OBSERVING SYSTEM SIMULATION EXPERIMENTS AT GLAS

R. Atlas, E. Kalnay, W. E. Baker, J. Susskind, D. Reuter, and M. Halem
Laboratory for Atmospheres
NASA/Goddard Space Flight Center
Greenbelt, MD 20771 U.S.A.

1. INTRODUCTION

A series of realistic simulation studies is being conducted as a cooperative effort between the European Centre for Medium Range Weather Forecasts (ECMWF), the National Meteorological Center (NMC), and the Goddard Laboratory for Atmospheric Sciences (GLAS), to provide a quantitative assessment of the potential impact of proposed observing systems on large scale numerical weather prediction. A special objective of this project is to avoid the unrealistic character of earlier simulation studies. Following a brief review of previous simulation studies and real data impact tests, the methodology for the current simulation system and preliminary results utilizing this system will be described.

2. EARLY SIMULATION STUDIES

Since the advent of meteorological satellites in the 1960s, a considerable research effort has been directed toward the design of spaceborne meteorological sensors, the development of optimal methods for the utilization of satellite soundings and winds in global-scale models, and an assessment of the influence of existing satellite data and the potential influence of future satellite data on numerical weather prediction. Observing system simulation experiments have played an important role in this research and in the planning of Data Systems Tests (DST) and the First GARP Global Experiment (FGGE). Such studies have aided in the design of the global observing system, the testing of different methods of assimilating satellite data, and in assessing the potential impact of satellite data on weather forecasting.

The earliest simulation studies proceeded according to the following sequence of steps: First, an artificial history of the atmosphere is created by numerical integration of a model. Second, simulated "data" are created from the history by addition of random variations to the history values for temperature, wind, and pressure. Third, the numerical integration that created the history is repeated, but with the meteorological variables in the model replaced by the simulated data at locations and times corresponding to the assumed pattern of observations.

For example, if the observing subsystem under study is designed to produce wind data, the winds in the history are replaced by simulated wind "data" at locations, heights, and times corresponding to the coverage expected from the observing system. If the study is directed at the performance of an observing subsystem design to yield temperature or pressure information, the temperature or pressure values in the history are replaced by the respective simulated "data" in a similar fashion.

If the data had no errors, and therefore were identical with the history values, and were inserted at all grid points, the new integration would be identical with the history. However, when errors are present, the inserted data perturb the computed circulation, causing it to depart from the history. The difference between the history and the perturbed circulation resulting from the data insertion is a measure of the effect of the errors in the simulated data. The effect of the errors usually is expressed in terms of differences of the meteorological variables such as wind components, averaged over all points of the model grid. These differences are considered to represent the errors in the determination of the global atmospheric states, resulting from the assumed errors in the observing system.

In order to simulate different types of data and data coverage and assess their impact on forecasting skill, a somewhat different approach has been utilized (Cane _et al._, 1982). In this procedure a forecast model is integrated for a long period, such as one or two months. This long run is then assumed to be "nature." "Observations" are then extracted from the nature run, following a suitable geographical and temporal distribution, and random "observational" errors are added. These simulated observations are then assimilated with an analysis cycle, and the same model is used as a "forecast model" from the analyzed fields.

Simulation studies conducted by Charney _et al._ (1969), Halem and Jastrow (1970), Jastrow and Halem (1970, 1973), Williamson and Kasahara (1971), Kasahara (1972), Gordon _et al._ (1972), and others indicated that all three of the primary meteorological variables--wind, pressure, and temperature--could be determined if a continuous time history of any one of these variables were inserted into a general circulation model. In addition, these studies provided an analysis of the GARP data requirements, the "useful" range of predictability, the need for reference level data, and the relative usefulness of asynoptic versus synoptic measurements and analysis. From the results, it was concluded that the assimilation of satellite-derived temperature profiles meeting the GARP data specifications should yield a substantial improvement to the accuracy of numerical weather forecasts.

An examination of the underlying rationale for the simulation studies as previously conducted (Jastrow and Halem, 1973), as well as a comparison of the results of the above studies with the results of subsequent real data impact tests indicates several important limitations. The most important weakness stems from the fact that the same numerical model has been used both to generate the simulated observations and to test the effectiveness of these observations. Other weaknesses relate to the model-dependence of the studies and the specification of observational errors as random.

