Derivation and application of satellite-derived winds: From the 1970s into the 2020s

David Santek

CIMSS/SSEC
University of Wisconsin-Madison

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The Early Days

Prof. Vern Suomi was striving to exploit the geostationary satellites for time domain information

- Cinematic technique by Fritz Hasler (1968)
- Pasting printouts together
  - Covered 1000 ft^2
  - Staff would walk around in stocking feet to find a landmark or cloud.

The Early Days

Mechanical vs. Computer

Internal competition at SSEC circa 1970:

- Optical correlator (light table)
- Computerized cross correlation

- WINDCO was born, which evolved to the McIDAS (Man computer Interactive Data Access System)

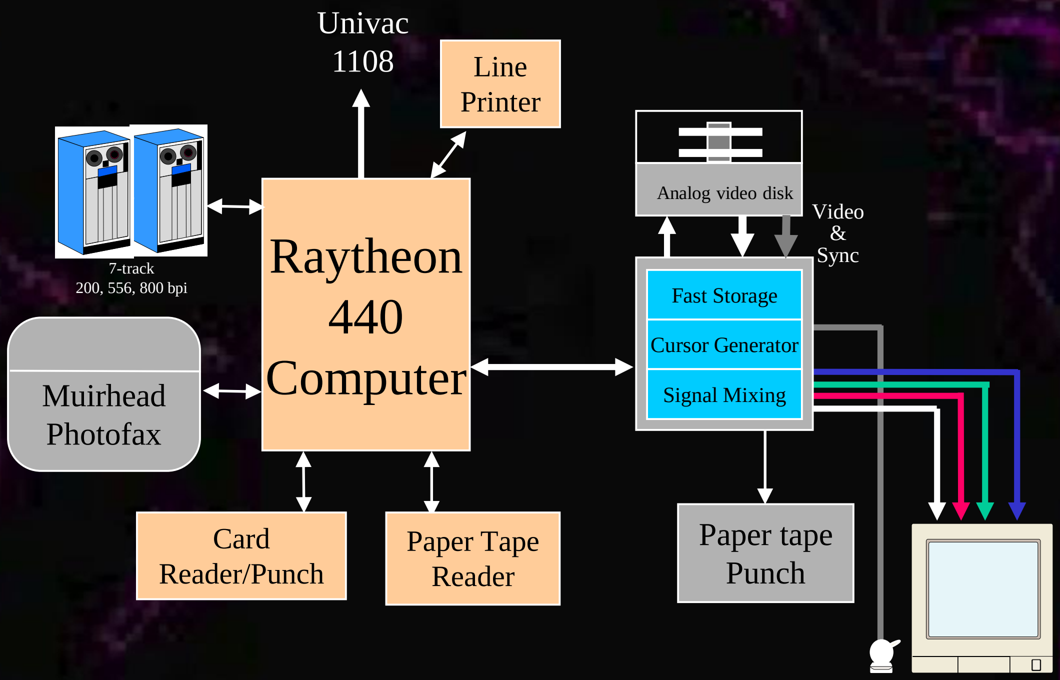
WINDCO

- Based on TV instant replay analog disk:
  - Image animations of 520 frames
  - Frame size: 500x640
  - Animation rate: up to 15 frames per second

Manual WINDCO process

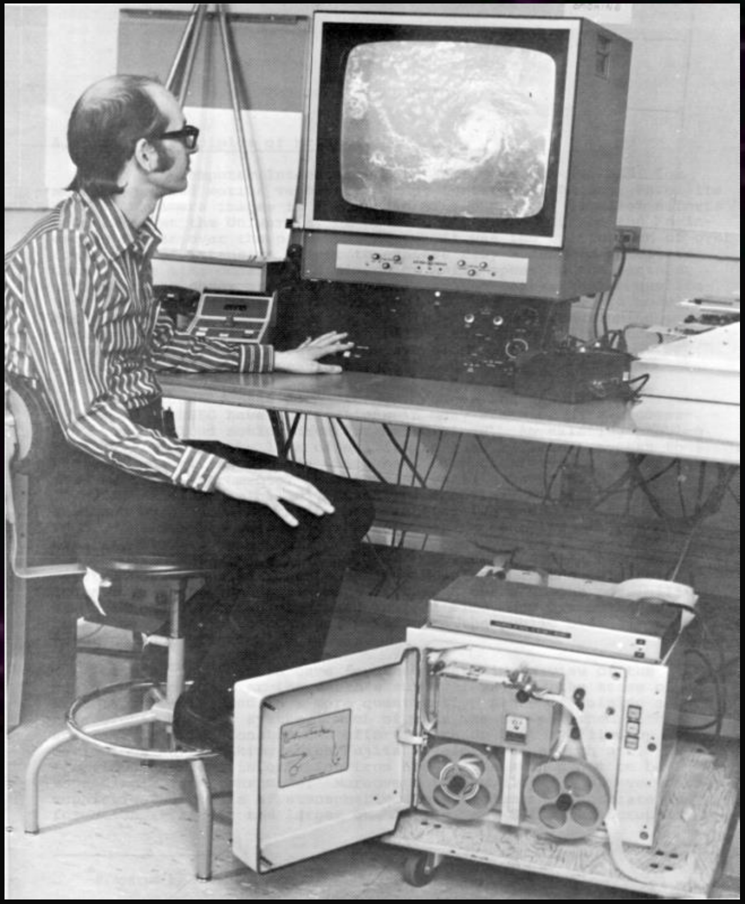
- A joystick used to control cursor location
- User pressed button to record frame number and cursor location of target clouds
- Location punched into paper tape
- Paper tape data were transferred to punch cards using a Raytheon 440
- Cards were walked across the street to the university’s Univac 1108 mainframe

