Feature-tracked 3D Winds from Satellite Sounders: Derivation and Impact in Global Models

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Abstract

The global measurement of 3D winds is recognized as an important dataset to improve medium- to long-range weather forecasts. At this time, vertical wind profiles through the troposphere are primarily from rawinsondes and aircraft ascents/descents, and are mostly confined to land areas. Wind information over mid- and low-latitude oceanic regions is limited to Atmospheric Motion Vectors (AMVs) from cloud and water vapor feature tracking using imagers on geostationary satellites. A similar technique is used with imagery from polar orbiting satellites over high-latitude regions. However, these geostationary and polar satellite-derived AMVs provide only single-level wind information at a particular geographic location.

To attain a 3D distribution of wind information, an AMV product has been developed based on tracking water vapor features retrieved from satellite sounders. The retrievals produce spatial maps of humidity on pressure surfaces in clear sky and above clouds. The initial AMV product, available in near real-time, is based on retrievals from the Aqua Atmospheric Infrared Sounder (AIRS) and is being evaluated by several Numerical Weather Prediction (NWP) centers.

This is a summary on the status of: (a) The 3D wind derivation technique as applied to AIRS; (b) assimilation statistics from the Gridpoint Statistical Interpolation (GSI) system; (c) the forecast impact in the Global Forecast System (GFS); (d) and, the assimilation impact in the NASA/GMAO GEOS-5.

INTRODUCTION

The MODIS polar winds product is composed of both IR-W and WV tracked features. However, 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. Despite their limited usage, 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.

The new generation of polar satellites beginning with S-NPP has the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument, which unlike MODIS, does not have a WV channel. Therefore, a potential data gap will result as no WV features can be tracked, resulting in only the standard IR-W derived AMVs. This scenario presents itself as an opportunity to investigate using Single Field of View (SFOV) 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 of the project was to create a blended product of MODIS imager- and AIRS retrieval-derived AMV datasets. This capability could be extended to S-NPP for generating cloudy AMVs from VIIRS and using moisture retrievals derived using the Cross-Track Infrared Sounder (CrIS) to produce clear-sky AMVs.

In addition to comparing AIRS winds to MODIS winds, we ran three experiments in which we blend the experimental AIRS moisture retrieval AMVs with the already proven MODIS AMVs to create 3-D polar wind fields. Lastly, we performed 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).

AIRS Retrievals

The AIRS Standard Retrieval Product provides profiles of retrieved temperature, water vapor, and ozone. The product is generated from 3x3 Fields of View (FOV) of AIRS radiances that results in a horizontal resolution of 40 km. However, 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 was developed at the SSEC using SFOV AIRS footprints, which retained the native horizontal resolution at 13.5 km/pixel and resulted in temperature, humidity, and ozone profiles at 101 pressure levels from 0.005 to 1100 hPa. This algorithm is available in the International MODIS/AIRS Processing Package (IMAPP).

We utilized the SFOV product in our AIRS AMV generation, since it provides the best spatial resolution for our application. The SFOV AIRS product software is available in the IMAPP package. Example retrieved profiles (magenta) are shown in *Figure 1* for clear sky, low cloud, and high cloud as compared to the GFS model background (black). Generally, the agreement between the retrievals and the GFS is good.

