Four-Dimensional Data Assimilation Experiments in the Southern Hemisphere

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ABSTRACT

An attempt has been made to isolate some of the problems likely to be associated with the practical implementation of four-dimensional data assimilation schemes in the Southern Hemisphere. In particular, the requirement for a reference-level specification over the Southern Hemisphere, and the importance of assimilation frequency (i.e., the period between data insertions) are investigated.

The assimilation scheme used consists of three components: a "sigma" surface analysis model to "insert" data as they become available, an initialization module of the Nitta-Hovermale type to remove high-frequency inertio-gravitational oscillations, and a multi-level primitive equation model to "advect" the assimilated atmosphere state forward in time. In all experiments, real data consisting of both the conventional and satellite-derived type are used. Verifications concentrate on the synoptic verisimilitude of the assimilation process, and where possible, the impact of various assimilation procedures on subsequent numerical prognosis.

Results underline the critical importance of reference-level pressure in the scheme evaluated. There is also some suggestion of improved performance when the assimilation frequency is increased.

1. Introduction

Recently there has been considerable scientific speculation and discussion as to the optimal design and utilization of observation systems similar to those currently being proposed for the Global Atmospheric Research Program (see, e.g., Kasahara, 1972; Gordon *et al.*, 1972). These new systems will provide observations which are more evenly distributed in time and space than at present. As a result it is generally accepted that some form of four-dimensional assimilation will be essential in future operational systems.

In this paper, an attempt has been made to isolate some of the problems likely to be associated with the practical implementation of four-dimensional assimilation schemes in the Southern Hemisphere. In particular, we will attempt to provide some preliminary answers to two questions. First, how important is a reference-level pressure specification in a viable Southern Hemisphere assimilation scheme? Second, what is the importance of assimilation frequency (or the period between data insertions) in such a scheme? Both of these questions have previously attracted the interest of several investigators with varying conclusions. Jastrow and Halem (1973) present a concise summary and critique of these earlier experiments.

In the experiments reported only real data have been used. Considerable emphasis has been focused on the synoptic quality of various assimilation results as evidenced by their impact on subsequent numerical prognoses, and also, their accuracy compared with withheld conventional data. This contrasts with earlier authors (e.g., Jastrow and Halem, 1970; Williamson and Kasahara, 1971) who used synthetic data and based assessments primarily on various domain-averaged error statistics. Hayden (1973) has recently reported an assimilation study using real data. However, in respect of model configuration and experimental procedure Hayden's study differs considerably from ours.

2. The assimilation procedure

Figs. 1 and 2 show, respectively, an overall representation of the assimilation scheme, and the specific procedures adopted during each assimilation cycle. The data are not assimilated individually but in batches covering some period Δt which is an experimental parameter. This strategy is adopted not only for practical convenience but also because, as pointed out by Hayden (1973), temperature tendencies over the period of an orbit are probably less than observational errors in the data.

The assimilation procedure in its present form considers only two types of input data. These are SIRS A data from the November 1969 GARP data collection experiment (Phillpot *et al.*, 1971) and "reference level" surface pressure data compiled from both conventional and satellite picture interpretation sources (e.g., Streten and Troup, 1972; Guymer, 1969). Accordingly, two types of data assimilation points are distinguishable in Fig. 1. At some points in time, both SIRS

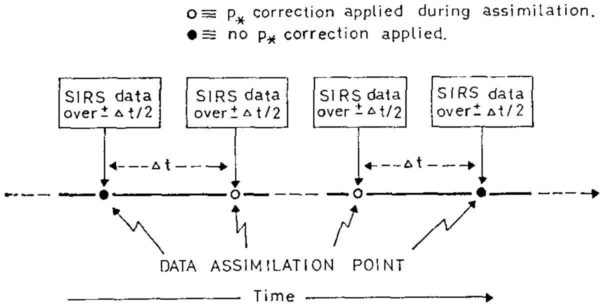

FIG. 1. The general processing strategy for the assimilation scheme when reference pressure at the surface is used as a periodic control.

data and a reference surface pressure (p_*) correction are applied, while at others only SIRS data are incorporated.

Fig. 2 shows the specific procedures associated with the assimilation of data at a particular point in time. Three components may be identified: data insertion (analysis), dynamic adjustment (initialization), and advection forward for a period Δt (prognosis). These components are discussed separately below.

a. Analysis

The analysis scheme is designed to operate on sigma surfaces compatible with those of the forecast model. In four-dimensional applications of the type reported herein this avoids the repetitive and general vertical interpolation error which arises when analyses are performed on conventional pressure surfaces and are subsequently transformed to the grid of the prognosis model. However, because the SIRS A data used are only available on pressure surfaces, vertical interpolation errors over limited areas are still associated with the introduction of each new swath of satellite data into the analysis model. These errors are minimized by the deliberate selection of sigma surfaces which, in most instances, bear a close vertical correspondence to the pressure surfaces on which the SIRS A data were available.

