Feature-tracked 3D winds from hyperspectral infrared sounders: Status and requirements for future missions

David Santek[1], Bill Smith[1], Will McCarty[2]

[1]Space Science and Engineering Center/University of Wisconsin – Madison
[2]NASA Global Modeling and Assimilation Office

International TOVS Study Conference (ITSC-21)
Darmstadt, Germany
1 December 2017

Outline

1) What are 3D winds?
2) Apply feature tracking to retrievals of moisture
    1) MODIS cloud/water vapor tracking heritage
    2) SFOV retrievals from hyperspectral sounder
3) Assimilation and forecast impact
4) Future: Global coverage from small sat constellations

What are 3D winds?

- Pressure-assigned atmospheric motion vectors (AMV), throughout the troposphere and stratosphere, currently:
  - Cloud and water vapor features tracked from satellite imagers
  - Satellite-derived AMVs are single level at specific geographic location

What are 3D winds?

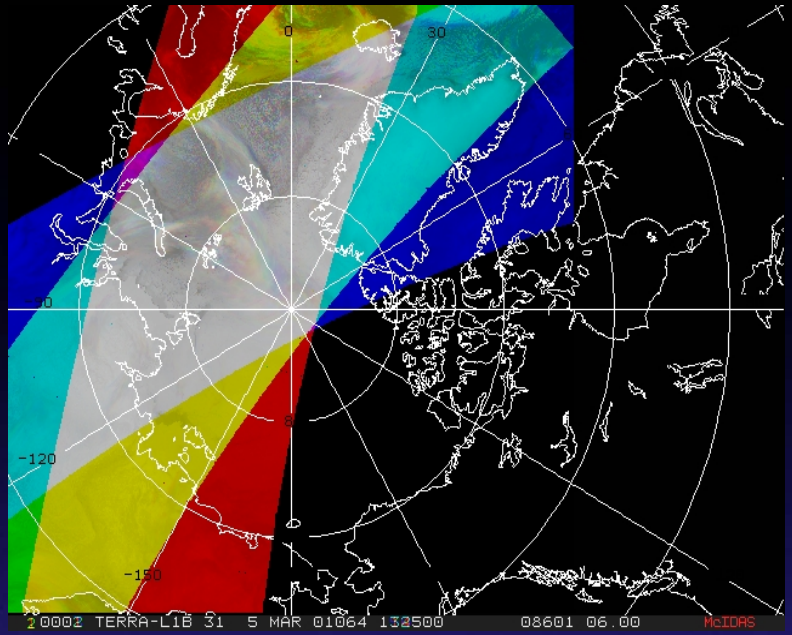
- Use hyperspectral IR retrievals of moisture and ozone, to generate maps of humidity and ozone concentration on pressure surfaces
- 3D AMVs can be derived from tracking these features on pressure surfaces, distributed vertically
- Feature tracking based on heritage algorithms used for tracking clouds and water vapor gradients from satellite imagers (GOES, MODIS, AVHRR, etc.)

Why 3D winds?

Importance of global 3D winds in weather predictability

- Fill in data void regions, most notably over oceanic, tropical, and polar regions.
- This lack of data, especially wind information, is "the number-one unmet measurement objective for improving weather forecasts." (NRC 2007)
- Decadal Survey recommended a 3D tropospheric wind mission, using a space-based LIDAR instrument.
- NASA's 2015 workshop: Scientific Challenges and Opportunities in the NASA Weather Focus Area suggested other instruments to derive 3D winds, including the use of hyperspectral infrared

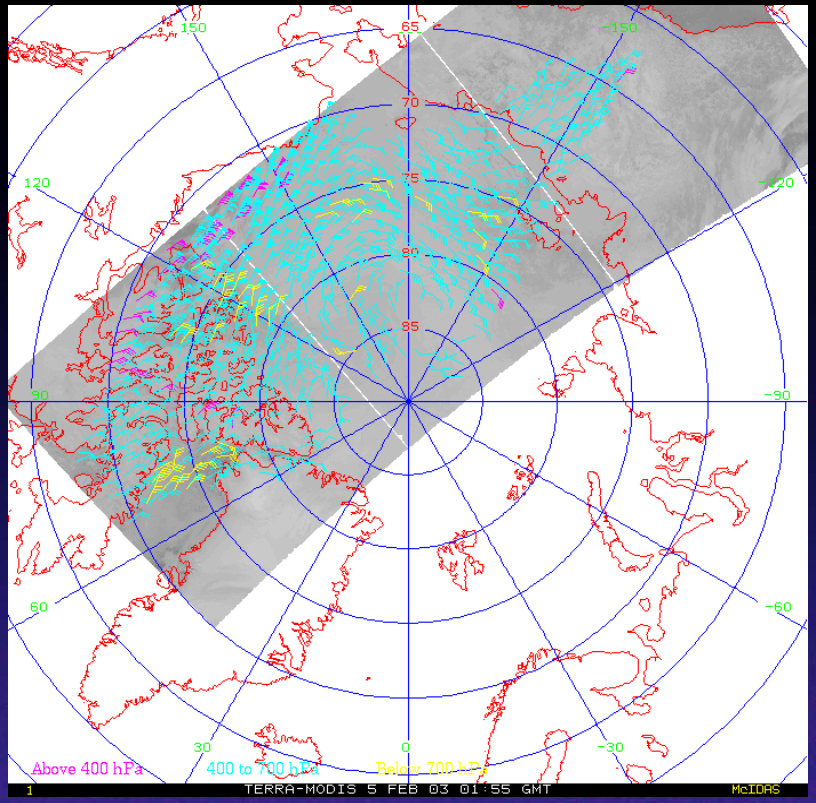
Heritage: MODIS Satellite-derived Polar Winds



