An experiment in the Assimilation of Data in Dynamical Analysis

By LENNART BENGTSSON[1], *National Center for Atmospheric Research, Boulder, Colorado 80 302, USA, and* NILS GUSTAVSSON, *Swedish Meteorological and Hydrological Institute, Stockholm, Sweden*

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ABSTRACT

A system for continuous data assimilation is presented and discussed. To simulate the dynamical development a channel version of a balanced barotropic model is used and geopotential (height) data are assimilated into the models computations as data become available. In the first experiment the updating is performed every 24th, 12th and 6th hours with a given network. The stations are distributed at random in 4 groups in order to simulate 4 areas with different density of stations. Optimum interpolation is performed for the difference between the forecast and the valid observations. The RMS-error of the analyses is reduced in time, and the error being smaller the more frequent the updating is performed. The updating every 6th hour yields an error in the analysis less than the RMS-error of the observation. In a second experiment the updating is performed by data from a moving satellite with a side-scan capability of about 15°. If the satellite data are analysed at every time step before they are introduced into the system the error of the analysis is reduced to a value below the RMS-error of the observation already after 24 hours and yields as a whole a better result than updating from a fixed network. If the satellite data are introduced without any modification the error of the analysis is reduced much slower and it takes about 4 days to reach a comparable result to the one where the data have been analysed.

1 Introduction

The purpose of this investigation is to study how the accuracy in the analysis depends upon different kinds of observational updating. In order to understand the basic problems in such a comparison we will undertake the experiments by as simple a system as possible. In order to let the experiments have some connection to reality, however, we will investigate a non-linear system.

The updating will thus be performed with a balanced barotropic model and the data to be used are data generated by that model. A very similar experiment also performed with the barotropic model has quite recently been reported by Miyakoda & Talagrand (1971*a*, 1971*b*).

[1] Permanent affiliation: Swedish Meteorological and Hydrological Institute, Stockholm, Sweden.

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Two experiments in updating will be considered here. In the first experiment we will update with observations from a network corresponding to the actual network of upper air soundings. This updating is performed at synoptic observation times only. The second experiment simulates updating with observations from a polar-orbiting satellite.

The assimilation of past data in a scheme of meteorological dynamical analysis is by no means any new idea. In fact, it has been used operationally in numerical objective analysis for a long time (Gilchrist & Cressman, 1954; Bergthorsson & Döös, 1955).

The different procedures which have been applied operationally have been fairly heuristic and only a few systematic experiments have been performed to investigate how the degree of accuracy depends upon the different techniques used.

Among the different methods of objective analysis which have been investigated so far, there are clear indications that the one based upon the so-called optimum interpolation is the most efficient to minimize the error in the analysis (Eliassen, 1954; Gandin, 1963; Kruger, 1968).

In the following we have used a version of the optimum interpolation, where we have analysed the difference between the valid forecast and the actual observations. In the case of the simulation of satellite updating the procedure of optimum interpolation has been somewhat modified and the autocovariance is assumed to vary in time and space. At every time step and at every grid point the autocovariance is modified by the probable mean square error of interpolation combined by an assumed mean square error in the numerical forecast.

Since the updating also is performed every time step some adjustment must be done between odd and even time step in order to get a stable solution. This was achieved by reanalysing observations from the proceeding time step modified by the predicted changes for the corresponding time.

2. The objective analysis

Before we start to give a description of the objective analysis, we will introduce some definitions:

$\psi_i(t)$ = the "true" value of ψ in the point i at the time t,

$\psi_i^F(t)$ = the forecasted value of ψ in the point i at the time t,

$\psi_i^A(t)$ = the analysed value of ψ in the point i at the time t,

$\psi_i^o(t)$ = the observed value of ψ in the point i at the time t,

ψ_i^N the "normal" value of ψ in the point i,

$\{\psi_i'(t)\}^N = \psi_i(t) - \psi_i^N$ = deviation from the normal,

$\{\psi_i'(t)\}^F = \psi_i(t) - \psi_i^F(t)$ = deviation from the forecast,

$\{\psi_i^{A'}(t)\}^F = \psi_i^A(t) - \psi_i^F(t)$ = deviation between analysis and forecast,