The quantity analyzed is the deviation of the observation from the forecast. The deviation anlaysis is subsequently added to the forecast to obtain the final analysis, which is input to the initialization stage. The reason for analyzing deviations rather than the observations themselves is to retain the topographically induced detail in the forecast fields on sigma surfaces. Such detail would otherwise tend to be lost during smoothing in the analysis procedure.

During these experiments, the deviations were analyzed by the standard Cressman (1959) procedure, using a "first guess" deviation field of zero. The analysis package is so designed that optimal interpolation procedures (Gandin, 1963) could be used, were the appropriate forecast error autocorrelation functions known.

During the experiments reported below, no observational wind data were used. In order to provide a first approximation to the wind field prior to initialization, provision was made in the analysis module to diagnose the wind over data areas from analyzed temperature and surface pressure fields, using either the geostrophic or gradient wind relation.

b. Initialization

A problem of particular importance in all assimilation schemes is the control of inertial-gravity waves resulting from discontinuities which arise when the current atmospheric state (as inferred by the numerical assimilation model) is updated with new meteorological data. The necessity for some form of damping mechanism has been recognized and studied by many authors (e.g., Williamson and Dickinson, 1972; Talagrand, 1972). In this study, the dynamic filtering concepts of Nitta and Hovermale (1969) have been adopted. This procedure was introduced following the successful results achieved by Gauntlett *et al.* (1972) within the context of conventional three-dimensional

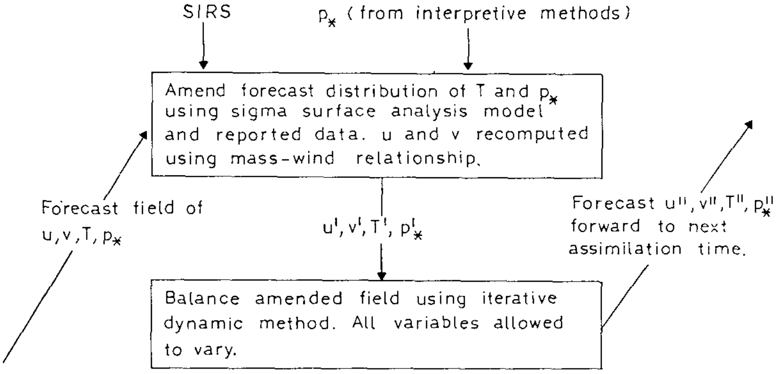

FIG. 2. Specific procedures associated with the assimilation of data at a particular point in time.

analysis-prognosis operations. There was, however, a further reason which is associated with what is now commonly referred to as the reference-level problem.

Kasahara (1972) has discussed at some length the precise nature of the reference-level problem. In essence the problem arises indirectly from an anticipated deficiency in future observation systems, namely the difficulty in obtaining wind observations of sufficient accuracy and density over oceanic areas. One possible method of overcoming this deficiency is to adopt procedures such as those used in the experiments of Jastrow and Halem (1970). In these experiments, temperature data are inserted over long assimilation periods and natural adjustment mechanisms inherent in the equations of the assimilation model are used to correct the wind field to its "true" value. However, the convergence process may take many days of assimilation time. Additionally, Gordon *et al.* (1972) suggest that there may be some qualifications concerning actual convergence especially in low latitudes. Another possible method of remedying observational deficiencies in the three-dimensional wind specification is to utilize some form of diagnostic mass-wind relationship in conjunction with temperature profiles obtained, for example, from the inversion of vertical radiometric soundings. In order to apply such relationships, however, wind or pressure must be specified in time at some known geometric altitude. The achievement of this latter specification is generally referred to as the reference-level problem. In limited experimentation, Seaman (1971) has suggested that the iterative dynamic technique of Nitta and Hovermale (1969) may have some diagnostic potential in this regard. Consequently, we have independently adopted the same general balancing procedure as described by Hayden (1973), i.e., a combination of "static balancing" via diagnostic wind-pressure relationships during analysis with "dynamic balancing" via the Nitta-Hovermale method during initialization.

