growth may also be insufficient accuracy in the time interpolation. The mean analysis error is about 30 m and almost the same for the synoptic and the non-synoptic updating.

An examination of the error as a function of wave number (Fig. 6) shows fairly large errors for the ultra-long waves especially in the case of satellite updating. This is contrary to the result in the earlier experiment. It probably is a result of the incapability of the barotropic model to predict the ultra-long waves. The reason why the error is more pronounced for the satellite updating seems to be the fact that the stabilizing effect from the monthly normal field has not been included in the satellite updating.

A general conclusion from this experiment is therefore that we need a model which can give *accurate short-range predictions for all scales of motion* if we really are going to be able to use all the benefits from the non-synoptic observations.

A second experiment in updating from an independent set of analyses was repeated for a series of data from the period of the 15th of August 00z GMT 1966 to the 20th of August. During this period the barotropic model was describing the 500 mb flow in quite a satisfactory way. As can be seen from Fig. 7 there is a comparatively good agreement between this updating and the updating with the model-dependent data.

For this case we have also combined the synoptic and non-synoptic data. As can be seen from Fig. 7 this reduces the analysis error below 20 m.

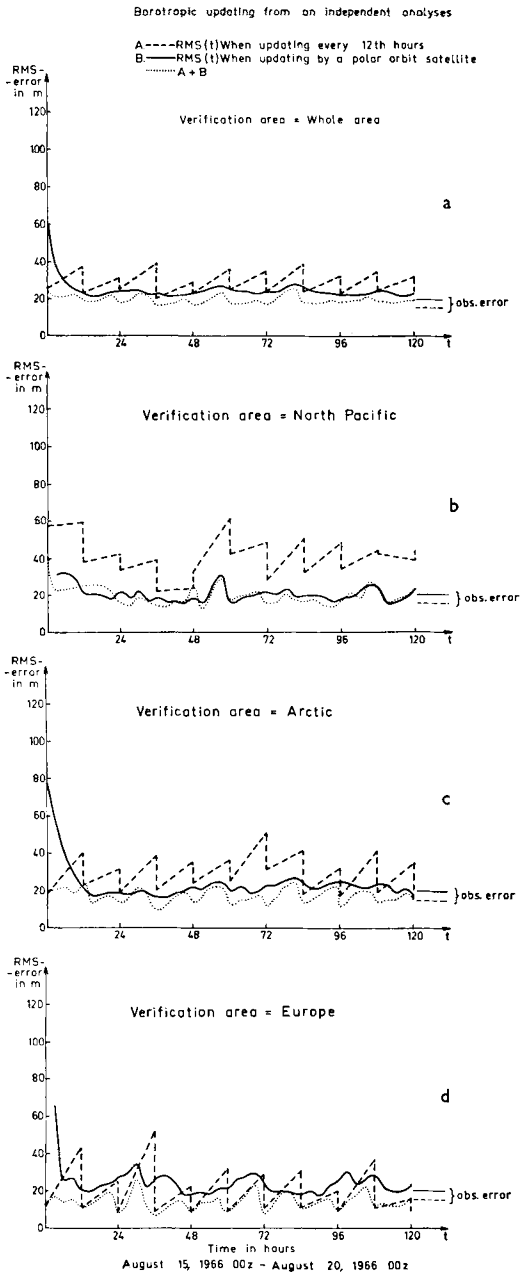

Fig. 7. The same as Fig. 5 but for the period August 15, 1966 00z – August 20, 1966 00z. The dotted line shows the analysis error when we combine the synoptic and the non-synoptic observations.