3. REAL DATA IMPACT TESTS

In recent real data impact studies, most of the qualitative conclusions of the preceeding observing system simulation experiments have been confirmed, although in some respects the results appear to be overly optimistic. In particular, it was clear from estimates of the quality of satellite temperature soundings and cloud-track wind data obtained during the NASA Data Systems Test (DST), (Desmarais _et al._, 1978) that the accuracies of the FGGE satellite observing systems would be considerably poorer than were needed to infer wind profiles of the accuracy specified in the GARP data requirements. Moreover, as a result of these DST studies, expectations that the FGGE observing system would significantly improve the forecast skill and range of useful predictability also were questionable. For example, a forecast impact test by Ghil _et al._ (1979) with a coarse resolution second-order model showed only a modest beneficial impact of the DST-6 satellite sounding data, while a similar study by Tracton _et al._ (1980) revealed a slight negative impact for DST-5 and a slight positive impact for DST-6, both of which were meteorologically insignificant. More recently, however, when the same DST-6 temperature-sounding impact test was repeated with a more accurate forecast model employing higher resolution, Atlas (1979, 1982) and Atlas _et al._ (1979, 1982) showed that the DST data were in certain cases capable of making modifications to the analyzed atmospheric states that produce meteorologically significant improvements in the 72 h forecasts over North America. Also, the first FGGE case studies reported by Bengtsson (1981a,b) with the ECMWF model, indicated improvements in short- and extended-range forecasts with the FGGE data. Similarly, Gustaffson (1979), employing the Swedish operational forecast/analysis system (i.e., a 300 km, quasi-geostrophic model), showed periods during the first Special Observing Period (SOP-1) in which the satellite information had a positive impact on the objective analysis which also resulted in improved numerical forecasts.

These results are supported by our recent investigation of the FGGE satellite observing system for the SOP-1 period (Halem et al., 1982). Utilizing the GLAS Fourth Order Global Atmospheric Model, an extensive series of data assimilation/forecast impact experiments have been conducted. These experiments show that although the GARP data accuracy requirements for the satellite observing systems were not met, assimilation of FGGE satellite data is capable of providing a reasonable determination of the complete atmospheric state. In general, a small improvement to forecast skill in the Northern Hemisphere and a larger improvement in the Southern Hemisphere results from the assimilation of satellite soundings and cloud-track winds.

4. REMAINING PROBLEMS AND THE PRESENT STUDY

The results of the real data impact studies indicate that major deficiencies in the global observing system still exist and that the FGGE satellite sounders are far from optimal. Advanced passive infrared and microwave sounders and active scatterometer and lidar sounders in a variety of combinations have recently been proposed to improve the accuracy of satellite observations and extend the useful range of numerical weather prediction. Realistic observing system simulation experiments are required to determine which of the proposed instruments will provide the greatest improvements as well as the optimal design of the future global observing system.

As indicated before, previous simulation studies have been characterized by the use of the same model to simulate "nature" and observations and to produce forecasts. This "identical twin" problem may distort the conclusions derived from such studies, as discussed in the following section.

In the present study, we attempt to avoid these limitations by designing a more realistic simulation system and calibrating its results by comparison with real data experiments performed with a similar system, and by accurately simulating the expected accuracy and characteristics of observational systems. The simulation system is then used to study the potential impact of advanced passive sounders and lidar temperature, pressure, humidity and wind observing systems.

5. DESIGN OF THE SIMULATION SYSTEM

The analysis/forecast simulation system consists of four elements: 1) An atmospheric model integration to provide a complete record of the "true" state of the atmosphere (called nature). This record is then used to fabricate observational reports and to evaluate analyses and forecasts. 2) A conventional data assimilation cycle that is used as the "control experiment." The control experiment is like an operational forecast-analysis cycle based on conventional observations, except that it makes use of fabricated conventional data obtained from the nature run to produce the analyzed fields. 3) A satellite data assimilation that differs from the control in also including fabricated satellite data incorporated in an

intermittent or time-continuous manner, in the forecast-analysis cycle.
4) Forecasts produced from both control and satellite initial conditions. Comparison of these forecasts with nature provides an assessment of the impact of satellite data.

