OBSERVING SYSTEM SIMULATION EXPERIMENTS RELATED TO SPACE-BORNE LIDAR WIND PROFILING. PART I: FORECAST IMPACTS OF HIGHLY IDEALIZED OBSERVING SYSTEMS

M. Halem[1] and R. Dlouhy[2]

Space Data and Computation Division
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

ABSTRACT

Simulation experiments are performed to determine the relative accuracy of inferred atmospheric states for an idealized LIDAR wind profiling system and then compared with idealized temperature and pressure sounding systems. The experiments are carried out for three distinct representations of the 'true' atmosphere to assess the validity of the interpretation of the results. Three fields used in this study are obtained respectively from: (i) a long general circulation integration of the GLAS 4th Order Model (4° lat x 5° lon x 9 levels), (ii) a continuous sequence of real NMC operational analysis and, (iii) a simulated long integration from the ECMWF high resolution (1.875° lat x 1.875° lon x 15 layers) operational forecast model. These fields are interpolated to the grid resolution of the GLAS model and used to simulate the observed global analysed fields of winds, temperature, moisture and surface pressure. The same interpolated fields are also used for verification of forecast impact. The effects of clouds, aerosol concentrations, and instrument accuracies on the simulated observation are discussed in Part II.

The experiments compare first, the inferred 12 h forecast fields made from an assimilation of complete, instantaneous, global fields of the primary variables, i.e., wind, temperature, and surface pressure, respectively. A subsequent series of experiments compares composite systems of the above basic variables, i.e., wind and surface pressure, temperature and surface pressure.

Results show that the LIDAR wind fields can infer most meteorological fields in the extratropics signficantly more accurately than can be inferred from temperature or pressure observing systems. The results obtained are consistent for all three "nature" fields. The 12 h forecast errors in the extratropics from wind data alone are almost as accurate as that obtained from the complete specification of all initial conditions. In tropical latitudes, only the LIDAR wind system showed the capability of inferring useful 12 h forecast winds. The experiments indicate that the accuracy of inferred states from temperature data are greatly enhanced by the addition of surface pressure data more so than are the wind data fields. The derived fields for temperatue and surface pressure are still considerably less accurate than those of an idealized LIDAR wind system alone. A by-product of these simulation studies is a measure of sensitivity to the 'nature' assumption. The identical twin experiments using the GLAS model and the GLAS 'nature' provide the most optimistic performance estimates, while the results from real NMC data and ECMWF model integration 'natures' are much more similar to each other than to the identical twin.

1. INTRODUCTION

Extended-range numerical weather prediction requires, at initial forecast times, complete global and accurate 3-dimensional fields of temperature, moisture and winds as a function of pressure throughout the troposphere, lower stratosphere and at the earth's surface. By supplementing land-based observing systems with space-borne meteorological observing systems, reasonably accurate complete, global fields of temperature analysis are currently available. The accuracies of the space-borne temperature sounders are still limited by their vertical resolution and to some extent by cloud effects. Vertical profiles of wind fields are generally available over large land masses from rawinsondes, but depend mainly on cloud-track winds from geostationary satellites to provide coverage over vast oceanic regions. The cloud-wind distributions turn out to yield essentially single level fields and moreover occur only where there are sufficient clouds (Halem et al., 1981). Like the winds, moisture fields are available over land masses from remote sensors, but only total column water vapor is currently derived with reasonable accuracies. Thus, our global observing system is still severely deficient for purposes of NWP, especially with respect to winds and moisture.

[1] Work formerly initiated at Laboratory for Atmospheric Sciences, NASA/GSFC.

[2] M/A COM Sigma Data Corp., NASA/GSFC.

In recent years, however, new technology has appeared which offers the potential of global space-borne systems with the accuracy of land-based radiosondes. In particular, substantial technical progress has been made in the development of coherent active CO_2 LIDAR systems (Hardesty, 1983; Pace and Lacombe, 1978), which measure the doppler shift in the backscatter from aerosols. From these measurements, it has been shown that one can infer wind motions with accuracies and vertical resolution of a rawinsonde (Hall et al., 1983). Studies have been carried out by Huffaker (1978, 1980), Lockheed (1981) and RCA (1983), indicating the feasibility of free flying space shuttle launched LIDAR wind profiling system known as WINDSAT. In addition to overcoming the significant technological problems involved in the design of instruments that have to work at the limits of quantum theory, substantial progress has been made in the signal processing and computer algorithm developments needed for the extraction of the wind information (Lawrence, 1983).

