NMC NOTES

The New Global Operational Analysis System at the National Meteorological Center

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ABSTRACT

At the National Meteorological Center (NMC), a new analysis system was implemented into the operational Global Data Assimilation System on 25 June 1991. This analysis system is referred to as Spectral Statistical Interpolation (SSI) because the spectral coefficients used in the NMC spectral model are analyzed directly using the same basic equations as statistical (optimum) interpolation. The major differences between the SSI analysis system and the conventional optimum interpolation (OI) analysis system previously used operationally at NMC are:

-The analysis variables are closely related to the coefficients of the NMC spectral model.

-Temperature observations are used, not heights as in the previous procedure. As a result, aircraft temperatures are being used for the first time at NMC.

-Nonstandard observations, such as satellite estimates of total precipitable water and ocean-surface wind speeds, can be easily included.

-No data selection is necessary. All observations are used simultaneously.

-The dynamical constraint between the wind and mass fields is more realistic and applied globally.

-Model initialization has been eliminated. The analysis is used directly as the forecast model initial condition.

Extensive pre-implementation testing demonstrated that the SSI consistently produced superior analyses and forecasts when compared to the previous OI system. Improvement in skill is shown not only for the 3–5-day forecasts, but also in one-day aviation forecasts.

1. Introduction

The production of high-quality global forecasts requires the creation of a complete and accurate description of the atmosphere's initial state. At the National Meteorological Center (NMC), this is done through the use of the NMC Global Data Assimilation System (GDAS; Kanamitsu 1989). Since the observational network at any one time contains large data voids, and the observations, when available, contain errors and may not be representative of a larger-scale region, the global atmospheric state cannot be determined by observations alone. To help overcome this inadequacy in the observational network, data from earlier times are included by the GDAS system through a 6-h forecast from the previous analysis. Using known error properties of both the observations and the 6-h forecast, an objective analysis procedure combines the new observations with the 6-h forecast to produce an estimate of the true atmospheric state.

Most of the major operational numerical-prediction centers perform analyses using some form of statistical or optimum interpolation (OI). These systems are based on the ideas of Gandin (1963), but are ultimately derived from the curve-fitting methods pioneered by Gauss early in the 19th century. At the NMC, OI was introduced in 1978 (Bergman 1979). This marked the first time at NMC that a system was designed from a carefully formulated mathematical/statistical theory. Prior to the introduction of OI, analysis systems were designed heuristically to simulate the procedures used by skilled hand analysts. As pointed out by Dey (1989), there are three principle considerations guiding the design of automated analysis: spatial coherence, temporal continuity, and dynamic consistency in the analyzed fields. The theoretical framework of OI-based procedures implicitly incorporates these three properties.

Unfortunately, OI is not really optimal, because exact application of the underlying theory will never be computationally feasible. As a result, approximations must be made, and implementation details are crucial elements for the design of OI-based schemes. For this reason, several changes were made to the NMC OI system during its 11-year lifespan (Dey and Morone 1985; DiMego 1988; Kanamitsu 1989). Thus, improvements to existing OI-based systems and development of entirely new procedures can still be expected in the pursuit of the theoretical optimum.

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This paper describes the latest change to the GDAS analysis at NMC, involving a completely new analysis system. While it is still based on the same underlying OI theory, the differences from conventional OI are so extensive that a new name was given—the spectral statistical interpolation (SSI) analysis. This type of analysis has also been referred to as 3-D variational analysis (Pailleux 1990). There are three principal differences between the SSI and conventional OI analysis schemes. First, the SSI analysis variables are not required to be the same as the observation variables. Thus, the analysis variables are closely related to the NMC spectral-model variables, while the observational dataset has the potential to contain many nonconventional observation types. The previously operational NMC OI, on the other hand, uses observations of heights, winds, and relative humidity to analyze gridpoint values of heights, winds, and relative humidity on isobaric surfaces, and then transforms the results into the spectral-model variables.

The second principal difference between the SSI and the previous operational OI is that the SSI uses all observations at once to perform the analysis globally. This is the proper application of the mathematical theory underlying OI and is necessary in this system because the SSI analysis variables are defined spectrally. Until now, it seemed computationally impractical to solve such a large problem, so all previous OI schemes have used a local approximation in which the analysis problem is solved for one gridpoint (or a group of points) at a time, using only the observations nearby. This approximation requires the development of an imperfect algorithm to choose which observations are to be used for a particular gridpoint.

Finally, the SSI, since it analyzes directly in the model coordinates, can utilize a dynamical constraint between the analysis variables, which is more accurate and globally applicable. In the current implementation of the SSI, the geostrophic relationship between height and wind used in the previous NMC OI system has been replaced with a globally defined linear balance equation, which also includes a parameterization of surface friction effects. This improved balance constraint, along with the global use of the data, has made the use of an initialization step that removes imbalances between the winds and heights superfluous. Moreover, the SSI analysis produces a smoother correction to the 6-h forecast than the previously operational system, yet the rms fit to the observations is as good or better.

It is tempting to view the SSI as an updated version of the analysis based on the use of Hough functions (Flattery 1971), which was in use at NMC prior to the introduction of OI. There are indeed some similarities. Both systems use globally defined functions, both have global balance constraints, and both use all data simultaneously, with no data-selection algorithms required. But there are also major differences. First, the Hough analysis uses full fields, while SSI works with just the correction to a 6-h forecast. This is an important distinction, because the balance imposed by both systems is linear and much less appropriate for the full fields. Second, the Hough wind analysis is strictly rotational, while the SSI includes divergence and ageostrophic height components. Third, the SSI analysis variables are very similar to those of the assimilating forecast model, while the Hough analysis variables required vertical interpolation and conversion to model variables. Finally, and most importantly, the SSI is derived from a comprehensive theory, while the Hough analysis was crafted by trial and error to produce what were, for its time, very good analyses. The SSI is a step closer to the theoretically correct application of OI, and in that sense is more closely related to the OI analysis than the Hough analysis.