WINDCO - McIDAS Prototype
(1971-1973)



WINDCO - McIDAS Prototype

Workstation (early 1970s)



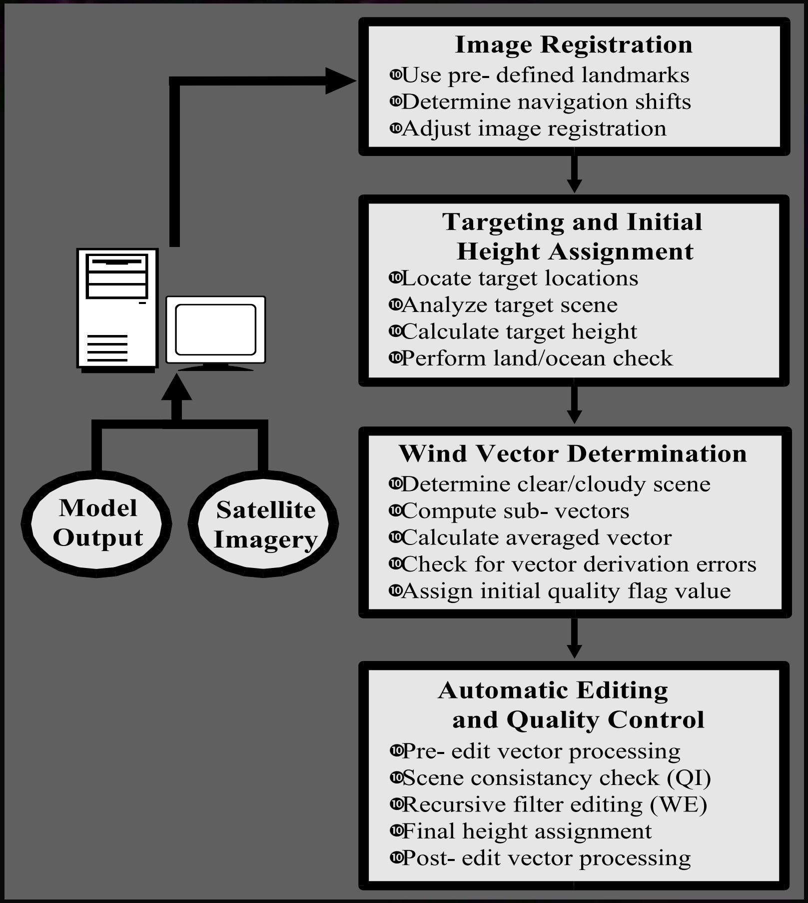
McIDAS I
Terminal (mid 1970s)

Global Winds in 1978

Cloud-drift winds were manually generated from five geostationary satellites for a year as part of the First GARP Global Experiment (FGGE)

Automated WINDCO process [1990s]

1. Target selection
2. Target height assignment
3. Wind tracking
4. Auto-editing
   (including quality control)

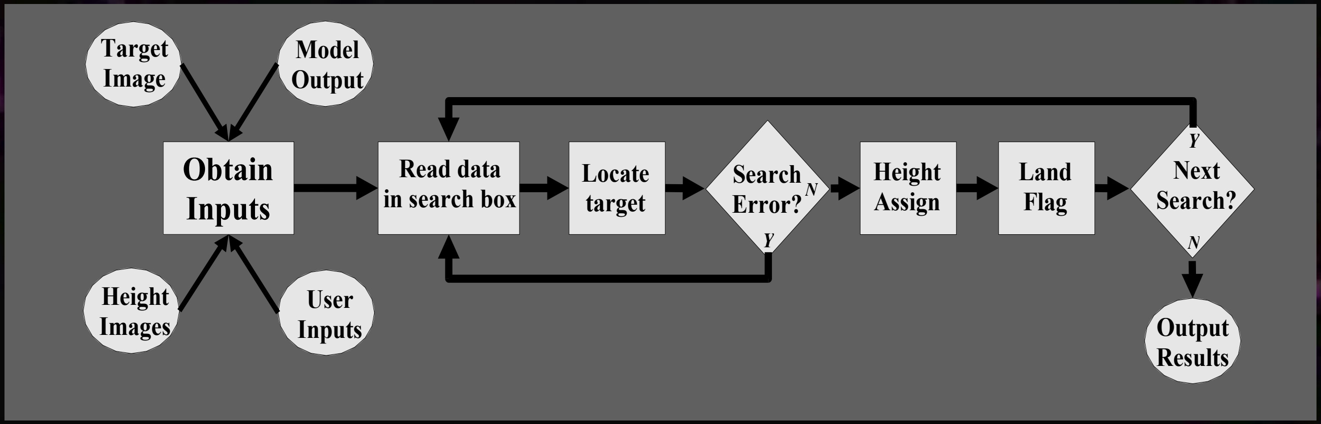


Data

- Input three time-ordered satellite images
- Three images: consistency between vector pairs
- Model output: determine target heights and a first guess for tracking; the 6-, 9- or 12-hour

Target Selection

- Middle image used for potential targets
- Determine where bidirectional gradient in brightness temperature exceeds a threshold
- Typically a cloud edge, a cloud feature, or water vapor gradients.