At the same time, there has been significant progress in obtaining higher vertical resolution from advanced temperature soundings through higher spectral resolutions in the wings of specific spectral lines (Kaplan et al., 1977; Reuter and Susskind, 1984). In addition, recent developments in the use of incoherent LIDAR systems (Korb et al., 1983), indicate the feasibility of obtaining pressure as a function of height with presumably very high vertical resolution and accuracy.

Since placing a LIDAR system in a spaceborne operational environment will involve enormous expenditures by the national funding agencies, a compelling scientific justification on the relevant importance of wind profile data with respect to enhanced sounder system capabilities will be required before management makes such an investment. Surprisingly, there have been very few observing system studies on the effect of complete wind data relative to other systems. Many of the early simulation studies by Jastrow and Halem (1970, 1973) and Kasahara et al. (1972) were concerned mainly with the impact of sounding temperature profiles or single level wind data on forecasts. There were a number of studies on the design of the GARP Global Observing System concerned with the importance of data systems in the tropics. One such important study by Gordon et al. (1974) showed that when complete vertical wind profiles in the tropical band 10°N to 10°S are added to a global temperature sounding system, the inferred extratropical wind accuracies are improved. More recently, theoretical and statistical studies carried out by Daly (1980) and Phillips (1983) indicate that winds should greatly enhance the inferred atmospheric states in the extratropics as well. However, simulation studies with a more realistic account of atmospheric processes and structures are still required to quantify the relative performance of such systems, especially in terms of forecast improvements.

In Section 2 we present an overview of the methodology we used in performing the simulation experiments and in Section 3 we present the results from these experiments. The experiments are divided into two classes. We first study the relative performance of a primary variable to infer other primary variables, and second the effect of composite systems of variables. In Section 4, we summarize the results. In a subsequent paper in this volume, we investigate the sensitivity of the observed data by introducing some simplified atmospheric and instrumental influences.

2. GENERAL DESCRIPTION OF OBSERVING SYSTEMS SIMULATION EXPERIMENTS

The objective we have in performing these simulation experiments is to assess the effect of a particular observing system, in the context of contributing to an operational analysis. The experiments proceed in three steps. First, one attempts to assimilate a particular observing system configuration and determine its level of performance or accuracy. This requires a data set from which one can simulate observations of any degree of accuracy and a data set which can be used to statistically validate the simulated analysis. For this purpose, one can use a long simulated computer integration from a general circulation model containing detailed physical parameterizations of most of the important atmospheric processes. We customarily refer to the continuous sequence of model generated fields as 'nature'. Since the model outputs are complete in terms of all variables, any proposed observing system (with arbitrary coverage, frequency and error structure) can be derived from this 'nature' data set. For more realism, one could interpolate the model outputs to the proposed locations of an actual observing system with appropriate noise and error statistics added to conform to instrument and flight specifications.

Second, one has to convert the simulated data taken at the points of observation into a gridded field by a process called objective analysis. Thus, in addition to the 'nature' assumption, the role of the the analysis system itself is also a critical element of the assimilation. Employing an analysis system requires both a forecast model to provide first guess estimates of all simulated data at their points of observation, and the application of an appropriate objective analysis system of which there are several in operational use, (Bergman, 1979), (Lorenc, 1981), (Baker, 1983). In practice, this is very often carried out using the same GCM model for assimilations and for forecasting.