Unlike geostationary satellites at lower latitudes, it is not be possible to obtain complete polar coverage at a snapshot in time. Winds must be derived for areas that are covered by three successive orbits. The gray area is the overlap between three orbits.

MODIS Polar Winds

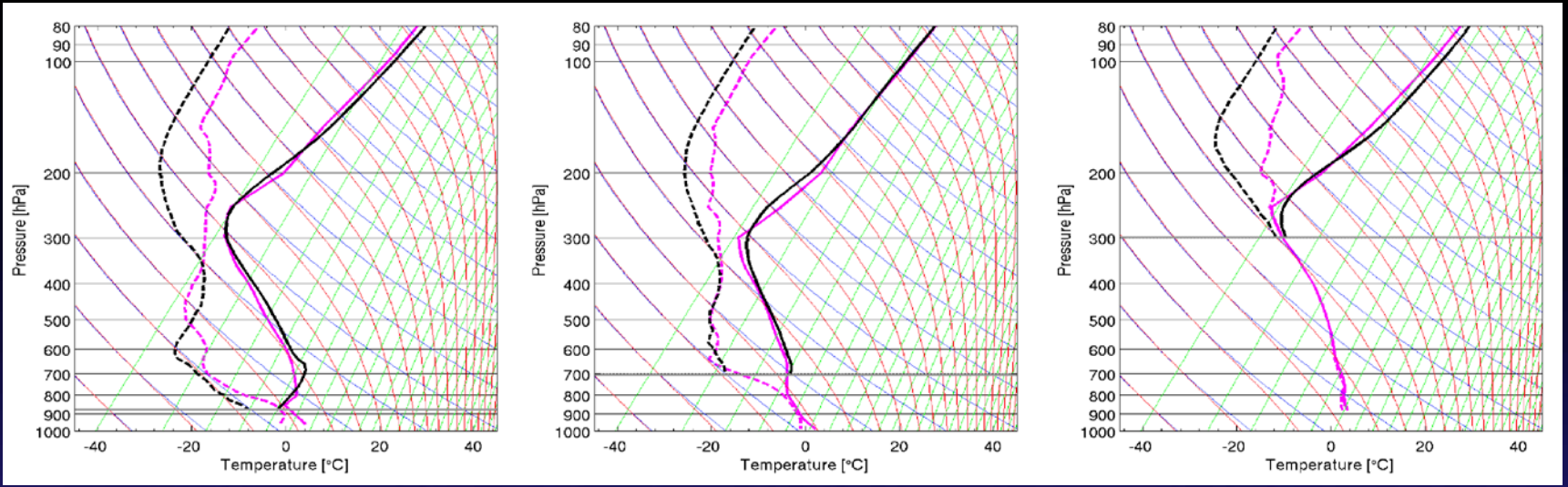
One day coverage



AIRS Retrieval

- Use the CIMSS SFOV AIRS retrieval algorithm
  a) Need highest possible resolution
  b) Retrievals of moisture and ozone mixing ratio at 101 pressure levels:
     i. Away from tropopause and surface for AMVs
     ii. Ozone: 103 to 201 hPa
     iii. Moisture: 359 to 616 hPa
  c) Elisabeth Weisz and Bill Smith, Sr.