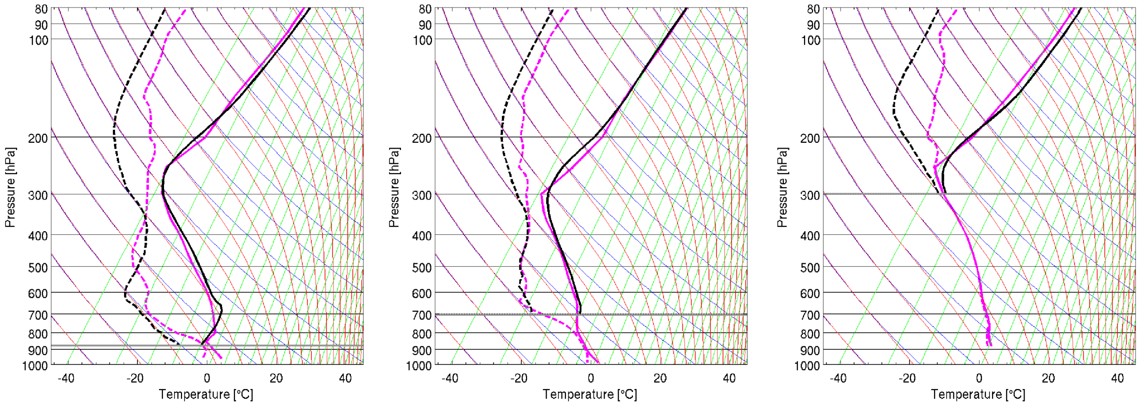

Figure 1: An example of temperature and dewpoint profiles for clear sky (left), low cloud (middle), high cloud (right). The satellite-derived retrievals are in black; NCEP/GFS in magenta.

DATA COVERAGE

The AIRS AMVs were extracted from a time sequence of three images. In order to achieve overlapping images, the AMVs could only be derived in high latitudes (poleward of 70º latitude). The geographic coverage of AMVs from polar orbiting satellites is over small regions at any particular time. Because the AIRS instrument has a narrower swath width than MODIS, the spatial coverage of the AIRS AMVs is also reduced. An entire day is needed to get complete AMV coverage over the polar regions.

The AMVs were derived on pressure surfaces away from the tropopause and the Earth's surface. Specifically, we used moisture levels from 359 to 616 hPa (17 levels) and ozone levels from 103 to 201 hPa (12 levels).

GEOS-5 IMPACT EXPERIMENTS

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

- Gridpoint Statistical Interpolation (GSI) analysis at ~½° resolution with 72 vertical levels.
- 3DVar
- 6-h assimilation cycle
- 7-day forecasts, adjoint-based 24 hour observations

- Impacts at 0000 UTC (dry energy norm, sfc-150 hPa)
- QI > 40; increased the assimilation observation error

Experiments

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

- Control: The Control run contained all of the standard data sources, including the MODIS IR and WV AMVs.
- Exp. 1 (AIRS AMVs): Exp. 1 was run identically to the Control, with the addition of the AIRS moisture and ozone AMVs. This allowed the incremental impact due to the addition of AIRS winds to be highlighted, as all other data sources remained constant.
- Exp. 2 (ex2): Exp. 2 was run identically to Exp. 1, with the removal of the MODIS WV winds. The experiment replaces the MODIS WV winds with the AIRS WV winds, which were in similar clear sky regions, testing the usage of 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.
- Exp. 3 (ex3): Exp. 3 was run identically to the Control, however with all MODIS winds removed. This tests the impact of AIRS winds (only from Aqua) as a complete replacement of MODIS winds (from Aqua and Terra).

Assimilation Impact

The measure of how the AIRS AMVs behaved in the GEOS-5 was to compare the winds with the GEOS-5 background and analysis fields. The results of the northern hemisphere analysis are favorable:

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

Since there is very little moisture in the southern hemisphere during winter, they were not considered for this time period.

The impact per observation (*Figure 2*) 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 a several meter per second speed bias as compared to the background.

Forecast Impact

The forecast impact was statistically neutral as measured by the ACC score for the first 24 days of July 2012. *Figure 3* depicts the 500 hPa die-off curves for the control (blue) and the three experiments:

- Although not statistically significant, the addition of the AIRS AMVs (red) shows a slight improvement in the ACC score after Day 4.
- The removal of the MODIS AMVs (blue) shows a decrease in the ACC score, as the AIRS AMVs are unable to offset the loss of the MODIS AMVs, indicating that the AIRS AMVs complement the MODIS AMVs and should not be considered a replacement. This was expected as the AIRS AMVs are in clear sky or above cloud regions, while the MODIS AMVs include cloud-tracked features.
- Note: The arbitrary ordering of the placement of the curves makes it more difficult to observe some of the experiment's curve if they are "below" a different curve.

The neutral, or slightly positive, impact due to the addition of the AIRS retrieval AMVs is encouraging 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).