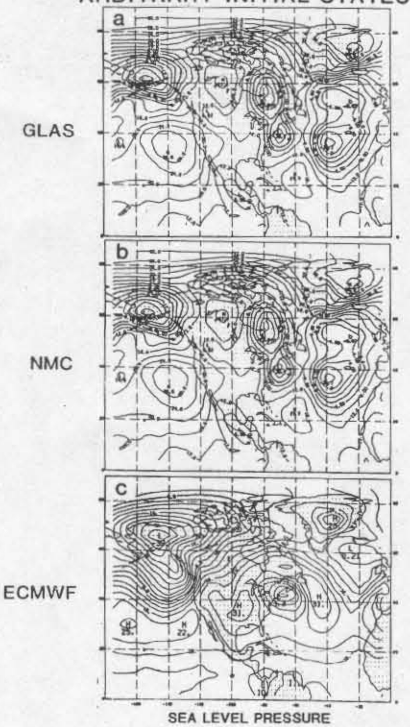
Third, one determines the improvements possible for numerical weather prediction by assessing the forecast sensitivity of the new observing systems. This is done by making forecasts from the respective analysis with and without the observing system in question and then verifying the forecasts against 'nature'. However, the most critical assumption that pervades all three elements of this study and perhaps the weakest link arguing against the realism of such simulation experiments rests on what we use as 'nature,' since it provides both the expected data and the validation.

For the purposes of this study, we have attempted to minimize these aspects of the of the problem by making simplifying assumptions and dealing only with a highly idealized observing system. We will assume that we have somehow produced a global instantaneous gridded analysis of any given meteorological field which is perfect. This is done by merely taking the field in question from the 'nature' and replacing the evolving analysis by that entire field. For example, if we are studying wind observing systems, we might replace both wind components in the assimilation cycle every 12 hours by the wind components from 'nature'. However, since we have circuited the analysis cycle by using the 'nature' field directly and plan to assess the inferred fields in terms of forecasts, this creates a dual influence of the 'nature'. In earlier experiments, it has been shown by Williamson (1973) that using the identical model to produce the 'nature' and the forecast leads to highly model dependent results.

Recognizing the serious limitations of the 'nature' assumption, we have conducted simulation experiments employing three distinct representations of 'nature' to avoid the dependence of the results on our 'nature' assumption. The three 'nature' sets are produced from long integrations made with the GLAS 4th Order General Circulation Model (Kalnay et al., 1980), the ECMWF model (Bengtsson, 1982), respectively, and a continuous sequence of real operational analysis produced by the National Meteorological Center. The respective 12 hr forecasts and analyses were kindly provided to the authors for use in this study by Drs. E. Kalnay and L. Bengtsson. The real data analysis consists of National Meteorological Operational analysis and were obtained from the National Climate Center, Asheville, North Carolina.

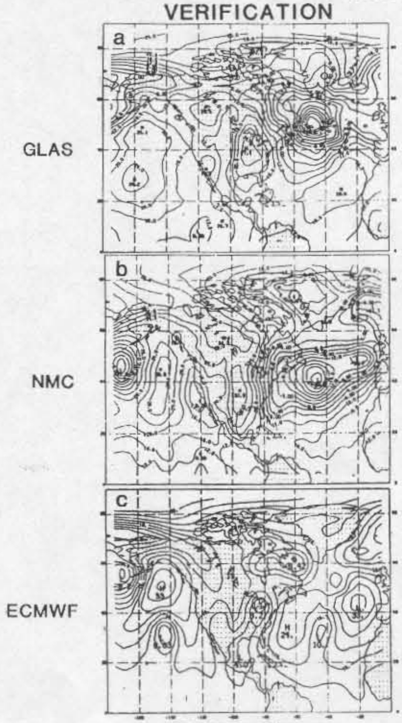
The simulation experiments are carried out by integrating the GLAS 4th Order GCM in all three cases for 30 days, continuously updating one or more meteorological fields every 12 hrs by the appropriate data set from 'nature.' This may involve an interpolation to the same grid as the GLAS model. The initial conditions at the start of the GLAS and ECMWF data assimilation cycle are taken from the respective 'nature' data set 30 days in advance[1]. The NMC data assimilation starts from the GLAS initial conditions. The impact of these data is presented in terms of the 12 hr rms forecast fields verified against the respective 'nature.' Figures 1a, b and c show the initial conditions of sea level pressure for the three types of 'nature' experiments. Figures 2a, b, and c show the corresponding verification fields from 'nature.' The initial

ARBITRARY INITIAL STATES



SEA LEVEL PRESSURE
Figure 1

VERIFICATION



SEA LEVEL PRESSURE
Figure 2

[1] For ECMWF only 20 days are available.

conditions are clearly seen to be relatively uncorrelated with 'nature' for the three experiments. Similar differences occur for the other variables.