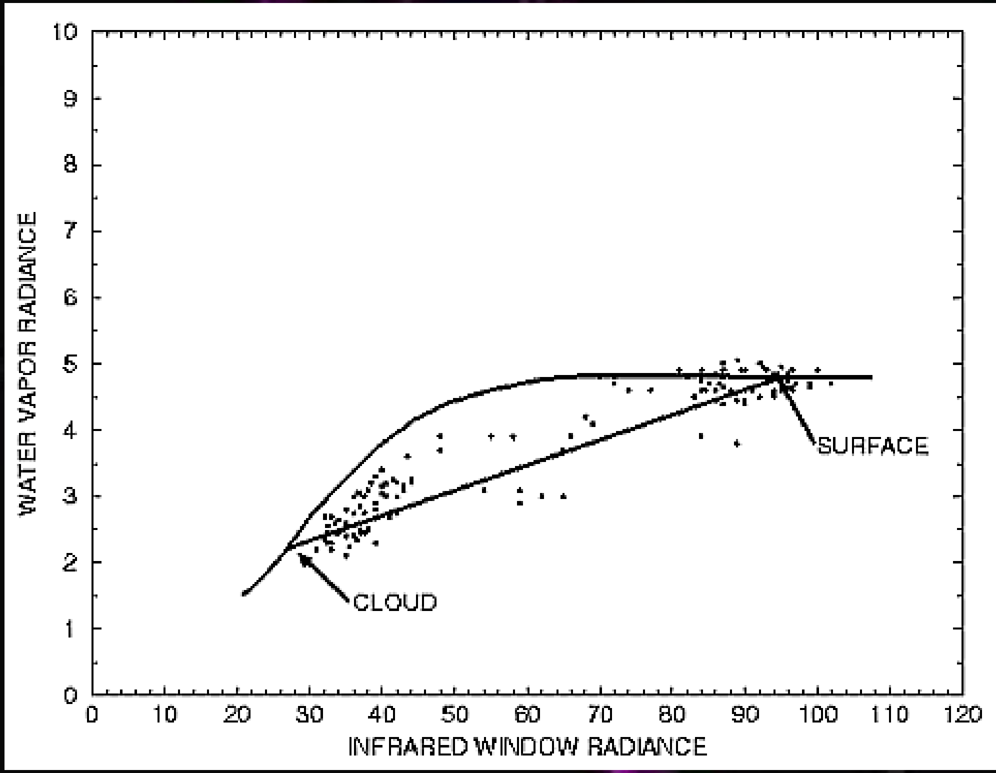


Height Assignment

- Infrared Window and Water Vapor Histogram
  - Good for opaque (thick) clouds
  - Averaged coldest pixels
  - Look up height in model temperature profile

Height Assignment

- H_2O Intercept
  - Good for thin or variable cloud amounts in scene
  - Radiances from two different spectral bands are linearly related for different cloud amounts