$\{\psi_i^{o'}(t)\}^F = \psi_i^o(t) - \psi_i^F(t)$ = deviation between observation and forecast,

$\{\psi_i^{A'}(t)\}^N = \psi_i^A(t) - \psi_i^N$ = deviation between the analysis and the normal,

$\{\psi_i^{o'}(t)\}^N = \psi_i^o(t) - \psi_i^N$ = deviation between observation and the normal.

If k and l are two different points in the area we also have:

$$\textit{autocovariance} \quad m_{klt} = \overline{\{\psi_k'(t)\}\{\psi_l'(t)\}}$$

$$\textit{variance} \quad m_{kkt} = \overline{\{\psi_k'(t)\}\{\psi_k'(t)\}}$$

where we take ensemble averages.

$$\textit{standard deviation} \quad \sqrt{m_{kkt}}$$

$$\textit{autocorrelation} \quad \mu_{klt} = \frac{m_{klt}}{\sqrt{m_{kkt} \cdot m_{llt}}}$$

We now assume that $\{\psi_i^{A'}(t)\}$ can be expressed as a linear combination of the available observational deviations. In the following index i refers to the grid points and k and l to the observations.

$$\{\psi_i^{A'}(t)\} = \sum_{k=1}^{n} p_k \{\psi_k^{o'}(t)\} \tag{1}$$

n is here the number of observations influencing the analysis in the grid point and p_k is the weight of observation k.

In order to find the weight p_k, we require that the mean square error between the "true" state and the analysis should be a minimum:

$$E = \overline{[\{\psi_i'(t)\} - \{\psi_i^{A'}(t)\}]^2}$$

or

$$E = \overline{\left[\{\psi_i'(t)\} - \sum_{k=1}^{n} p_k \{\psi_k^{o'}(t)\}\right]^2} \tag{2}$$

we now introduce

$$\overline{\{\psi_k^{o'}(t)\}\{\psi_l^{o'}(t)\}} = \begin{matrix} m_{klt} \text{ at } k \neq l \\ m_{kkt} + \sigma_k^2 \text{ at } k = l \end{matrix}$$

$$\overline{\{\psi_i'(t)\}\{\psi_k^{o'}(t)\}} = m_{ikt}$$

$$\overline{\{\psi_i'(t)\}^2} = m_{iit}$$

We have also assumed that the observational error is constant in time. m_{klt} is the value of the autocovariance function of ψ for the points k and l at the time t and σ_k^2 is the mean square error of observations at the observational point k.

Formula (2) can now be written

$$E = \sum_{k=1}^{n}\sum_{l=1}^{n} p_k p_l m_{klt} + \sum_{k=1}^{n} p_k^2 \sigma_k^2 + m_{iit}^2 - 2\sum_{k=1}^{n} p_k m_{ikt} \tag{3}$$

At the minimum value of E, we must have

$$\frac{\partial E}{\partial p_j} = 0 \quad (j = 1, 2, \dots n)$$

Derivation of (3) with respect to p_j yields

$$0 = \sum_{k=1}^{n} p_k m_{jkt} + \sum_{l=1}^{n} p_l m_{ljt} + 2p_j\sigma_j^2 - 2m_{ijt}$$

Since according to definition $m_{jkt} = m_{kjt}$ we obtain the minimum value for,

$$\sum_{k=1}^{n} m_{klt} p_k + \sigma_l^2 p_l = m_{ilt} \quad (l = 1, 2, \dots n) \tag{4}$$

where we now have replaced j by l.