Two important considerations are involved in the design of the control assimilation run: the nature of the initial conditions, and the forecast model used. In reality, short-range forecasts have errors stemming from three different sources: 1) inaccuracy of the initial state; 2) model errors that can be ascribed to numerical truncation (horizontal and vertical truncation errors due to insufficient resolution); and 3) model errors that can be ascribed to the "physics" of the model. The latter include parameterization of subgrid processes like radiation, cumulus convection, and friction, as well as sources of external forcing, like orography, sea/land contrast, and even the use of an artificial rigid top boundary condition, common to all numerical models. Numerical and "physical" deficiencies introduce systematic errors in the model integrations which are most evident in the differences between model and observed climatological averages. A striking example of these climatological errors is apparent in the stationary, forced planetary waves. Even though these large scale waves are numerically well resolved, they are not well simulated by numerical models. In a numerical forecast, a model tends to drift towards its own climatology, so that serious errors in the stationary waves are apparent after even a short time. For realistic simulation studies, all three sources of errors should be simulated. In previous simulation experiments, the same model was used to produce the "true" state and "forecasts." Therefore, the errors in the forecasts were due only to errors in the initial conditions. This method ("identical twin experiment") has the apparent advantage that it isolates the effect of initial data errors and avoids both numerical and "physical" errors. On the other hand, it has a very important shortcoming: since the model and "nature" have the same climatology, the accuracy of the simulated forecasts may be far superior to the accuracy of real forecasts. As a result, the external error growth due to the fact that current models are only approximations of the atmosphere is not present in the "identical twin" experiments. This has the effect of increasing the skill of conventional forecasts at low levels of data coverage, because the perfect forecast model is able to "fill up" data gaps. Consequently, at low levels of data, the impact of an observing system is overestimated, whereas the impact of high levels of data, such as provided by satellites can be underestimated. In addition, if the "nature" and "forecast" models are not realistic enough, i.e., don't possess a realistic model climatology, the data impact may be distorted. For example, a forecast model that cannot simulate the "roaring forties" regime in the Southern Hemisphere will not be helped by better low level winds in the Southern Hemisphere. The forecast model used should be sufficiently accurate that error growth should be dominated by initial data errors rather than by model dominated errors such as truncation errors. Otherwise, the experiment may overestimate the skill of the forecast and underestimate the influence of the data on the analysis.

Finally, if simulation studies are to provide an accurate indication of how simulated data will influence forecasts in the real world, it is crucial that their error characteristics be realistic. For simulated observational errors to be representative of real observational errors they should be introduced at actual observing locations and should not be just white noise. Random errors with a standard deviation of the order of GARP errors saturate the spectrum at high frequencies and their effect is mostly averaged out. Horizontal and vertical correlations of error and their dependency on the synoptic situation should be introduced appropriately.

In the current simulation studies, we attempt to minimize difficulties of earlier studies discussed previously. In order to avoid the "identical twin" character of previous studies, the high resolution (1.875° x 1.875° x 15 levels) ECMWF model is used as nature, and the 4° x 5° x 9 levels GLAS model is used as the assimilation and forecast model.

6. GLAS SIMULATION OF OBSERVATIONS OF SPACE-BASED SOUNDING SYSTEMS

In this study, we will be simulating forecast impacts using the current passive HIRS2/MSU sounding system as well as other passive systems using the Advanced AMTS and AMSU infra-red and microwave sounders alone and in various combinations. In addition, we will simulate active lidar systems which measure pressure, temperature, and wind profiles. The location and times of the passive soundings will be identical to those produced operationally in November 1979. In the case of the operational HIRS2/MSU sounding system, one could simulate atmospheric soundings in a manner analogous to those of the conventional observing system by using actual statistics relating accuracies of retrieved atmospheric soundings with colocated radiosonde reports. This approach has two important drawbacks. First, this procedure cannot be used with future sounders, for which we have no error statistics. Secondly, and much more significantly, the errors of temperature profiles retrieved from passive sounders are not random, but are highly correlated in the horizontal and vertical and are dependent on the nature of the synoptic situation, including the interrelationship between atmospheric temperature-humidity profile, ground temperature, and cloud fields.