Retrieved profiles of temperature and humidity



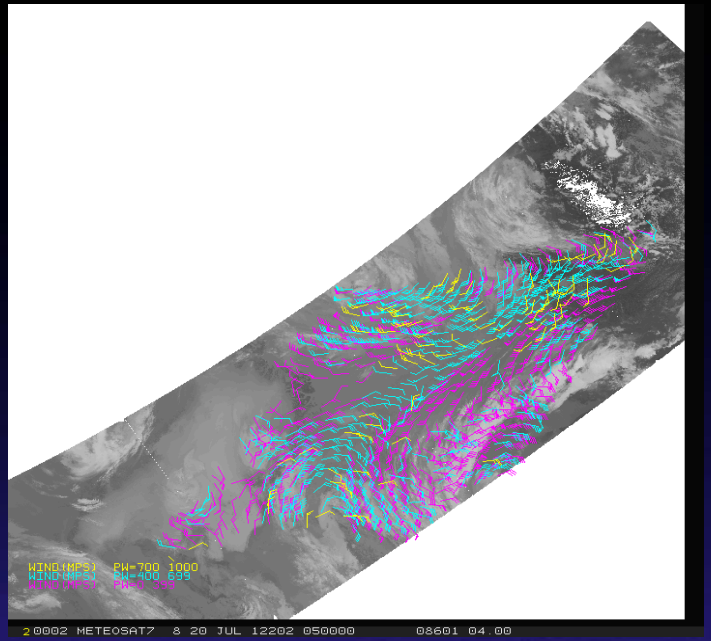
Clear sky | Low Cloud | High Cloud

Example of temperature and dewpoint profiles. Retrievals (black) and NCEP/GFS (magenta).

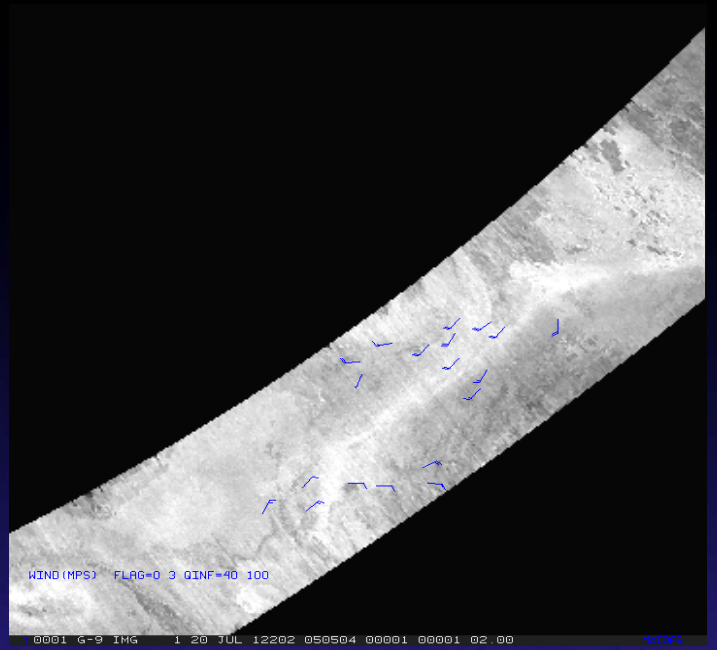
What are 3D winds from satellite sounders?

- Create images humidity and ozone on constant pressure surfaces
- Track the humidity and ozone features over time
- Advantages:
  a) 3D wind distribution
  b) Implicit AMV height
  c) Clear sky and above cloud
- Disadvantages:
  - Lower spatial resolution compared to MODIS (13.5 vs. 1 km)
  - Narrower swath

Aqua MODIS AMVs
AIRS Retrieval AMVs at All Levels



MODIS 20 July 2012 0551 UTC
Infrared and Water Vapor
(including clear sky)



AIRS 20 July 2012 0505 UTC
Ozone: 103 to 201 hPa
Moisture: 359 to 616 hPa

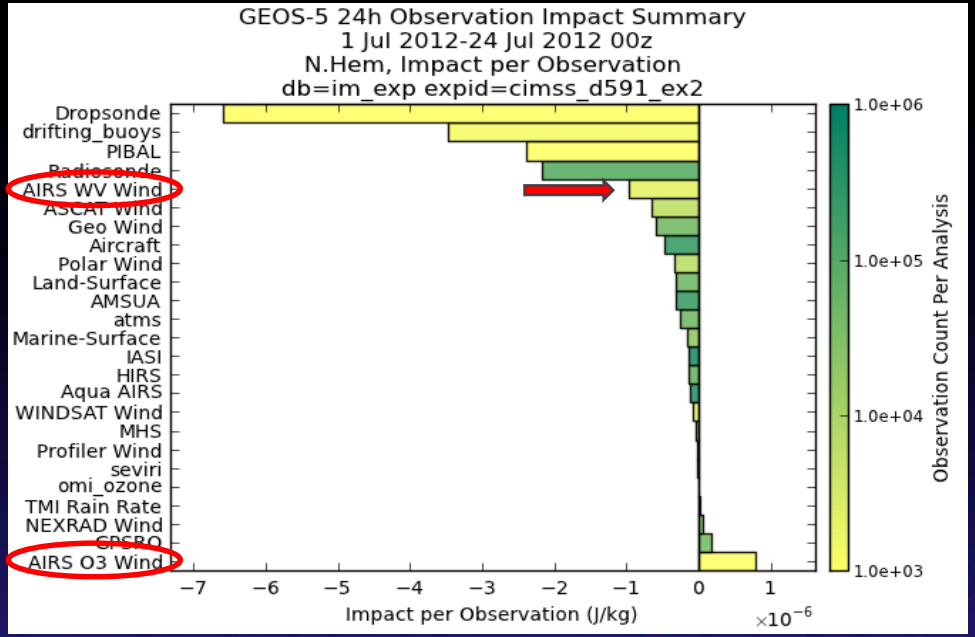
Experiments

GEOS-5 Forecast System (reduced resolution)
- GEOS-5 AGCM + GSI analysis (~½˚ L72)
- 3DVar
- 6-h assimilation cycle
- 7-day forecasts, adjoint-based 24h obs
- Impacts at 00z (dry energy norm, sfc-150 hPa)
- QI > 40; increased the observation error