Let us now first assume that we are interested in making an objective analysis at the time $t = 0$. We also assume that we have no valid forecast available at that time so we put

$$\{\psi_i'(o)\}^N = \psi_i(o) - \psi_i^N$$

According to Gandin we assume that the variance of $\{\psi_i\}$ is the same at all points and all times, that is

$$m_{kko} = m_{llo} = m_{ooo}$$

Dividing the expression (4) by m_{ooo} yields

$$\sum_{k=1}^{n} \mu_{kl} p_k + \eta_l p_l = \mu_{il} \quad (l = 1, 2, \dots n) \tag{5}$$

where $\eta_l = \sigma_l^2/m_{ooo}$ is called the relative square error of observation.

Solution of equation (5) gives us then the weights p_k and it is then easy to compute $\{\psi^{A'}(o)\}$.

In the case of large n and when stations are close to each other the system (5) might be ill-conditioned resulting in very large positive and negative numbers for the weights. If the observation errors are large this can lead to very serious errors in the solution. However, it is possible to check the system for ill-conditioning and if necessary change it by, e.g. averaging of closely situated observations (Kruger, 1969). In order to avoid ill-conditioning and also according to experience (Gandin, 1963) n is taken to be 8. (See Fig. 2).

It should be pointed out that this technique of objective analysing differs from the so-called correction method, still used operationally by many weather services, in that the correction method does not take into account the proper *combined* effects of the different observations. The simplified expression (5) will not be used for the more general case when we are analysing the difference between the observations and the valid forecast, $\{\psi_i^{o'}(t)\}^F$ instead of the difference between the observations and the normals $\{\psi_i^{o'}(t)\}^N$. In such a case, both the autocovariance and the autocorrelation will change in time.

The time dependence is naturally very large for the autocovariance since this is now simply a measure of the error in the forecast. However, for the autocorrelation the time dependence is not so pronounced. (Fig. 1 shows the forecast error autocorrelation for the 500 mb geopotential in a quasi-geostrophic model computed from about 200 cases.)

The physical explanation for this is quite obvious. Even short-range forecasts have an error spectrum which is fairly wide. The error spectrum becomes slowly wider and wider as the forecast interval is extended. For a 5-day barotropic forecast, it is almost comparable to the one computed from the monthly mean.

In this experiment, we would like to simplify the problem as much as possible and we have therefore assumed that the autocorrelation is constant in time. We will, however, let the autocovariance vary. For the autocovariance, we then get

$$m_{klt} = \sqrt{m_{kkt} \cdot m_{llt}} \cdot \mu_{klt} = \sqrt{m_{kkt} \cdot m_{llt}} \cdot \mu_{kl} \tag{7}$$

One somewhat heuristic way to do this is to compute the probable mean square error of

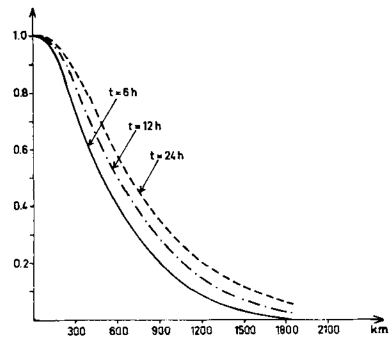

Fig. 1. The autocorrelation for different time intervals.

interpolation at every time and in every point and then modify this estimated error, by an assumed mean square error in the numerical forecast.

The interpolation error can be computed with respect to the following. Let us multiply (4) by p_l and sum from 1 to n. This gives:

$$\sum_{l=1}^{n} p_l \sum_{k=1}^{n} m_{klt} p_k + \sum_{l=1}^{n} p_l^2 \sigma_l^2 = \sum_{l=1}^{n} p_l m_{ilt} \tag{8}$$

Inserting (8) in (3) yields:

$$E = m_{iit}^2 - \sum_{k=1}^{n} p_k m_{ikt} \tag{9}$$

The first term to the right is an expression of the forecast error in the actual point and the second term is a mixed expression of the forecast error and the error of the observation and its distribution.