To simulate atmospheric temperatures determined from passive sounders, we therefore take the more fundamental approach of first simulating radiance observations seen by the satellite and then retrieving temperature profiles from the observations. The simulations are performed using the radiative transfer model described in Susskind et al. (1983) and temperature retrievals as in Susskind et al. (1984). In order to simulate radiances for the channels for a given observation, one needs the surface pressure, atmospheric temperature-humidity-ozone profile, the ground temperature and emissivity as a function of frequency, and the multi-layer cloud field together with the spectral properties of the clouds. In addition, one needs the viewing angle of the satellite and location of the sun. In order to simulate a sounding reported at a given time and location, the atmospheric temperature-humidity profile is taken from the "nature" run, as obtained from ECMWF, interpolated in space and time to the satellite coordinates. The surface pressure is obtained using interpolated sea level pressure values, again given by "nature," and topographical fields. The fields obtained from ECMWF did not contain information about ozone, ground temperature and emissivity, and clouds however. Of these, ozone is the least significant and was fixed as a function of latitude according to climatological values. The ground temperatures and surface emissivities were simulated according to reasonable values determined from analysis of HIRS2/MSU data for November 1979 as in Susskind et al. (1984).

In the case of ground-temperature, we generated fields of T_G-T_A, that is ground temperature minus surface air temperature, and examined their mean and standard deviation over a 2°x2° grid for the month. Ground temperatures for a given location were then defined as $T_G = T_A + \overline{T_G-T_A} + \delta$ where T_A is the interpolated surface air temperature as above, $\overline{T_G-T_A}$ is the mean ground-surface air temperature difference for the location as determined from real HIRS2/MSU data for the month, and δ is a random component consistent with the observed standard deviation. Surface emissivity, ε, at 50.3 GHz, which is an important factor affecting MSU and AMSU observations, was determined in an analogous manner, using mean and standard deviation values of ε determined for November 1979 from the real HIRS2/MSU data. It was interesting to note, looking at these maps, that the standard deviations of ε were in general small, except for those areas where the ice edge was changing during the month or in regions of variable snow cover. Surface emissivity for the infra-red channels was taken as fixed as described in Susskind et al. (1983).

Perhaps the single most important factor affecting the observations and accuracy of passive retrievals is clouds. In order to get the proper spatial correlations of errors as a function of synoptic situation, the cloud fields must be very realistically related to the synoptic situation. We used the relative humidity fields, r_j, to produce up to four levels of broken clouds at each sounding location, with pressures at 850 mb, 700 mb, 500 mb, and 300 mb. The cloud fraction α_j at a given level j, is simulated according to

$$\alpha_j = \frac{r_j - r_{cj}}{1 - r_{cj}}$$

where r_{cj} is a pressure dependent relative humidity cutoff value whose values were provided by NMC.

The radiances for channel i observed by the satellite are computed as

$$R_i = \sum \overset{*}{\alpha}_j R_{ij} + (1-\sum\overset{*}{\alpha}_j) R_{i,CLR}$$

where R_{ij} is the radiance which would be observed in channel i if the field of view were completely covered by clouds at level j. $R_{i,CLR}$ is the radiance which would be observed if there were no clouds, and α_j^* is the fraction of the sky covered by clouds at layer j as seen from above. Clearly, while α_j can be as large as 1, $\sum\alpha_j^*$, can only be between 0 and 1. To insure this, we assume the clouds in each layer are totally correlated in space and fix $\alpha_j^* = \alpha_j - \sum_k \alpha_k^*$ for layer j where α_k^* represents all layers above j, but constrain α_j^* to be no less than zero. In other words, α_j^* equals zero if α_j is less than the cloudiness above, and α_j^* is the difference between α_j and the largest cloudiness above otherwise. All cloud radiances are simulated assuming the clouds are opaque at infra-red frequencies and transparent at microwave frequencies.

The GLAS retrieval method uses two field of view to perform a cloud correction to be used on the observed infrared radiances. In the simulation of radiances, observations in two fields of view were simulated for each sounding. The radiances are simulated assuming only the cloud fractions α_j^* differ in the two fields of view. For a given level, $\alpha_{j,1}^*$ and $\alpha_{j,2}^*$, corresponding to cloud fractions in both fields of view, were simulated from α_j^* in the following way. At $\alpha_j = 0$ or 100, both cloud fractions are set at 0 to 100. Otherwise $\alpha_{j,1}^*$ is less than α_j^*, varying linearly between the following points (0, 0), (20, 10), (90, 60) and (100, 100), and $\alpha_{j,2}^*$ is greater than α_j^* varying linearly between the points (0,0), (20,30) and (100,100). This allows for reasonable discrimination between the cloud fraction and radiances in both fields of view. In analysis of actual data, this discrimination, which is necessary for performing the cloud correction, is obtained by separating and then averaging observations in the warmest and coldest individual spots in an area.

