IMPLEMENTATION OF THE NRL ATMOSPHERIC VARIATIONAL DATA ASSIMILATION SYSTEM

Edward Barker*, Roger Daley, and James Goerss.
Naval Research Laboratory, Monterey, CA

1. INTRODUCTION

After a long and successful utilization of multivariate optimal interpolation (MVOI) (see Barker(1992) and Goerss and Phoebus(1992)) to satisfy the Navy's data assimilation needs, technological advances required a massive overhaul of the Navy's data assimilation system. After a review of existing methods, a new scheme, the Navy Atmospheric Variational Data Assimilation System (NAVDAS), was designed and developed that would not only bring the Navy system in line with the more modern three-dimensional variational techniques but would also provide a platform from which a four-dimensional representer method could be developed (Daley and Barker, 2001). NAVDAS provides an advancement over its predecessors (Parrish & Derber, 1992; Cohn et al. 1998) in the way it computes its solution and in its vertical coordinate system. As NAVDAS is prepared for operational implementation at Fleet Numerical Meteorology and Oceanography Center (FNMOC), some of its beneficial advantages are starting to be recognized. This paper is a progress report on this work, and also a brief description of the overall system.

2. ANALYSIS ALGORITHM

Let $\mathbf{x}$ represent the atmospheric state on a grid and in a form required by the prediction model. Using $\mathbf{x}_b$ as column vectors of forecast (background or prior), $\mathbf{x}_a$ as the analyzed values, and $\mathbf{y}$ as the column vector of observations, then the most probable (i.e. maximum likelihood estimate) analysis state vector $\mathbf{x}_a$ is obtained by minimizing the scalar cost function J with respect to $\mathbf{x}_a$, where,

$$J = 0.5[\mathbf{y} - H(\mathbf{x}_a)]^T\mathbf{R}^{-1}[\mathbf{y} - H(\mathbf{x}_a)] + 0.5[\mathbf{x}_b - \mathbf{x}_a]^T\mathbf{P}_b^{-1}[\mathbf{x}_b - \mathbf{x}_a] \quad , \qquad (2.1)$$

The matrix $\mathbf{H}$ is the *Jacobian matrix* corresponding to the (possibly) non-linear forward operator H, $\mathbf{R}$ is the symmetric positive-definite *observation error covariance matrix*, and $\mathbf{P}_b$ is the square, symmetric positive-definite *background error covariance matrix*. The minimization of J is achieved through solution of

$$\mathbf{x}_a - \mathbf{x}_b = \mathbf{P}_b\mathbf{H}^T[\mathbf{H}\mathbf{P}_b\mathbf{H}^T + \mathbf{R}]^{-1}[\mathbf{y} - H(\mathbf{x}_b)]. \qquad (2.2)$$

The order of this equation is equivalent to the number of observations going into the analysis, which is usually between 200,000 and 300,000. Unlike the operational multivariate optimal interpolation, the solution is performed over the entire grid using a pre-conditioned conjugate gradient method. NAVDAS uniquely transforms the vertical space to coefficients of the background error covariance matrix, giving a ten-fold improvement in time needed for computing covariances between profile observations such as rawinsondes, satellite retrievals, and aircraft ascents and descents.

There are a number of other options unique to NAVDAS, such as computing error covariances on isentropic surfaces, non-separable correlation functions that vary correlation lengths with analysis level and location, and direct assimilation of satellite radiance brightness temperatures. However, the NAVDAS configuration undergoing testing for operational implementation so far has been nearly identical to that of the operational MVOI, and tests for implementation of the other options await completion of the direct assimilation of satellite radiance module.

3. THE FULL DATA ASSIMILATION SYSTEM

Early in the NAVDAS development, it became obvious that having a fully portable data assimilation system capable of being run at regional sites as well as FNMOC meant that the software would have to be self contained, thereby eliminating all interfaces except that required to retrieve the observations from the local database management system. Consequently, the preparation, data quality control, thinning, and display of observations are all part of NAVDAS. The database interfaces are isolated from the rest of the code so that they can be readily modified without affecting the functionality of the whole system.