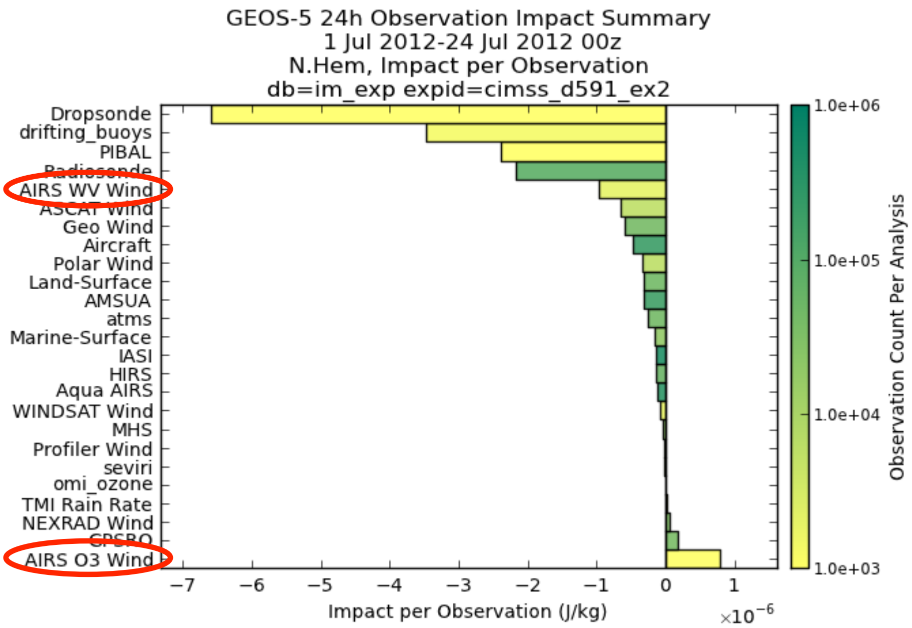

Figure 2: Impact per observation for 01-24 July 2012 0000 UTC for the AIRS WV (moisture) and O3 (ozone) AMVs.

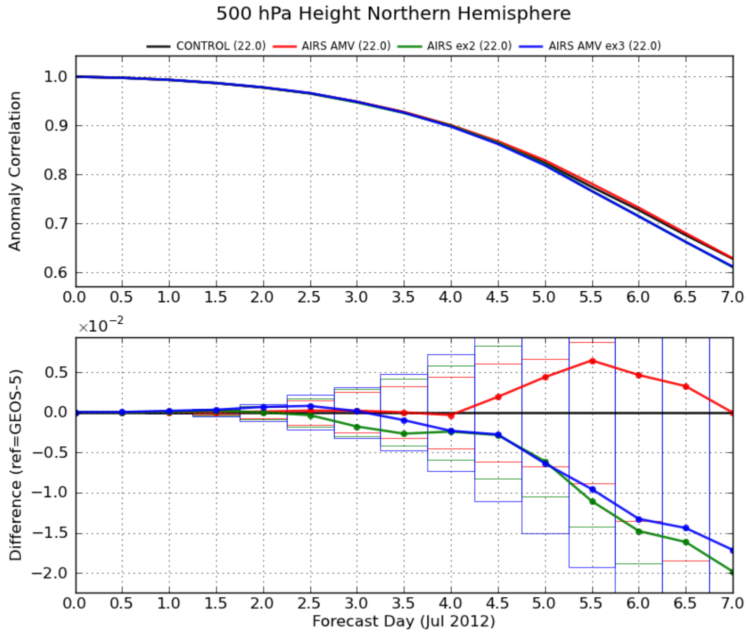

Figure 3: The 500 hPa Northern Hemisphere ACC die-off curves (top) for 1-24 July 2012 00 UTC. The control (black) and three experiments (red, green, and blue) are shown. The lower figure shows the difference between the control and the experiments. Positive difference is an improvement in the forecast; to be statistically significant, the curve must lie outside of its threshold rectangle.

REAL-TIME GENERATATION OF AIRS RETRIEVAL WINDS

In order for other NWP centers to evaluate the AIRS AMVs, NASA funded a proposal to generate this product in real-time. The following is the methodology used:

- 6-minute AIRS Level 1B granules are downloaded from LANCE, as available in real-time
- The SFOV retrieval algorithm is run on the individual granules.
- Images of the humidity retrievals are generated at each pressure level, reprojected to a polar stereographic projection at 16 km resolution, and merged to provide a swath over the polar regions.