Except for the removal of irreversible terms associated with viscous dissipation and non-adiabatic convective heating, the differential equations actually used during dynamic balancing were identical to those used during prognosis (Gauntlett and Hincksman, 1971). All variables were allowed to vary freely throughout a mandatory sequence of 90 iterations and no attempt was made to force the direction of the adjustment process. This procedure has given the best results in conventional three-dimensional operations and to some extent has been theoretically validated by Temperton (1973).

Thus if we represent a general forecast equation by

$$\frac{\partial u}{\partial t}=F(x,y,\sigma,t),$$

then for a forward step of a particular iteration ν,

$$u^*=u^\nu+\left(\frac{\partial u}{\partial t}\right)^\nu\Delta t,$$

and for the backward step,

$$u^{**}=u^*-\left(\frac{\partial u}{\partial t}\right)^\nu\Delta t,$$

where ** denotes an approximate initial value. Finally, the $(\nu+1)$th value of the initialized u is given by

$$u^{\nu+1}=3u^\nu-2u^{**}.$$

c. *Prognosis*

The forecast model described by Gauntlett and Hincksman (1971) was used. This model employs the flux form of the primitive equations and was derived from the earlier general circulation model of Smagorinsky *et al.* (1965). In brief, the characteristics of the model are as follows: primitive equation, six vertical levels using Phillips' sigma coordinates ($\sigma=0.1$, 0.2, 0.3, 0.5, 0.75, 0.95), hemispheric, N30 horizontal resolution, energy-conserving finite-difference scheme (as in Smagorinsky *et al.*); non-radiative; hydrological processes are incorporated including a parameterization for subgrid-scale convection and the effect of a smoothed orographic field; horizontal momentum changes due to internal viscosity are modelled using a simple "del-squared" formulation; and Prandtl mixing length theory is used for the vertical in the manner of Smagorinsky *et al.*

3. Results and discussion

a. *Introductory remarks*

In addition to the assimilation system described previously, the following procedures were common to all experiments.

Data insertion began at 0000 GMT 2 November 1969. The first-guess fields for this time were N30, six-level primitive equation prognoses from a normal synoptic analysis at 1200 GMT 1 November.

The success of each assimilation run was assessed in the following ways. First, error statistics of the assimilated states versus withheld conventional observational data were compared after data insertion at each assimilation time. The withheld station data were located over the Australian continent and adjacent islands. Second, prognoses were run from the assimilated states at 0000 GMT 4 November, and the usual error statistics were computed versus independent verifying analyses. Finally, subjective assessment of the synoptic evolutions were made.

