Title of Grant / Cooperative Agreement:	A Blended Polar Winds Product using Atmospheric Motion Vectors from MODIS Imager and AIRS Moisture Retrieval Data
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Name of Principal Investigator:	David Santek
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Name and Address of recipient's institution:	University of Wisconsin System, 21 N. Park St. Ste 6401, Madison, WI 53715-1218
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Reference 14 CFR § 1260.28 Patent Rights *(abbreviated below)*
The Recipient shall include a list of any Subject Inventions required to be disclosed during the preceding year in the performance report, technical report, or renewal proposal. A complete list (or a negative statement) for the entire award period shall be included in the summary of research.

Subject inventions include any new process, machine, manufacture, or composition of matter, including software, and improvements to, or new applications of, existing processes, machines, manufactures, and compositions of matter, including software.

Have any Subject Inventions / New Technology Items resulted from work performed under this Grant / Cooperative Agreement?	No ◉	Yes ○
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Attach the Summary of Research text behind this cover sheet.

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A Summary of Research (or Educational Activity Report in the case of Education Grants) is due within 90 days after the expiration date of the grant, regardless of whether or not support is continued under another grant. This report shall be a comprehensive summary of significant accomplishments during the duration of the grant.

A Blended Polar Winds Product using Atmospheric Motion Vectors from MODIS Imager and AIRS Moisture Retrieval Data

NNX11AE97G

Final Report
February 2011 to August 2013

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Proposed Work

The study and generation of polar winds from the Moderate Resolution Imaging Spectroradiometer (MODIS) imagery was pioneered at the University of Wisconsin by NOAA and the Cooperative Institute for Meteorological Satellite Studies (CIMSS) in the early 2000s. The MODIS polar winds product is composed of both infrared window (IR-W) and water vapor (WV) tracked features, resulting in atmospheric motion vectors (AMVs). The WV AMVs are only attainable at mid- and upper- tropospheric levels due to the MODIS WV atmospheric contribution function, while IR-W images also provide cloud tracers for vectors at lower levels. However, the WV AMVs yield a better spatial distribution than the IR-W because both cloud and clear-sky features can be tracked in the WV images.

As the next generation polar satellite era approaches, it is recognized that there is currently no WV channel planned on the Visible/Infrared Imager/Radiometer Suite (VIIRS), potentially resulting in a data gap with only IR-W derived AMVs possible. This scenario presents itself as an opportunity to investigate using Single Field of View (SFOV) Atmospheric Infrared Sounder (AIRS) moisture retrievals from consecutive overlapping polar passes to extract atmospheric motion from clear-sky regions on constant (and known) pressure surfaces; i.e., estimating winds in retrieval space rather than radiance space.

The goal is to generate a blended product of MODIS imager- and AIRS retrieval-derived AMV datasets. This ability will be important in using data from Suomi National Polar-orbiting Partnership (SNPP) where moisture retrievals derived using the Cross-Track Infrared Sounder (CrIS) could provide the fields to produce clear-sky AMVs.

We propose to:

1. Determine to what extent AIRS-derived AMVs can provide coherent and good quality wind information, and characterize the errors. This technique has the potential to provide a 3-dimensional (profiles of wind) dataset, which would improve on the traditional cloud drift AMVs, while also addressing issues with AMV height determination.
2. Blend the experimental AIRS moisture retrieval AMVs with the already proven MODIS AMVs in an optimal way to create superior 3-D polar wind fields.
3. Perform Numerical Weather Prediction (NWP) experiments with the blended product to determine the overall impact on numerical forecasts and the relative contributions of each data type (MODIS vs. AIRS).

Summary of Accomplishments

The following accomplishments follow the three items in the proposed work above.

1. Quality: The AIRS AMVs were compared to co-located MODIS AMVs for a six-week period. There is a zero speed bias with a standard deviation of 3.5 ms^{-1}. The zero bias indicates the AIRS AMVs are (on average) similar to the MODIS AMVs. The 3.5 ms^{-1} standard deviation is likely due to the much lower spatial resolution of the AIRS data, as compared to MODIS.
2. Blended product: Since there is good agreement between the AIRS and MODIS AMVs and less than 10% of the winds are co-located, the blended product is simply defined as the union of the two datasets.