- A bi-linear interpolation technique is used to smooth gradients to improve the performance of the cross-correlation algorithm used in tracking features
- Winds are computed on 22 pressure levels (343 to 753 hPa)
- The AMV product is available in near real-time
    - Delayed by several hours, which is similar to other polar winds products
    - 13-15 AIRS winds datasets are processed per day at each pole
- The AMVs generally cover the area poleward of 70º latitude over the course of a day

Preview images with retrieval AMVs overlayed:
http://stratus.ssec.wisc.edu/cgi-bin/polarwinds?airs

The AIRS retrieval AMV product files:
ftp://stratus.ssec.wisc.edu/pub/winds/retrieval_winds/airs/

The format is text files in a format similar to other AMV products provided by CIMSS, such as those from MODIS, AVHRR, and Leo/Geo.

NASA GMAO EVALUATION

The NASA/GMAO evaluated of a three-month period of AIRS retrieval winds in their Goddard Earth Observing System (GEOS-5) data assimilation system. All wind observations were assimilated every six hours from 0000 UTC 1 May 2015 to 1800 UTC 31 Jul 2015. The normalized observation counts for both MODIS water vapor and AIRS water vapor winds are shown for the northern hemisphere in *Figure 4*. Of note is the higher percentage of the AIRS retrieval-derived AMVs in the mid-troposphere (below 400 hPa) than from MODIS.

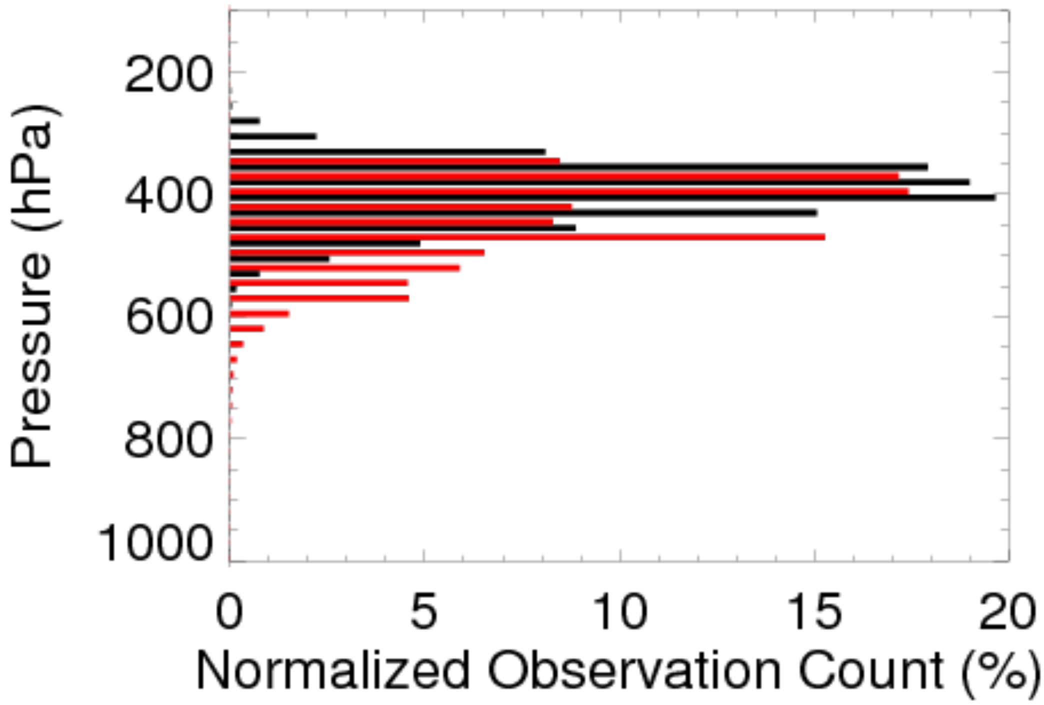

Figure 4: Vertical histogram showing the average observation counts per 6-hour assimilation cycle for MODIS (black) and AIRS (red) water vapor AMVs. These are for all AMVs before thinning or quality control in the GEOS-5 assimilation system.