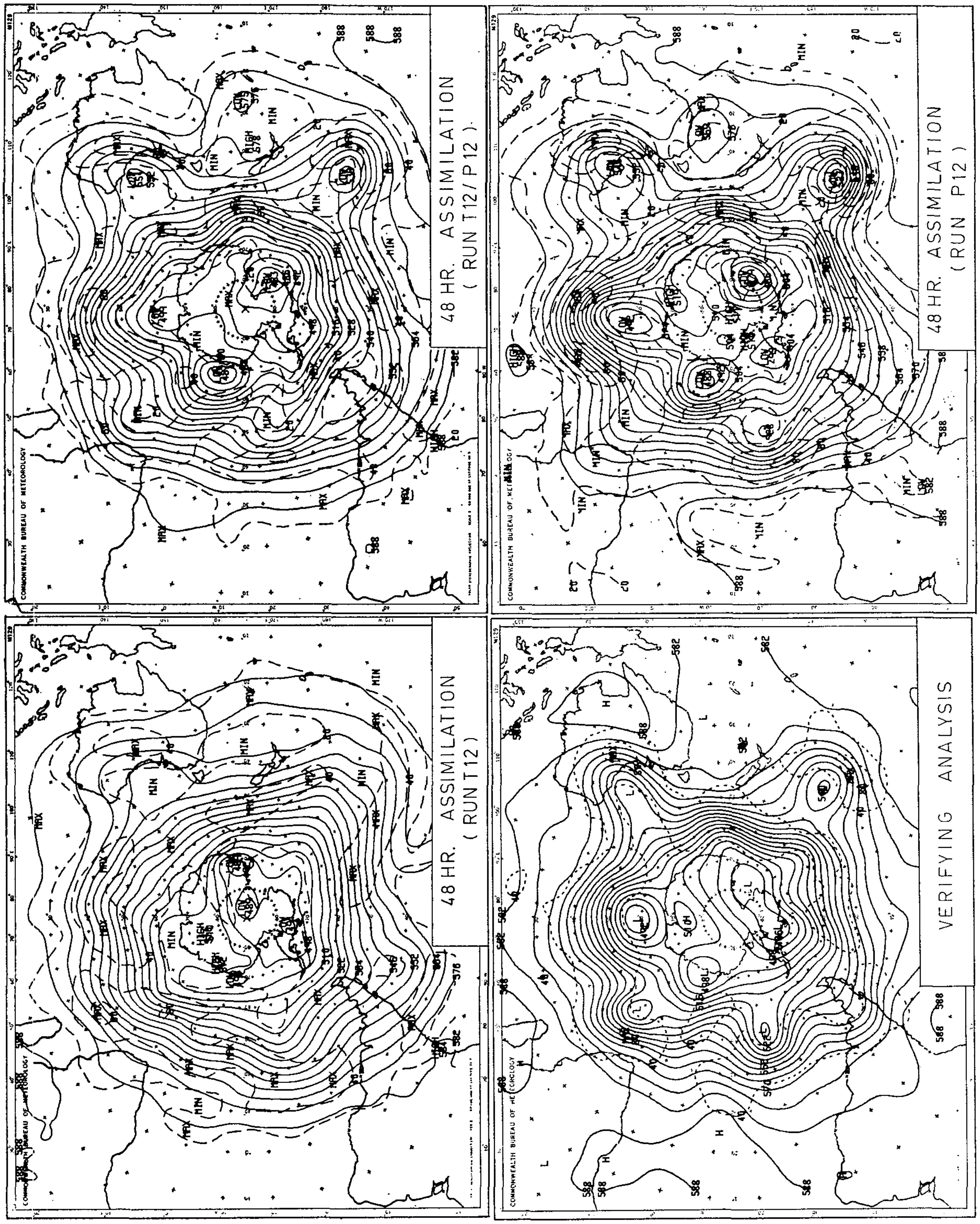

FIG. 3. A comparison of 48 hr assimilation results at 500 mb for the exclusive assimilation of temperature [run T12], the conjunctive assimilation of temperature and mean sea level pressure [run T12/P12], and the exclusive assimilation of mean sea level pressure [run P12]. An independent verification analysis is also shown.

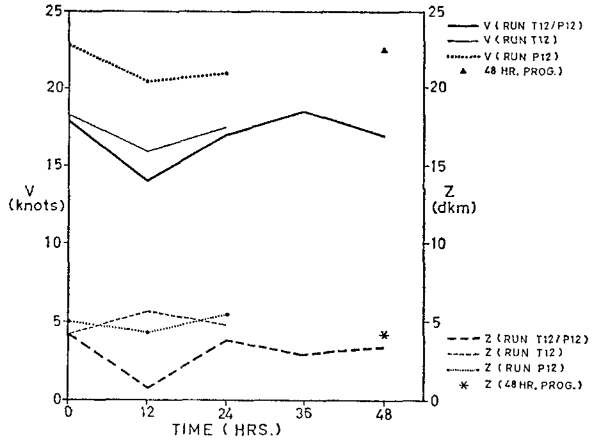

FIG. 4. Time variations during assimilation of the rms error at 500 mb in geopotential Z and the wind speed V based on comparisons with withheld conventional data, for runs T12, P12 and T12/P12. The accuracy of a direct 48 h prognosis without assimilation of data is also included.

b. *Reference-level experiment*

The purpose of this experiment was to assess the effect of periodically specifying a reference level pressure. In run T12, temperature data only were specified, and in run T12/P12, both temperature and mean sea level pressure data were used. In both, the assimilation frequency was 12 hr, and the geostrophic relation was used during analysis for the purposes of static balancing.

The resultant fields at 500 mb prior to data insertion at 0000 GMT 4 November for each run, and the corresponding verifying analyses are shown in Fig. 3. The verification statistics against withheld conventional data at each assimilation time prior to data insertion are shown in Fig. 4.[1] At least in the Australia-New Zealand sector, the assimilation system in run T12 has failed to maintain the intensity and in certain instances the identity of synoptic systems. In particular, depressions in the Great Australian Bight and to the east of New Zealand are poorly represented, both at sea level and 500 mb. In run T12/P12, there is considerable improvement in the above respects, although the intensity of synoptic systems, in general, is still less than the observed. This is no doubt due in part to the dissipative character of the prognosis model used in driving the assimilation scheme. Verification statistics confirm the improvement of run T12/P12 over run T12.

A question that can be posed regarding the validity of the above results is, how important is the accuracy of the SIRS data in determining the need or otherwise for a reference-level specification? Perhaps, for example, the differences between runs T12 and T12/P12 are due solely to the influence of surface pressure. In order to test this hypothesis run T12/P12 was repeated, with no SIRS data being included in P12. The result (Fig. 3) was inferior as far as synoptic intensities are concerned to that obtained with run T12/P12, indicating the positive value of including SIRS data. This conclusion is also substantiated by the verifications based on comparison with withheld conventional data which are included in Fig. 4.