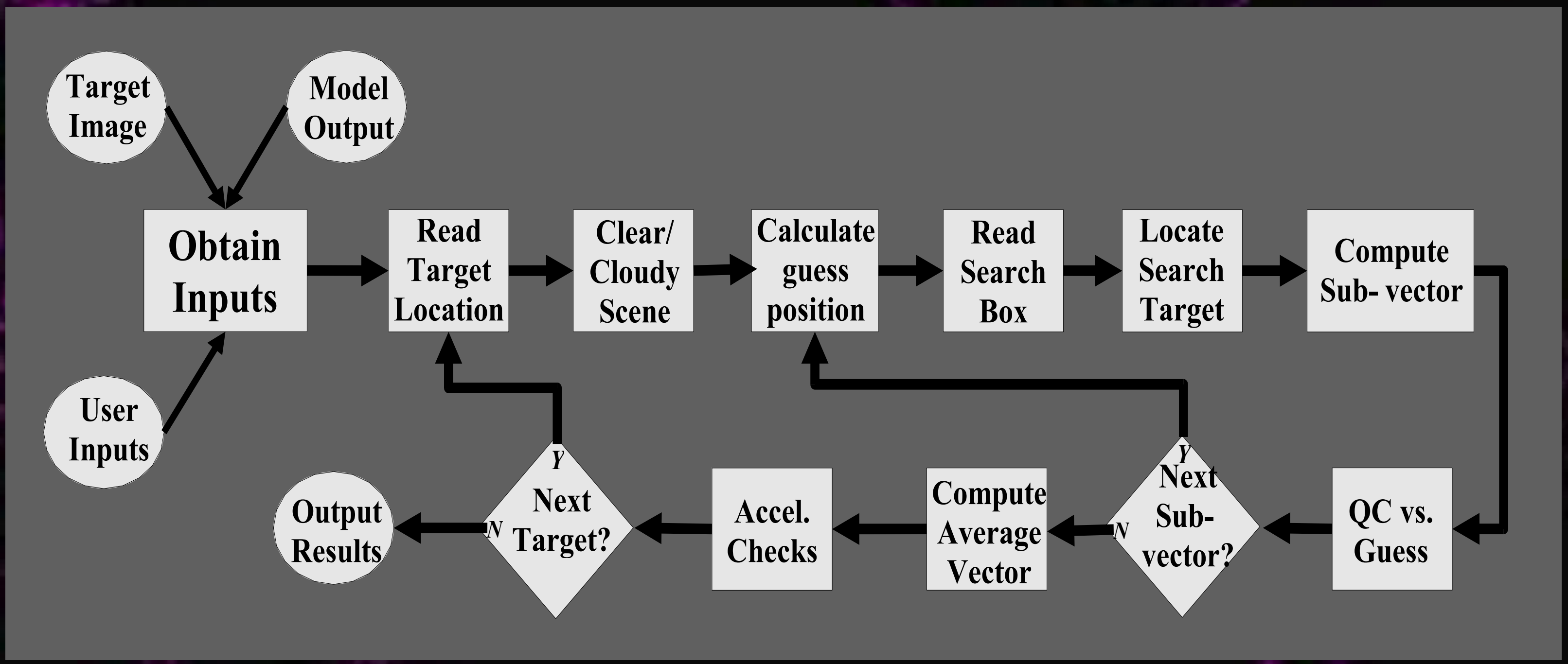
Height Assignment

- CO_2 Slicing
  - Good for semi-transparent clouds
  - Emissivities of ice clouds and the cloud fractions for the Infrared Window (11 µm) and CO_2 (13 µm) channels are roughly the same
  - Based on ratio of radiances

Feature Tracking

- First guess wind is interpolated from the model forecast at the location and height of the target.
- Guess is used to calculate a position in the first and third images of the sequence where the cloud feature should be.
- Cross correlation is computed between the target and subregions throughout the search box for the 1st pair of images, then the 2nd pair

Feature Tracking

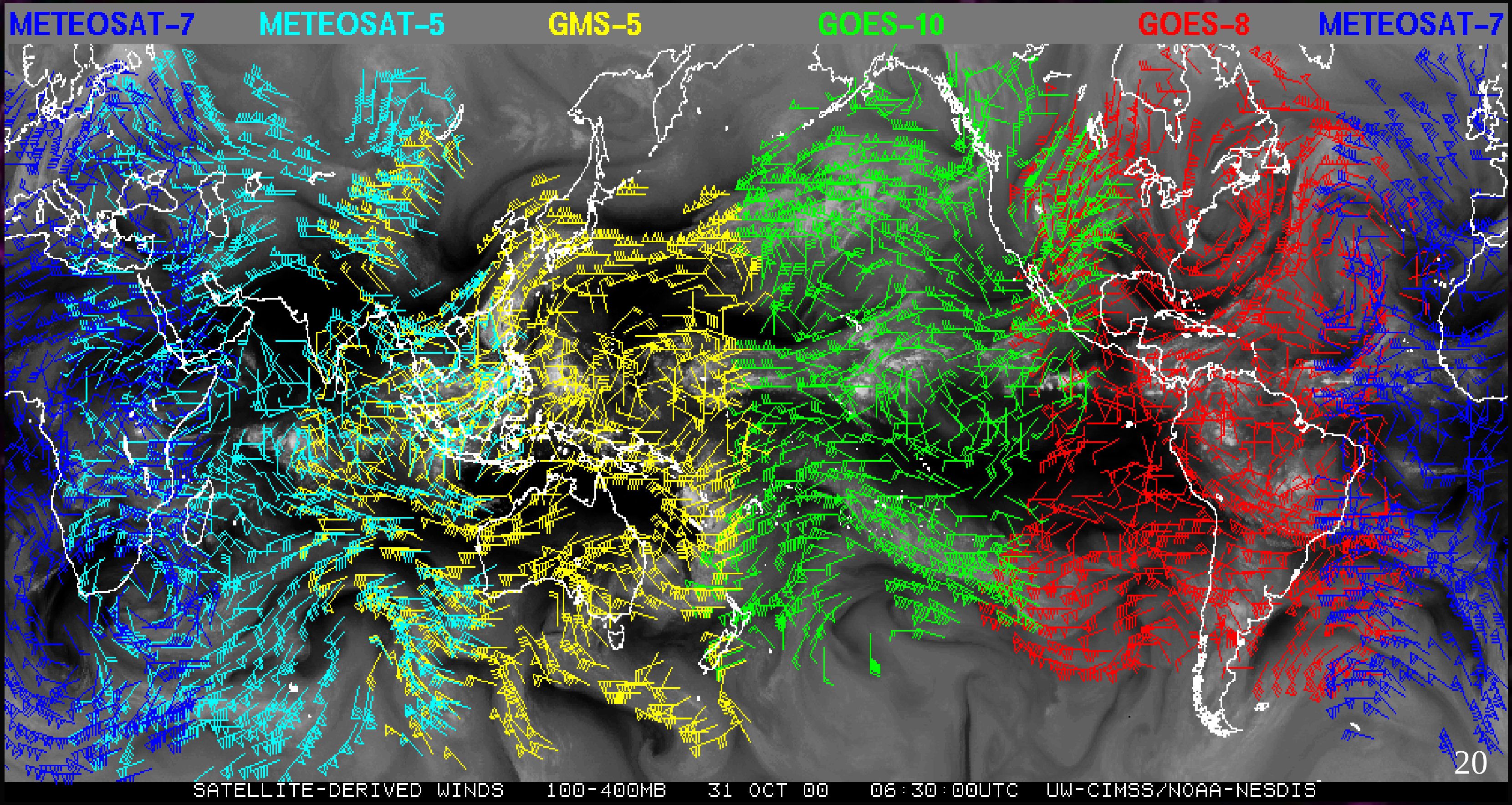


Quality Control

- Consistency between vector pairs (statistical)
- Buddy check
- Recursive filter
  - objective analysis
  - minimization of a penalty function (wind vector, temperature, pressure) as compared to model background