3a. SIMULATION STUDY RESULTS: PRIMARY VARIABLES

Two sets of experiments are analyzed in this section. The first set of experiments are intended to study and quantify the relative forecast impact of analyses inferred from the basic meteorological fields of temperature, pressure and winds alone. The second set of experiments investigate results of composite systems and their relative forecast impact.

GLAS 'nature'. We first present results of experiments where the data are taken from the GLAS model 'nature' described earlier. Figures 3a, b, and c compare the rms 12 hr forecast errors for the synoptic assimilation of complete fields of temperature, wind and pressure data, separately. We verify the forecast rms errors for three derived fields of sea level pressure, 500 mb geopotential heights and 400 mb zonal winds, respectively. These fields were chosen to assess the ability of a single field to infer not only its own field but the other primary atmospheric states. In the upper panel of each figure, we plotted the rms errors along a typical extratropical latitude, at 50°N, every 12 hours, and in the lower panel along a tropical latitude, 2°N. For all three verification fields, the assimilation of sea level pressure data alone has only a slight effect in reducing the initial randomly correlated rms error fields in the extratropics. For example, the mean asymptotic 12 hr forecast error level of sea level pressure is reduced from 16 mb to 10 mb, 500 mb geopotential heights from 200 m to 140 m, and 400 mb zonal winds from 16 m/s to perhaps 14 m/s. The temperature data does significantly better, reducing the initial rms errors by more than 50% for all of these fields. The wind data, however, virtually eliminates the 12 hour forecast errors in all the verification fields. Moreover, the wind data has a very rapid adjustment period of less than a week to reach its asymptotic error levels, while temperature data requires several weeks. The results for these experiments in the tropics again show that pressure makes no reduction in the initial rms errors. Temperature data also shows very little influence on inferring 500 mb heights and wind data in the tropics, but does show some skill for inferring surface pressure fields. The assimilation of wind data in the tropics, however, improves the forecast of wind fields substantially, and has about the same influences as temperature data on the forecast error in 500 mb geopotential and surface pressure fields.

NMC 'nature'. Figures 4a, b and c again compare the rms 12 hr forecast impact errors of the same fields as before but for temperature and wind fields taken from the real data 'nature'. Pressure data in these experiments had no effect and is not shown on the charts. Instead, we have added a curve as a reference level which shows the 12 hour forecast of the GLAS 4th Order Model made from the full FGGE data analysis cycle as reported in (Halem et al., 1981). In the extratropics, the insertion