3. NWP experiments: Several NWP experiments were run using the Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System Model, Version 5 (GEOS-5) to determine the impact of the AIRS AMVs on the assimilation and forecast, with and without the MODIS AMVs. In the assimilation of the AIRS AMVs, the impact per observation is greater than all other satellite-derived winds. There is also a slight improvement in the 500 hPa Anomaly Correlation Coefficient (ACC) in the Day 4 to 6 forecasts. Because these AMVs are confined to the polar regions, while the ACC scores are hemispheric, even a small improvement is encouraging. These two results indicated that there is potential value in the AIRS AMVs.

Data Processing Components

The data processing (on a Linux workstation) is controlled by shell scripts, which make use of the:

- International MODIS/AIRS Processing Package (IMAPP),
- Interactive Data Language (IDL)
- Man computer Interactive Data Access System (McIDAS), and
- the winds software, which was developed at the Space Science and Engineering Center (SSEC).

There are three main components needed to process the AIRS retrieval winds, which are described below.

AIRS Retrievals

The AIRS Standard Retrieval Product provides profiles of retrieved temperature, water vapor, and ozone. This product is generated from 3x3 Fields of View (FOV) of AIRS radiances that results in a horizontal resolution of 40 km. This is much too coarse for tracking features from successive orbits as a one-pixel displacement corresponds to 6.7 ms^{-1}. A similar algorithm (the University of Wisconsin-Madison CrIS, AIRS and IASI Hyperspectral Retrieval Software) was developed at SSEC using Single FOV (SFOV) AIRS footprints, which retains the native horizontal resolution at 13.5 km/pixel and results in temperature, humidity, and ozone profiles at 101 pressure levels from 0.005 to 1100 hPa. We utilize the SFOV product in our AIRS AMV generation, since they provide the best spatial resolution for our application.

Winds Software

The winds software package was developed at CIMSS/SSEC for use with geostationary and polar orbiting satellite data. However, using AIRS is a new challenge due to low spatial resolution (13.5 km) compared to MODIS (1 km) and geostationary infrared images (4 km). The cross-correlation technique used to track features did not perform well using the AIRS data at its native resolution; so additional image processing was needed (see next section).

Image Processing

The AIRS retrieval algorithm generates profiles of moisture and ozone at each AIRS footprint, in the original satellite swath projection. These profiles are used to create horizontally sliced swath images on constant pressure surfaces. The pixel-to-pixel variation in moisture and ozone is such that the winds software was not able to track features. Therefore, the gradients were smoothed by increasing the resolution of the images by a factor of 4 using a bi-linear interpolation. These swath slices are then reprojected to a polar stereographic projection at 4 km resolution. The cross correlation technique in the winds algorithm performed much better using the smooth gradient images.

Data Coverage

The AIRS AMVs are extracted from a time sequence of three images. In order to achieve overlapping images, these AMVs can only be derived in high latitudes (poleward of 70º latitude).

Geographic Coverage

The geographic coverage of AMVs from polar orbiting satellites is over small regions at any particular time. Figure 1 illustrates the swath overlap for three consecutive passes for MODIS (left) and AIRS (right). Because the AIRS instrument has a narrower swath width than MODIS, the spatial coverage of the AMVs is also reduced. An entire day is needed to get complete AMV coverage over the polar regions.