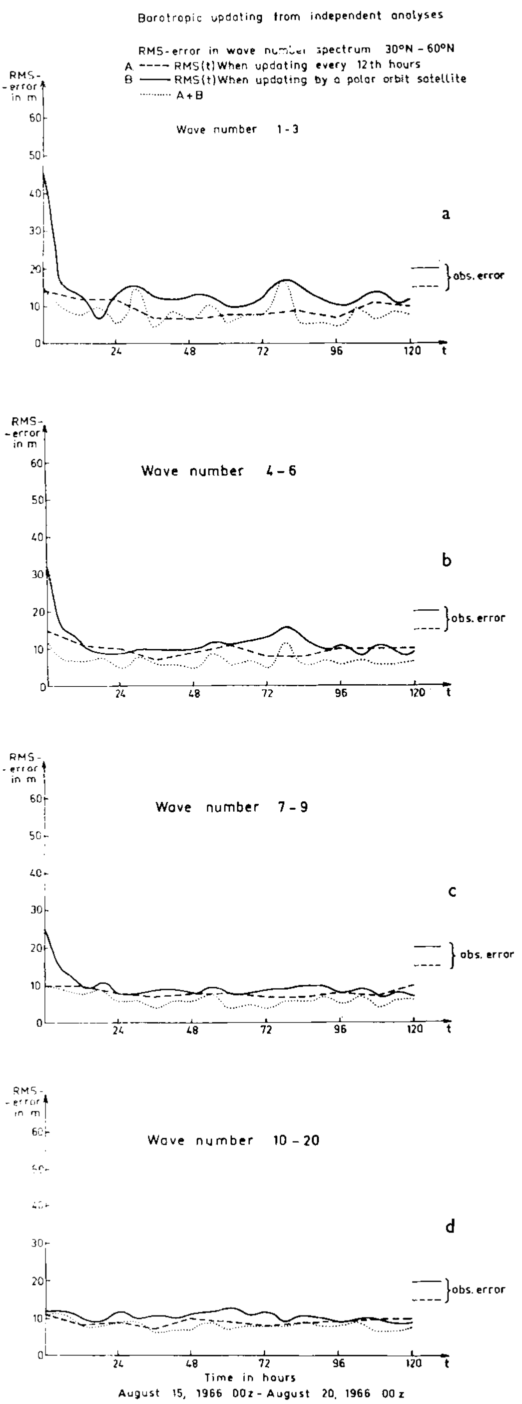

Fig. 8. The same as Fig. 6 but for the period August 15, 1966 00z – August 20, 1966 00z. The dotted line shows the analysis error when we combine the synoptic and the non-synoptic observations.

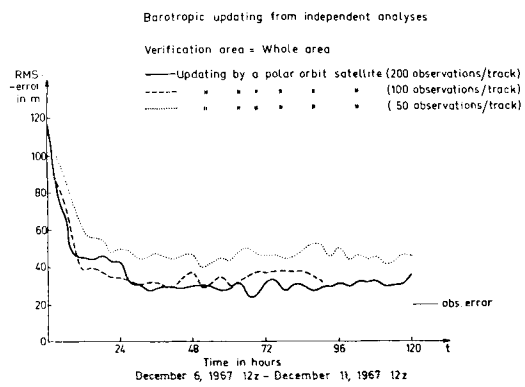

Fig. 9. Time variation of the analysis error for the whole area. Barotropic updating from independent analyses. December 6, 1967 12z – December 11, 1967, 12z. Non-synoptic observations. Full line, 200 observations/track. Dashed line, 100 observations/track. Dotted line, 50 observations/track.

4.3. *Dependance of the analysis on the available amount of data*

An experiment of great interest is to investigate how sensitive the analyses are to the number of non-synoptic observations.

Fig. 9 shows the result from three different experiments where the number of observations have been varied. The experiments have all been performed for the case described in Figs. 5 and 6, that is a simulation based on model-independent data from the December situation. A reduction of the number of observations from 200/track to 100/track implies a fairly small increase in the error of the analysis. When the number of observations are further reduced the error increases more rapidly. A reduction from 100/track to 50/track increases the error almost by 50 %.

4.4. *The dependance of analysis error on errors of observations*

Another instructive experiment is to investigate how the error in the analysis depends on the error of the observations. For the aerological network there are clear indications that the observational error has a normal distribution with a zero mean error. However, very little is known about the structure of the observational error for the satellite measurements. In general we may say that if there is a spatial correlation for the errors of the observations this is equivalent to a larger random error.