In the next section, we present a brief description of SSI. Section 3 contains results of individual analyses and long-term data-assimilation runs and resulting forecasts. This section is followed by some results from a subjective evaluation by NMC's Meteorological Operations Division (MOD). Because of the nature of this report, many details have been left out. A more complete description can be found in Parrish and Derber (1991). Note that the results shown in this system are slightly different from those in Parrish and Derber (1991), because several changes have been made to the system since the publication of the earlier paper. These changes have included a change in the resolution of the forecast model (Kanamitsu et al. 1991), a reestimation of some of the statistics, the removal of the initialization procedure, and the inclusion of the empirical friction term in the balance equation. The results in this paper are from the system that was made the operational objective analysis system on 1200 UTC 25 June 1991.

2. The analysis procedure

Both SSI and conventional OI attempt to make the analysis as close as possible to the observations and the 6-h forecast from the previous analysis. The proximity of the analysis to the observations and the 6-h forecast is measured in terms of weighted squared differences, where the weights control the relative importance of the various terms. Thus, if the observations were exactly equal to the 6-h forecast, then the analysis would also be exactly equal to the 6-h forecast. Otherwise, the analysis is always a compromise between the observations and the 6-h forecast.

The mathematical theory common to conventional OI and SSI requires that all observations be combined simultaneously with the 6-h forecast to produce the analysis. This global problem is approximated as a series of local subproblems in conventional OI. These subproblems solve the analysis problem for a particular gridpoint or small volume of gridpoints based on a local set of observations. The choice of observations is known as data selection. The data-selection algorithm can become extremely complex logically, is usually computationally expensive, and may not always make the best decisions. The SSI analysis eliminates this local approximation, solving the analysis globally as a single problem. Thus, the data-selection problem has been eliminated.

It is extremely important to make the correct choice of relative weights that determine the confidence to be placed in each observation and in the 6-h forecast, which is just a summary of observations (and model dynamics, physics, etc.) from the recent past. These weights are determined by the known error properties of the 6-h forecast and of the individual observation types. The weights applied to the fit to the observations are constructed from two components: the observational error and the representativeness error. The observational error results from instrument errors. The representativeness error accounts for the fact that the instrument taking the observation is usually observing at a scale much smaller than the scale of the analysis. Thus, the observation is not representative of the scale of the features that are being analyzed. For example, if a radiosonde with no instrument error is rising through a thunderstorm, it may sample convective-scale winds, temperatures, and moisture that are not representative of the weather in a larger 100-km × 100-km area. Of course, this representativeness error depends on the resolution of the analysis. If the analysis scale is that of the thunderstorm, then the radiosonde data are representative of the analysis scales and should be retained by the analysis. Whenever possible, we have attempted to keep the observational and representativeness error consistent between the previous operational system and the SSI analysis system.