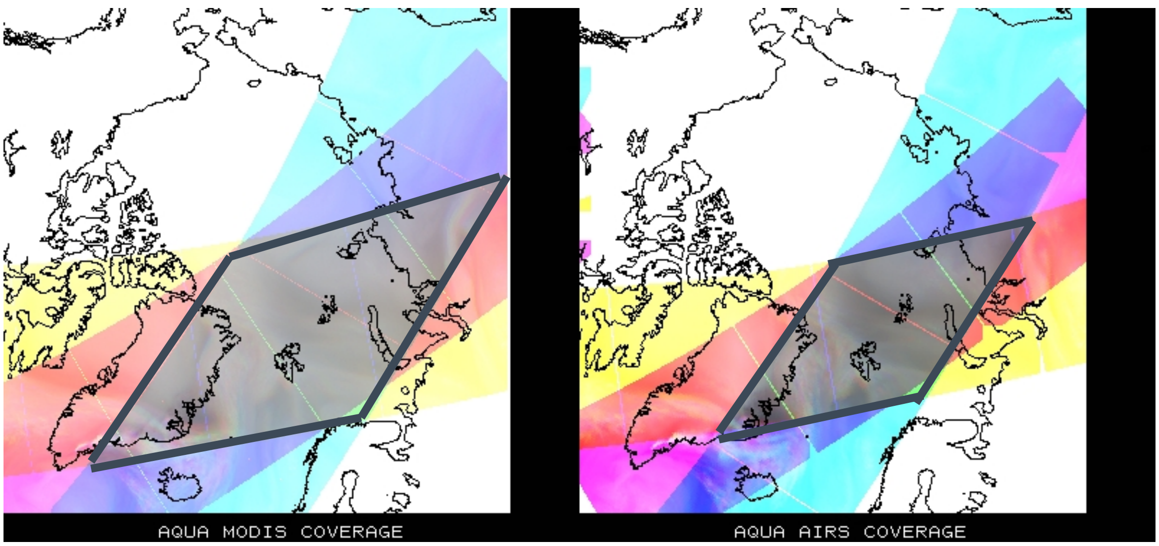

Figure 1: Three overlapping passes from Aqua MODIS (left) and AIRS (right). The region of intersection shows where features can be tracked.

Vertical Coverage

The AMVs are determined away from the tropopause and the Earth's surface. Specifically for this project, we use moisture levels from 359 to 616 hPa (17 levels) and ozone from 103 to 201 hPa (12 levels).

Year 1 Accomplishments

Summary

During the first year we:

- Obtained scripts from NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC) Mirador system to easily retrieve HDF files of AIRS level 1b radiances.
- Installed the International MODIS and AIRS Processing Package (IMAPP) software to process SFOV AIRS radiances to vertical profiles of temperature, humidity, and ozone.
- Modified the SSEC winds software to track features on constant pressure surfaces.
- Developed procedures to access the Level 1B AIRS granules, process, and derive winds from tracking humidity features:
    - Create images of specific humidity and ozone on constant pressures surfaces.
    - Track features from a triplet of images.

Year 2 Accomplishments

Summary

During the second year we:

- Installed the 26 November 2012 International MODIS and AIRS Processing Package (IMAPP) software to process SFOV AIRS radiances to vertical profiles of temperature and humidity. This update results in less noisy moisture and ozone images.
- Applied a bi-linear interpolation technique to the image data to smooth the gradients between individual pixels. This procedure artificially increases the image resolution from 16 km to 4 km. However, the cross correlation used in the winds algorithm is much better behaved at this resolution with smoother gradients.
- Generated two seasons of AIRS retrieval AMVs: 02 December 2011 to 09 January 2012 (winter) and 14 June to 31 July 2012 (summer).
- Retrieved from our archive the Aqua MODIS AMVs for the same time period, as above.

Comparison to MODIS winds

During the northern hemisphere summer, there is more moisture (as compared to winter) resulting in many features to track. For the 14 June to 13 July 2012 time period, 650 wind sets were generated resulting in 164,000 AIRS moisture and 135,000 ozone AMVs (see Figure 2 for an example spatial distribution of one wind set). During that same time, nearly 3 million Aqua MODIS winds were generated (Figure 3 is an example of one MODIS wind set). The following statistics and results are based on this time period.

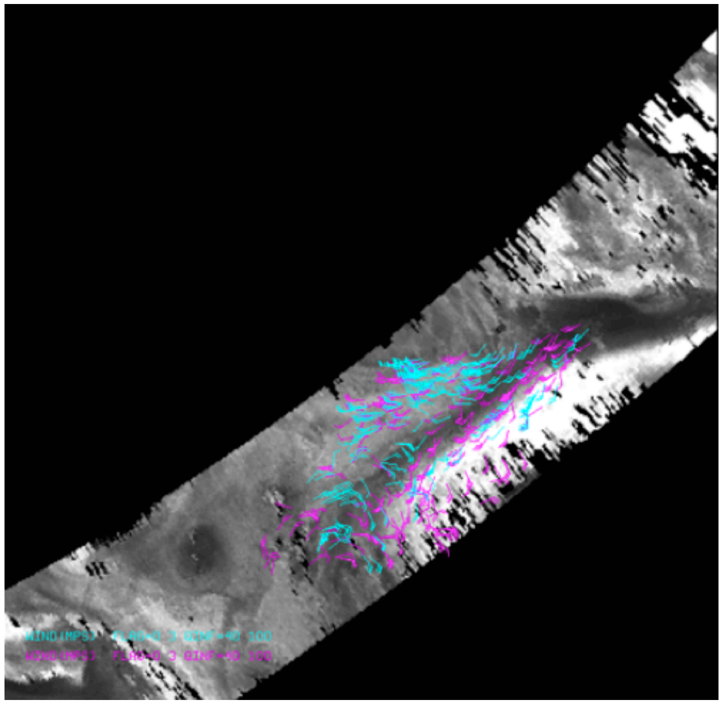

Figure 2: AIRS retrieval AMVs over a 400 hPa AIRS retrieved moisture field from 20 July 2012 0551 UTC. The north pole is in the center of the picture, with Greenland in the lower left region (not visible). These wind barbs are all moisture and ozone tracked AMVs color coded by pressure level: yellow 700 to 1000 hPa; cyan 400 to 699 hPa; magenta above 399 hPa.

