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AN OVERVIEW OF THE NRL ATMOSPHERIC VARIATIONAL DATA ASSIMILATION (NAVDAS) AND NAVDAS-AR (ACCELERATED REPRESENTER) SYSTEMS

Nancy L. Baker*, Jim Goerss, Keith Sashegyi, Pat Pauley, Rolf Langland,
Liang Xu, Clay Blankenship, Bill Campbell and Benjamin Ruston
Naval Research Laboratory
Monterey, CA

Tom Rosmond
SAIC
Monterey, CA

Randy Pauley
Fleet Numerical Meteorology and Oceanography Command
Monterey, CA

1. INTRODUCTION

The U.S. Navy, by virtue of operating primarily over coastal and open ocean areas, is extremely concerned about the accurate analysis and forecast of high impact weather systems that affect the safety of personnel, ships, and aircraft. Specific high impact weather events of interest include tropical cyclone forecasting, topographically enhanced high wind events, high winds and seas, dust storms and other obscurations to visibility. Accurate NWP analyses and forecasts are also used for determining the environmental picture that is critical for the safety of ships, aircraft, personnel and other assets; sea-basing and ship fuel economy; accurate delivery of precision ordnance; theatre air and missile defense; and homeland security.

The operational data assimilation system for the U.S. Navy's global and mesoscale NWP systems is described in section 2. The four-dimensional developmental data assimilation system is described in Section 3. Adjoint techniques to assess the impact of observations on forecast error are discussed in section 4, while other applications of the data assimilation system are described in sections 5 and 6. A brief look at future plans is presented in section 7.

Corresponding author address: Nancy L. Baker, Naval Research Laboratory, 7 Grace Hopper Ave., Stop 2, Monterey, CA 93943;
e-mail: nancy.baker@nrlmry.navy.mil

2. THREE-DIMENSIONAL VARIATIONAL DATA ASSIMILATION WITH NAVDAS

NAVDAS (Daley and Barker 2001) is the U.S. Navy's three-dimensional variational data assimilation system used for the global model NOGAPS[1], the relocatable mesoscale model COAMPS®[2], and its on-scene counterpart, COAMPS-OS®[3]. NAVDAS became operational at Fleet Numerical Meteorology and Oceanography Center (FNMOC) on October 1, 2003 for NOGAPS and on Dec 12, 2006 for the first COAMPS® operational area.

Numerous NAVDAS upgrades have been installed since then, including direct assimilation of AMSU-A radiances (Baker et al., 2005), MODIS polar winds (Pauley and Pauley, 2004; Pauley and Pauley, 2005), and scatterometer, SSM/I and WindSat ocean surface winds and total precipitable water (Goerss et al., 2007), and specialized aircraft winds (Pauley et al., 2006).

NAVDAS is formulated in observation space, so that the computational costs are proportional to the observation count rather than the NWP model grid resolution (number of grid points). This makes NAVDAS an ideal choice for applications with high resolution data

[1] Navy Operational Global Atmospheric Prediction System (NOGAPS)
[2] COAMPS is a registered trademark of the Naval Research Laboratory, Monterey.
[3] COAMPS-OS® is also a registered trademark of the Naval Research Laboratory.

assimilation in data-sparse regions. However, it also imposes a limitation of the number of observations that can be assimilated for the global NWP model, due to operational timing requirements. Fortunately, this limitation is removed with our developmental 4D-var system NAVDAS-AR (see section 3).

The data assimilation code for NAVDAS is unified in that the same data processing and solver core routines are used to produce analysis for NOGAPS, COAMPS® and CAAPS used at FNMOC.

2.1 Global NWP Applications

NOGAPS is a high-resolution (T239L30) spectral global numerical weather prediction modeling system that was also developed at NRL-Monterey. NOGAPS version 4.0 (Hogan and Rosmond, 1991; Hogan et al., 2003) has been in operational use at FNMOC since 1998. NOGAPS is currently run at a resolution of T239L30 with an effective model top at 4 hPa. Operational forecast out to 7 days are produced every 6 hours. NOGAPS provides the input and boundary conditions for the mesoscale, ocean, wave and ice prediction models, ensemble forecasting system, and the tropical cyclone forecast model (GFDN). It also provides NWP forecast input to the Navy's optimal aircraft and ship routing program. NOGAPS is also used for NRL's basic research into atmospheric predictability, adjoint sensitivity studies, and adaptive observation-targeting.

Data counts from a recent operational global NAVDAS run are given in Table 1 below, which shows not only the large number of observations that are used but also the variety of observations that are currently being assimilated. A significant number of observations (70-100K observations) arrive after the real-time data cut of +3:00. For this reason, a post-time reanalysis is performed at +8:00 to provide the 3-9 hr forecasts needed as the background for the next analysis update cycle.

Table 1. Global Operational Data Counts for a 00 UTC 31 May 2007 (+3:00 data cut). Each variable is counted as a separate observation. T is temperature, Td is dewpoint depression, Z is geopotential height, dd is wind direction, ff is wind speed; pmsl is mean sea-level pressure, Tb is brightness temperature, and TPW is total precipitable water. Total observation count was 443,000.