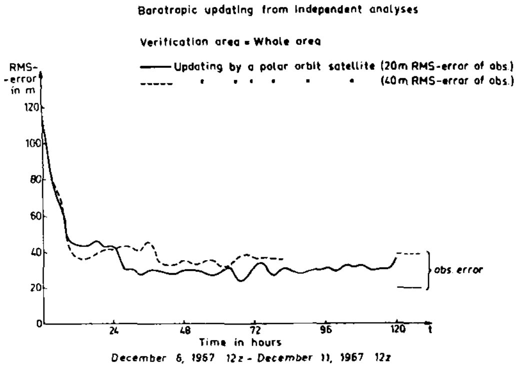

Fig. 10. Time variation of the analysis error for the whole area for observational error of 20 m (full line) and 40 m (dashed line).

Fig. 10 shows an increase in the mean analysis error from 30 to 35 m when the RMS-error of the observations is increased from 20 to 40 m.

A comparatively large observational error can thus be tolerated provided the error has no space correlation. According to experiments (Smith, 1971) the errors in the satellite soundings seem to increase by about 50 % in areas covered by middle and high clouds. Since such areas can be fairly large they may influence the analysis of medium and large scale systems.

There is no satisfactory way to simulate the existence of clouds in a barotropic model. We have therefore to postpone such an investigation of the effect of increased errors in cloud covered areas until we have a baroclinic model available for updating experiments.

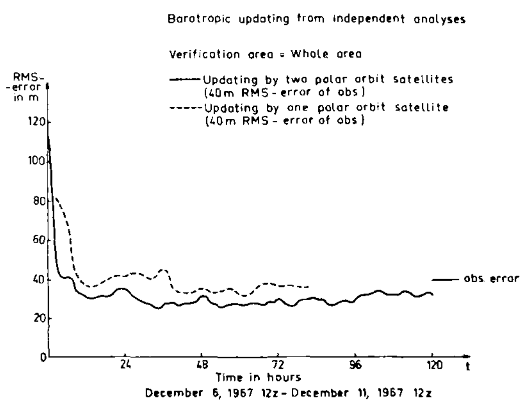

Fig. 11. Time variation of the analysis error for an observational system with one satellite (dashed line) and two satellites (full lines).

Table 1.

11.5.1971		12.5.1971	
Time	No.	Time	No.
07z	10	06z	6
09z	7	08z	2
10z	3	10z	5
11z	14	14z	6
12z	8	15z	4
13z	4	19z	10
14z	5	20z	2
16z	11	21z	12
21z	3	22z	4
22z	4	23z	6
23z	16		

4.5. *The use of data from two polar orbiting satellites*

If the satellite observing system consists of two satellites in polar orbits and 90° out of phase it is found that this implies a considerable reduction in the error of the analysis (Fig. 11). Two satellites making observations with an RMS-error of 40 m yield better analyses than one satellite with a corresponding observational error of 20 m.

4.6. *Experiments with real satellite data*

We shall finally describe an experiment which has been performed using actual SIRS-soundings from NIMBUS IV. These observations were received during a period in May 1971 in Stockholm over the ordinary telecommunication network.

Table 1 gives the number of observations at the 500 mb surface for every hour from the 11th of May 1971 07 GMT to the 12th of May 1971 23 GMT. The total number of observations were only 142 and the distribution of the observations can be seen from Fig. 1. The distribution of observations is not very good since we did not receive any observations between 00 and 06 GMT during anyone of the two days. Very little information is thus available from America and Asia.

Fig. 12 shows the analysis at the 11th of May 23 GMT based entirely on SIRS-soundings during the preceding 16 hours. Fig. 13 shows the corresponding analysis based on the observa-