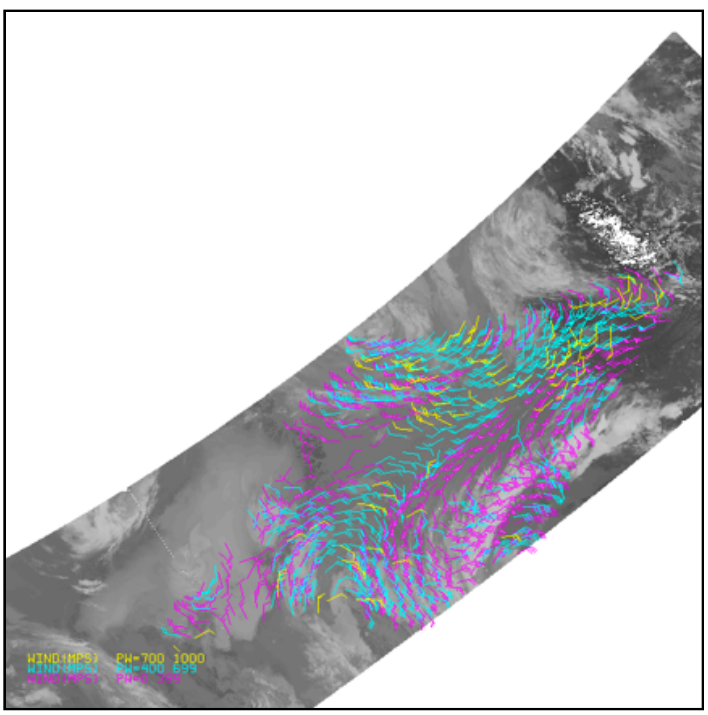

Figure 3: Same geographic region and time as Figure 2, with the Aqua MODIS AMVs displayed over a MODIS 11 μ image. The AMVs are from tracking clouds and features in both infrared and water vapor channels.

To compare co-located vectors from AIRS and MODIS AMVs, the following criteria were used:

- Located within 25 km
- Assigned pressure level within 15 hPa

This resulted in approximately 25,000 matches, or only 8% of the total AIRS winds. This percentage is low for two reasons: the AIRS AMVs are distributed vertically while the MODIS AMVs are at a single level at a specific geographic region and the AIRS dataset contains winds in the stratosphere.

Figure 4 depicts the distribution of the speed difference between the 25,000 matched AIRS and MODIS AMVs for the northern hemisphere summer. There is no bias (mean difference is -0.06 ms^{-1}) in this approximately Gaussian distribution.