* Corresponding author address: Edward Barker, NRL, 7 Grace Hopper Ave, Monterey, CA 93943

Experience with the first data assimilation systems at the regional centers and even on occasion at FNMOC, showed that blocks of observations could get clobbered in many different ways resulting in a degraded forecast. These failures might be due to an erroneous coding change, a data format change, instrument faults, or even data distribution failures. Because it is hard to monitor the data going into the system, a web-based browser is being developed to display the data in such a way as to emphasize potential problem areas. This way, even with limited personnel, problems can be spotted and corrected earlier than currently possible.

4. DATA QUALITY CONTROL

There are numerous data quality control modules in place to tag and remove errors in the observations. These consist of two general types, rule-based and the buddy check.

The rule-based quality control is capable of finding known problems with the data. Some examples of this include a stuck clock on an automated aircraft observing system, duplication because of transmission errors, or improper radiosonde launch techniques. To catch these kinds of errors, specialized software that handles radiosondes (Collins, 2000), satellite winds, satellite radiances, aircraft (Pauley and Stephens, 1998), and surface observations (Baker, 1992) has been developed to tag known errors so they are not used in the analysis. This is a continuous task, as the formats, instruments, and processing software are constantly changing. Also, the more one looks at the data, the more one finds. So even after years of developing rule-based programs, we have hardly touched the surface of what still needs to be done.

The buddy-check algorithm is actually in the analysis itself. First, data that may affect the condition number of the solution matrices are removed (these are usually co-located observations). Then, data that depart too far from the background are deleted. Finally, during the iterative solution, outliers are determined by comparing their values to the pending solution. This method is multivariate since the observations have been normalized so that, for example, a temperature observation can be identified to be in error even though it only has wind observation neighbors.

The tolerances used to remove faulty observations depend on the variance of the local portion of the innovation vector (observation minus background values) and the surface pressure change of the background in the six-hour period surrounding the analysis time. These indicators are intended to detect when the background is likely to be in error, thereby lessening the chance of rejecting good data where it is critically needed to overcome the faulty background (Onagi, 1998). The thinning algorithms also use these parameters to maximize the observation counts where there is least confidence in background quality.

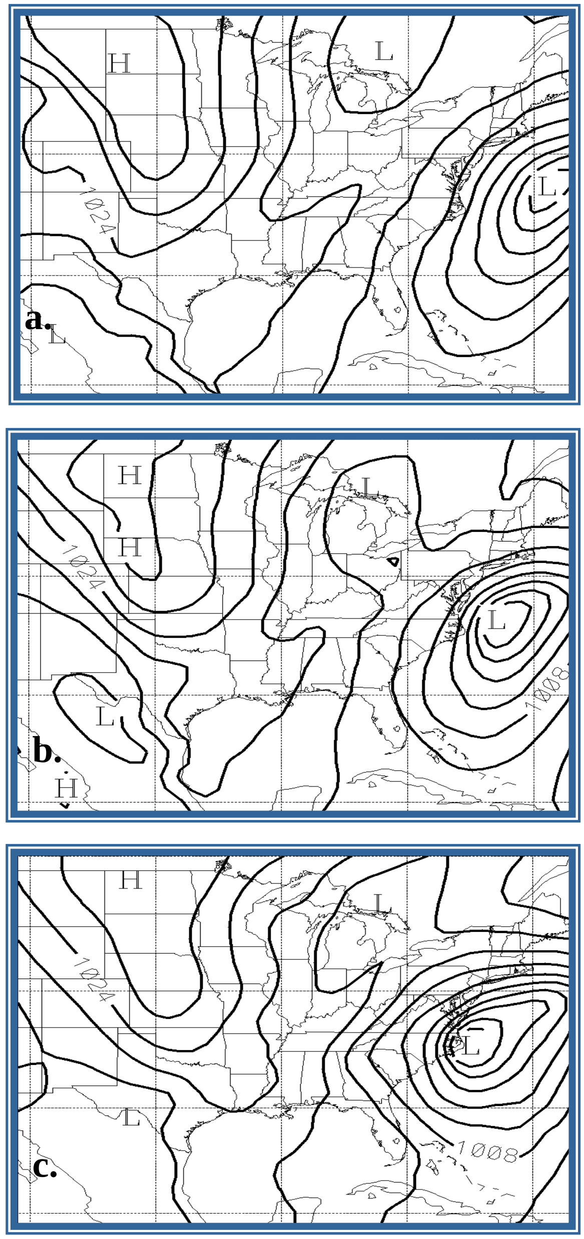

Figure 1 Thirty six-hour forecast from MVOI (a) and NAVDAS (b) analyses shown with the verifying analysis of 12Z January 25, 2000 (c).