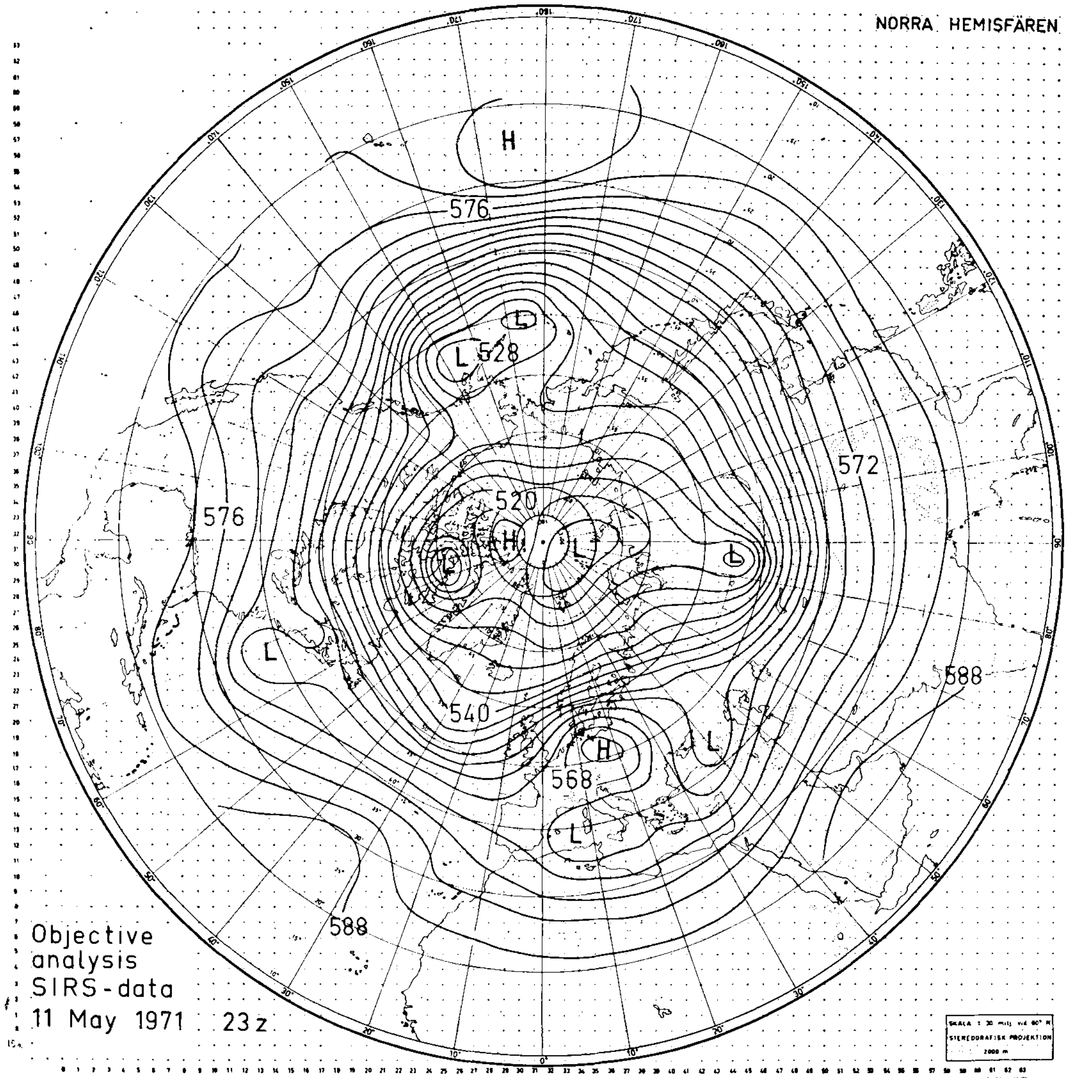

Fig. 12. Analysis for May 11, 1971 23z based on SIRS-data.

tions from the regular aerological network at the 12th of May 1971 00 GMT. The 500 mb monthly mean for May has been used as a first guess in both cases. In general the kinetic energy, especially the eddy part of it, is much lower for the analyses based on the SIRS-soundings since due to lack of observations the monthly mean dominates the flow too much. In areas where the non-synoptic observations have been relatively frequent as for instance over Europe and the Arctic region the resemblance is quite good.