We will now simply assume that the variance m_{iit} increases linearly in time and that it reaches a maximum variance, $m_{ii}^{\max}$ after a certain time $t = T$. In the experiment $T = 48$ hours. In order to simplify the notations, let us introduce the relative variance

$$r_{it} = \frac{m_{iit}}{m_{ii}^{\max}} \tag{10}$$

To compute the change of the relative variance over one time step, we have thus the simple relation

$$r_{i(t+\Delta t)} = \frac{m_{iit}}{m_{ii}^{\max}} + \frac{(\Delta t/T)\, m_{ii}^{\max}}{m_{ii}^{\max}} = r_{it} + \frac{\Delta t}{T} \tag{11}$$

We also introduce a relative covariance

$$q_{klt} = \frac{m_{klt}}{m_{ii}^{\max}} = \mu_{kl} \sqrt{r_{kt} r_{lt}} \tag{12}$$

We now devide equation (4) by $m_{ii}^{\max}$ and we also introduce $\eta = \sigma_l^2 / m_{ii}^{\max}$ after which we get the following system for optimun interpolation.

$$\sum_{k=1}^{n} q_{klt} p_k + \eta p_l = q_{ilt} \tag{13}$$

for $l = 1, 2, \ldots n$.

Formally, this is the same expression as (5) with the exception that we here have replaced the autocorrelation μ_{klt} by the "normalized" covariance q_{klt}.

Equation (13) can be written in the form

$$\sum_{k=1}^{n} \sqrt{r_{kt} r_{lt}}\, \mu_{kl} p_k + \eta p_l = \sqrt{r_{it} r_{lt}}\, \mu_{il} \tag{14}$$

We see that when $r_{it} = 1$, then equation (14) reduces to equation (5); that is, the autocovariance is in that case constant in time. When r_{it} decreases, it follows that the weight of the observation is reduced and correspondingly the relative influence of the forecast increases.

3. The dynamical system

For the experiment, we have used the non-divergent balanced barotropic model in the form:

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

where J is the Jacobian operator and f the Coriolis parameter.

For the numerical computation, the finite-difference approximation is used. The finite-difference scheme conserves vorticity, the square of the vorticity and the kinetic energy each integrated over the whole area (Arakawa, 1966).

The domain is a zonal channel circling the globe with the northern and southern boundaries at 70° N and 30° N latitudes. Cyclic boundary conditions are applied in the east–west direction and ψ is constant along the northern and southern boundary. The total number of grid points

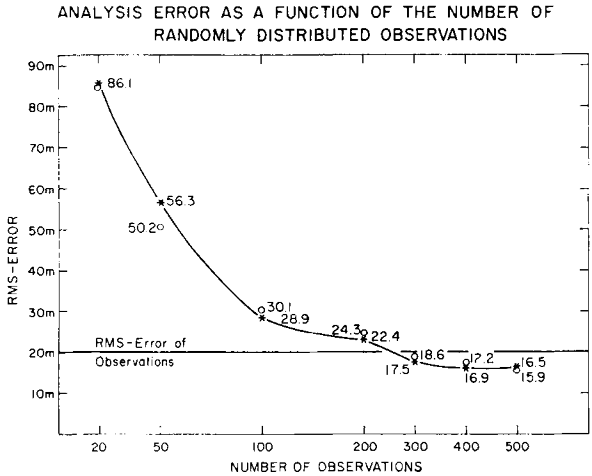

Fig. 2. The error in the analysis as a function of the number of randomly distributed observations and fo some different values of n. (Number of influencing stations.) $n = 8$ is indicated by x and $n = 12$ by o.

in the area is 80×15 corresponding to mean grid distance of about 300 km. The time step in the integration has been 1 hour.

The experiment has been performed in the following way. A forecast for a given period was made from an initial state taken from a real 500 mb flow of the 1st of Januray 12.00 Z GMT 1970. This solution is then used as a reference forecast and it is assumed that this time sequence represents the "true" 500 mb flow.

With the aid of this reference atmosphere we will now make two basic experiments in observational updating with the purpose to compare an asynoptic satellite observing system and a conventional synoptic observing system. We will also investigate the benefit of increasing the frequency in observations from 24 and 12 hours to 6 hours for a fixed synoptic network of observing stations.