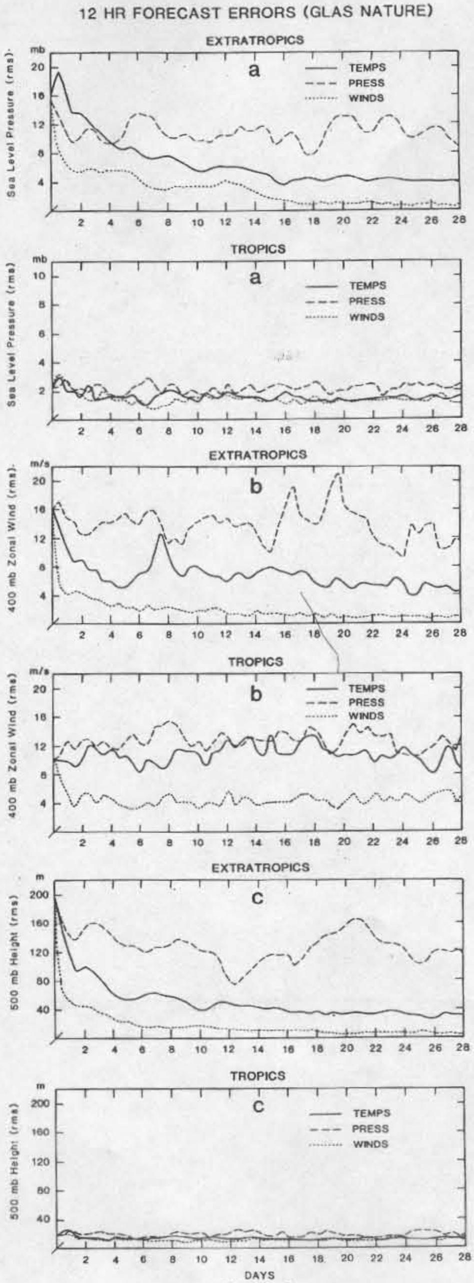


Figure 3

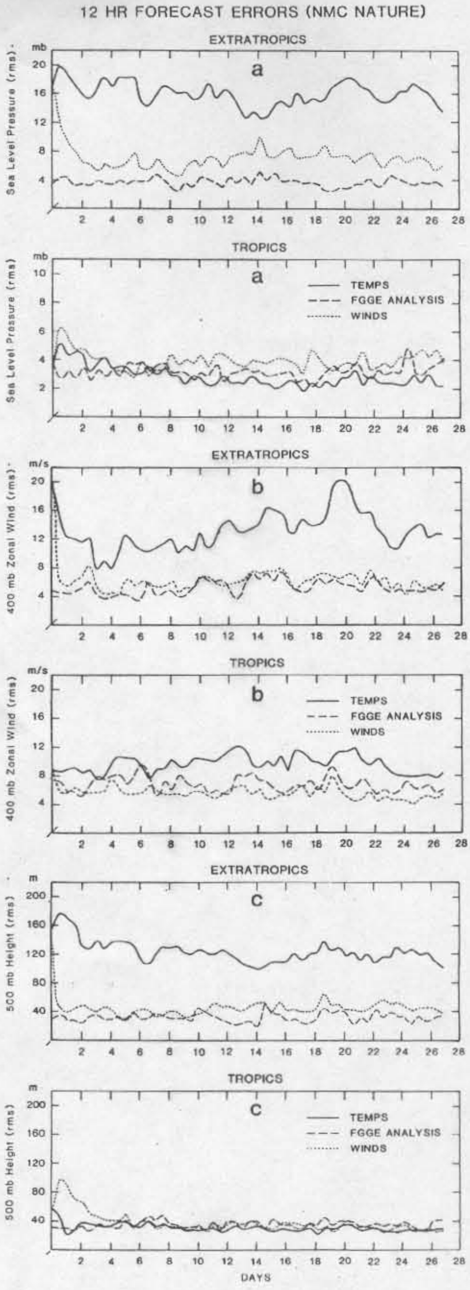


Figure 4

of temperature data shows only slight improvements in the 12 hr forecast relative to the arbitrary initial fields. For wind data alone, the 12 hr forecast 500 mb geopotential heights and zonal winds are almost as good as those obtained using the full FGGE analysis system. There is, however, about a 2-4 mb degradation in the 12 hr surface pressure forecast from the wind data alone. As before, the adjustment process of the inferred fields from wind data seems to occur in about 4 days.

In the tropics, the results are mixed and require some interpretation. For the sea level pressure 12 hr forecasts, the temperature data alone have an rms 1 to 2 mb more accurate than the FGGE reference level and wind data forecasts, respectively. The situation is reversed for the 12 hour forecast zonal wind fields where wind forecasts are 2 to 4 m/s more accurate than forecasts from FGGE and temperature data. No apparent trends are observable in the 500 mb height forecasts. A possible explanation of these results may be related to the fact that the integrated column density of the NMC height data is obtained from relatively accurate sounding systems whereas the wind data from geostationary cloud winds may have systematic errors inconsistent with the thermal fields. In comparing the accuracies of the 400 mb winds, we may be validating against a data set with the same bias thereby enhancing the wind simulation since FGGE winds have been influenced by other wind data not included in the NMC fields.