Observe for instance the high over the middle part of Europe and the low over the Baffin Island. Figs. 14 and 15 show the corresponding analyses 24 hours later. The high over Europe has moved to the southeast and the low over Baffin Island has slowly moved eastward. The eastward movement of the small trough outside the east coast of United States is also well described. Yet there are differences between the two analyses and the lows to the west of France and over the Great Lakes cannot be found in the satellite analyses. However, these

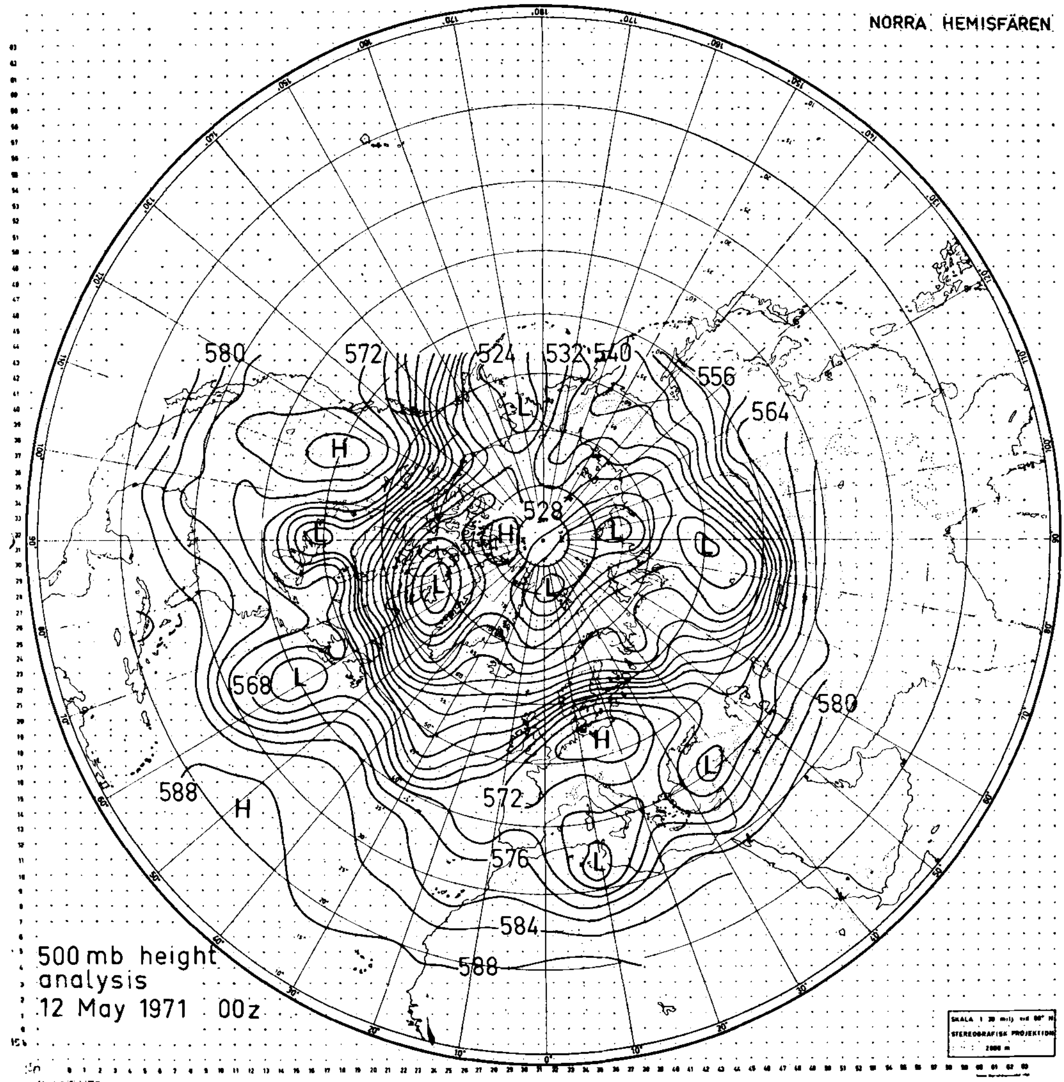

Fig. 13. Analysis based on the regular synoptic 500 mb observations for May 12, 1971 00z.

differences can easily be explained as due to lack of data for the satellite updating. All observations which have been assimilated by the system have been checked according to the description in section 2. It was found that only a few observations were rejected.