Further perspective on the above results may be obtained by comparing the assimilation after 48 hr with a direct 48 hr prognosis from the initial state. Such a comparison is also included in Fig. 4. Again the positive effect of assimilation with reference level control is evident, especially in regard to wind accuracy specification.

A criticism that may be levelled is the limited 48 hr extent of each assimilation experiment. It is conceivable that the "temperature only" assimilation may have converged if allowed to proceed for several more days. Such slow convergence rates would present some problems from an operational viewpoint due to the inefficiency of reconstituting the atmospheric state following system failures. Furthermore, there is no obvious indication of convergence in our limited results.

c. *Assimilation frequency experiment* (*geostrophic wind*)

The purpose of this experiment was to assess the effect of varying the assimilation frequency. In runs T12/P12, T6/P12 and T2/P12 temperature data were assimilated at frequencies of 12, 6 and 2 hr. In each run, mean sea level pressure was specified at 0000 and 1200 GMT. The geostrophic relation was again used

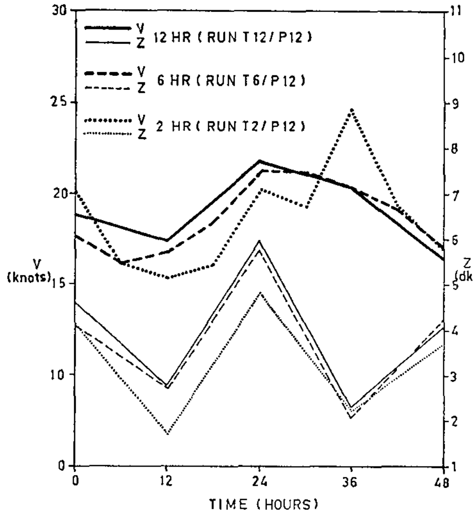

FIG. 5. The time variations during assimilation of the rms error at 500 mb in geopotential Z and the wind speed V based on comparisons with withheld conventional data, for runs T12/P12, T6/P12 and T2/P12.

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[1] Curves relating to experiments P12 and T12 are incomplete due to the physical destruction of a data tape through hardware malfunction.

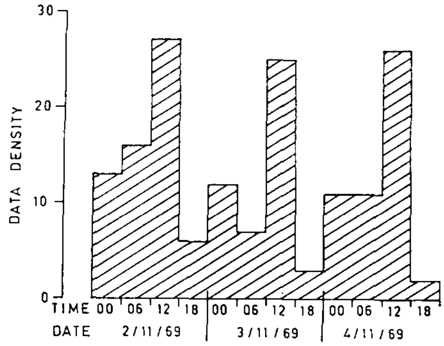


FIG. 6. Time variation in 6 hr intervals of the density of SIRS observations in the Australia area (20–60S, 90–180E).

for static balancing during analysis over those areas affected by new data.

Verification statistics against withheld conventional data at each assimilation time prior to data insertion are shown in Fig. 5. The considerable variation in the level of absolute error for all assimilation frequencies is correlated qualitatively with the movement of individual synoptic systems through the geographically restricted verification area. The result is not conclusive although there is some suggestion of a lower error with more frequent assimilation. A factor which has no doubt blurred the result of this experiment is the non-homogeneous temporal character of SIRS data relative to a particular geographical area. Fig. 6 shows the time variation of the density of SIRS observations over the Australian region (20–60S; 90–180E) for the duration of the assimilation experiments. There is obviously a strong bias for observations to be centered on either 0000 or 1200. As a result one would expect differences resulting from 12 and 6 hr assimilation frequencies to be somewhat minimized.