4. Updating from a fixed network of observations

In our first experiment, we will first study how much the analysis error depends upon the density of stations. For that reason, different numbers of "observation stations" were randomly chosen from the reference atmosphere at time $t = 0$. A random observation error with a normal distribution is added to the "observaservations". The statistical mean of the error is 0 and the standard deviation is 20 m.

The geopotential height is given by $z = (f_k \psi)/g$, where g is the acceleration of gravity and f_k is the Coriolis-parameter at 50° N (in the middle of the channel). An objective analysis is performed according to the description in section 2. The normal in this case is equal to wave number (0,1) for the reference state. (0 refers to x-direction and 1 to y-direction, computed for twice the width of the channel). The normal thus represents only the first mode of the zonal flow and the RMS of the normal is about 130 m.

Fig. 2 shows that the analysis error strongly depends upon the number of observations up to about 300 observations. (In this and in the following experiments we have assumed that the observations only are situated in the grid points.) A further increase in the number of observations contributes very little to the accuracy of the analysis. This agrees quite well with much more complete investigations, e.g. Mashkovitch (1964).

It is also possible to evaluate the root mean square error of the analysis alone. This has been done by Miyakoda & Talagrand (1971*a*) for a similar experiment and it turned out that the analysis error was 17.5 m. It seems, therefore, impossible to improve the analysis by making use of historical updating if the number of observations is large enough and if they have a homogeneous distribution over the area.

This is, however, not the case in reality where we in the area between 30° N and 70° N have vast areas over the oceans where the density of observations is very low. With the same density over the whole area as over the oceans, we

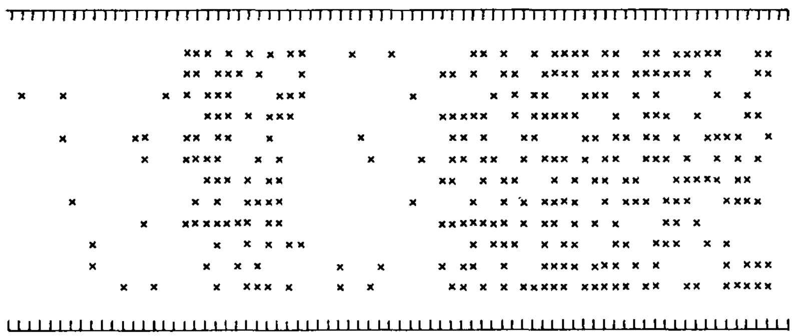

Fig. 3. Distribution of 420 observations in 4 different areas with different degrees of density. Every *x* indicates an observation.

Table 1.

Longitudinal interval	Number of observations
10° W – 138.5° E	300
138.5° E – 122.5° W	20
122.5° W – 64.0° W	90
64.0° W – 10° W	10

would have a RMS-error of the analysis between 40 and 50 m according to Fig. 2.

In order to get a very crude simulation of the existing network of upper air soundings, we have, therefore, distributed the observations randomly in 4 different areas (see Table 1 and Fig. 3).

An objective analysis of the differences between the observations with the same observational error distribution as in the first experiment gives a figure for the error in the analysis of somewhat more than 30 m (see Fig. 4).

It may be interesting to point out that this corresponds to a value of about 100 stations randomly distributed over the *whole* area.

We may, therefore, expect that an updating of observations more frequent than the time it will take for the forecast error to reach the climatological mean will yield some improvement. The analysis procedure is the one earlier described. When updating every 6th, 12th and 24th hour, we have applied autocorrelation functions valid for the corresponding intervals. At every time for which new data have been introduced, we have analysed the difference between the forecast and the observation. Thereafter, we have restarted the forecast by a forward time step. The last is done only to simulate the operational scheme of objective analysis.