5. Conclusions

We have found in this investigation that the results obtained during very idealized conditions in I are also valid in realistic situations. When the updating is performed by data which have been generated by the model itself it is found that the satellite updating is better than the updating from the actual aerological network for all scales of motion. This part of our experiment is not representative for the present situation but possibly reflects what will happen when much more realistic models than the barotropic will be used for the updating.

Assuming a 500 mb RMS-error of 20 m for the satellite soundings and 15 m for the observations the mean analysis error is 22 m for the satellite

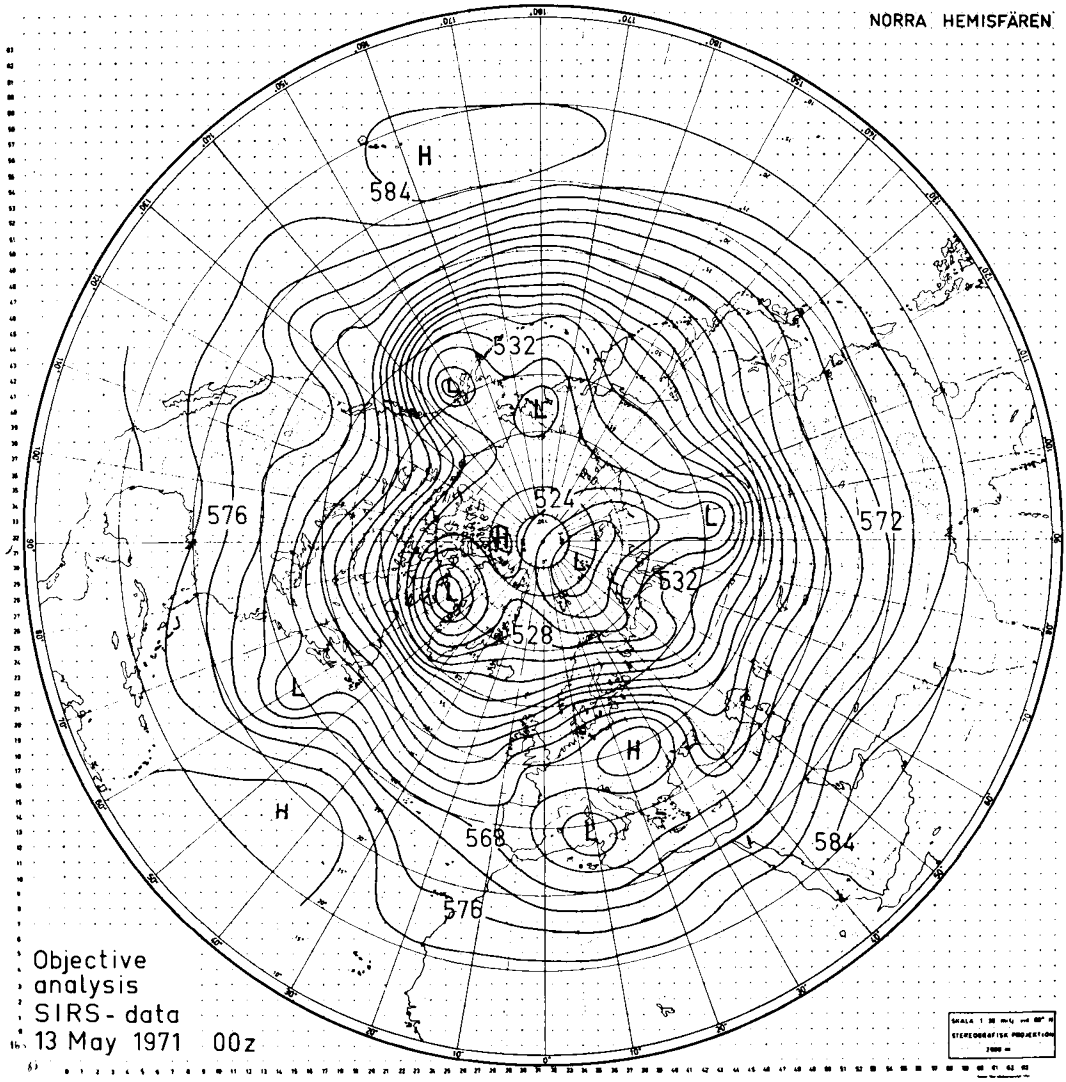

Fig. 14. The same as Fig. 12 but for May 13, 1971 00z.

updating and 28 m for the synoptic updating. For the satellite updating the error is uniform over the whole area but naturally varies very much for the synoptic updating. Over the oceans the error varies between 40 and 60 m, but over Europe and United States it is as small as 10 m.