The definition of the weights for the fit to the 6-h

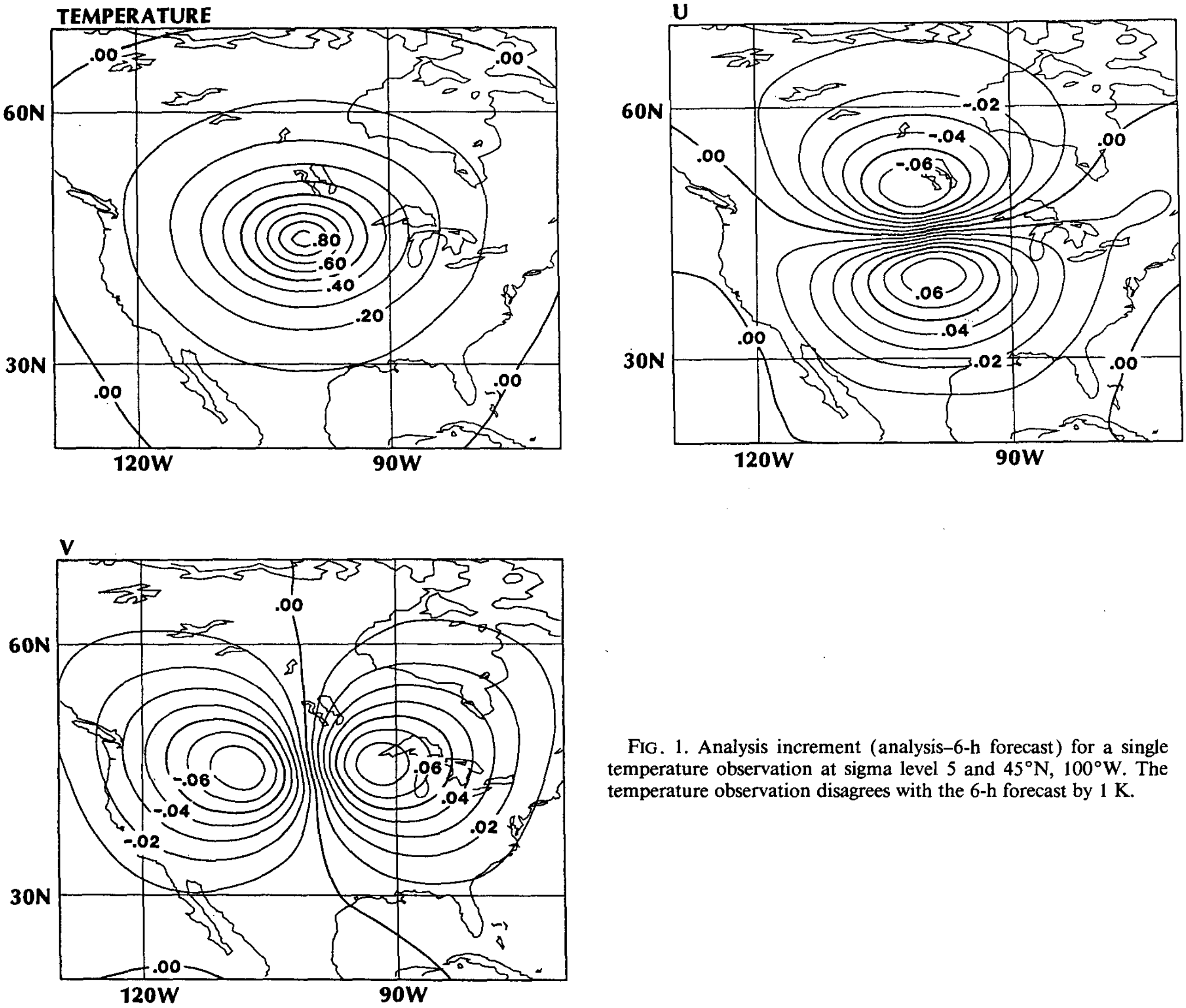
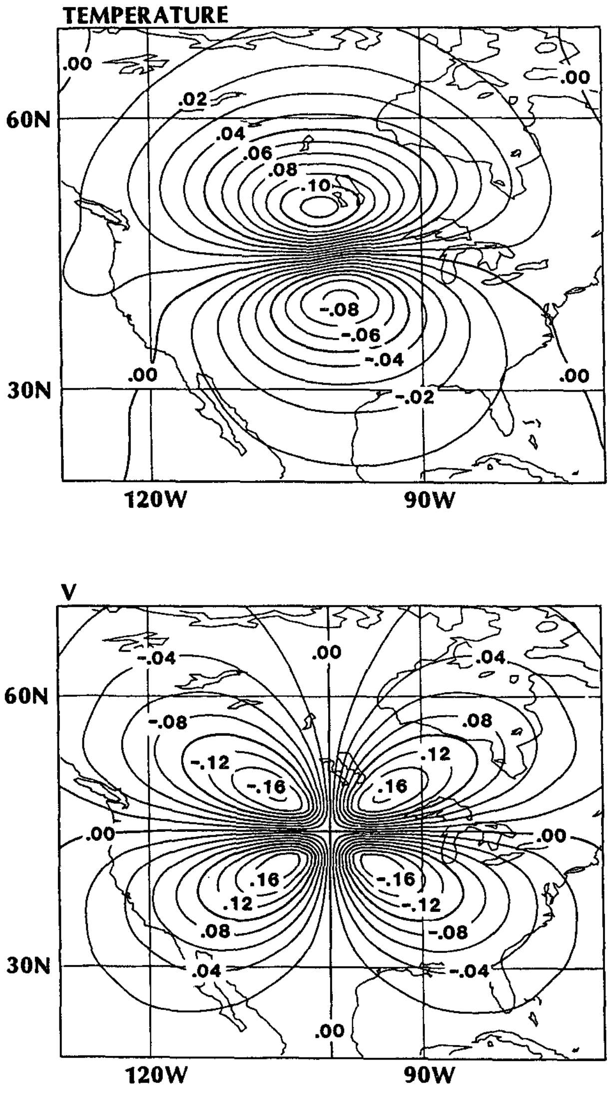


FIG. 1. Analysis increment (analysis–6-h forecast) for a single temperature observation at sigma level 5 and 45°N, 100°W. The temperature observation disagrees with the 6-h forecast by 1 K.

forecast is also very important to the success of the analysis system, since they determine the scale of the analysis and its suitability as initial conditions for the forecast model. The statistics that enter into these weights are very difficult to define directly from data spectrally, as is required for this analysis system. A crude estimate of these statistics has been obtained using an ensemble of differences between 24- and 48-h forecasts valid at the same time. The impact of the statistics on an analysis can be inferred from the analysis of a single point of data. Figure 1 shows the resultant adjustment that would be made to the 6-h forecast of temperature and wind for a single temperature observation at sigma level 5 (about 850 mb) and 45°N, 100°W, which disagrees with the 6-h forecast by 1 K. Figure 2 shows a similar result for a single observation of the wind, which disagrees with the forecast by 1 m s^{-1} in the east–west direction. The changes to the wind field by a temperature observation and *vice versa* result from the use of the balance imposed by the analysis system discussed below. These fields are qualitatively similar to those that would be produced by the previously operational system, except the spatial scale is larger. However, tests of the system show that the use of these statistics consistently produces fits to radiosonde observations as good or better than the previous operational system. Note that because of the more general balance between height and wind fields in the SSI system (as compared to the previous operational system), a relationship between the winds and heights is globally defined, including the tropics. Thus, some problems resulting from applying the previously operational geostrophic constraint only outside the tropics are eliminated.