Geostationary Atmospheric Motion Vectors (AMVs)

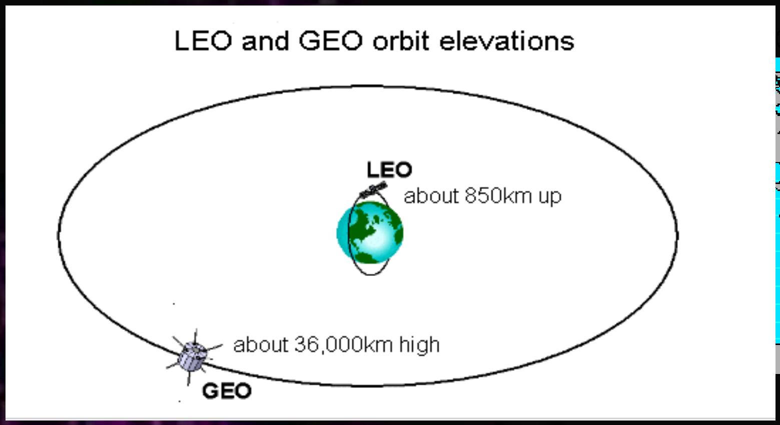
Five geostationary satellites provide coverage for winds in the tropics and mid-latitudes. However, the total number of wind vectors drops off steadily beyond a 30 degree view angle, with a sharp drop off beyond 60 degrees. The process has been entirely automated since the late 1980s.

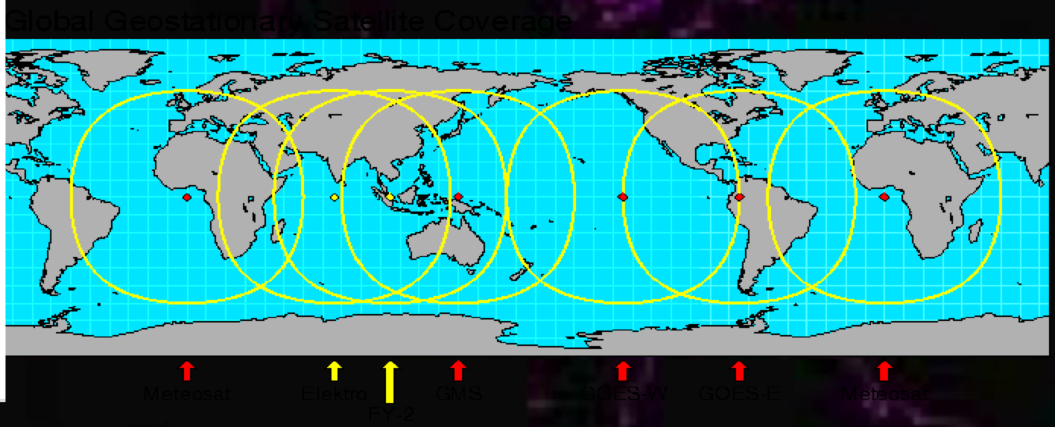


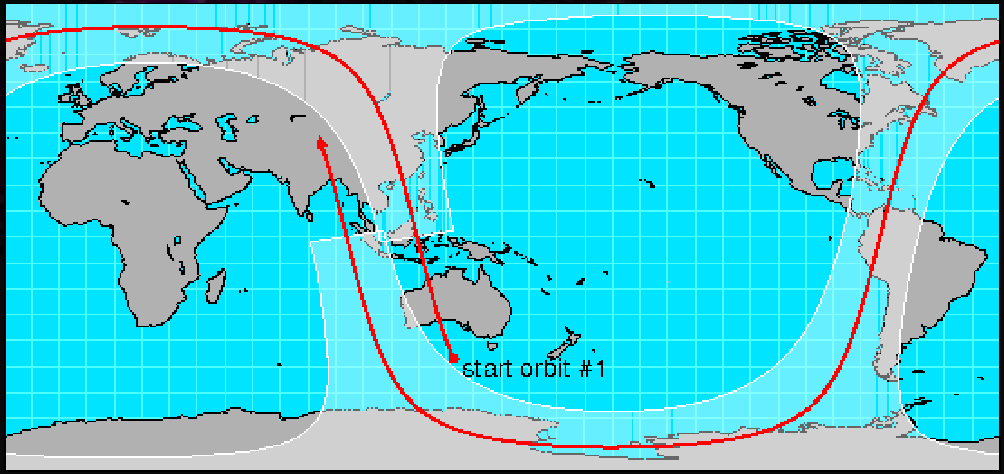
Geostationary-derived AMVs have had a positive impact on model forecasts for many years.