When the updating is performed with model-independent data (the regular 500 mb maps from NMC Washington have been used) the result differs very much especially for the satellite updating, but still the satellite updating is better than synoptic updating. The mean analysis error for the satellite updating increases to 30 m and the synoptic updating to 33 m. There is a substantial increase of the analysis error for the ultra-long waves especially for the satellite updating. This is partly due to inconsistencies in the time interpolation from the NMC analyses, but also to the inability of the barotropic model to predict the ultra-long waves. The updating should therefore be performed with a model making accurate short-range predictions for all scales of motion. If

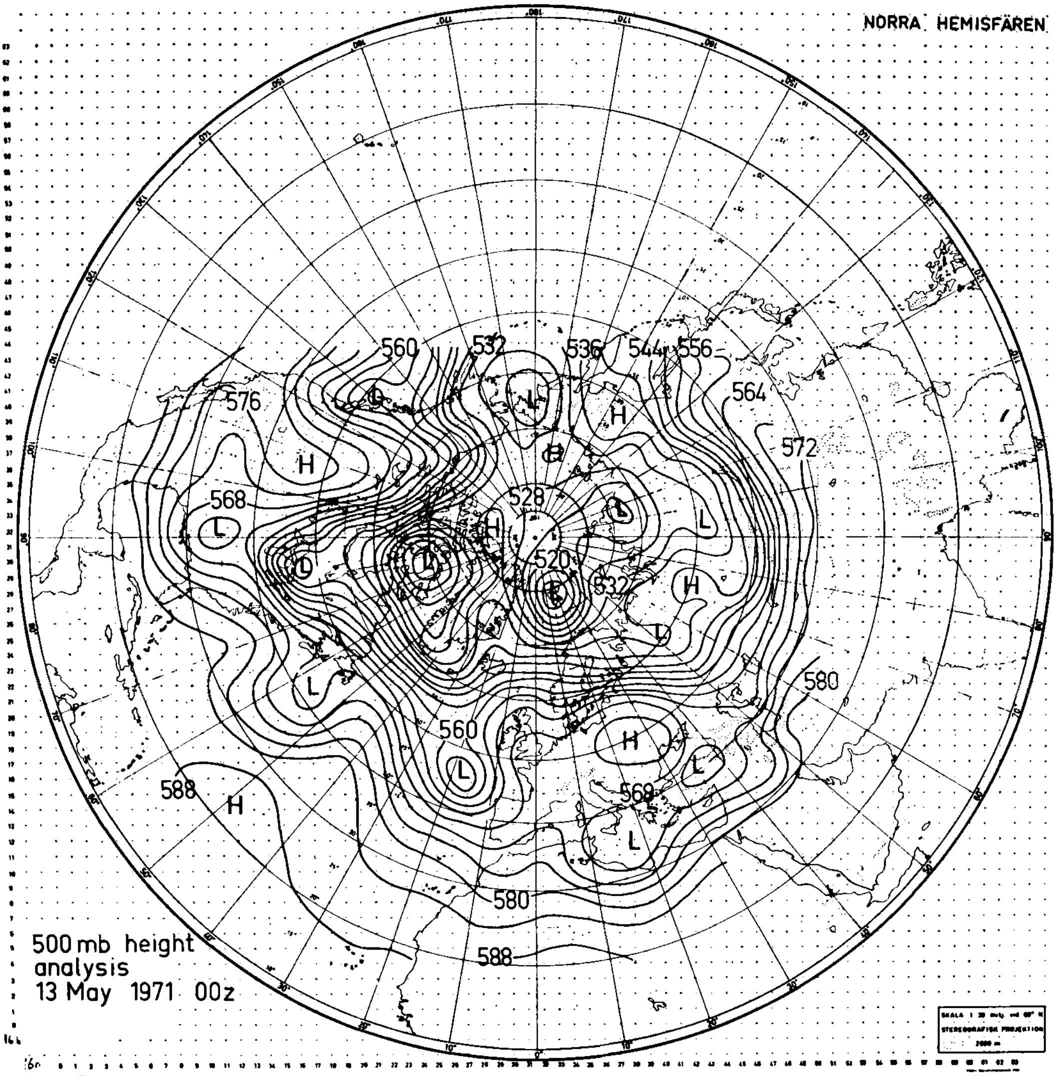

Fig. 15. The same as Fig. 13 but for May 13, 1971 00z.

this is not the case it is likely that even the most sophisticated system for objective analysis will be of little aid.

For most of the experiments with the satellite updating we have assumed the satellite to perform 200 usable soundings/track. It is found that the number of soundings/track can be reduced to about 100 without any appreciable deterioration of the analyses. Any further decrease implies a more rapid deterioration and for 50 soundings/track the error is almost twice as large as for 100. If the RMS-error of the observations increases, the error of the analyses increases slowly. If the RMS-error of the observations increases from 20 to 40 m this yields a 20 % increase in the error of the analysis.

It is also found that an observing system using two satellites 90° out of phase implies a substantial improvement.

The system of non-synoptic updating has also been tried on actual SIRS-soundings from NIMBUS IV. In this case the soundings have also been controlled by a modified system of optimum interpolation developed by the authors.

The observations are rejected if the difference between the observed and the interpolated values is larger than a tolerance proportional to the square-root of the mean interpolation error. Only a few per cent of the soundings have been rejected.

Preliminary experiments have started to update a 5-level quasi-geostrophic model and there are no indications that such a model will present any further complications compared to the barotropic model.