It is not necessary for the analysis variables to be the same as those of the observations. Rather, it is only



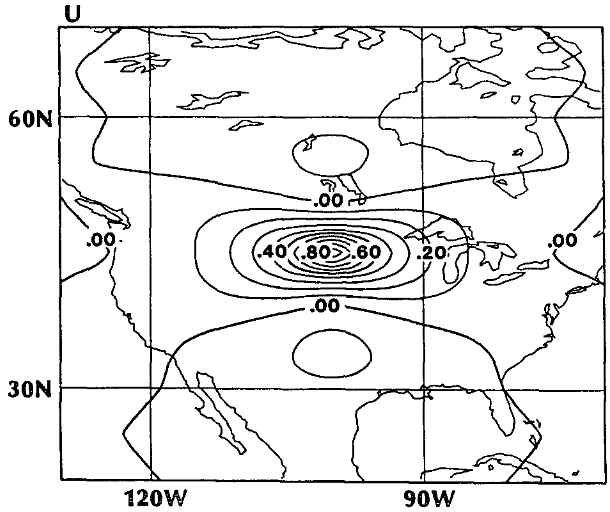


FIG. 2. As in Fig. 1, but for a single u-component observation. The wind observation disagrees with the 6-h forecast by 1 m s^{-1} in the east–west direction.

necessary to be able to calculate observed variables from the analysis variables in order to compare the analysis to the observations. This calculation may include both a horizontal interpolation to the observation locations and a transformation of variables. Thus, the analysis variables could be vorticity and divergence and the observations could be wind speeds without directions available. This flexibility in the definition of the analysis variables allows the easy use of nonstandard observation types and the use of analysis variables closely related to those used by the forecast model. For example, we are currently experimenting with precipitable water observations in the SSI. In principle, more complicated observations can be included. This is the case for the European Center for Medium-range Weather Forecasting (ECMWF), which has plans to include satellite radiance observations directly into an analysis system similar to the SSI (Pailleux 1990).

The analysis variables in the SSI system are vorticity, divergence, unbalanced heights, and specific humidity, while the input observation variables are wind components, temperature, surface pressure, and specific humidity. The height field in the analysis is described by adding the unbalanced part to a balanced part, which is derived from the vorticity and divergence fields through a linear balance equation. This linear balance equation contains an empirical divergence term to partially account for surface friction. The approximate geostrophic balance between the heights and winds is maintained through this balance equation. It is important to emphasize that this balance relationship is only being applied to the departure of the analysis from the 6-h forecast height and wind fields. Strong ageostrophic flow, which is present in the 6-h forecast, is maintained. In addition, errors in the ageostrophic component can still be partially corrected by observations through the unbalanced height variable and the divergence.

The solution to the analysis problem is found using an iterative algorithm. The current version of the SSI uses 100 iterations for both the moisture analysis and the dynamical variables. Most of the expense in each iteration comes from the transformation from spectral space to the model grid. Note that currently the moisture analysis is completely independent from the analysis of the other variables. Despite the large amount of computation, the SSI system runs as fast as the previous operational analysis system.

3. Objective evaluations

The system described in the previous section has been subjected to a long period of testing and evaluation. In this section, some of the characteristics of the system are presented, with emphasis on the differences from the previous operational system. The discussion will be divided into four main subsections. First, the analyses created using the same 6-h forecast are compared for both the previously operational OI system and the SSI system. To evaluate the extent of imbalances in the resulting analyses, the changes made by the initialization procedure are presented next. Then evaluations of the forecast skill from the previously operational OI and SSI assimilation systems are shown. Finally, hurricane forecast results from the 1990 operational T80 conventional OI system and the T126 SSI system applied to the period 25 August–19 September 1990 are presented.

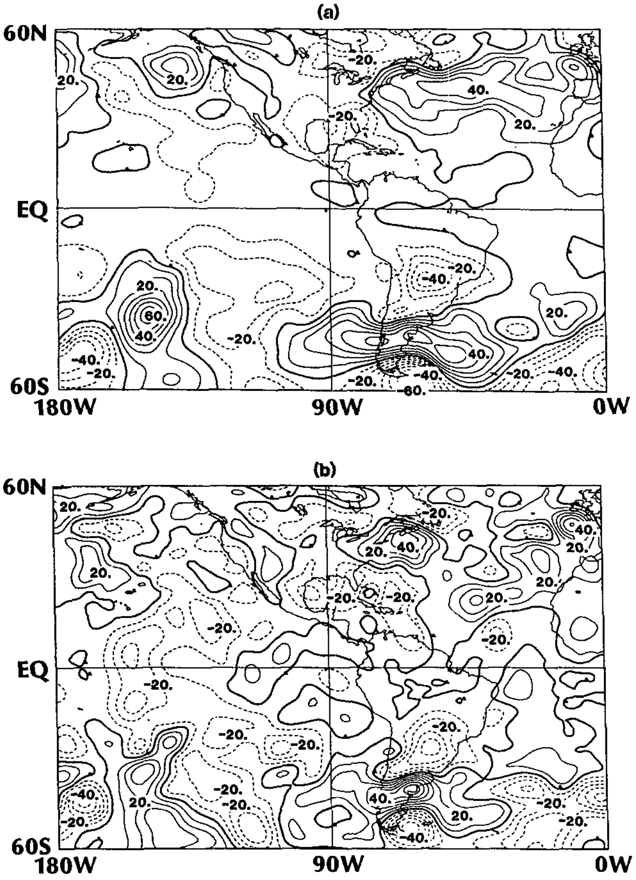


FIG. 3. The 250-mb height analysis increments (analysis–6-h forecast) for (a) SSI and (b) previous operational from 5 June 1991. Both were created using previously operational 6-h forecast. Contour interval is 10 m.

a. Analysis comparisons

The previous NMC global operational objective analysis technique (Dey and Morone 1985; DiMego 1988; Kanamitsu 1989) produced good quality results over many years of usage (Kalnay et al. 1990). In this section, the same 6-h forecast is inserted into both analysis systems, along with comparable observational datasets. Thus, the results differ primarily because of the different statistics, different use of data, and the different balance constraints used in each system.