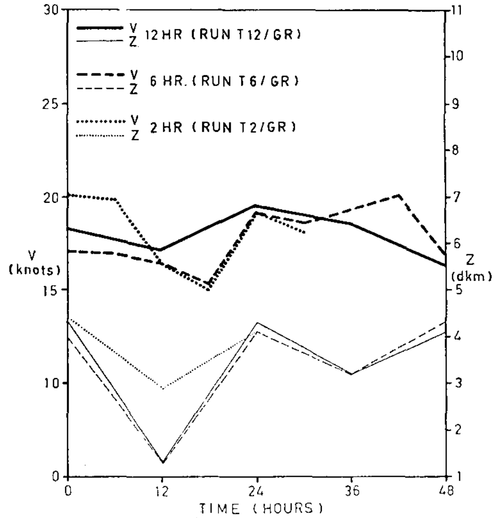
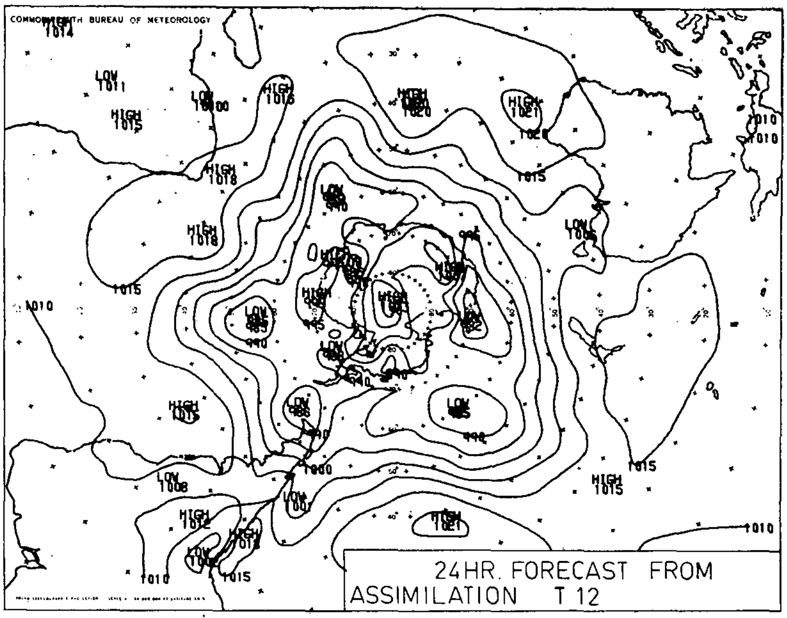
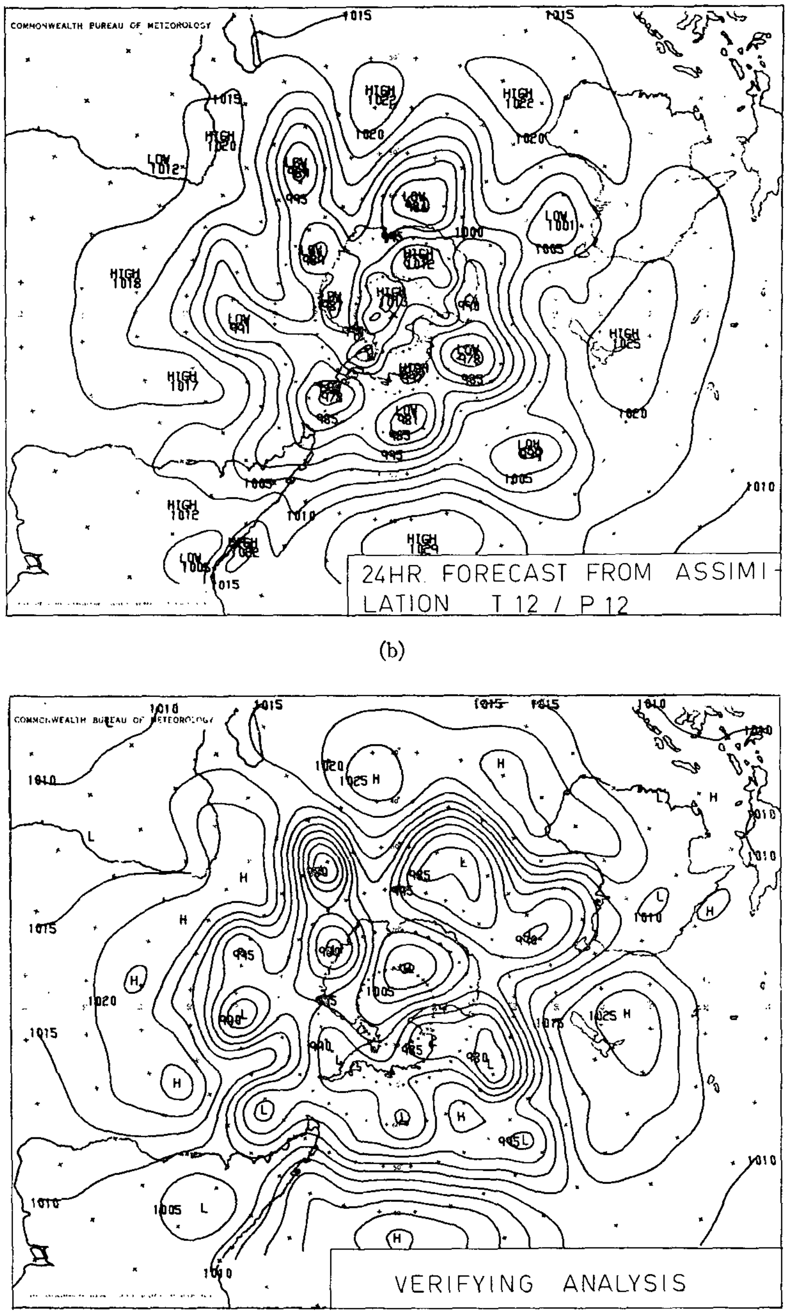