If the updating of the mass field is performed by a primitive model shock effects will be induced in the wind field every time the mass field is changed. For model-independent data this can yield serious errors as has been demonstrated by (Morel, 1971) and by (Baumhefner, 1971, personal communication). A possible way to eliminate such an effect, at least at high and middle latitudes, is to introduce a local balancing over the area for which satellite soundings are available. Such experiments can be performed by the system developed here and experiments are planned for the near future.

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УСВОЕНИЕ НЕСИНОПТИЧЕСКИХ НАБЛЮДЕНИЙ

Описанная недавно система для непрерывного усвоения данных (Бенгтссон и Густавссон, 1971) обобщается и испытывается в более реалистических условиях. Используется сбалансированная баротропная модель, интегрирование проводится для 1/8 полушария севернее 20° с. ш. Проделано сравнение между использованием данных фактической аэрологической сети и данных со спутника на полярной орбите. Результаты анализа изучались для разных подобластей, как с густой, так и с редкой сетью данных. Ошибки анализа изучались также спектральным методом. Восполнение данных производилось как путем использования данных, генерируемых самой моделью, так и путем использования независимых данных. Два эксперимента дали значительное расхождение, особенно в отношении ультрадлинных волн. Более реалистический подход привел ко значительно большим ошибкам анализа. Восполнение данных со спутника дало несколько лучшие резуль-

таты, чем использование данных обычной аэрологической сети, особенно в областях с редкими данными над океанами. Большинство экспериментов проводилось с использованием спутника, делавшего 200 наблюдений на витке, с широтой сканирования 40° и средней квадратичной ошибкой 20 *м*. Найдено, что эффект увеличения числа спутниковых наблюдений со 100 до 200 на виток почти пренебрежим. Аналогично этому мал эффект снижения средней квадратичной ошибки наблюдений. Также анализировалась наблюдательная система, использующая два спутника со сдвигом фазы 90°. Найдено, что она приводит к значительному улучшению прогноза. Наконец, проводился эксперимент с использованием фактических результатов зондирования прибором SIRS со спутника «Нимбус-IV». Имея ввиду очень малое число зондирований на 500 *мб* (142 за 48 час), результат можно рассматривать как вполне удовлетворительный.

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