In Fig. 3, the 250-mb height increments (analysis–6-h forecast) are shown for 0000 UTC 5 June 1991. These results are typical of those found on any day or at any vertical level. Both were created using the same 6-h forecast from 1800 UTC 4 June 1991. The height increments from the SSI analysis are smoother and smaller than those from the previous operational system. While some of the difference results from the statistics in the SSI emphasizing the larger scales, some of the smoothness is also due to the global use of all data. In the previous operational system only the closest subset of data was used to perform the analysis from a particular grid point. Thus, when moving from one grid point to the next, the data being used in the analysis could change. This change in the data from one point to the next introduces noise into the analysis. Despite the fact that the analysis increments are smoother and smaller in the SSI system, the resulting analysis produces a comparable fit to the data. Finally, note the much smaller changes in the tropics apparent in the height increments of the SSI analysis. One would expect the tropical height field to be smooth, without large changes from one time period to the next. As is demonstrated in the next subsection, many of the changes introduced in the tropics by the previous operational analysis were removed by the initialization procedure.

The time mean analysis differences between independent assimilations using the SSI and the previous operational analysis were also examined. The two most significant differences, weaker tropical precipitation and a weaker mean Hadley circulation, are related to each other. The zonal mean v-component for 16 June 1991 and the 5-day forecast fields are shown in Figs. 4 and 5. The operational assimilation system tends to produce a stronger Hadley circulation that decays with time. The SSI Hadley circulation is similar to the model Hadley circulation after a 5-day forecast and does not decay with time. Thus, the strength of the SSI Hadley circulation appears not to be controlled by the analysis system but rather the model dynamics and physics of the forecast model. The difference is significant, although it is difficult to determine which analysis is better. However, it is obvious that the SSI analysis system produces analyses that are more consistent with the forecast model.

b. Initialization

In most operational assimilation systems, the temperature, surface pressure, moisture, and winds are not well balanced at the end of the analysis procedure. This imbalance generates noise in the initial stages of the forecast. Balancing of the fields to eliminate the noise is known as initialization. Unfortunately, the initialization is usually done as an independent step after the analysis and thus usually adjusts the fields away from the data. Ideally, the necessary balance would be imposed by the analysis procedure, making the initialization unnecessary (see Williamson and Daley 1983). Thus, the magnitude of the adjustment by the initialization is a measure of the quality of the balance imposed in the analysis procedure.

In Fig. 6, the initialization increments (initialized fields minus analysis, see Ballish et al. 1991 for details on the initialization procedure) for the 250-mb heights are shown for the same case as shown in the previous section. The initialization makes very small changes to the SSI analyses, while the operational analyses are altered substantially. Often in the tropics, the initialization removes features introduced by the analysis. The SSI analysis does not produce these features, so it is not necessary to remove them. The very small

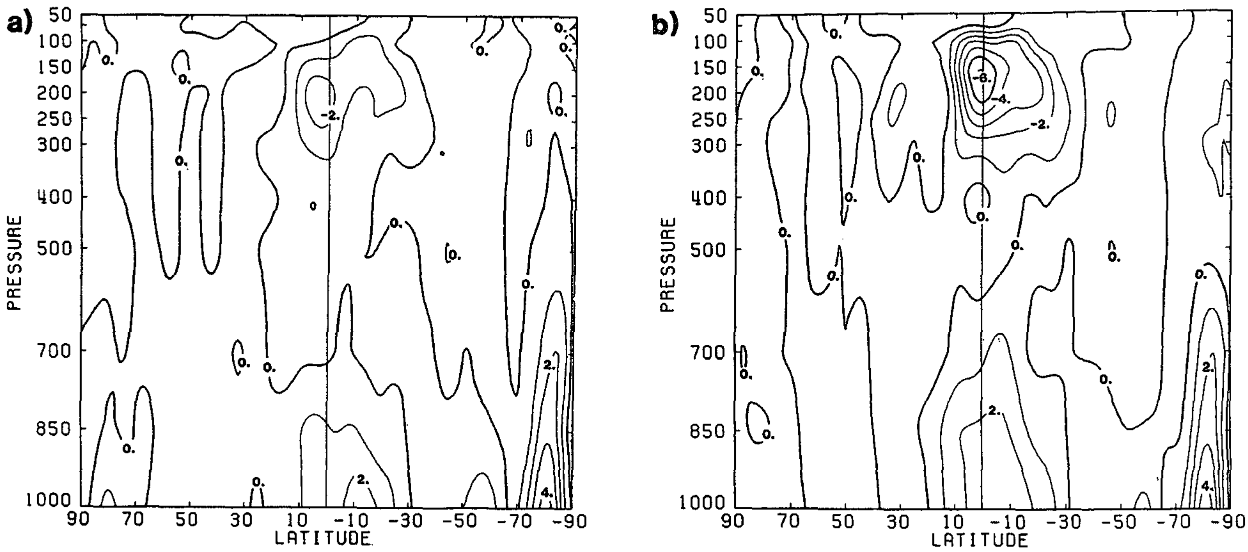


FIG. 4. Zonal mean v from 16 June 1991 for a) SSI and b) previously operational system.