As in the analysis of real HIRS2/MSU data, soundings are rejected if the radiances indicate too much cloudiness in the field of view (typically more than 70% in a sounding area) or if no atmospheric solution can be found from which computed radiances match the cloud corrected radiances to within 1°K. AMTS and AMSU observations and retrieved temperatures are produced in an analogous way.

In the case of active sounders, the errors obtained from analysis of the data are more nearly random and uncorrelated with each other. Therefore, the approach of generating random uncorrelated errors will be used in simulating retrieved quantities. To begin with, the coverage of sounding data will be taken as in the passive sounders for comparison purposes. Later, more realitic scan patterns for the active sounders will be used. Studies will be made as a function of assumed noise level and scan pattern. In all cases, signal to noise values will be attenuated at given levels according to the effective cloud cover, α_j^*, as defined above.

7. PRELIMINARY RESULTS

For all of the experiments which have been completed to date, the nature run is a twenty-day integration from 0000 GMT 10 November 1979 using the 15 level, 1.875° resolution, ECMWF model. All types of FGGE and conventional data were simulated by NMC by interpolating the nature fields to observation locations and adding assumed random or systematic errors to the interpolated values (C. Dey, personal communication). Only satellite temperature soundings were assumed to have systematic errors. These were generated using the first approach described in Section 6. GLAS simulated retrievals using the second approach described in Section 6 are currently being generated but have not yet been used in our experiments. LIDAR wind profiles were simulated at TIROS observation locations with 1-3msec^{-1}

accuracy. Wind profiles were not generated at levels below which the integrated cloud amount exceeded 90%.

Experiments have been conducted to calibrate the simulation system and determine its realism, and to begin to assess the relative impact of temperature and wind profile observing systems. To this end, two real data assimilation cycles, a control and FGGE (see Halem *et al.*, 1982 for descriptions), and five simulated data assimilation cycles, control, FGGE, control plus TIROS, control plus perfect temperatures, and control plus wind profiles were performed for the period 0000 GMT 10 November to 0000 GMT 25 November 1979.

The NMC analysis for 0000 GMT 10 November was used as initial conditions for the real data assimilation cycles. Initial conditions for the simulated data assimilations were provided by a real data control assimilation from 0000 GMT 4 November to 0000 GMT 10 November. Eight five-day forecasts were generated from each assimilation at 48 h intervals beginning on 11 November. In addition, a twelve-day integration from the ECMWF analysis at 0000 GMT 10 November was generated with the GLAS model. This forecast was then compared to the nature run as a measure of the differences between the two models.

Fig. 1. shows that there are substantial differences between the GLAS and ECMWF sea level pressure forecasts from 10 November as verified over North America. For the first four days the differences between the two model forecasts are about as large as the differences between the ECMWF forecast and its analysis. However, from five to eight days the two model forecasts resemble each other more closely than either forecast represents the analysis. In addition an examination of global difference