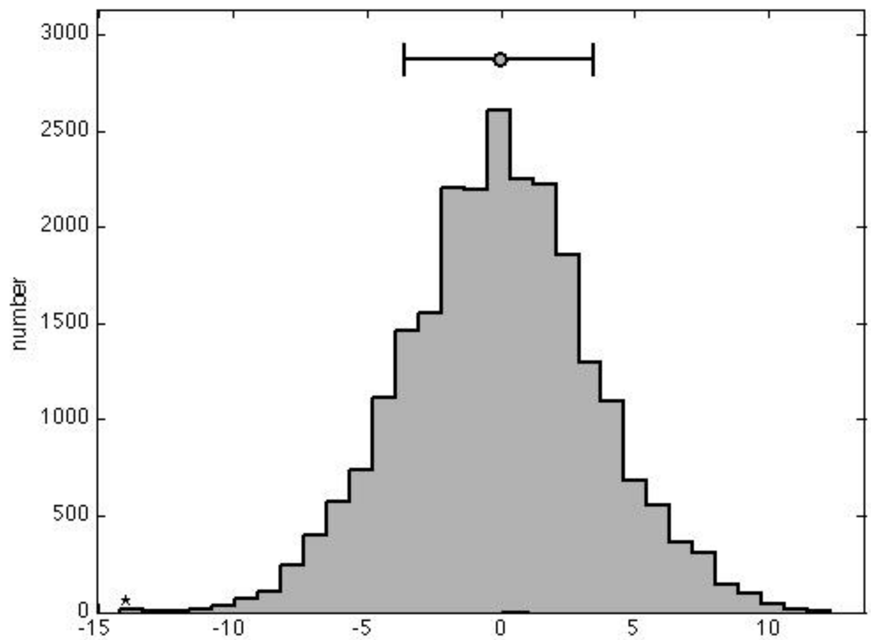

Figure 4: Histogram of the speed difference between co-located Aqua MODIS and AIRS retrieval AMVs. This is for the northern hemisphere summer: 14 June to 31 July 2012. Mean=-0.06 ms^{-1}; Standard Deviation=3.54 ms^{-1}.

These results are encouraging, as:

- The MODIS and AIRS co-located AMVs are similar and without a bias. The standard deviation of the speed difference was expected to be several meters per second, due to the different spatial resolution (2 km for MODIS vs. 16 km for AIRS).
- Only 8% of the MODIS and AIRS AMVs are co-located within 25 km and 15 hPa, therefore the AIRS AMVs should provide additional observations over the MODIS-only dataset.

GEOS-5 Impact Experiments

We ran the GEOS-5 Atmospheric Global Climate Model (AGCM) on the NCCS 'discover' system, with these features and configuration:

- Gridpoint Statistical Interpolation (GSI) analysis at ~½° resolution with 72 vertical levels.
- 3DVar
- 6-h assimilation cycle
- 7-day forecasts, adjoint-based 24h observations
- Impacts at 0000 UTC (dry energy norm, sfc-150 hPa)

Resources

The process to set up accounts on the NCCS computers, request computer time, and complete security training were completed early in Year Two. However, we learned that the NCCS support staff could not assist us in running the GEOS-5 in the configuration we need. We were instructed to contact Michele Rienecker (director of the GMAO at that time) to work with her group directly. She designated Dagmar Merkova to assist us, which was key for the success of the project. Dagmar provided scripts, guidance, and assisted with all aspects of processing and analysis, throughout the time we were running the GEOS-5.

Experiments

The northern hemisphere summer time period was selected (14 June – 31 July 2012) to run several experiments. The input AIRS AMVs were from 103 to 201 hPa (ozone) and 359 to 616 hPa (moisture).

A control and three experiments were run:

- Control: The Control run contains all the typical data sources, including the MODIS IR and WV AMVs.
- Exp. #1 (AIRS AMVs): This is the same as the Control, with the addition of the AIRS moisture and ozone AMVs. This scenario will show the incremental impact due to just the addition the AIRS winds, with all other data sources remaining the same.
- Exp. #2 (ex2): This is the same as Exp. #1, but MODIS WV winds are excluded. This experiment replaces the MODIS WV winds with the AIRS WV winds, which will be in the similar clear sky regions. This tests the situation of using sounder winds instead of AMVs from the water vapor channel on MODIS. This is important as the Terra MODIS WV winds were turned off in mid-2013 due to a degraded band 27 channel. Also, VIIRS on S-NPP does not have a water vapor channel, which may be compensated by using sounder AMVs from CrIS and ATMS.
- Exp. #3 (ex3): This is the Control with all MODIS winds removed. This tests the impact of AIRS winds as a complete replacement of MODIS winds. Note: the AIRS winds are only from Aqua, while MODIS winds are from both Aqua and Terra.

Assimilation Impact

A first measure of how the AIRS AMVs will behave in the GEOS-5 is to compare the winds with the GEOS-5 background and analysis fields. Figure 5 depicts the moisture

AMV speed departure from the background (blue) and the analysis (yellow) for the northern hemisphere. The distributions of these departures are favorable as:

- The bias is small (approximately 0.2 m^{-1}), and
- The standard deviation is reduced from 3.2 (background) to 3.0 ms^{-1} (analysis), indicating that the AIRS AMVs that are assimilated have an impact on the analysis.

Since there is very little moisture in the southern hemisphere winter (green and red curves), those are not considered for this time period.