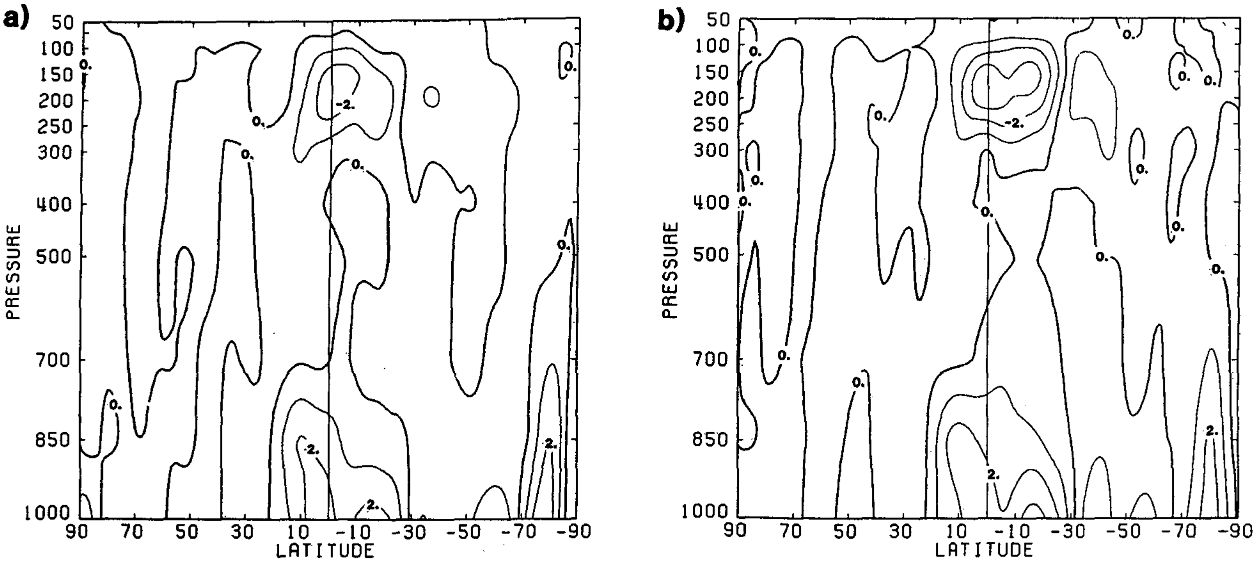


FIG. 5. Same as Fig. 4, except 5-day forecasts from 16 June 1991.

changes by the initialization for the SSI system suggests the possibility of removing the initialization step. We have done so, and after two months of assimilation, no detrimental effects have been noted. This is very advantageous, since now the analysis fields and the initial conditions to the forecast model are identical.

c. Forecast results

The most important operational test of analysis quality is the resultant accuracy of the forecasts. Five-day forecasts were produced from the SSI assimilation in parallel with the previous operational system between December 1990 and July 1991 (T80 before 6 March 1991). These forecasts were produced in real time using the operational database. In addition, a 30-day case from August 1990 was examined in a retrospective mode. The quality of a forecast can vary greatly from one day to another, so we will present average results for a period from June and July 1991. These results are similar to those found in the other periods. The forecasts are all verified against analyses from the previous operational system.

Figure 7 shows average anomaly correlation scores over the 27-day period for zonal waves 1–20, verified against the operational analysis. The anomaly correlation is a measure of the forecast skill ranging from +100% to −100%. It is the pattern correlation between the forecast anomaly (i.e., the difference between the forecast and climatology) and the verifying analysis anomaly. Forecasts with anomaly correlations of 60% or larger are usually considered synoptically useful. Figure 7a shows the result for 1000 mb in the Northern Hemisphere. The improvement by day 5 is about 3%. Similar but slightly smaller improvement is evident at 500 mb for the Northern Hemisphere (Fig. 7b). The Southern Hemisphere results are also encouraging. The low correlation at day 0 for 1000 mb and 500 mb (Figs. 7c and d) indicates that the two systems have departed from each other significantly. Still, by the end of the period, even with the handicap of verifying against the operational system, the SSI results equal those from the OI system. Similar results are found by looking at other measures of the forecast skill.

d. Hurricane forecast results

One of the uses of the global operational forecasts is to provide fields for the suite of hurricane-track forecast models used by the National Hurricane Center. Two of the primary models are the QLM (Mathur 1991) and the NHC90 (McAdie 1991; Neumann 1988). Changes to the global model or the data-assimilation system may have an undesirable effect on the performance of the hurricane models. Since the last hurricane season (1990), two major changes have been made to the analysis and forecast system. First, the model was changed in horizontal resolution from T80 to T126 and several changes were made in the model physics as described by Kanamitsu et al. (1991). The second major change was the introduction of the SSI as described in this paper. This section will summarize results from a comparison of the NHC90 and QLM forecasts from the 1990 system and the new T126/SSI system.

The evaluation was performed by rerunning the GDAS and 72-h forecasts at 0000 and 1200 UTC over the period from 25 August to 19 September 1991 with the new T126/SSI system. The analysis and forecast fields were then input to the QLM and NHC90 models, and 72-h forecasts were made from each model. These forecasts were compared to results from the 1990 op-

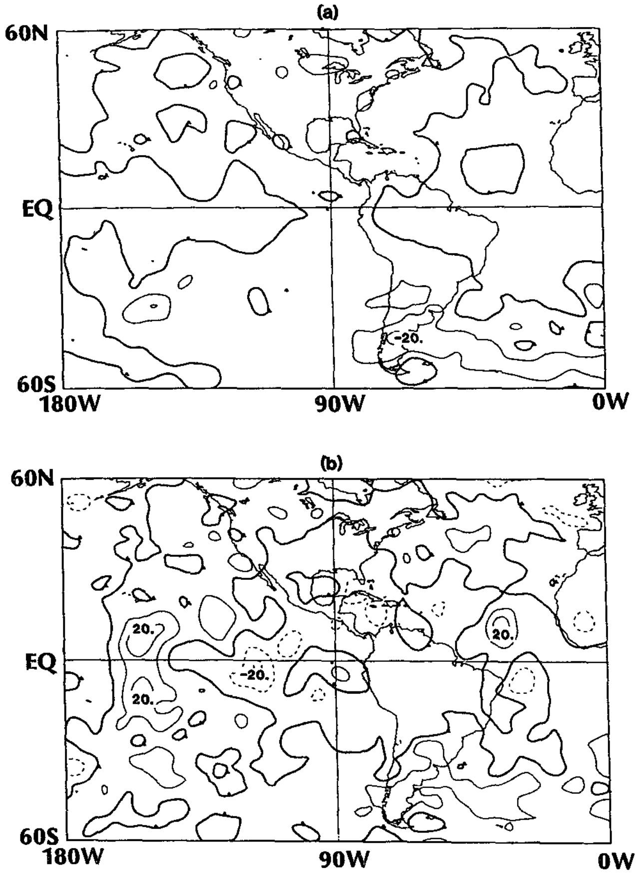


FIG. 6. Same as Fig. 3, except initialization increments (initialized–analysis).