5. OPERATIONAL IMPLEMENTATION

In this section we will discuss the operational implementation at FNMOC of the NAVDAS/NOGAPS data assimilation system. Before NAVDAS can be implemented operationally, it must be demonstrated for both winter and summer seasons, the NAVDAS/NOGAPS extra-tropical and tropical forecast skill is equal to or better than the current operational system. Furthermore, NAVDAS must be shown to be robust, reliable, and efficient enough to run within the time constraints of the FNMOC operational environment.

Early in the implementation process it was discovered that analyzing temperature instead of geopotential heights, as done in MVOI, posed some unique problems. The model interface for temperature was restructured. Also, the number of analysis levels was increased from forty to sixty to permit especially fine resolution near the surface, and this kept the detailed temperature structure provided by radiosonde and aircraft soundings from being lost in the assimilation process.

A noteworthy forecast comparison between the two systems was made on the east-coast storm of 25 January 2000, when a low pressure was forecast to track much further from the coastline than actually occurred. The 36-hour forecast and resulting verification for the two systems is shown in figure 1. The NAVDAS/NOGAPS combination did a much better job of holding the storm close to shore than did the MVOI/NOGAPS. Studies are ongoing to compare the analyses from the two systems so as to determine the cause for the better forecasts. We will be examining the wind observation differences first, as NAVDAS uses both significant and mandatory level radiosonde data and considerable wind data from commercial aircraft that would not have gotten into the MVOI analysis.

While the validation process is currently ongoing, the NAVDAS/NOGAPS system has shown consistent improvement over the MVOI/NOGAPS system. A comparison of the 500 mb geopotential height anomaly correlations for the two systems for August 1999 is displayed in Figs. 2 and 3. A comparison of forecast geopotential heights with rawinsonde observations for the two systems is displayed in Figs. 4 and 5. With NAVDAS, the gain in forecast skill in the Northern Hemisphere is almost twelve hours (Figs. 2 and 4). This extraordinary improvement is very encouraging. The NAVDAS/NOGAPS forecast skill in the Southern Hemisphere is comparable to that of the MVOI/NOGAPS system (Figs. 3 and 5). As mentioned previously, the configuration of the NAVDAS system undergoing testing is quite similar to the MVOI and is utilizing satellite temperature retrievals. We expect to see significant improvements in the Southern Hemisphere with the NAVDAS system when we incorporate the direct assimilation of radiances.

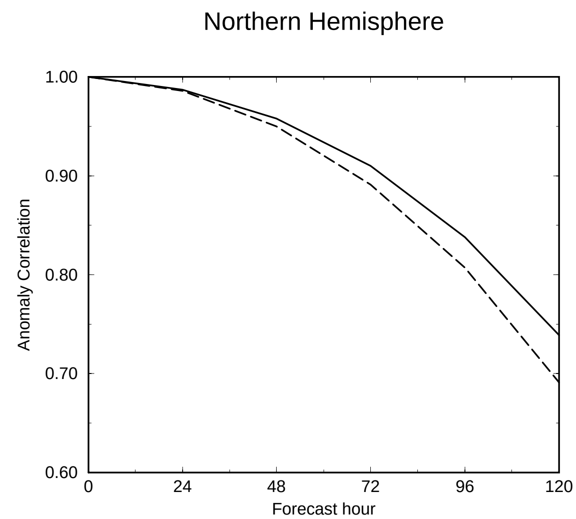

Fig. 2 Comparison of Northern Hemisphere 500 hPa geopotential height anomaly correlations for NAVDS/NOGAPS (solid) and MVOI/NOGAPS (dashed) for August 1999.