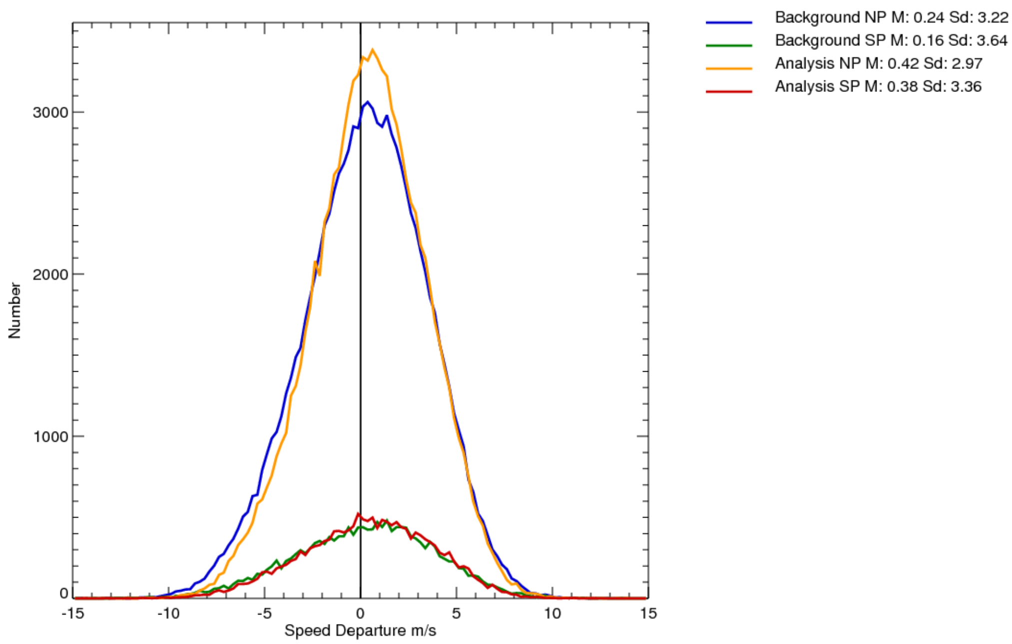

Figure 5: Distribution of speed departure for 01-29 July 2012 for the AIRS moisture AMVs. Compared to background (Arctic - blue; Antarctic - green) and analysis (Arctic - yellow; Antarctic - red).

The speed departure for the ozone AMVs is shown in Figure 6. These distributions are skewed (non-Gaussian distribution) and shifted to the right of zero. This indicates a fast bias in the AMVs of 1.7 ms^{-1} for the northern hemisphere, as compared to the background. With very few observations in the stratosphere, it was not possible to determine if the ozone AMVs actually had a fast bias compared to an independent measure of wind speed.

The impact per observation (Figure 7) is very good for the AIRS moisture AMVs, as they are ranked higher than all other satellite-derived wind datasets. However, the AIRS ozone AMVs have a negative impact, which is likely due to the fast speed bias noted in Figure 6.

