The Impact of Satellite Atmospheric Motion Vectors in the U.S. Navy Global Data Assimilation System – NWP Results

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Abstract

An often asked question within the data assimilation community is why the U.S. Navy global atmospheric forecast model obtains a relatively larger impact from satellite-derived Atmospheric Motion Vectors (AMVs), when compared to models at other forecast centers. Possible reasons for the larger impact are (1) the greater number of satellite wind data assimilated in the Navy model, (2) the use “super-ob” wind vectors, (3) differences in quality control and data selection procedures, or (4) data assimilation methods, including assumptions about observation and background error covariances. This study, and the companion study led by Merkova and Gelaro, examines the significance of these various factors, and concludes that the leading contribution is the increased number and improved spatial coverage, of the AMV winds assimilated by the Navy system.

INTRODUCTION

Atmospheric Motion Vectors (AMVs) have a much larger adjoint-based observation impact in the U.S. Navy’s global operational numerical weather prediction (NWP) system compared to other global NWP centers. Conversely, the observation impact from microwave and infrared atmospheric sounders is less. The total observation impact for the Navy and GMAO global NWP systems is summarized in Figure 1. The top five (six) observation categories for Navy are: AMV, radiosonde, aircraft (AMDAR and MDCRS), land surface, IASI, (SSMIS integrated water vapor), and AMSUA. The top five categories for GMAO are AMSUA, radiosonde, aircraft, IASI and AMV. The Navy system uses a moist total energy error norm, while the GMAO system uses a dry total energy norm, and this accounts for large impact from SSMIS integrated water vapor (which GMAO does not assimilate).

Figure 1: Observation impact for the Navy system (left) and for the NASA GMAO system (right), for the month ending on May 28, 2012. The NRL observation impact is computed for each update cycle, e.g. four times per day, while the GMAO observation impact is computed for 00 UTC only.
The global operational NWP system is composed of NAVDAS-AR (NRL Atmospheric Variational Data Assimilation System—Accelerated Representer), a 4D-Var (four-dimensional variational) global data assimilation system in observation space (Xu et al. 2005, 2006; Rosmond and Xu 2006; Chua et al. 2009), and NOGAPS (Navy Operational Global Atmospheric Prediction System), a global atmospheric model currently run with a resolution of 319 spectral triangular truncation on 42 levels (Hogan and Rosmond 1991; Peng et al. 2004).

As discussed in our companion paper (Pauley et al. 2012), the NRL system differs from other operational centers in that we use of geostationary AMVs from operational data providers (NESDIS, EUMETSAT, and JMA), the University of Wisconsin-Madison’s Cooperative Institute for Meteorological Satellite Studies (CIMSS), and AFWA (Air Force Weather Agency). Another difference is the AMVs are used as “super-obs”, as described Pauley et al. (2012).

The AMV winds (or super-obs) selected by NAVDAS-AR were saved for subsequent use in the GMAO global data assimilation system in order to compare the impact of these same wind vectors in the different system. This transplant experiment is designed to provide additional insight into the reasons for the large impact of AMV winds in the Navy’s systems.

**EXPERIMENT DESIGN**

The experiments used a configuration of NAVDAS-AR and NOGAPS that closely matched the FNMOC operational configuration. For the assimilation component, NAVDAS-AR was run with T319 outer loop resolution (approximately 42 km), and a T119 inner loop resolution (approximately 110 km), with 42 vertical levels from the surface to 0.4 hPa (around 70 km). Approximately 2.2 million observations were assimilated every 6 hours. The NOGAPS forecast model using Eulerian differencing, with the Emanuel cumulus scheme. The satellite radiance bias correction method follows an offline two-predictor approach following Harris and Kelly (2001) and uses the past 15 days of radiance innovations to generate the bias coefficients, which are updated each assimilation cycle. The runs were initialized 15 days prior to the first initial starting period, starting from operational spectral history files and zero bias coefficients for the radiances.