FIG. 7. As in Fig. 5 except for runs T12/GR, T6/GR and T2/GR.

There are further factors which, in the present experimental context, are likely to inhibit the attainment of significantly improved accuracy with higher assimilation frequency. Ideally, the frequency of the reference-level specification should be matched to the assimilation frequency of SIRS data. Practical expediency was a determining factor in choosing a 12 hr specification of reference-level pressure in the present preliminary experiments. Another factor of probable importance is the accumulated error resulting from



(a)



(b)

(c)

FIG. 8. A comparison of 24 hr MSL forecasts made from assimilations T12 and T12/P12. An independent verification analysis is also shown.

physical and numerical inadequacies in the forecast model used to drive the assimilation system. These errors may well obscure the asynoptic errors one is trying to detect.

A further unsatisfactory feature of this particular sequence of assimilation experiments was a significant fall (over 10 mb at extreme points) of surface pressure in the vicinity of intense depressions during dynamic initialization. It was suspected that this spurious deepening was caused by the systematic overestimation of the true wind in areas of strong cyclonic curvature. The above experiments were therefore repeated using the gradient relation instead of the geostrophic during static balancing.

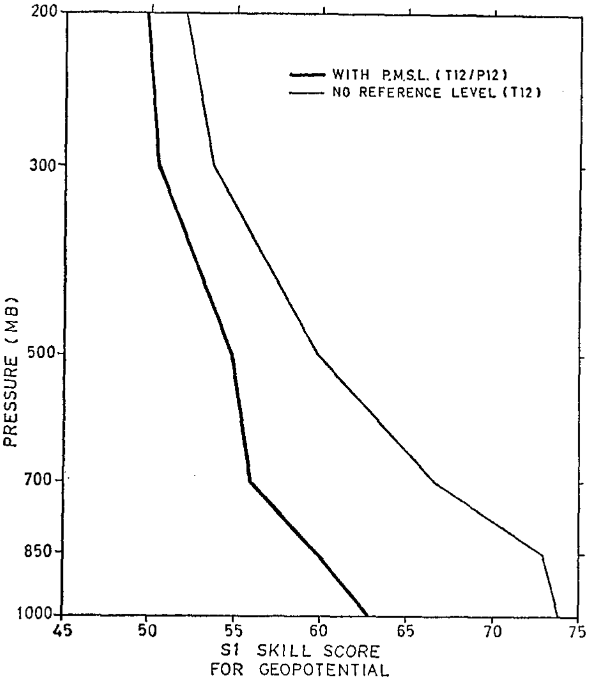


FIG. 9. Variation with height of the S1 skill for 24 hr forecasts made from assimilations T12 and T12/P12.

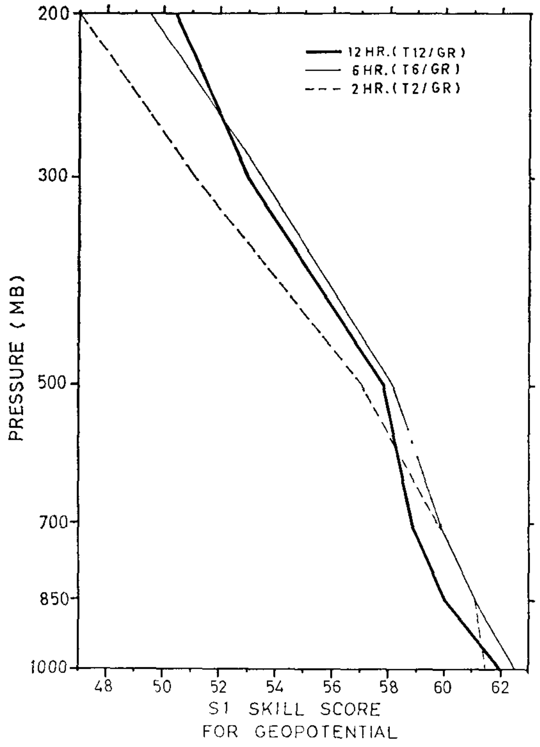


FIG. 10a. Variation with height of the S1 skill score for 24 hr forecasts made from assimilations T12/GR, T6/GR and T2/GR.