Experiments (14 June – 31 July 2012)

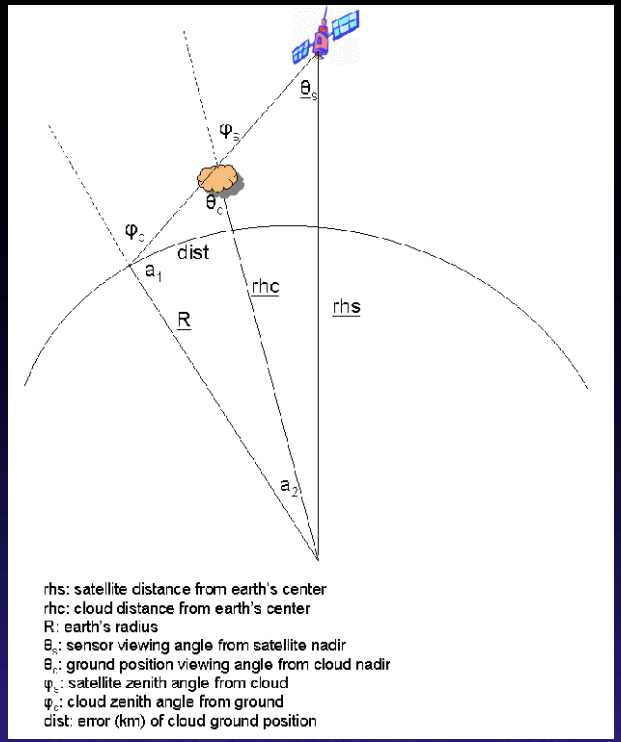
1. Control
2. + AIRS winds
3. + AIRS winds - MODIS WV winds
4. - AIRS winds - MODIS all winds

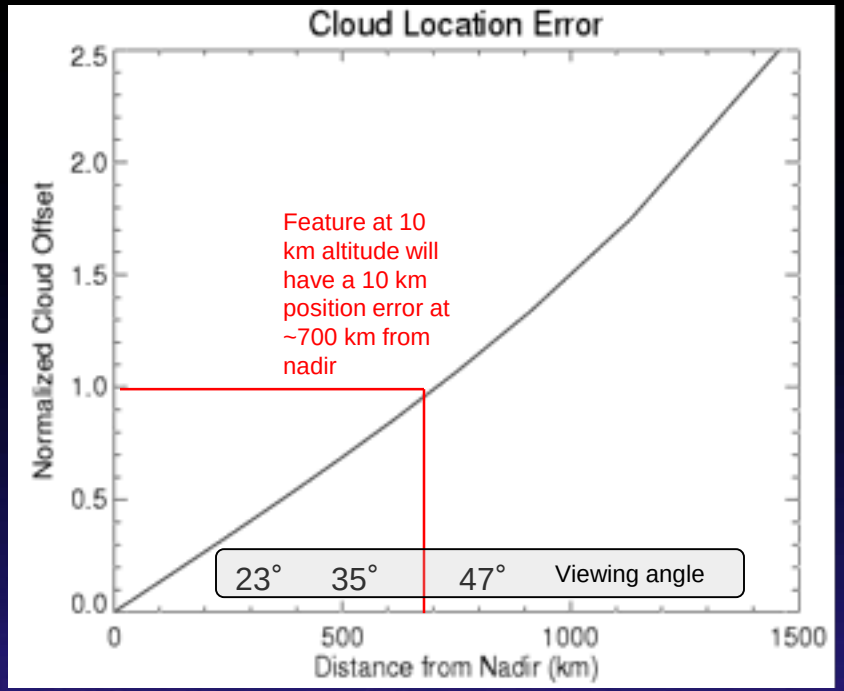
Impact per observation



1 – 24 July 2012 00 UTC

Parallax effect?