The following four experiments were run: (1) Northern Hemisphere Winter AMV Denial, (2) Northern Hemisphere Summer AMV Denial, (3) Northern Hemisphere Winter Polar AMV Denial and (4) Northern Hemisphere Winter Thinning vs. SuperOb assimilation experiment.

The AMV denial runs excluded all geostationary and polar atmospheric motion vectors, while the polar AMV run excluded only AVHRR, MODIS and LEO/GEO AMVs. The combined LEO/GEO winds were available only for the winter runs, as operational assimilation of these winds did not begin until November 10th, 2010. The specific observing platforms and data providers are presented in Table 1.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Orbit</th>
<th>Frequency Band</th>
<th>Data Providers</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOES-11</td>
<td>Geostationary</td>
<td>IR, SWIR, WV, WVCLD, VIS</td>
<td>NESDIS, CIMSS, AFWA</td>
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<td>EUMETSAT, CIMSS, AFWA</td>
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<tr>
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<td>EUMETSAT, CIMSS, AFWA</td>
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<td>MTSAT-2</td>
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<td>IR, SWIR, WVCLD, WV, VIS</td>
<td>JMA, CIMSS</td>
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<td>MODIS Terra</td>
<td>Polar</td>
<td>IR, WV</td>
<td>CIMSS</td>
</tr>
<tr>
<td>MODIS Aqua</td>
<td>Polar</td>
<td>IR, WV</td>
<td>CIMSS</td>
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<td>MODIS Terra/Aqua mixed</td>
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<td>CIMSS</td>
</tr>
<tr>
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<td>IR</td>
<td>CIMSS</td>
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<tr>
<td>METOP-A</td>
<td>Geostationary &amp; Polar</td>
<td></td>
<td>CIMSS (winter case only)</td>
</tr>
</tbody>
</table>

*Table 1: Sources of AMVs, according to satellite, orbit, wind type and data providers.*

For the Northern Hemisphere winter case, the control run was initialized on November 15, 2010 at 00 UTC, and spun up until November 30th at 18 UTC. The initial conditions, bias coefficients and bias statistics for this date and time were archived to provide the starting point for the two AMV denial runs. The first denial date for the winter runs was December 1st at 00 UTC. The 5-day forecasts were initialized from the 12 UTC analyses. The ending date for the NH winter case was January 15, 2011 at
12 UTC. The assimilation cycles were continued for another 5 days to provide verifying analyses for the long forecasts.

For the Northern Hemisphere summer case, the control run was initialized on August 1, 2010 at 00 UTC, and spun up until August 14th at 18 UTC. The first assimilation cycle with the AMV wind denial was for August 1st at 00 UTC. The 5-day forecasts were initialized from the 12 UTC analyses. The ending date for the NH summer case was September 30th, 2011 at 12 UTC. The assimilation cycles were continued for another 5 days to provide verifying analyses for the long forecasts.

**NORTHERN HEMISPHERE WINTER AMV AND POLAR AMV DENIAL RESULTS**

The 500 hPa geopotential height anomaly correlation die-off curves for the NH winter AMV denial case are displayed in Figure 2. These figures suggest that the largest impact from AMV winds is in the summer (southern) hemisphere, with minimal impact in the winter (northern) hemisphere.

![Figure 2](image)

In Figure 3, the 250 hPa denial minus control mean wind speed and vector 250 hPa wind speed differences for December, 2010 are plotted. The largest differences are in the tropics, where the assimilation of the AMV observations appreciably alters the wind flow at 250 hPa. Most of the wind differences are in areas with few conventional wind observations from radiosondes, pibals or aircraft.

![Figure 3](image)

The 24-hr forecast 200 vector wind RMS errors in the tropics, as verified against radiosondes (not shown) are noticeably less when AMVs are assimilated. However, as illustrated in Figure 3, the
radiosondes coverage is sparse in the areas where the AMV observations contribute to the greatest analysis differences. The results for the polar AMV wind denial experiments (also not shown) follow the same trend as for the AMV denial experiments, with the greatest impact from the AMVs in the summer hemisphere.