<u>ECMWF 'nature'.</u> In this experiment, we again show in Figures 5a, b, and c the rms 12 hour forecast impact errors of the same fields, but now we use the ECMWF 'nature' field. The rms forecast sea level asymptotic pressure error for temperature data in the extratropics is about 12-13 mb compared to 4 mb for wind data insertion. This is very similar to the results with real data. The similarity also holds for the 500 mb height fields except that the asymptotic error levels for wind data are substantially better than those with the full FGGE data. The inferred 400 mb zonal winds for the temperature data is now substantially improved to about 9 m/s while the wind data is about the same as with real data. This indicates that the consistent accurate global temperature fields can reduce the 12 hr forecast wind errors.

The results in the tropics for the ECMWF 'nature' experiment are more consistent with the idealized twin simulation experiment than obtained with the real NMC data. The two fields are comparable in the 12 hr forecast errors for sea level pressure wind 500 mb geopotential heights but wind data forecasts have half the rms zonal wind error than that from temperature data in the tropics.

3b. SIMULATION STUDY RESULTS: COMPOSITE SYSTEMS

In the following series of experiments we couple surface pressure fields with both wind and temperature data since pressure data is readily available over most of the globe from land-based stations and ship reports.

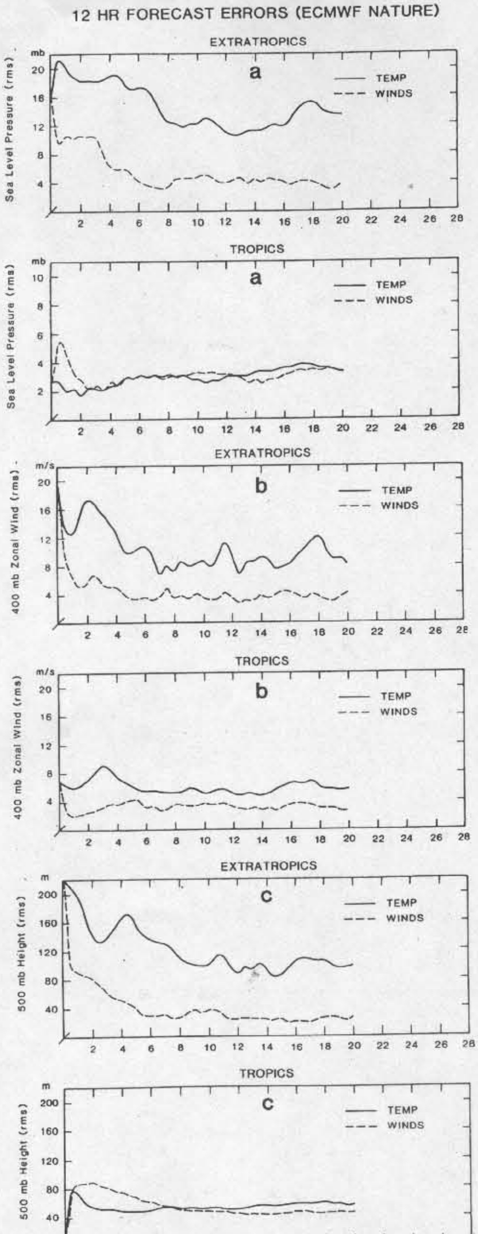


Figure 5

GLAS 'nature'. Figures 6a, b, and c compare the 12 hour forecast errors of temperature and pressure with wind and pressure data for the same basic three validation fields. The 'nature' data set for these figures is from the GLAS model. These experiments show that the composite temperature data has reduced the sea level forecast errors to 2 mb, 500 mb heights to 20 m, and zonal winds to about 3 m/s, almost 40% less than the errors obtained without the pressure data. The composite wind system had similar asymptotic errors as those without pressure. In the tropics, the use of composite systems had the same asymptotic error levels as the systems without pressure data.