The mean and standard deviation of the observation departures, or the difference between the observation and the 6-hour forecast (Observation minus Forecast, O-F), is shown in *Figure 5* for AIRS and MODIS water vapor winds. Minimal quality control is applied to eliminate large outliers. It is seen that the MODIS winds have a persistent negative bias above 300 hPa, but AIRS does not have any measurements at these levels. Similar biases in magnitude are seen 500 and 300 hPa for both instruments, though not necessarily of similar sign. From 500 to 600 hPa, MODIS shows an increase in bias not reflected in the AIRS observations. It is also noted, though, that the observation counts below 500 hPa are very small for MODIS. For AIRS, the bias is largest in magnitude below 700 hPa, though this is again a layer of few observations. When considering the standard deviations, the MODIS observations show less variance than AIRS at layers above 500 hPa, and AIRS shows less variance at regions below 500 hPa. Both show a reduction in variance to about 500 hPa, while the variance is more consistent layer-to-layer below that point. It is noted that there are gross error checks that discard the largest outliers applied to both datasets, but the tuning coefficients of the AIRS gross check have not been thoroughly investigated.

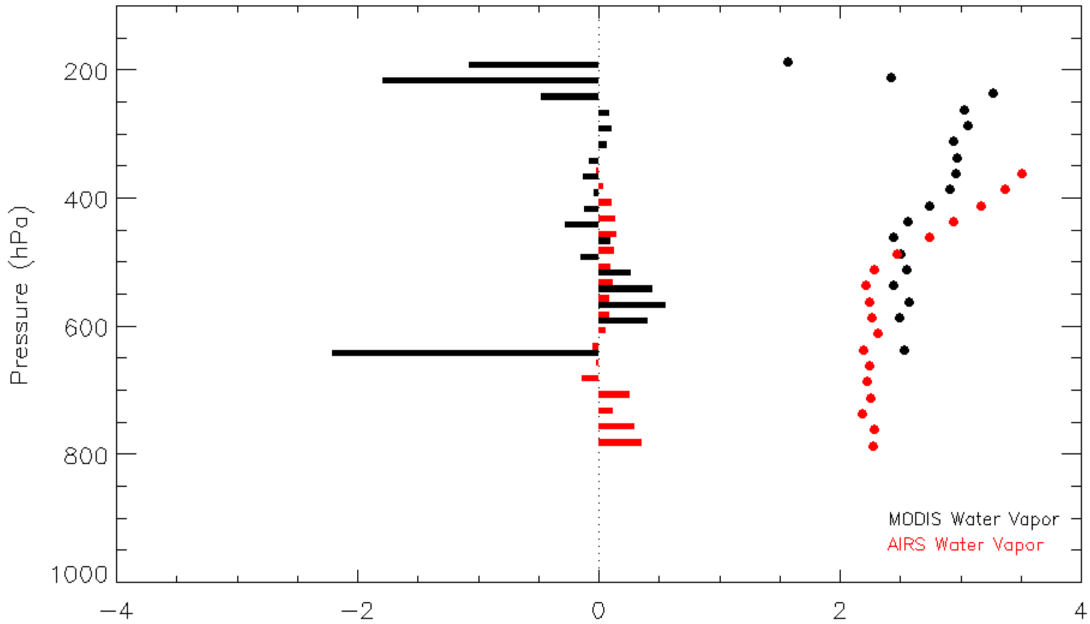

Figure 5: Mean (bars) and standard deviation (circles) of observation departures (ms^{-1}) (observed minus 6-hour forecasted wind) for MODIS (black) and AIRS (red) water vapor AMVs 0000 UTC 1 May 2015 to 1800 UTC 31 Jul 2015.

FUTURE APPLICATIONS

The AIRS retrieval winds technique can be applied to other satellites. For example, polar imagery winds are currently being generated from AVHRR (Metop-A and –B) and VIIRS (S-NPP). And, the SSEC SFOV retrieval algorithm has been applied to IASI (Metop) and CrIS (SNPP). Therefore, similar blended AMV products could be generated for:

- AVHRR/IASI on Metop-A and -B
- VIIRS/CrIS on S-NPP and JPSS

Also, we have a proposal to NASA to investigate cross-platform humidity feature tracking, which would result in shorter time intervals between images and extend the coverage further south.

ACKNOWLEDGMENTS

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