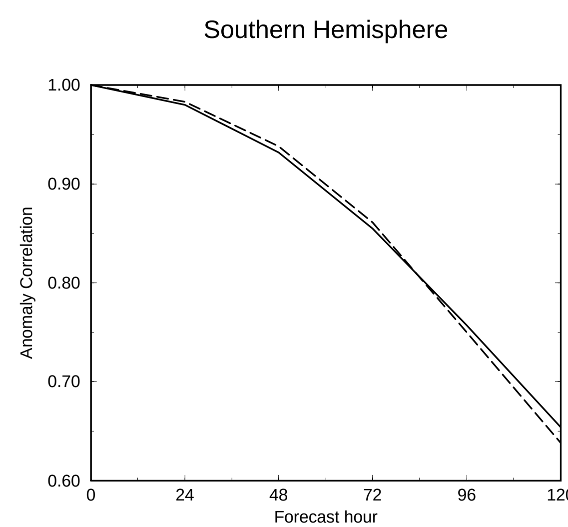

Fig. 3 As in Fig.2 but for the Southern Hemisphere.

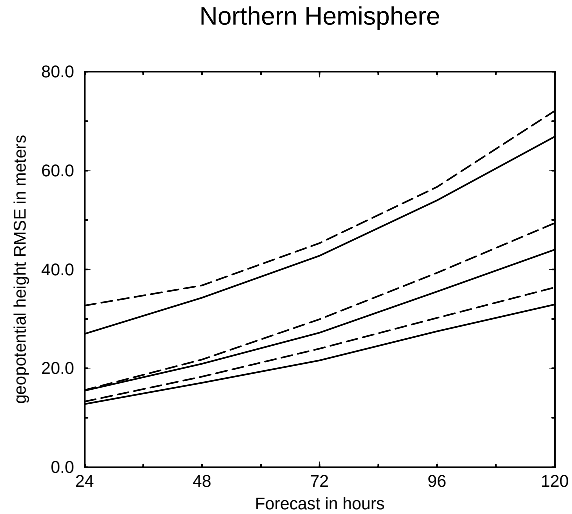

Fig. 4 Comparison of Northern Hemisphere geopotential height rms with respect to rawinsonde observations for NAVDAS/NOGAPS (smooth) and MVOI/NOGAPS (dashed) for August 1999. Curves are for 200hPa (upper pair), 500hPa (middle pair), and 850hPa (bottom pair).

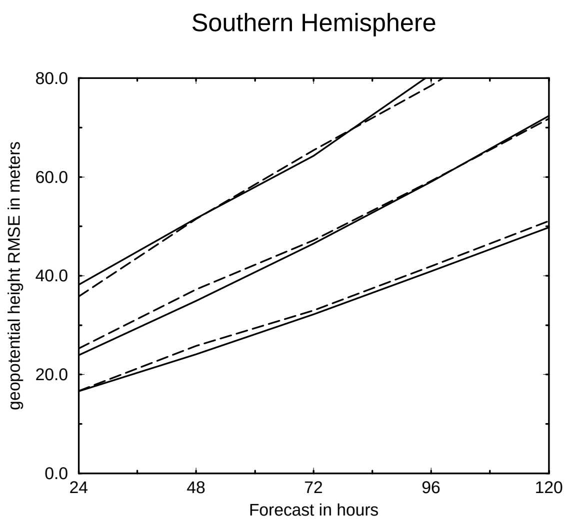

Fig. 5 As in Fig. 4 but for the Southern Hemisphere.

Over the course of these experiments, the NAVDAS system has been shown to be robust and reliable. In terms of running time, NAVDAS produces a global analysis on a one-degree grid using on the order of 250,000 observations on the new massively parallel computer cluster at FNMOC in about the same time as the MVOI system did on the older vector machine. To achieve this wall time of about five minutes, the analysis uses sixty processors with the Message Passing Interface standardized software.

6. SUMMARY

The implementation phase of NAVDAS has gone quite smoothly, with a dramatic improvement in forecast skill expected. If it holds up, the twelve-hour improvement of forecast skill will be the largest single improvement to NOGAPS since its implementation twenty years ago. Numerous test runs are still needed before NAVDAS becomes operational, and results from some will be added to the presentation.

7. ACKNOWLEDGEMENTS

The support of the sponsor, the Office of Naval Research, NRL base, through program element 0602435N, is gratefully acknowledged.

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