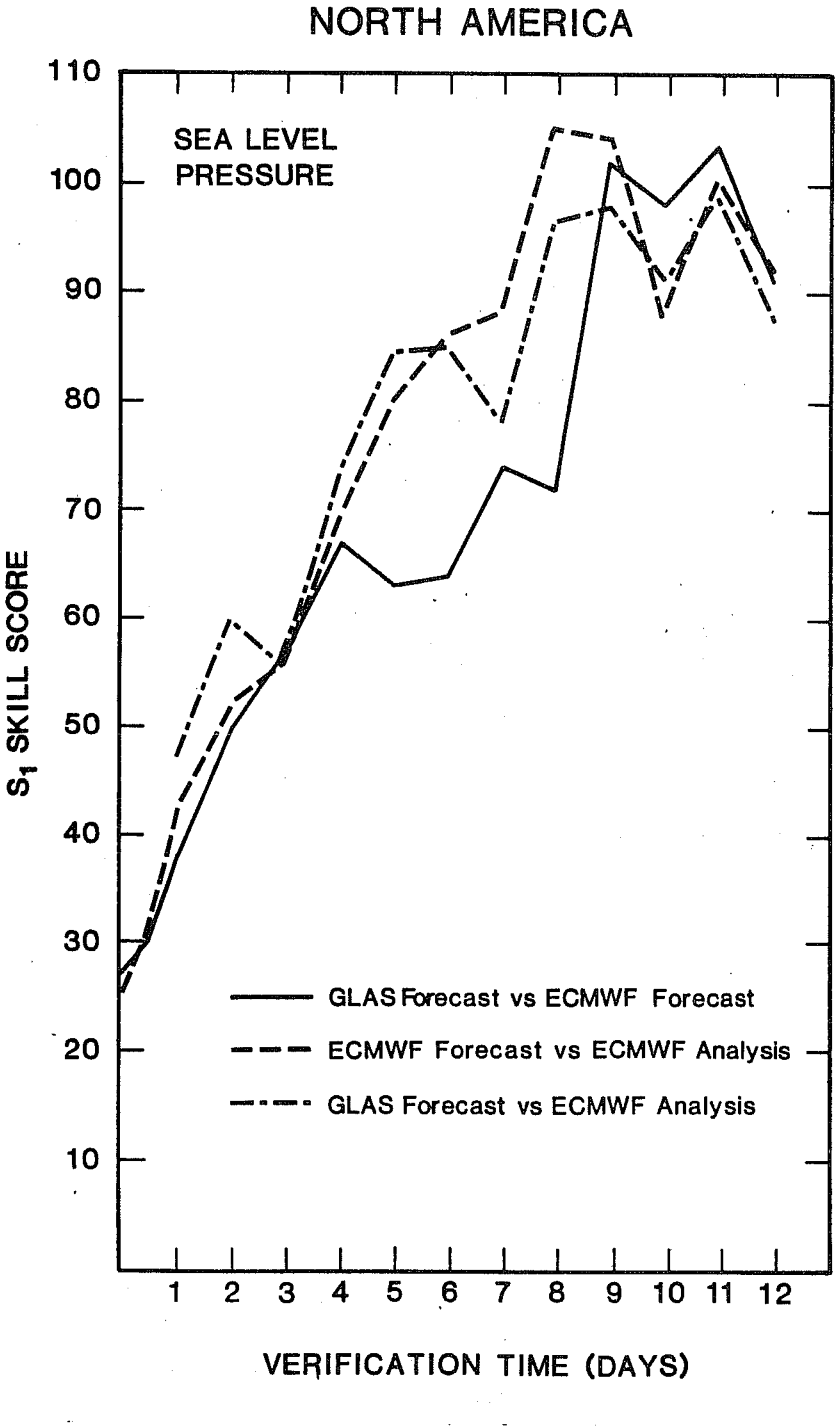

Fig 1. Sea level pressure S_1 scores for North America for the ECMWF Nature run verified against the ECMWF analysis, and the corresponding GLAS model forecast from the ECMWF analysis at 0000 GMT 10 Nov 79 verified against the ECMWF analysis and the ECMWF Nature run.