Satellite at altitude 700 km

GEOS-5 Forecast Impact: ACC
Two experiments

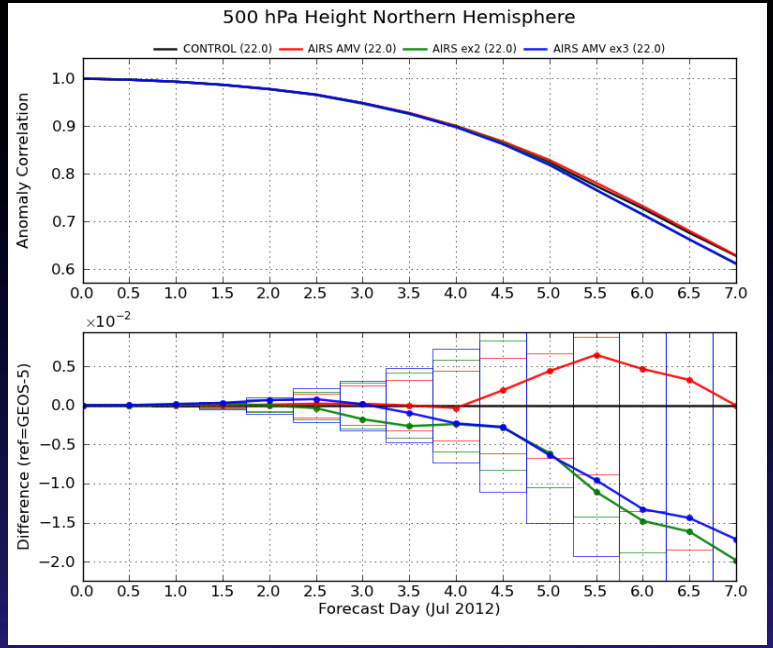
Control in black.

Red: Addition of AIRS AMVs. Slight improvement after Day 4 (not statistically significant).

Blue: Removal of the MODIS AMVs decreases ACC score. AIRS AMVs can not offset loss of MODIS AMVs

AIRS AMVs complement the MODIS AMVs

AIRS AMVs are in clear sky or above cloud regions; MODIS AMVs include cloud-tracked features.



500 hPa Northern Hemisphere
1 – 24 July 2012 00 UTC

Summary of AIRS AMVs

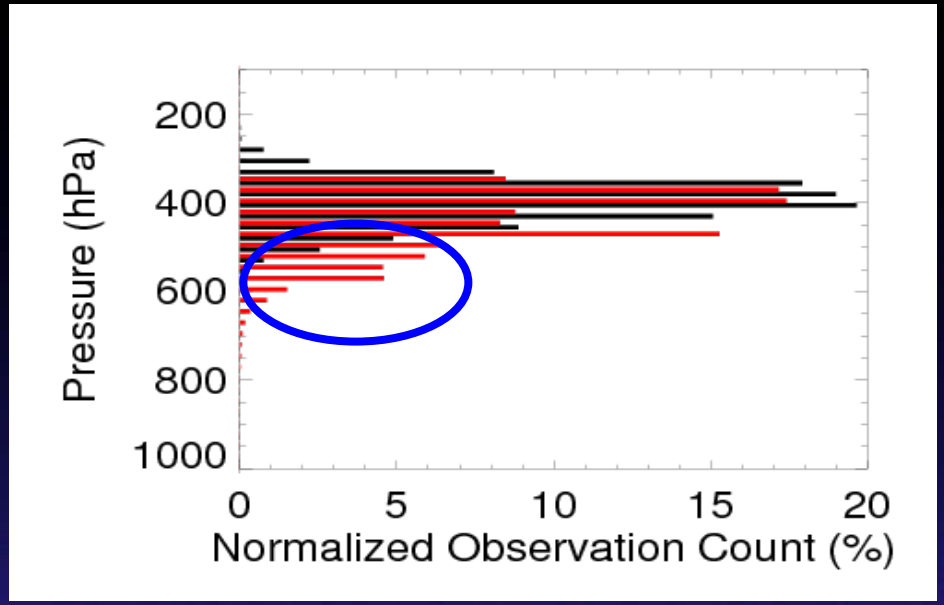
- Impact per AIRS moisture AMV is ranked higher than all other satellite-derived wind datasets
- Neutral, or slightly positive, forecast impact due to the addition of the AIRS retrieval AMVs is encouraging:
  - AMVs only in polar region: poleward 70° latitude
  - Impact in the longer range forecast over the entire northern hemisphere (20° – 90° N)
- Independent evalution by FNMOC and GMAO

AIRS winds preliminary evaluation
FNMOC (Randy Pauley)

- Observation impact looked good
- They are comparable to other polar winds in impact per observation and innovation statistics
- However, data volume low
  - Low resolution hyperspectral instruments
  - Only in the polar regions (dry atmosphere)