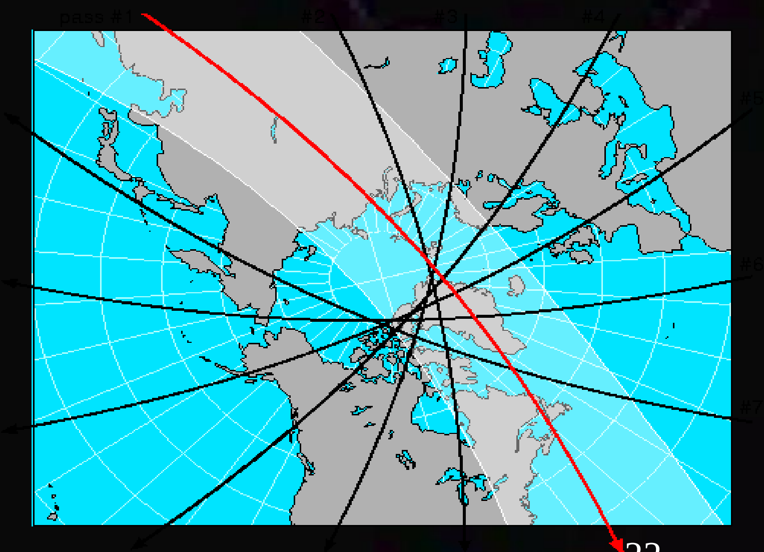
Can this same technique be applied to polar orbiting satellites for better polar coverage?

Orbits



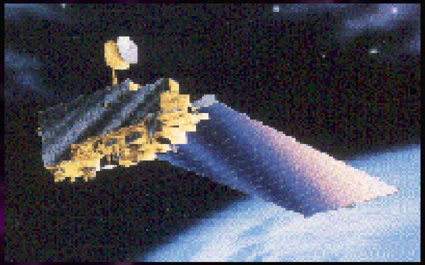






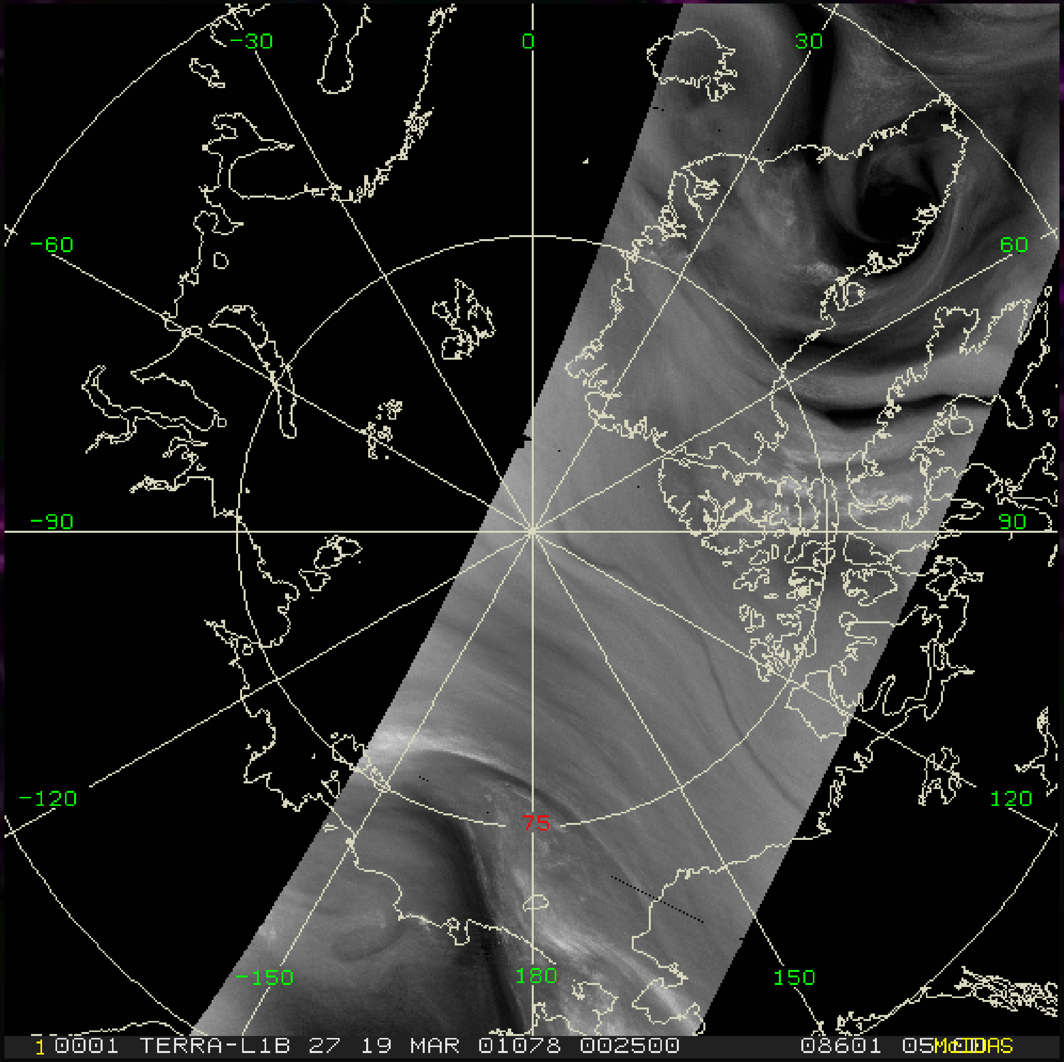
Figures from http://www.rap.ucar.edu/~djohnson/satellite/coverage.html