**NORTHERN HEMISPHERE SUMMER AMV DENIAL RESULTS**

In this section, we summarize the results from the Northern Hemisphere summer AMV denial experiments. The 500 hPa geopotential height anomaly correlation scores (Figure 4) are analogous to those presented for the NH winter experiments (Figure 2), in that most of the benefit from the AMV assimilation appears to be in the summer hemisphere, with minimal impact in the winter hemisphere.

**Figure 4:** Anomaly correlation die-off curves for 500 hPa geopotential heights for the Northern Hemisphere (left panel) and the Southern Hemisphere (right panel) for August 15, 2010 through September 30, 2010, at 12 UTC. The forecast lead time in hours is given on the abscissa, and the anomaly correlation is given on the ordinate.

In Figure 5, the 250 hPa denial minus control mean wind speed and vector 250 hPa wind speed differences for August 15th through September 30th, 2010 are plotted. As in Figure 3, the largest differences are in the tropics, where the AMV assimilation changes the wind flow at 250 hPa. More modest analysis differences are present in the Southern Hemisphere, predominantly in areas with few conventional wind observations from radiosondes, pilot balloons or aircraft.

**Figure 5:** Mean and vector wind analyzed (T+00) differences at 250 hPa (left panel). The differences are computed from the denial minus control analysis for 12 UTC, and averaged from August 15, 2010 through September 30, 2010. The color shading indicates the mean wind speed difference and the arrows give the mean wind vector difference (both in ms⁻¹).

The 24-hr forecast 200 and 850 hPa vector wind RMS errors for the tropics, as verified against radiosondes, are plotted in Figure 6. Although the differences are not statistically significant (partly due to the low number of verification radiosondes in the tropics, as illustrated in Figure 3), there is a clear trend for lower vector wind RMS errors in the forecast when AMVs are assimilated.
Figure 6: Verification of the 200 hPa vector wind RMS errors in the tropics for the Northern Hemisphere summer AMV control experiment (blue line; IWWGCS) compared to the AMV denial experiment (green line; IWWGDS), as verified against radiosondes. The forecast lead time in hours is given on the abscissa, and the vector wind error in (ms⁻¹) is given on the ordinate.

The homogeneous tropical cyclone track forecast errors for the control and denial experiments are given in Figure 7. The storm position in the forecast is determined by the NOGAPS TC storm tracker, and the verification is against the TC warning position (not post-season best-track). Although there were not many individual tropical cyclones during the test period, these results demonstrate the importance of AMV assimilation for TC track forecasting.

Figure 7: Tropical cyclone track prediction error in nautical miles (nm; ordinate) as a function of forecast lead time (hrs; abscissa) for August 15, 2010 through September 30, 2010. The control experiment errors are given by blue bars, and the denial experiment errors are given by the green bars. The number of verifying storm positions for this homogeneous comparison, for each forecast lead time is given by the number below the graph. The differences are significant for all forecast lengths to t+72 at the 99.0 – 99.5% confidence levels.

NORTHERN HEMISPHERE SUMMER– OBSERVATION IMPACT RESULTS

The observation impact (Langland and Baker, 2004) was computed for each 6-hr update cycle, using a moist total energy error norm. The observation impact for the major observing platforms/categories is presented in Figure 8 for the control experiment and the AMV denial experiments. These results show that in the absence of AMVs, other observations largely compensate for the missing winds. The largest increases are for the satellite radiances and other wind observations. The contribution to the observation impact from the different categories of AMVs is presented in Figure 9. The most overall impact is from the IR winds, although the VIS winds provide more impact that WV winds. The per-observation impact reveals why, as the WV winds especially for MTSAT have relatively larger per ob impact.
The observation impact results show that AMV assimilation contributes to a large reduction in the total moist energy norm (enorm). However, reducing the difference in the two enorms (e24-e30) is not the same as reducing the total 24-hr error (e24). We examined the 24-hr moist total energy error norm for the control and denial cases. For this discussion, we note that denying all satellite AMVs is a large change to the NRL global analysis/forecast system, and explicitly assume that the control analyses (with AMV assimilation) are more accurate than the analyses produced without AMV wind assimilation.