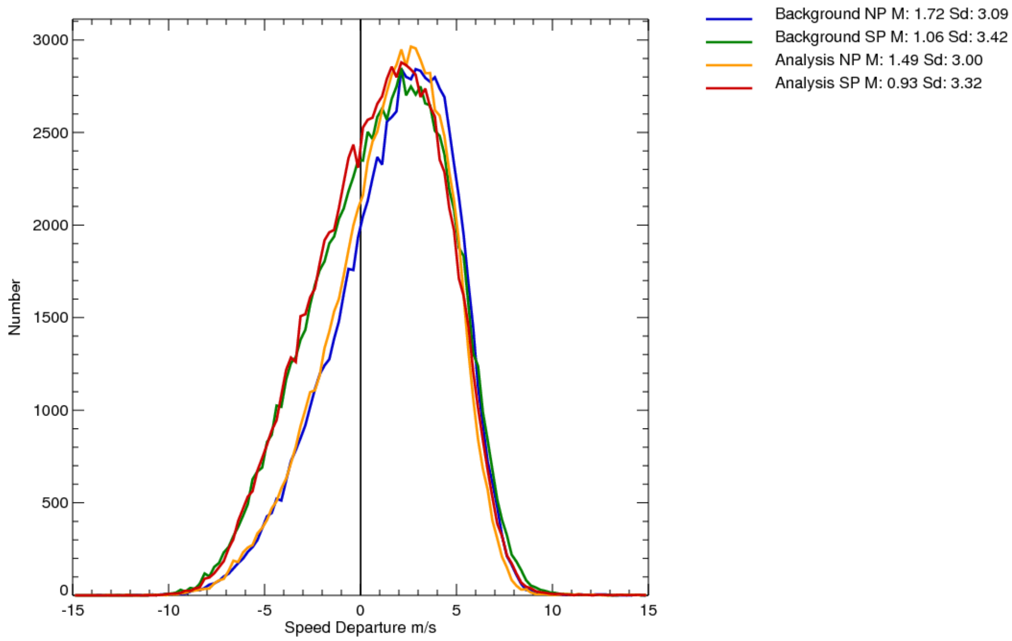

Figure 6: Distribution of speed departure for 01-29 July 2012 for the AIRS ozone AMVs. Compared to background (Arctic - blue; Antarctic - green) and analysis (Arctic - yellow; Antarctic - red).

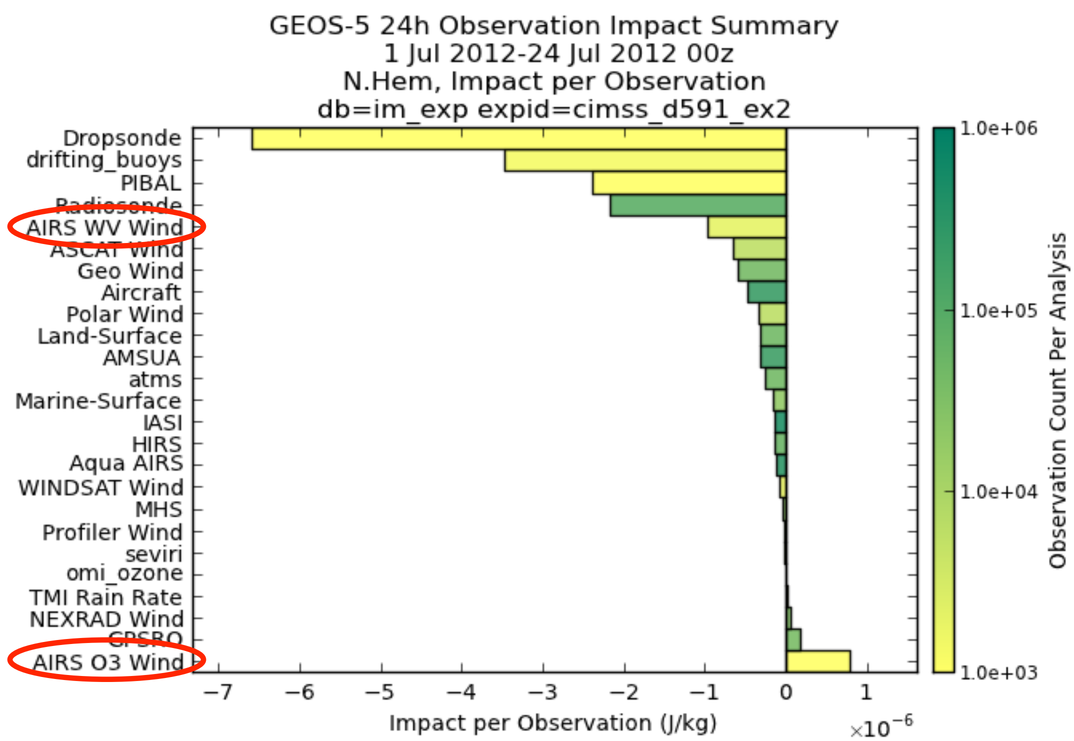

Figure 7: Impact per observation for 01-24 July 2012 0000 UTC for the AIRS WV (moisture) and O3 (ozone) AMVs.

Forecast Impact

The forecast impact is statistically neutral as measured by the ACC score for the first 24 days of July 2012. Figure 8 depicts the 500 hPa die-off curves for the control (blue) and three experiments:

- The addition of the AIRS AMVs (red curve) shows a slight improvement in the ACC score after Day 4, but it is not statistically significant.
- The removal of the MODIS AMVs (blue) shows a decrease in the ACC score, as the AIRS AMVs are not able to offset the loss of the MODIS AMVs. This indicates that the AIRS AMVs complement the MODIS AMVs, and should not be considered a replacement. This is expected as the AIRS AMVs are in clear sky or above cloud regions, while the MODIS AMVs include cloud-tracked features.

The neutral, or slightly positive, impact due to the addition of the AIRS retrieval AMVs is an encouraging result as these AMVs are poleward of 70º latitude, but they still have an impact in the longer range forecast over the northern hemisphere (20º – 90º latitude).