Polar Orbit Issues



- 100 minute orbits
  - 15 to 30 minute interval for geo satellites
  - Cloud and feature changes
- Coverage dependent on latitude
  - Better temporal coverage poleward of 70˚ latitude
- Coverage dependent on number of satellites
  - Better daily coverage with more satellites

One Day of Arctic Orbits, Terra MODIS



MODIS band 27 (water vapor at 6.7 µm)

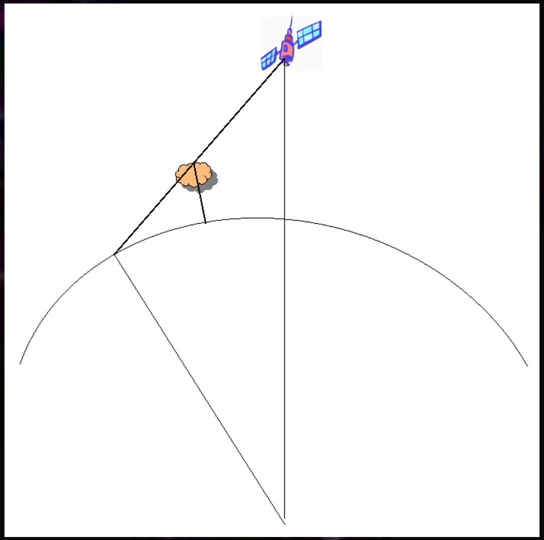
Wind Retrieval Methodology

- Based on geostationary satellite winds algorithm
- MODIS data from polar orbiting Terra and Aqua satellites
- Targeting
  - clouds in the IR window channel 11 µm
  - water vapor features in 6.7 µm
- Tracking
  - cross-correlation technique
  - GFS 6, 9, and 12 hour forecast grids as first guess
  - image triplets used for consistency check
- Wind height assignment: IR window or H_2O-intercept using the temperature profile forecasts from GFS

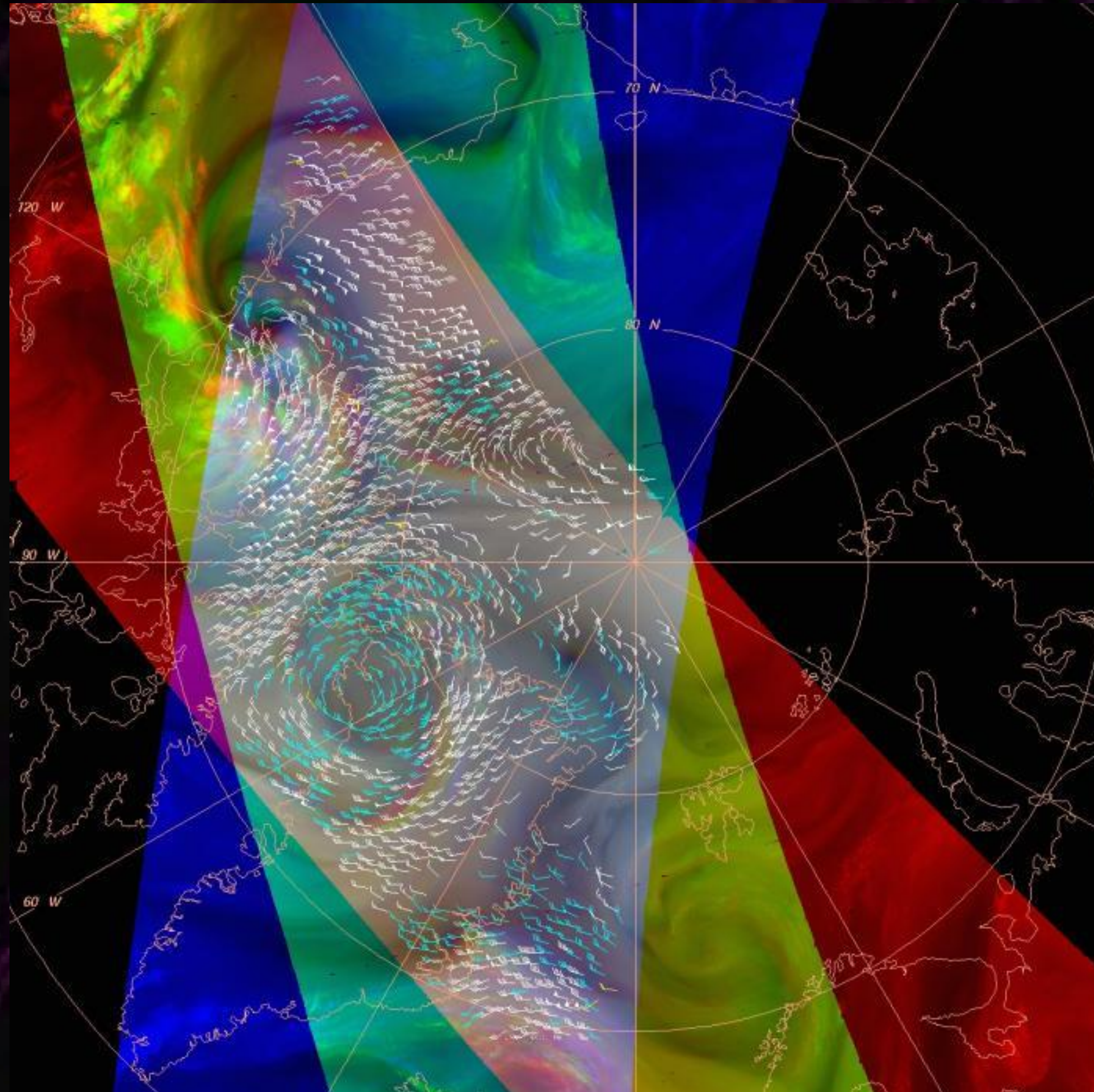
$$CrossCorr = \frac{\sum_i \left[(t(i) - \bar{t}) * (s(i) - \bar{s}) \right]}{\sqrt{\sum_i \left[t(i) - \bar{t} \right]^2} * \sqrt{\sum_i \left[s(i) - \bar{s} \right]^2}}$$