AIRS winds preliminary evaluation

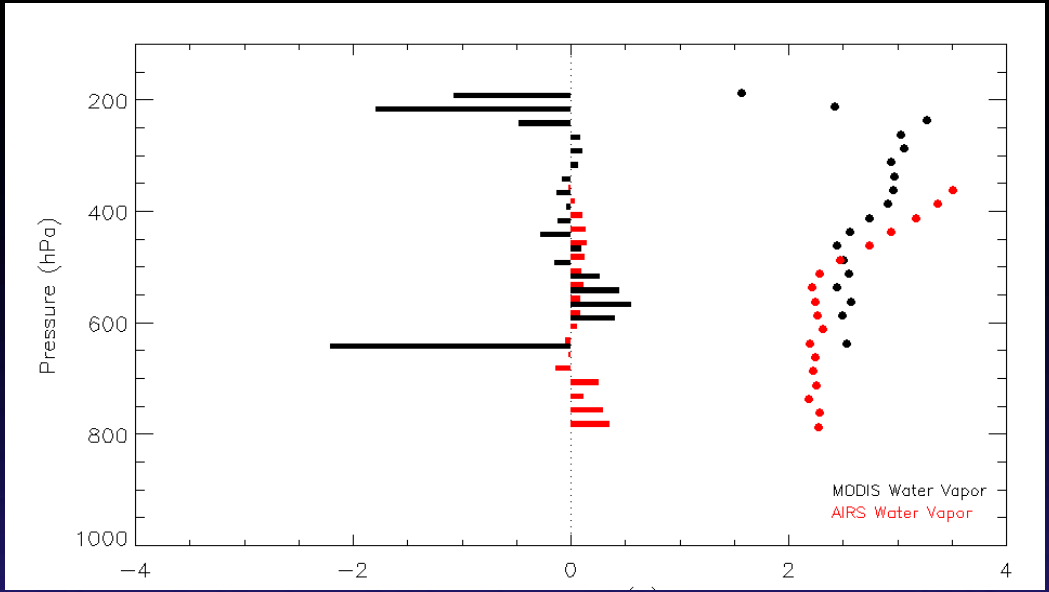
NASA/GMAO (Will McCarty)



Observation Counts: Histogram of averaged normalized counts for 6-hour cycles for AIRS (red) and MODIS (black) water vapor winds.
May to July 2015

AIRS winds preliminary evaluation

NASA/GMAO (Will McCarty)



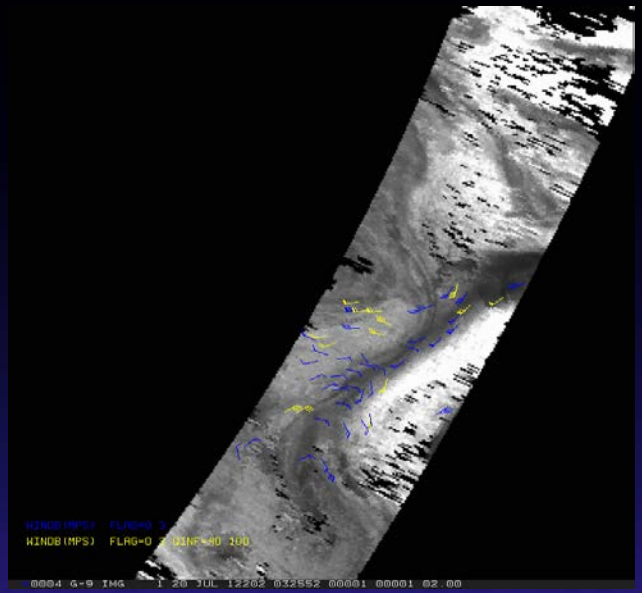
Observation Departures: Mean and standard deviation (ms^{-1})
for AIRS (red) and MODIS (black) water vapor winds
May to July 2015

Future Application of Technique

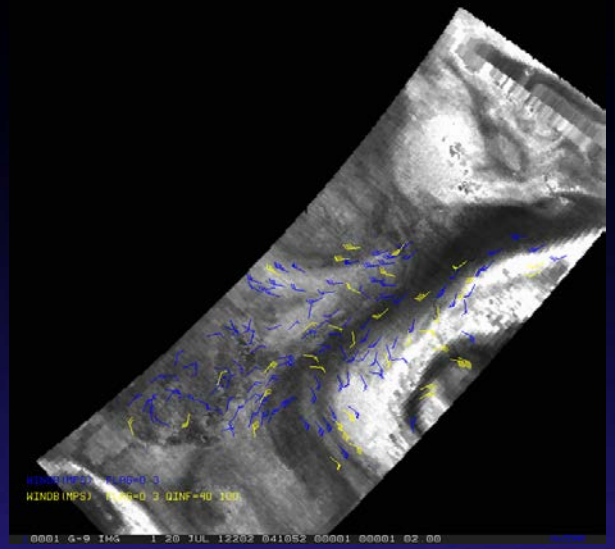
Technique can be applied to other satellites:

- Polar imagery winds are currently being generated from AVHRR (Metop-A and –B) and VIIRS (S-NPP)
- SSEC SFOV retrieval algorithm has been applied to IASI and CrIS
- Therefore, blended AMV products could be generated for:
  - AVHRR/IASI on Metop-A and -B
  - VIIRS/CrIS on S-NPP and JPSS-1 (1/2 orbit separation)
- Investigate cross-platform humidity feature tracking:
  - Shorter time interval between images
  - Coverage would extend further south
- And, perhaps other sounding instruments….