A small improvement was obtained if we

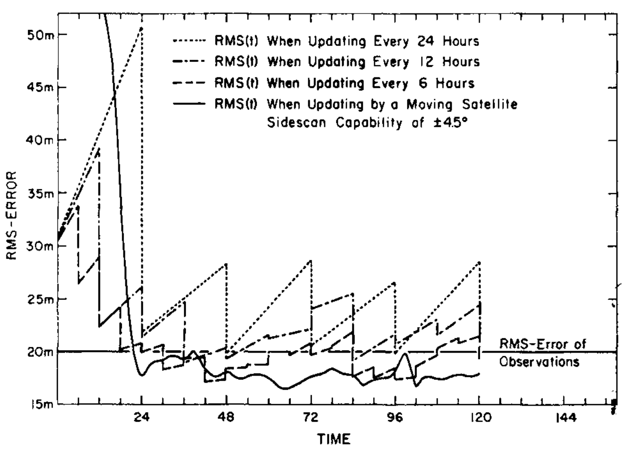

Fig. 4. Variation of the analysis error in time for different kinds of updating.

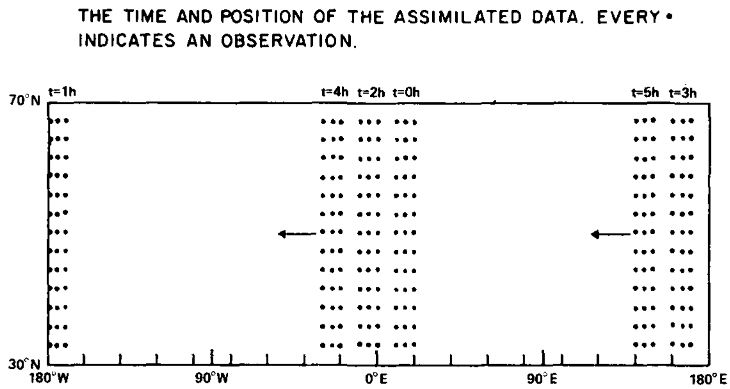

Fig. 5. Time and space distribution of observations from a satellite.

gave a very small weight to the normal field and also smoothed the result after the analysis. For the updating every 6th hour, we have a 5% weight to the normal field and used a smoothing coefficient of 0.125. It is planned to use a more refined smoothing, but that experiment has not yet been completed.

The procedure above corresponds very closely to that used in most schemes of objective analysis in operational use.

As can be seen from Fig. 4, the error in the successive updating reduces the error to about the same amount as the error in the observations. As can be seen from Fig. 4, there is a successive improvement when the updating interval is reduced.

5. Continuous updating with satellite observations

In the final experiment, we have investigated the problem where we have got observations which are assumed to come from a satellite making vertical soundings along its track. The orbit of the satellite is assumed to take 2 hours in accordance with the specification for the Global Observing System. In order to simulate an unfavourable situation, we assumed that the width of the band where we get observations is only about 600 km, which means that we have only 3 observations per latitude at every hour (see Fig. 5). It will thus take more than 24 hours to cover the whole area.

It should be pointed out that in the simulation experiment reported by Jastrow et al. (1970), 2 satellites, 90° out of phase, are used. It is also found that the minimum requirement for the side-scan capability is $\pm 30°$. It is easily seen that in Jastrow's experiment every grid point over the whole globe will be covered in 6 hours. It is assumed that side-scan capability is the largest angle between the senson and the vertical direction.

In this experiment with continuous updating we have used centered time integration all the time. We have also in order to obtain stability introduced a very simple but efficient way of adjustment between odd and even time steps. At every time step, we re-analysed the observations from the time step before plus the predicted change during the elapsed time. This implies a stable solution. Another very similar method of adjustment is to make a centered time step before the updating and then a non-centered time step for the corrections made. A more sophisticated way to adjust between odd and even time steps has been proposed by Thompson (1969).