NMC 'nature'. Figures 7a, b, and c show the composite system with the NMC 'nature' data set. In these experiments, we observe major reductions in forecast errors for real data composite systems relative to the earlier individual real data systems. For example, the sea level pressure asymptotic levels are 8 mb compared with 16 mb for the previous temperature only experiment, 80 m compared with 120 m for 500 mb geopotential heights and 10 m/s compared with 12 m/s. The height and wind forecast errors were about the same for the composite wind system but the sea level forecast errors were reduced in half to about 4 mb. In the tropics, the results are relatively unaffected by the addition of surface pressure for both composite systems.

ECMWF 'nature'. Figures 8a, b, and c compare the composite system for the third 'nature' data set, namely, the fraternal ECMWF model. In the extratropics, the asymptotic composite temperature system forecast error levels for sea level pressure, 500 mb heights and zonal winds are 4 mb, 40 m, and 6 m/s, respectively. These error levels are half again what the real data error levels were for the composite system and reduced the errors to more than half that of the same fraternal experiment without pressure data. In addition, the error levels are comparable to that of the wind only system for the fraternal experiment. In the tropics, the errors are also significantly reduced with the composite temperature system for sea level pressure and geopotential heights but slightly for zonal winds. Yet, the zonal wind errors at 500 mb are only 4-5 m/s compared to 2-3 m/s for the wind data system. In both cases, they are significantly better than those obtained for the real data composite systems.

4. SUMMARY

The general conclusions from the experiments using primary variables are that (i) wind data alone has a greater impact than temperature data alone for inferring the other state variables, (ii) that similar results are obtained for all three 'nature' experiments and are probably not model dependent, (iii) that atmospheric states adjust to wind data in extratropics as well as tropics, and (iv) that the adjustment times to wind data are much more rapid than to temperature data. The results of the composite system of temperature and pressure show significant improvements over those of temperature only.