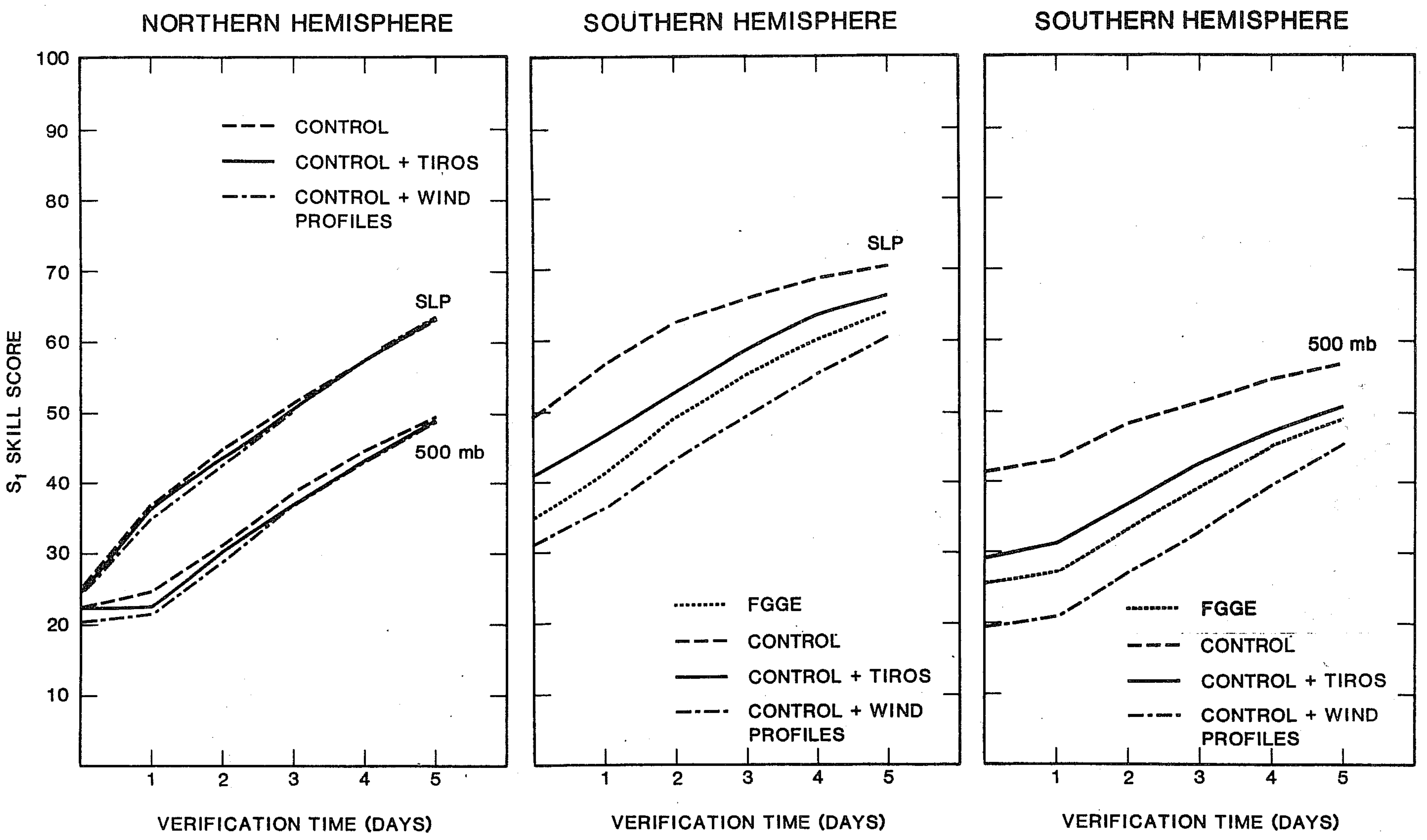

Fig. 2. Simulated data S_1 score verification.