In Table 2, the global total 24-hr enorm values are apparently smaller (less error) for the denial run (DS) than for the control run (CS). To better understand this apparent discrepancy, we partitioned the

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**NORTHERN HEMISPHERE SUMMER – 24-HR MOIST ENERGY ERROR NORMS**

**Figure 8:** Percent of the total observation impact (J kg⁻¹) for each major observing category for August 15th, 12 UTC through September 30th, 12 UTC, for the control experiment (left panel) and the AMV denial experiment (right panel). The observation impact is computed every 6 hrs.

**Figure 9:** Observation impact as a function of satellite and type (infrared, water vapor, visible). The left panel is the percent reduction in the total observation impact (J kg⁻¹), while the right panel gives the observation impact per observation.
global error into the main components of vorticity, divergence, temperature and humidity (neglecting the much smaller terrain pressure error). These results suggest that AMV assimilation increases the 24-hr error for all components except vorticity, and are contradictory with the prior results.

The 24-hr enorm values were further stratified by region, NHEM (20-80N), Tropics (20N-20S) and SHEM (20S-80S). For the Northern (summer) Hemisphere, AMV assimilation decreases the 24-hr enorm for all components, which is consistent with the 500 hPa geopotential height anomaly correction scores. For the Southern (winter) Hemisphere, AMV assimilation primarily reduces the vorticity errors, and slightly increases the humidity errors. In the tropics, however, AMV assimilation apparently increases all components of the 24-hr enorm values.

Table 2: Summary of 24-hr total moist energy error norms for the control run with AMV assimilation (CS), and the denial run (DS), as verified against self-analysis. The lower (smaller) 24-hr moist energy norm values are color-coded, red for control run (CS) or blue for the denial run (DS).

In Figure 10, the 24-hr moist energy error norms time series are plotted for August 15th through September 30th. The solid green line represents the 24-hr enorm for the control run as verified against the control analyses (CSCS), while the cyan line shows the 24-hr enorm for the denial run as verified against the denial analyses (DSDS). When verified against self-analyses, the control and denial runs have similar 24-hr moist energy error norms. However, when verified against the control analyses, the denial forecasts (DSCS) have much larger 24-hr errors using the total energy error norm, and all components of the error norm (vorticity, divergence, temperature, humidity) are larger when AMVs are excluded from the assimilation.

**CONCLUSIONS AND FUTURE WORK**

Overall, we see good benefit from the assimilation of AMVs by the NAVDAS-AR/NOGAPS global forecast system, with the largest beneficial impact primarily in the tropics and the summer hemisphere. The relatively large observation impact is due primarily to the assimilation of large numbers of AMVs from multiple data providers, which give good spatial and temporal coverage within the assimilation window. Independent results from GMAO (not shown) suggest that the use of super-observations increases the overall observation impact. Their study results also showed that NRL assimilates fewer radiance observations than GMAO. These results suggest that NRL could obtain more impact from
radiances by (1) using more observations, (2) decreasing the radiance observation errors, or (3) finding a more optimal balance between AMVs and radiance observations.

The assimilation of AMVs reduces the total 24-hr moist error norm for all components (temperature, vorticity, divergence and humidity) for the summer hemisphere. The error reduction is largest in the summer hemisphere, and for the vorticity component of the error. The evaluation of the 24-hr moist error norms clearly highlights how forecast verification against self-analyses can become problematic with large perturbations to the observing system configuration (e.g., denying all AMVs). Under these circumstances, the observation impact statistics or verification against other observations will provide more meaningful assessment.

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REFERENCES