AIRS and ATMS Retrieval Images at 400hPa



AIRS 20 July 2012 0505 UTC



ATMS 20 July 2012 0551 UTC

Specific humidity retrievals.
All winds (blue); Quality controlled winds(yellow)

What is needed?

Better quantification of errors in the winds (vector and height)

Improve assimilation in NWP models

Better spatial resolution

13.5 km FOV is too coarse; 4 km or better is needed

Increased spatial coverage

Global needed for significant impact in forecasts, especially mid-range forecasts (2 weeks)

IR sounder on geostationary or constellation of low-earth orbit satellites

Future: 3D Wind Measurements Using Constellation of Small-Sats

Concept: Time-Separated Moisture Field Soundings By Multiple Small Satellites Can Provide Winds at Multiple Vertical Layers

Leading Small-Sat

Trailing Small-Sat

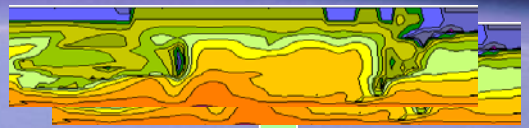
MWIR FTS is Optimized for Moisture Soundings

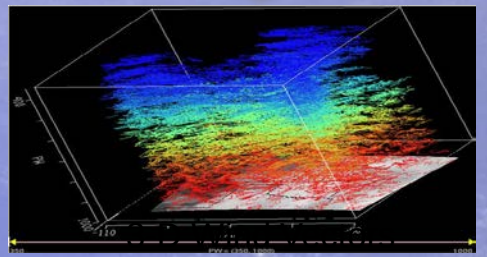
Cross-Track Step-Stare Scans

~15 minute time separation

One "Slice" Through the Atmosphere Every Few Seconds

Two 3-D Moisture Data Cubes





Observing System Simulation Experiment (OSSE)

Will McCarty

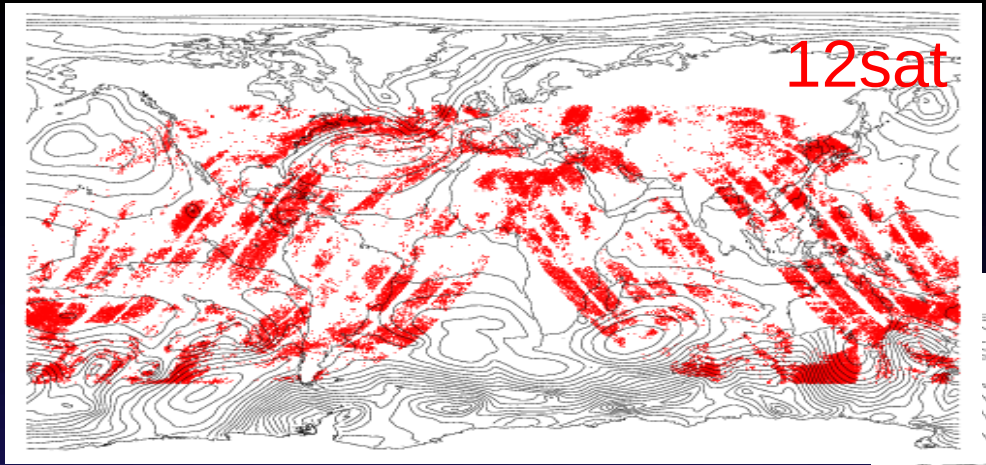
Nature run:

- 7 km GEOS-5 from the NASA/GMAO
- 2-year period, circa 2012
- A simulator was developed which probabilistically determines the 3D AMV fields at a given point along the swath of the orbital planes

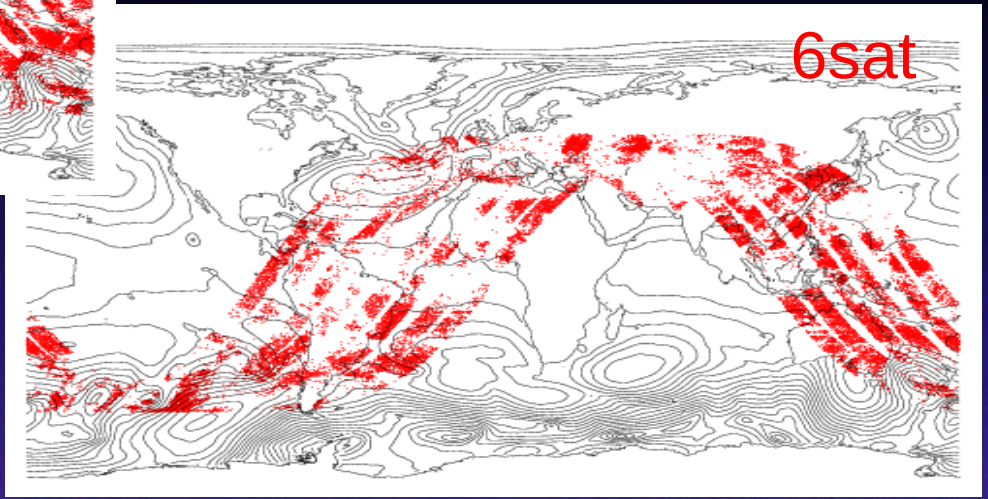
Assimilation:

- GEOS-5 data assimilation system
- 0.5˚ x0.625˚ horizontal resolution globally
- 72 vertical levels; surface to 0.01 hPa
- Cycled for a month
- Analyses every six hours

Simulated Observations
(12- and 6- satellite constellations)



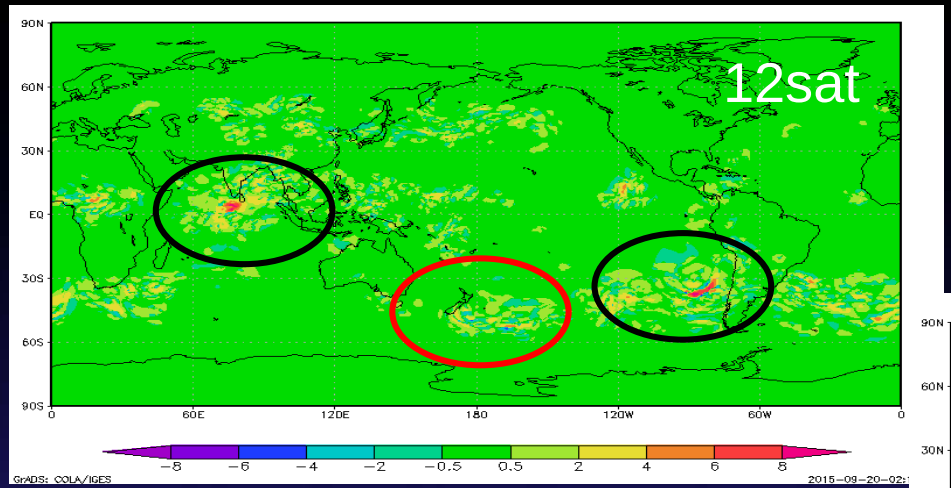
High inclination orbit to maximize mid- and low-latitude coverage



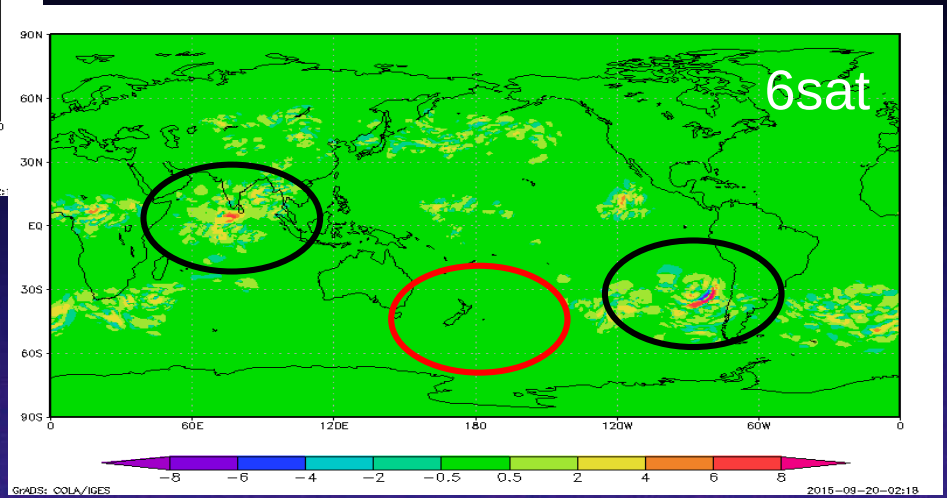
Simulated AMVs valid for 6-hour assimilation window

Black contours are surface pressure over ocean

Error Reduction



Reduction in wind speed error (ms^{-1}) at 300 hPa for a single analysis time in July



Positive impact (yellow to red)
Negative impact (blue to purple)

Summary

- AIRS retrieval polar AMVs are being produced routinely
- Interest in using other retrievals for winds:
  - CrIS, IASI: SSEC SFOV retrieval
  - ATMS: NOAA Unique CrIS/ATMS Processing System (NUCAPS)
- Global 3D winds from LEO satellite constellation:
  - 6-satellite: Minimum for demonstration mission
  - 12-satellite: Minimum for operational applications

dave.santek@ssec.wisc.edu

NASA Grants NNX11AE97G and NNX14AI77G

NOAA Grant NA14NES4830004