For continuous data-assimilation the following scheme can be applied:

1. Use a normal fields as initial field
2. Put $r_{it} = r_{io} = 1.0$
3. Perform a preliminary analysis using very few observations (20 in the experiment)
4. Compute $r_{io} := r_{io} - \sum_{k=1}^{n} p_k q_{iko}$
5. Perform a forecast step $t = \tau$, $\tau = 1, 2, 3, \dots$
6. Increase error estimate $r_{it} = \min\,(r_{i(\tau-\Delta t)} + \Delta t/T,\ 1.0)$
7. Analyse observations from $t = \tau$ together with observations from $t = \tau - \Delta t$ modified by the predicted change between $\tau - \Delta t$ and τ.

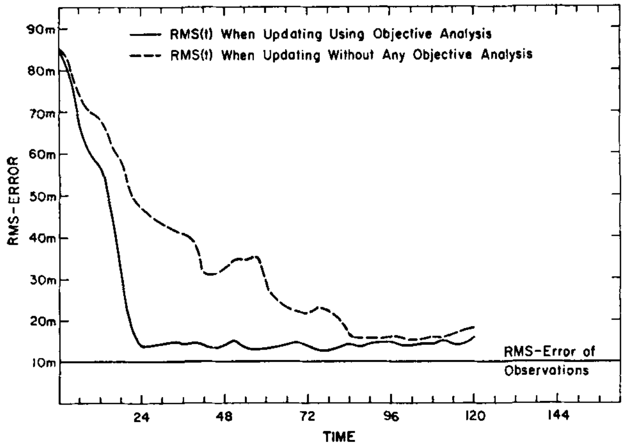

Fig. 6. Time variation for the RMS for 2 different kinds of data assimilation of observations from a satellite. Full line indicates that the observations have been objectively analysed, dotted line that they have been inserted without any space adjustment.

8. Compute error estimate

$$r_{i\tau} := \max\,(r_{i\tau} - \textstyle\sum_{k=1}^{n} p_k\, q_{ikt},\ 0.01)$$

9. Perform next forecast step (back to point 5).

When this scheme was applied a minimum error level of about 14 m was reached after 24 hours. The error remained constant during the whole integration period (see Fig. 6). This result can be compared with an experiment where the observations were introduced into the grid points without any kind of objective analysis. In this case a minimum error level of 17–18 m was reached after 80–90 hours. It is quite obvious that optimum interpolation substantially speeds up the updating.

It may also be very interesting to compare updating with a satellite with the updating from a conventional network. It can be seen from Fig. 4 that the updating with a moving satellite can be compared with a network of 400–500 randomly distributed stations and is more efficient that the investigated actual network.

6. Conclusions

Finally, the question is to what degree we can generalize the results from this investigation. We are quite convinced that a similar result would have been obtained if we had used a barotropic model for a hemispheric area. The next question is if a similar result would have occurred if we had used a balanced or quasi-geostrophic baroclinic model.

If the error distribution in the observations is random or has a small scale, we cannot foresee any problems by an updating of the complete 3-dimensional temperature field. In fact, as has been shown by Obukov (1960) and Holmström (1963), it is possible to describe more than 99% of the variance of vertical variations in the 3-dimensional mass-field by four empirical orthogonal functions. There is thus a high degree of redundancy in the vertical soundings and it may be possible, therefore, to substantially reduce the error in the measurement.

If, on the other hand, we would like to perform the updating with a primitive model, the problem is much more complicated. In the experiment which has been reported by Jastrow et al. (1970), it is found that one needs to insert temperature data almost every 3rd hour in order to reduce the error in the windfield to an acceptable level. The time for the adjustment was extremely long, about 14 days. At the moment, we do not know if this is due to adjustment problems in the tropics or if the time of adjustment will be comparable in time at high and middle latitudes.

It seems yet reasonalbe to assume that the shock effects created in Jastrow's experiment can be reduced considerably by a space analysis of the *mass-field*, every time we introduce new temperature values. The corresponding shock in the *wind field* may, except for the tropics, be eliminated by correcting the wind field with a value which can be computed by the balance equation from the analysed *change* of the temperature field. However, before we have got a satisfactory solution on the problem of updating with a primitive model, we may use a balanced model for the updating and then introduce the corrections in the primitive model by aid of the balance equation.