Data Type	Variables	Observation Count
Rawinsonde	T, Td, Z, dd, ff	96000
Surface land	T, Td, Z, dd, ff, pmsl	15,800
Surface ship/buoy	T, Td, Z, dd, ff, pmsl	3100
Australian synthetic obs	pmsl	150 (late arrival)
Tropical cyclone synthetic obs	T, Z, dd, ff	360
Manual AIREP	T, dd, ff	900
ADS (North Atlantic)	T, dd, ff	900
AMDAR (non-U.S. carriers)	T, dd, ff	23000
MDCRS (U.S. carriers)	T, dd, ff	40000
BUFR geostationary satwinds (EUMETSAT, NESDIS)	dd, ff	63000
ASCII geostationary satwinds (CIMSS, AFWA)	dd, ff	17000
MODIS polar orbiter winds	dd, ff	4000
SSMI speeds	dd	3400
WindSat wind vectors	dd, ff	5400
Scatterometer	dd, ff	6000
SSMI total precipitable water	TPW	72000
WindSat total precipitable water	TPW	26000
AMSU-A brightness temperature	Tb	67000

2.2 Mesoscale NWP Applications

COAMPS® is a fully coupled ocean/atmosphere data assimilation/forecast system well validated at predicting and simulating non-hydrostatic meteorological processes on meso (10 km) to micro (1 km) scales of atmospheric motion (Hodur, 1997; Chen et al., 2002). COAMPS® is suited to perform in regions of complex terrain (both land and land-water) where there is significant mesoscale forcing from the surface. COAMPS-OS® is used for a variety of tailored mesoscale data assimilation and forecasting applications including support of aviation and shipping operations, wave modeling, ocean circulation modeling, and chemical and biological plume dispersion modeling (Cook et al., 2007). NAVDAS has been tested with COAMPS® for many different operational and research grid configurations. It has successfully been run with up to 5 nested grids down to a horizontal resolution of 500m with 50 vertical model levels.

The NAVDAS analysis method successfully updates COAMPS® with current observations, maintaining both high resolution features in the innermost grid mesh and accurately representing features crossing mesh boundaries. Analyses with complex frontal structures demonstrated the improved predictability of COAMPS® forecasts in such cases. The potential to analyze deeper tropical cyclones in NAVDAS has been demonstrated by using tropical cyclone bogus observations and reducing the correlation length scale and geostrophic coupling in the vicinity of tropical cyclones.

For the application with COAMPS®, data innovations (observation-background) are obtained by successively interpolating the six-hour COAMPS® forecast fields to the observation locations and subtracting the result from the observations for each of the successively finer grid meshes. At the end of the procedure each observation innovation is therefore computed from the highest resolution background forecast available. In a boundary region around the coarse grid mesh, the Navy's global model NOGAPS forecasts are used to generate data innovations for observations outside the COAMPS® domain, alleviating the need for pseudo-observations to maintain continuity across the COAMPS® boundaries. An analysis grid is constructed by removing any duplicate grid points from the COAMPS® grid meshes. Following the analysis, the analysis corrections are added back to each background grid to provide the initial conditions for the next forecast run. An additional correction is added to the outer grid meshes to account for differences between the background forecasts on the grid meshes.

3. FOUR-DIMENSIONAL VARIATIONAL DATA ASSIMILATION WITH NAVDAS-AR

NAVDAS was specifically designed by the late Roger Daley[4] as a precursor for NAVDAS-AR, our four-dimensional weak-constraint variational data assimilation system. NAVDAS-AR (Accelerated Representer) is based on the representer technique first introduced by Bennett and McIntosh (1982). Xu and Daley (2000) designed a cycling version of the representer algorithm, and subsequent development (Xu et al. 2005; Rosmond and Xu 2006) has produced a computationally efficient algorithm for operational four-dimensional data assimilation. The computational cost for NAVDAS is proportional to the number of observations that are assimilated, whereas with NAVDAS-AR the computational cost is proportional to the model grid density. Currently, the computational cost for NAVDAS-AR with two outer nonlinear loops (outer loop resolution T239L30, inner loop resolution T79L30) is approximately five times the cost of NAVDAS.

NAVDAS-AR provides a flexible framework suitable for a wide variety of applications, including global and mesoscale atmospheric and oceanic data assimilation (Xu et al. 2005; Rosmond and Xu 2006). The data quality control and pre-processing algorithms are common with NAVDAS, thereby reducing the amount of computer code that must be maintained operationally. Switches are used to accommodate the specialized observation pre-processing, e.g., allowing for the temporal distribution of observations. NRL plans to transition NAVDAS-AR to FNMOC for operational implementation in late 2008.

[4] Roger Daley was a visiting scientist at NRL-Monterey from 1996-2001.