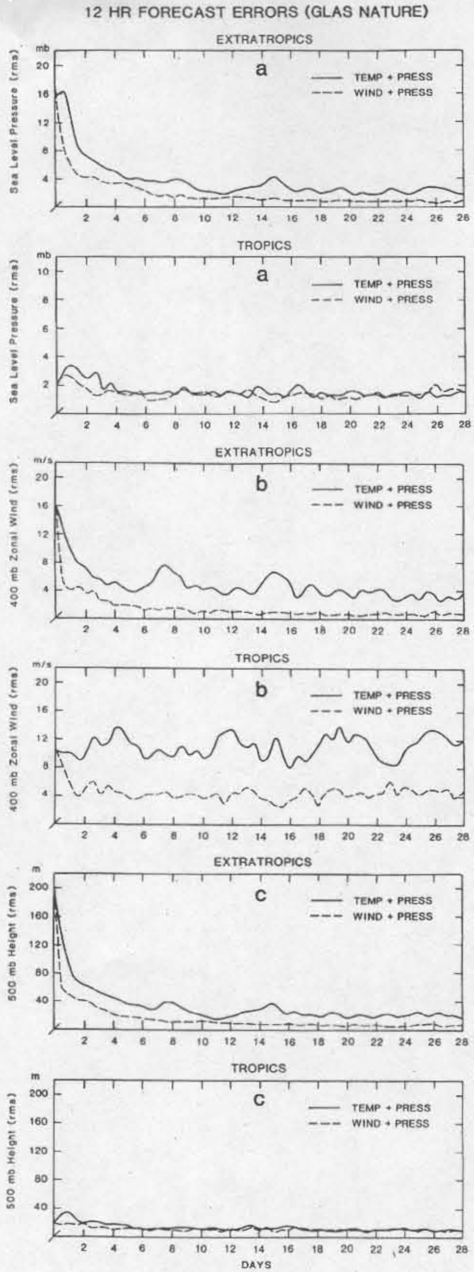


Figure 6

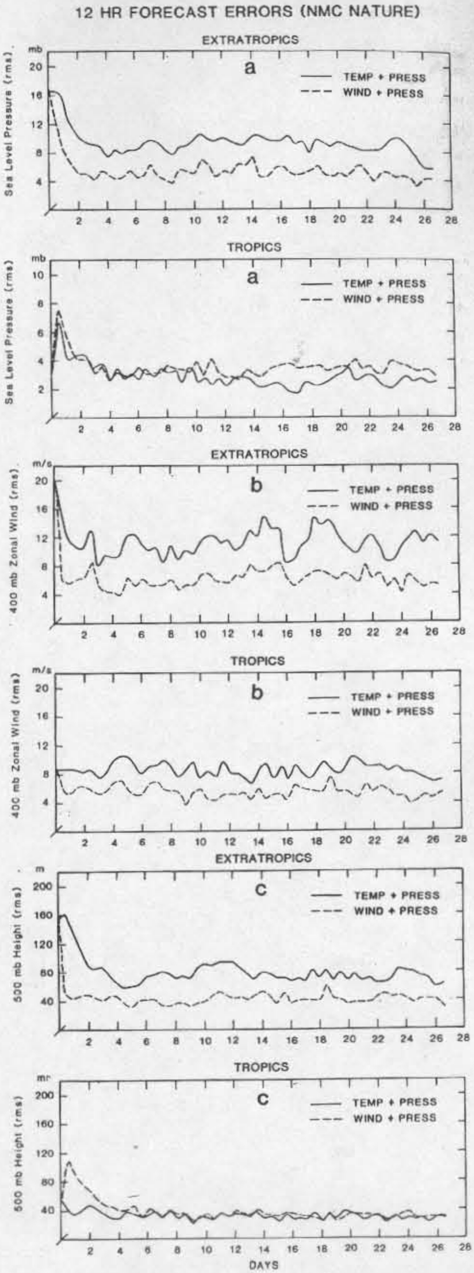


Figure 7

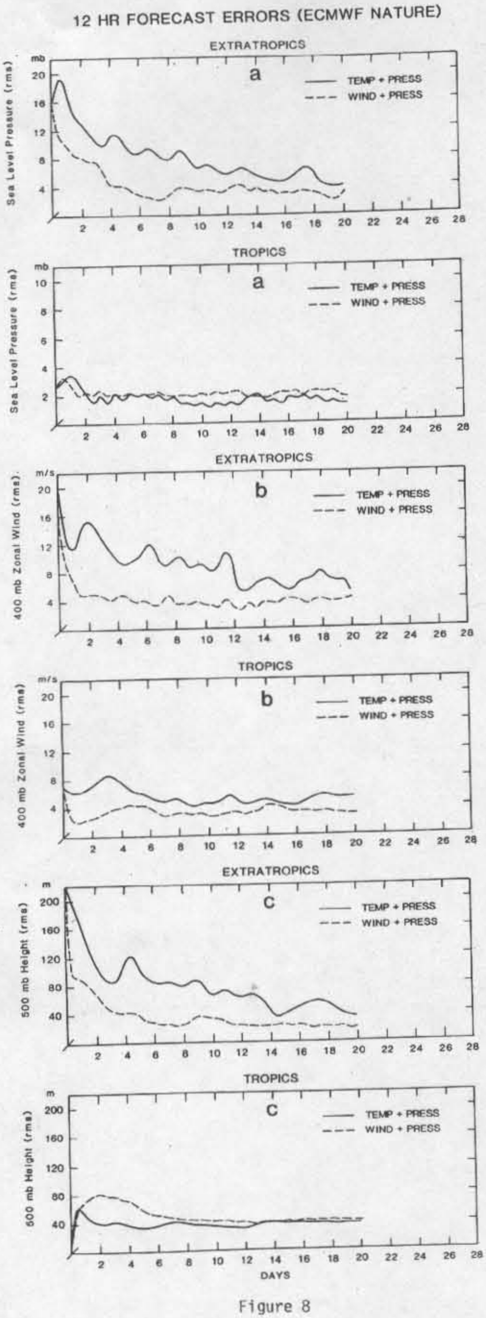


Figure 8

They also indicate that a composite wind system is neither helped nor hurt by the addition of surface pressure data. However, the most striking conclusions of the ECMWF results are that the composite system of temperature and pressure differs from the NMC results in that they provide useful inferred fields only slghtly poorer than the wind system in the extratropics and tropics as well. Thus, the importance of determining which of the three systems is most credible is a paramount issue in deciding the importance of committing major funding programs for the development of the LIDAR Windsat system.

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