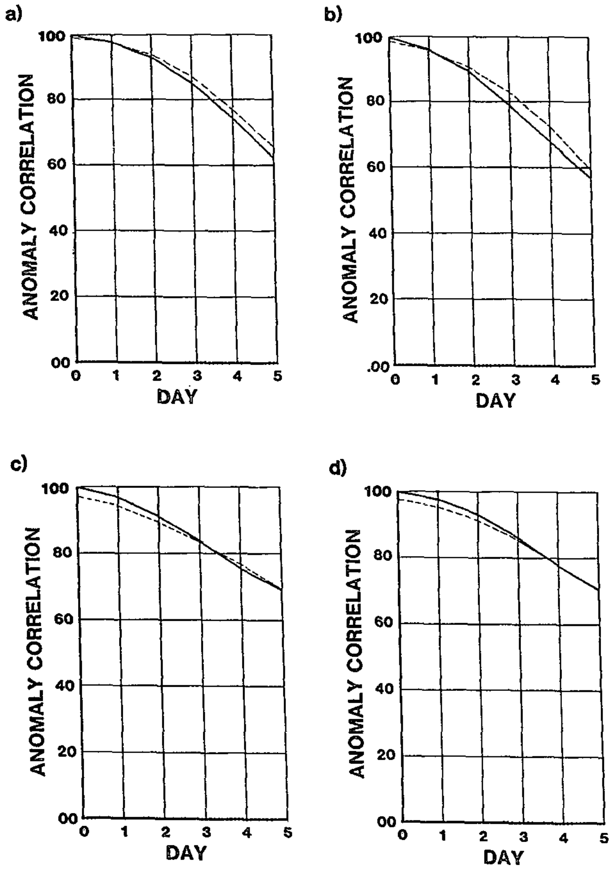


FIG. 7. 1–5-day anomaly correlation scores verified against operational analyses for a) Northern Hemisphere 1000-mb, b) Northern Hemisphere 500-mb, c) Southern Hemisphere 1000-mb, and d) Southern Hemisphere 500-mb. Thick solid line is from previous operational assimilation, thin dashed line is for SSI. Starting dates of the forecasts ranged from 24 May to 18 June 1991.

erational system. Ideally, the T126 changes and the SSI results should be tested separately and over a longer time period, but computational considerations limited the length of the period and required a combined evaluation of both model resolution and analysis. During this period there were three named storms in the Atlantic: Gustav, Hortense, and Isidore.

The results for the QLM in the Atlantic are presented in Table 1. Due to computer problems, the QLM forecasts for 1200 UTC 30 September to 1200 UTC 1 October 1991 were missing from the QLM forecasts. The results from the T126/SSI system were slightly better at both 12 and 72 h. However, at 24, 36, and 48 h, the 1990 system produced superior results.

For the NHC90 model (Table 2), the 12-h forecasts were very similar because formulation of the NHC90 model assumes a very strong component of persistence in the storm's track over the first 12-h period. At the 24- and 36-h periods the forecasts are still essentially equivalent in quality. However, for the longer forecast periods of 48 and 72 h, the T126/SSI system showed a substantial improvement in the forecast tracks. Examination of individual storms showed that the results from Isidore were essentially equivalent for both systems. However, the 48- and 72-h forecasts for Gustav and Hortense were substantially improved in some cases.

4. Subjective forecast evaluations

In addition to the objective scores, the analyses and forecasts were evaluated by operational forecasters in NMC's Meteorological Operations Division (MOD). These subjective evaluations were performed by both the Monitoring and Aviation Branch and the Forecast

TABLE 1. Mean forecast errors (MFEs) for QLM model. Results include forecasts every 12 hours for three hurricanes in the Atlantic (Gustav, Hortense, and Isidore) over the period 25 August to 19 September 1990. The MFEs are given in km.

Forecast hour	12	24	36	48	72
QLM 1990	115	179	222	267	474
QLM T126/SSI	110	194	268	331	449
Number of cases	41	39	36	34	30

Branch. Note that the two forecast systems were run completely independently from each other. The following is a summary of their results.

The 250-mb wind forecasts and analyses were evaluated over the Northern Hemisphere (concentrating on jet streaks) by Patrick Burek and John Leathers of the Monitoring and Aviation Branch of MOD. The results from this evaluation indicate that the analyses of the 250-mb winds from the SSI analysis were at least as good as the previous operational system. Where there was dense data coverage (e.g., over the continental U.S.), both analyses were quite similar. However, the SSI analyses often appeared smoother and more streamlined. From the experienced forecasters' subjective impression, the new analyses appeared to be more correct in capturing the structure of jets than the previous operational analysis. The 24-h forecasts from the SSI analysis system were usually better. The SSI forecast was superior in that it consistently placed jets further north over upper-air ridges. The apparent discrepancy between equal quality of the analyses and consistently better 24-h forecasts can be explained by the better initial balance between the mass and wind fields imposed by the SSI. Because the initial fields are more in balance, the jets are maintained and evolved more realistically in the SSI system.