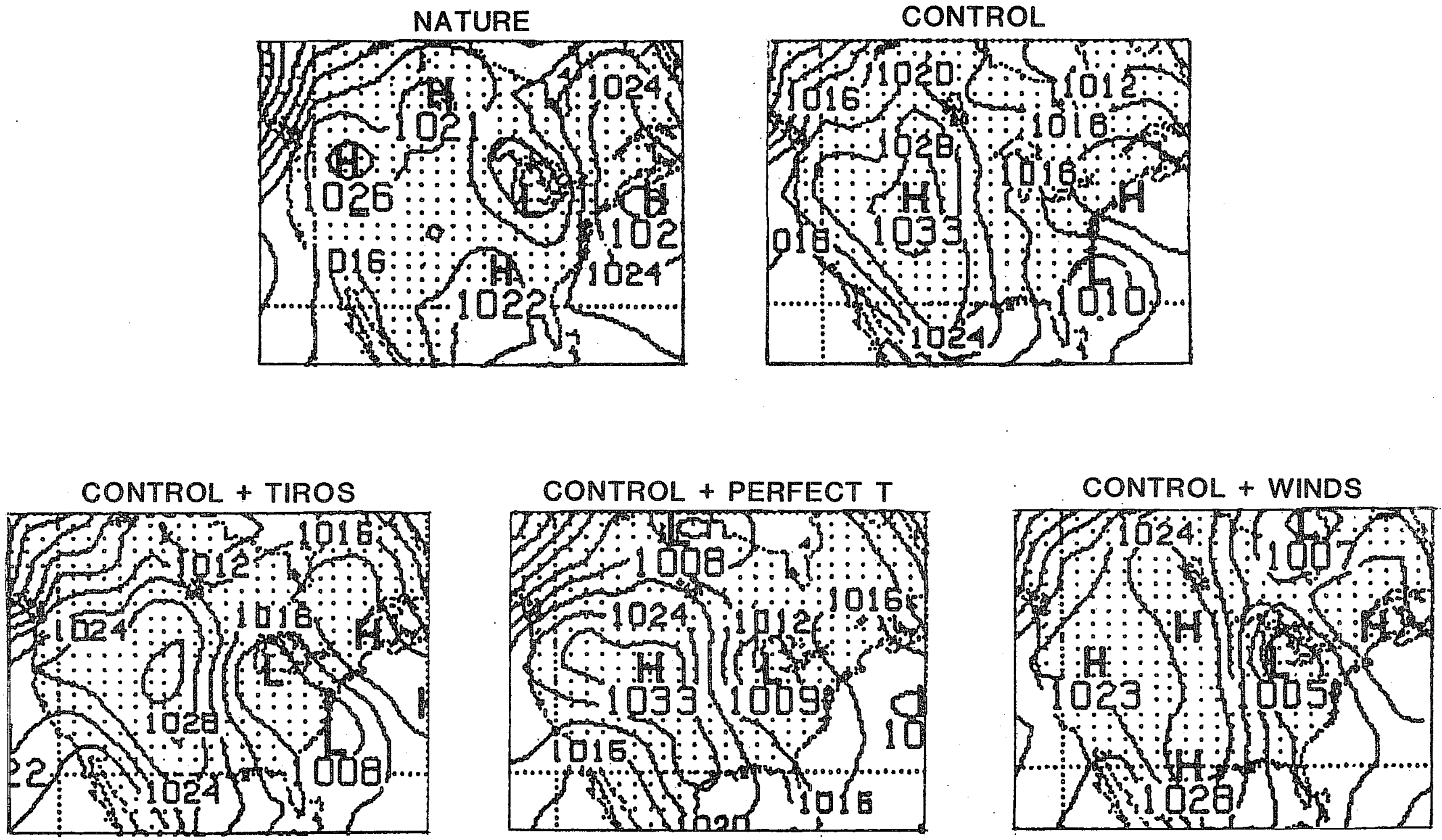

Fig. 3. Simulated 5 day sea level pressure forecasts from 23 Nov 79 and verification.

fields between the forecasts and between each forecast and the analysis (not shown) reveals that in the Northern Hemisphere, the model forecast differences are of a larger scale than the forecast versus analysis differences. These results indicate that the simulation system does differ significantly from the identical twin system described previously. But the differences between the models still may not be sufficiently realistic.

Fig. 2 summarizes the initial results of our simulation experiments. S_1 skill scores averaged for eight forecast cases are presented for the control, control plus TIROS and control plus wind profiles for the Northern Hemisphere, and for the control, control plus TIROS and control plus wind profiles and FGGE experiments for the Southern Hemisphere. The FGGE results were nearly identical to the control plus TIROS in the Northern Hemisphere and are not shown. Similarly the control plus perfect temperatures were on the average similar to the control plus TIROS and are not presented.

From Fig. 2, it can be seen that the use of simulated wind profile data shows a significant improvement over the TIROS or FGGE experiments in the Southern Hemisphere. For the Northern Hemisphere the impact of both simulated TIROS and wind profiles is only very slightly beneficial on the average. However in specific cases, significant forecast improvements occur for smaller regions. Fig. 3 shows a case of major improvement in the prediction of a storm over the United States which was poorly forecasted with the simulated control system. The use of TIROS data improved the prediction of the low near the Great Lakes. Significant further improvement resulted from either perfect temperatures or wind profiles.

To measure the realism of the simulation results, comparisons were made between the real and simulated data verifications for the same regions. These comparisons showed that the simulated control experiment was unrealistically accurate in the Northern Hemisphere but realistic in the Southern Hemisphere. In addition, the impact of TIROS and FGGE data appears to be slightly overestimated requiring a small calibration to the simulation impact results.

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