On the other hand, if the Global Observing System yields data with a frequency high enough and if there is no probability that the system will break down, we may not bother about the long time for adjustment. It would, however, be very interesting to make performance comparisons between 1) an updating with a balanced model followed by an initialization and 2) a continuous updating with a primitive model.

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REFERENCES

Arakawa, A. 1966. Computational design for long-term numerical integration of the equations of fluid motion: two-dimentional incompressible flow. Part I. *J. Comput. Phys. 1*, 119–143.

Bergthorsson, P. & Döös, B. 1955. Numerical weather map analysis. *Tellus 7*, 329–340.

Eliassen, A. 1954. Provisional Report on Calculation of Spatial Covariance and Autocorrelation of the Pressure Field. Inst. Weather and Climate Res., Acad. Sci. Oslo, Rept. No. 5.

Gandin, L. S. 1963. Objective analysis of meteorological fields Gidrometeorologicheskoe Izdatel'stvo, Leningrad, 1960. Translated from Russian into English, Israel Program for Scientific Translations, Jerusalem, 1965, pp. 242.

Gilchrist, B. & Cressman, G. P. 1954. An experiment in objective analysis. *Tellus 6*, 309–318.

Holmström, I. 1963. On a method for parametric representation of the state of the atmosphere. *Tellus 15*, 127–149.

Jastrow, R. & Halem, M. 1970. Simulation studies related to GARP. *Bull. Amer. Met. Soc. 51*, No. 6.

Kruger, H. B. 1968. General and special approaches to the problem of objective analysis of meteorological variables. *Quart. J. R. Met. Soc. 95*, No. 403, 21–39.

Machkovich, S. A. 1964. Some questions on planning the distribution of aerological stations in the light of the requirements of the objective analysis of aerological observations. Proceedings of the symposium on Numerical Methods of Weather Forecasting. Gidrometeoizdat, Leningrad.

Miyakoda, K. & Talagrand, O. 1971*a*. The assimilation of past data in dynamical analysis. Part I. To be published.

Obukov, A. M. 1960. The statistically orthogonal expansion of empirical functions. Izvestiya Geophys. Ser. 1960, pp. 288–291.

Talagrand, O. & Miyakoda, K. 1971b. The assimilation of past data in the meteorological dynamical analysis. Part II. To be published.

Thompson, P. D. 1969. Reduction of analysis error through constraints of dynamical consistency. *J. Appl. Met. 8*, 738–742.

ЭКСПЕРИМЕНТ ПО УСВОЕНИЮ ДАННЫХ В ДИНАМИЧЕСКОМ АНАЛИЗЕ

Представлена и обсуждается система для непрерывного усвоения данных. Для моделирования динамических процессов используется сбалансированная баротропная модель в полосе между двумя кругами широты. Моделью усваиваются данные по геопотенциалу по мере того, как они становятся доступными. В первом эксперименте данные поступают каждые 24, 12 и 6 часов по заданной сетке. Станции распределены случайным образом по 4 группам, с целью моделирования 4 областей с разной плотностью станций. Осуществляется оптимальная интерполяция разности между прогнозом и достоверными наблюдениями. Средняя квадратичная ошибка анализа уменьшаеся со временем и становится тем меньше, чем чаще поступают данные. Поступление данных каждые 6 часов делает ошибку анализа меньшей, чем средняя квадратичная ошибка наблюдений. Во втором эксперименте данные поступают с движущегося спутника с областью сканирования 5°. Если спутниковые данные анализируются на каждом шаге по времени до их введения в систему, ошибка анализа уменьшается до величины ниже средней квадратичной ошибки наблюдений уже после 24 часов и дает в целом лучший результат, чем в случае поступления данных с фиксированной сети. Если спутниковые данные вводятся без модификации, ошибка анализа уменьшается значительно медленнее и необходимо 4 дня для достижения результата, сравнимого со случаем, когда данные анализируются.