All of the forecasters from the Medium Range Forecast branch of MOD participated in the evaluation of the 3–5-day forecasts over North America from 15 March to 24 April 1991. Only 37 cases were available for evaluation during the period. The results were compiled by Paul Stokols and shown in Table 3, which categorizes the results in terms of the degree to which the SSI improved the forecast. When the models performed exceptionally well in difficult forecast situations involving the phasing of various extratropical systems (big wins), the SSI forecast was better three times out of five, with most of the improvement in days 3 and 4. The forecasters' comments usually emphasized the usefulness of the SSI forecast product in capturing major changes in trough/ridge patterns and subsequent storm development. In cases with small differences between forecasts, the SSI system appeared to handle the situation slightly worse. In these situations, the small differences could usually be handled well by the forecasters using statistical techniques (e.g., linear regression, climatology, consensus of models). Some of the small differences were caused by a greater tendency for the SSI system to overdevelop features. Nevertheless, the SSI system appeared to have fewer erroneous small-scale features in the forecasts. We suspect that this is a result of the smoother, better-balanced initial conditions resulting from the global use of all data.

TABLE 2. Same as Table 1 except results are from NHC90.

Forecast hour	12	24	36	48	72
NHC90 1990	104	180	268	377	639
NHC90 T126/SSI	104	183	261	348	522
Number of cases	44	42	40	38	33

TABLE 3. Subjective evaluation of SSI and the previously operational OI analysis system for period between 15 March and 24 April 1991.

	Big win		Small win		
Forecast day	SSI	OI	SSI	OI	Same
3	14	6	6	6	5
4	14	9	4	8	2
5	9	8	5	9	7

5. Discussion

The results that have been presented here on the performance of the SSI demonstrate a significant positive impact of the new analysis on forecast quality. These improvements were noted not only for the 3–5-day forecasts, but even in the short-range aviation forecasts. The success of the SSI can be understood by looking at the analysis increments (difference maps of analysis–6-hr forecast first guess), which are smaller, smoother, and better balanced than those from the previous operational system and still fit the data equally well. Initialization, which moves the initial state away from the observations, is no longer necessary, thus removing an additional source of error in subsequent forecasts. These favorable characteristics of the SSI are most likely a result of the elimination of data selection and careful application of a more realistic, global balance constraint.

The superior performance of the SSI system is especially exciting because the current version has the potential for substantial improvement. There are three areas where the SSI analysis system can be improved significantly. First, a more realistic representation of the statistics used for determining the weights in the analysis system has the most potential for improving the analysis. Second, the balance between the winds and heights in the SSI system is currently determined by a linear balance equation with the empirical inclusion of surface friction. This constraint can be improved, possibly even including advection terms. Finally, the system is ideal for incorporating nonconventional observations such as satellite observations of total precipitable water and wind speeds.

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REFERENCES

Ballish, B., X. Cao, E. Kalnay, and M. Kanamitsu, 1991: Incremental nonlinear normal mode initialization. Submitted to *Mon. Wea. Rev.*

Bergman, K., 1979: Multivariate analysis of temperature and winds using optimum interpolation. *Mon. Wea. Rev.,* **107,** 1423–1444.

Dey, C. H., 1989: The evolution of objective analysis methodology at the National Meteorological Center. *Wea. Forecasting,* **4,** 297–312.

——, and L. L. Morone, 1985: Evolution of the National Meteorological Center global data assimilation system: January 1982–December 1983. *Mon. Wea. Rev.,* **113,** 304–318.

DiMego, G. J., 1988: The National Meteorological Center Regional Analysis System. *Mon. Wea. Rev.,* **116,** 977–1000.

Flattery, T. W., 1971: Spectral models for global analysis and forecasting. *Proc. Sixth AWS Technical Exchange Con.* Annapolis, Maryland, Air Weather Service Technical Report 242, 42–54. [Available from National Meteorological Center, 5200 Auth Rd., Camp Springs, MD 20746.]

Gandin, L. S., 1963: Objective analysis of meteorological fields. *Gidrometeorologiches-koe Izdatelstvo,* Leningrad. English translation by: Israel Program for Scientific Translations, Jerusalem, 242 pp. [NTIS N6618047, Library of Congress QC996.G3313.]

Kalnay, E., M. Kanamitsu, and W. E. Baker, 1990: Global numerical weather prediction at the National Meteorological Center. *Bull. Amer. Meteor. Soc.,* **71,** 1410–1428.

Kanamitsu, M., 1989: Description of the NMC global data assimilation and forecast system. *Wea. Forecasting,* **4,** 335–342.

——, J. C. Alpert, K. A. Campana, P. M. Caplan, D. G. Deaven, M. Iredell, B. Katz, H.-L. Pan, J. Sela, and G. H. White, 1991: Recent changes implemented into the global forecast system at NMC. *Wea. Forecasting,* **6,** 425–435.

Mathur, M. B., 1991: The National Meteorological Center's quasi-Lagrangian model for hurricane prediction. *Mon. Wea. Rev.,* **119,** 1419–1447.

McAdie, C. J., 1991: A comparison of tropical cyclone track forecasts produced by NHC90 and an alternate version (NHC90A) during the 1990 hurricane season. Preprints, *19th Conf. on Hurricanes and Tropical Meteorology,* Miami, Amer. Meteor. Soc., 290–294.

Neumann, C. J., 1988: The National Hurricane Center NHC83 model. NOAA Tech. Memo. NWS NHC 41, 44 pp. [Available from National Hurricane Center, 1320 S. Dixie Hwy., Coral Gables, FL 33146.]

Parrish, D., and J. Derber, 1991: The National Meteorological Center's spectral statistical interpolation analysis system. Submitted to *Mon. Wea. Rev.*

Pailleux, J., 1990: A global variational assimilation scheme and its application for using TOVS radiances. Preprints, *WMO Int. Symp. on Assimilation of Observations in Meteorology and Oceanography,* Clermont-Ferrand, France, 325–328.

Williamson, D. L., and R. Daley, 1983: A unified analysis–initialization technique. *Mon. Wea. Rev.,* **111,** 1517–1536.