4. ASSESSING OBSERVATION IMPACT USING ADJOINT TECHNIQUES

An adjoint-based method (Langland and Baker, 2004; Baker and Daley, 2000) monitors in real-time (00 UTC only) the impact of all atmospheric observations assimilated by NAVDAS on the short-range NWP forecast error. The technique uses adjoint versions of NAVDAS and NOGAPS and has been developed and tested at NRL-Monterey over the past several years. The measure of observation impact is defined as the difference between forecast errors on an analysis and a background trajectory, whose initial conditions are separated by six hours. The difference of forecast errors on these two trajectories is due solely to the assimilation of the observations, and the separate forecast impact of every assimilated observation can be quantified using this approach. For each observation, the "observation impact" is obtained as the product of the observation innovation value and the observation sensitivity.

Currently, the adjoint-based observation impact is computed for the 00UTC operational and pre-operational runs of NAVDAS-NOGAPS, using vertically-integrated, moist energy-weighted global 24/30h forecast error as the cost function. The results over the past two years confirm that the adjoint-based observation impact information can identify specific observations with data quality problems - for example, individual radiosonde, land, or ship observations that provide non-beneficial observations caused by instrumentation problems, inaccurate master stations lists, or other issues. The information can also be partitioned for each observation variable so that, for example, a station can be placed on a reject list for just temperature, humidity, or wind observations. The observation impact statistics from the pre-operational parallel run are used as an additional check on the quality and forecast impact of new observations before transition to actual operations.

The computational cost of producing the observation impact information using the adjoint system is about the same as a single analysis and forecast model update cycle. It should be noted that this method evaluates the impact of all observation data simultaneously, in contrast to conventional data-denial sensitivity studies that estimate the forecast impact for subsets of observations that are withheld from (or added to) the analysis.

Observation impact information is also being used at NRL in a research mode to address other data assimilation issues, including channel selection for high spectral resolution IR sounders such as AIRS (Ruston, 2006). The adjoint-based approach to observation impact provides a computationally-feasible method to examine the separate impacts of hundreds or thousands of individual observation channels – information that would be difficult or impractical to obtain by conventional data denial experiments. The adjoint of NAVDAS-AR has been developed and is being used to evaluate the observation impact in a 4D-var context.

5. AEROSOL AND OZONE ANALYSES USING NAVDAS

The two-dimensional univariate version of NAVDAS has been adapted to provide an aerosol optical thickness analysis (Zhang et al., 2006) for the Navy Aerosol Analysis and Prediction System (NAAPS). Plans are to extend this to a three-dimensional aerosol analysis, using ground-based and CALIPSO/CloudSat lidar aerosol profiles and MODIS aerosol optical thickness. The three-dimensional univariate option within NAVDAS has been adopted for NRL's global ozone analysis using SBUV/2 retrievals and MLS ozone retrievals (non-operational data).

6. STRATOSPHERIC AND MESOSPHERIC ASSIMILATION USING NAVDAS

NAVDAS is used for the upper atmosphere assimilation and modeling efforts within the Remote Sensing and Space Sciences Divisions at NRL. Satellites provide the only observational data consistently available at these altitude ranges. The Special Sensor Microwave Imager Sounder (SSMIS), a microwave radiometer aboard DMSP F-16 and F-17 polar orbiting satellites, provides a new operational capability to infer atmospheric temperature information in the upper stratosphere and mesosphere, between 30 and 90 km, well above the range of previous operational sensors. We are developing NAVDAS assimilation capabilities for the SSMIS Upper Air Sounding channels using a prototype version of the Community Radiative Transfer Model (CRTM), a fast radiative transfer model that includes Zeeman splitting of the oxygen absorption lines (Han et al., 2007). Temperature, ozone and humidity profiles from the NASA AURA Microwave Limb Sounder (MLS) are also assimilated by NAVDAS; unfortunately these data are not available in real time.

7. A VIEW TO THE FUTURE

NAVDAS-AR is slated to be transitioned to FNMOC for operational implementation with NOGAPS in late 2008. Work to adapt NAVDAS-AR for COAMPS® beginning this fall.

One of the top priorities for the next few years will be implementing new satellite observations into the data assimilation system. Current development efforts are focused on AQUA AIRS and AMSU, DMSP SSMIS, AMSU-B/MHS, COSMIS-GPS and METOP-IASI. We plan to develop and implement variational assimilation of SSM/I and WindSat radiances.

Research and development is on-going to adapt NAVDAS for COAMPS-OS® hourly analyses and rapid update cycling. This work includes optimizing the assimilation of aircraft and satellite observations, and utilizing new datasets, such as satellite feature-tracked winds from GOES rapid-scan imagery, military Aircraft Communication Addressing and Reporting System (ACARS) data from US Air Force transport aircraft, and low-level Japanese Aircraft Meteorological Data Relay (AMDAR) data.

NAVDAS includes an option to define the vertical coordinate in terms of isentropic flow-following surfaces, allowing the background error covariances to vary synoptically and have more structure in regions of strong jet streams and fronts. This option will be tested and evaluated for COAMPS® and COAMPS-OS®.

Future plans NAVDAS and NAVDAS-AR also include implementing methods for variational bias correction and adaptive tuning of observation and background errors.

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