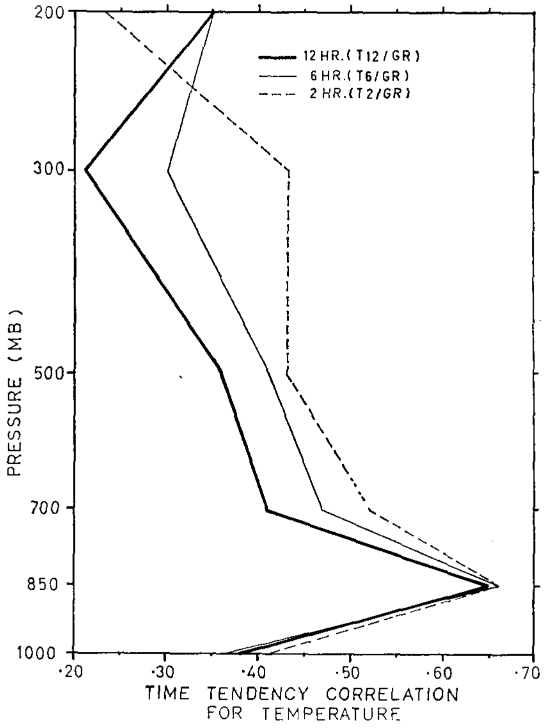


FIG. 10b. As in Fig. 10a except for time-tendency correlations of temperature.

d. Assimilation frequency experiment (gradient wind)

Runs T12/GR, T6/GR and T2/GR[2] are repetitions of T12/P12, T6/P12 and T2/P12 using the gradient relation. Fig. 7 (verification statistics) indicates a similar trend to Fig. 5 (geostrophic), with the errors slightly but generally lower. The spurious pressure changes during dynamic initialization were also much reduced from the corresponding geostrophic cases.

e. Impact of assimilation on subsequent numerical prognosis

An alternative and perhaps the most important method of evaluating a particular assimilation strategy is to verify the accuracy of subsequent numerical prognosis. Fig. 8 shows a comparison of 24 hr forecasts at MSL made, respectively, from 48 hr assimilations T12 and T12/P12. An independent verification analysis is also shown. The forecast results from the reference-level assimilation are clearly superior particurlarly with regard to the forecast intensity of synoptic systems. This result is further emphasized in Fig. 9 which shows the variation with height of the S1 skill score for forecast geopotential.

Figs. 10a and 10b show, respectively, the variation with height of the S1 skill for forecast geopotential

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[2] Curves relating to Run T2/GR are incomplete due to the physical destruction of a data tape through hardware malfunction.

and the variation with height of the time-tendency correlations of forecast temperatures for each of the gradient frequency assimilation experiments (T12/GR, T6/GR and T2/GR). These results are also compatible with previous verification statistics relating to the significance or otherwise of assimilation frequency. Again there is some suggestion of an improvement when the assimilation frequency is reduced to 2 hr. There is little difference, however, between the forecast based on 6 and 12 hr assimilations.

4. Concluding comments

This paper has attempted to provide some preliminary answers to two questions. How important is a reference-pressure level specification in a viable Southern Hemisphere assimilation scheme? What is the importance of assimilation frequency?

Our results indicate that for the SIRS A instrument with its limited coverage and frequency, and the assimilation scheme proposed in this study, the specification of reference-level pressure at the surface is most important. This is in qualitative agreement with the results of Kasahara (1972) who used synthetic data to simulate the twice-daily global coverage which would ensue from a comprehensive polar orbiting satellite system. No attempt has been made to quantify this reference-level requirement in terms of tolerable error limits in observed surface pressure or to evaluate the significance of specifying reference pressure at levels other than the surface.

As far as the significance of assimilation frequency is concerned, our experiments can only be described as inconclusive. Evaluation based on comparison with withheld conventional data for various assimilation frequencies indicate only small differences between 12, 6 and 2 hr assimilation. However, a small but fairly consistent improvement with a 2 hr assimilation frequency was detected in the accuracy of subsequent numerical prognoses.

Future experiments may clarify this indecision concerning assimilation frequency by including conventional data and more reliable VTPR temperature profiles in the assimilation process, and also by extending the assimilation evaluations to a larger variety of synoptic situations. Substantial computing economies are also foreseen in future experiments with the introduction of a semi-implicit forecast model currently undergoing separate evaluation.

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