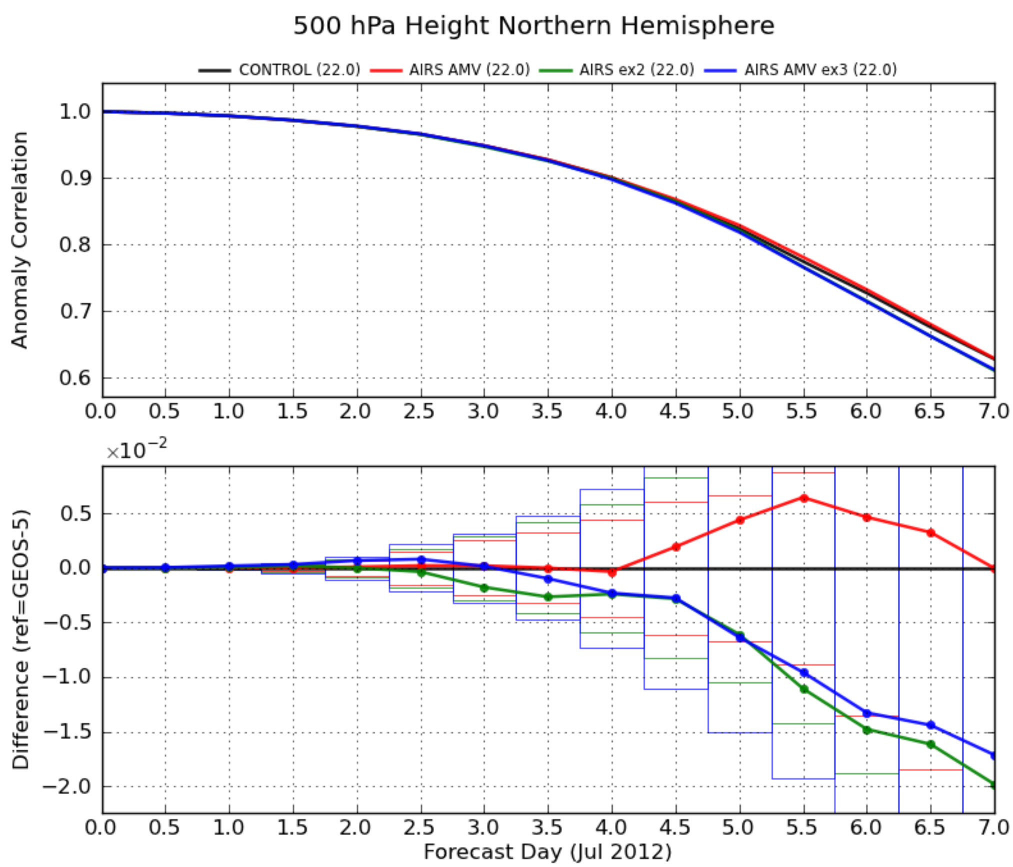

Figure 8: The 500 hPa Northern Hemisphere ACC die-off curves (top) for 1 – 24 July 2012 00 UTC. The control (black) and three experiments (red, green, and blue) are shown. The lower figure shows the difference between the control and the experiments. Positive difference is an improvement in the forecast; to be statistically significant, the curve must lie outside of its threshold rectangle.

Conferences and workshops

Santek, D., S. Nebuda, C. Velden, J. Key, D. Stettner, 2012. Deriving Atmospheric Motion Vectors from AIRS Moisture Retrieval Data. *12th International Winds Workshop*. 20-24 Feb 2012, The University of Auckland, New Zealand.

Santek, D., S. Nebuda, C. Velden, J. Key, D. Stettner, 2012. Using AIRS Moisture Retrieval Data to Derive Atmospheric Motion Vectors. *AIRS Science Team Meeting*. 24-27 April 2012, California Institute of Technology, Pasadena, California.

Santek, D., S. Nebuda, D. Stettner, 2012. Feature Tracked Winds from Moisture Fields Derived from Satellite Sounders. *2012 EUMETSAT Meteorological Satellite Conference*. 3-7 September 2012. Sopot, Poland.

Santek, D., S. Nebuda, D. Stettner, D. Merkova, 2013. Feature Tracked Winds from Moisture and Ozone Images Derived from Satellite Sounder Retrievals. *2013 EUMETSAT/AMS Meteorological Satellite Conference*. 16-20 September 2013. Vienna, Austria.