New Challenges

- Reduced temporal sampling compared to GOES
- Parallax
- Height assignment issues
  - low-level inversion
  - warm, thin clouds over cold surface
  - low water vapor amounts
- Validation

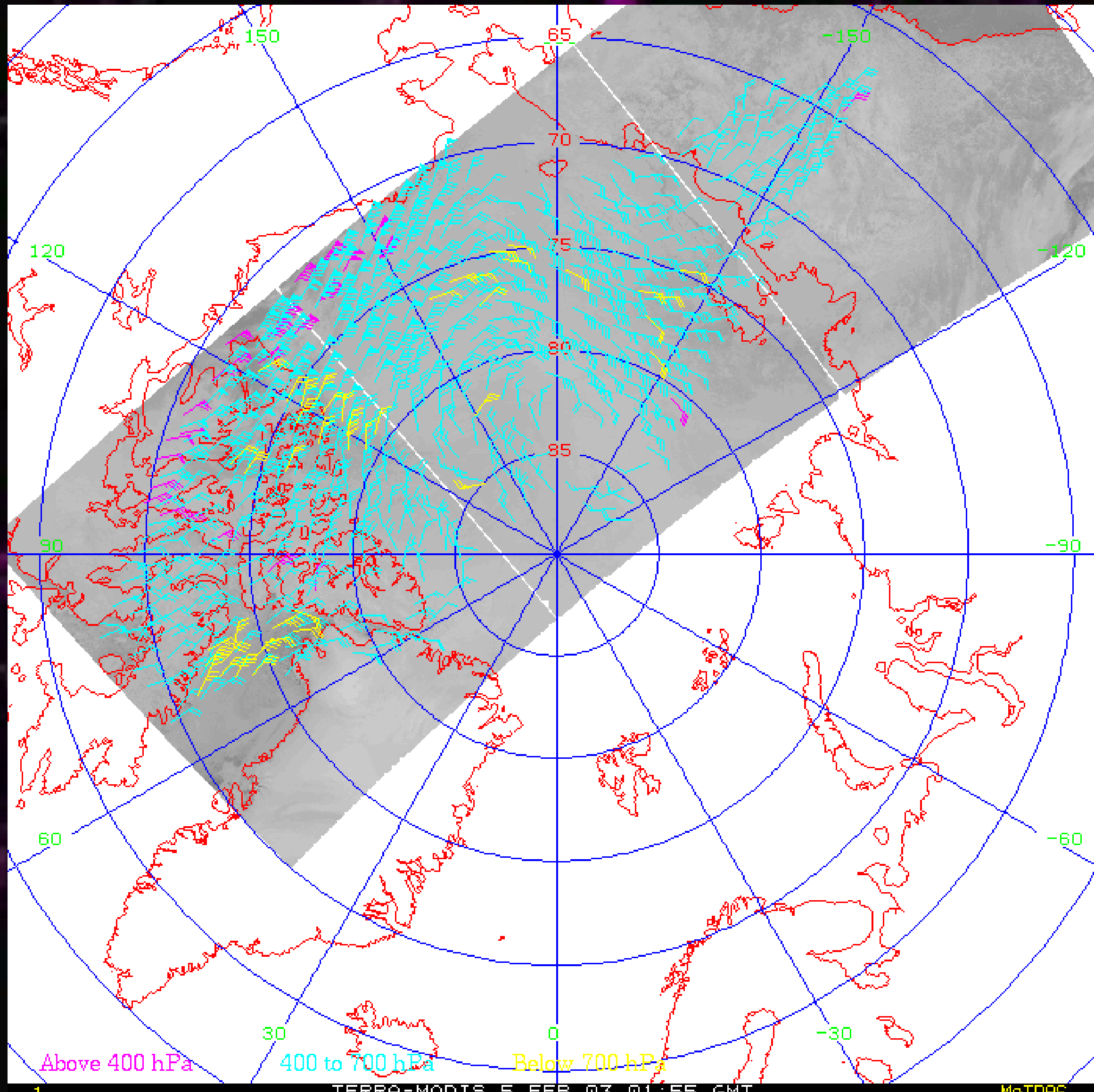


Unlike geostationary satellites at lower latitudes, it is not be possible to obtain complete polar coverage at a snapshot in time with one or two polar-orbiters. Instead, winds must be derived for areas that are covered by two or three successive orbits, an example of which is shown here. The whitish area is the overlap between three orbits.



Three overlapping Aqua MODIS passes, with WV and IR winds superimposed. The white wind barbs are above 400 hPa, cyan are 400 to 700 hPa, and yellow are below 700 hPa.

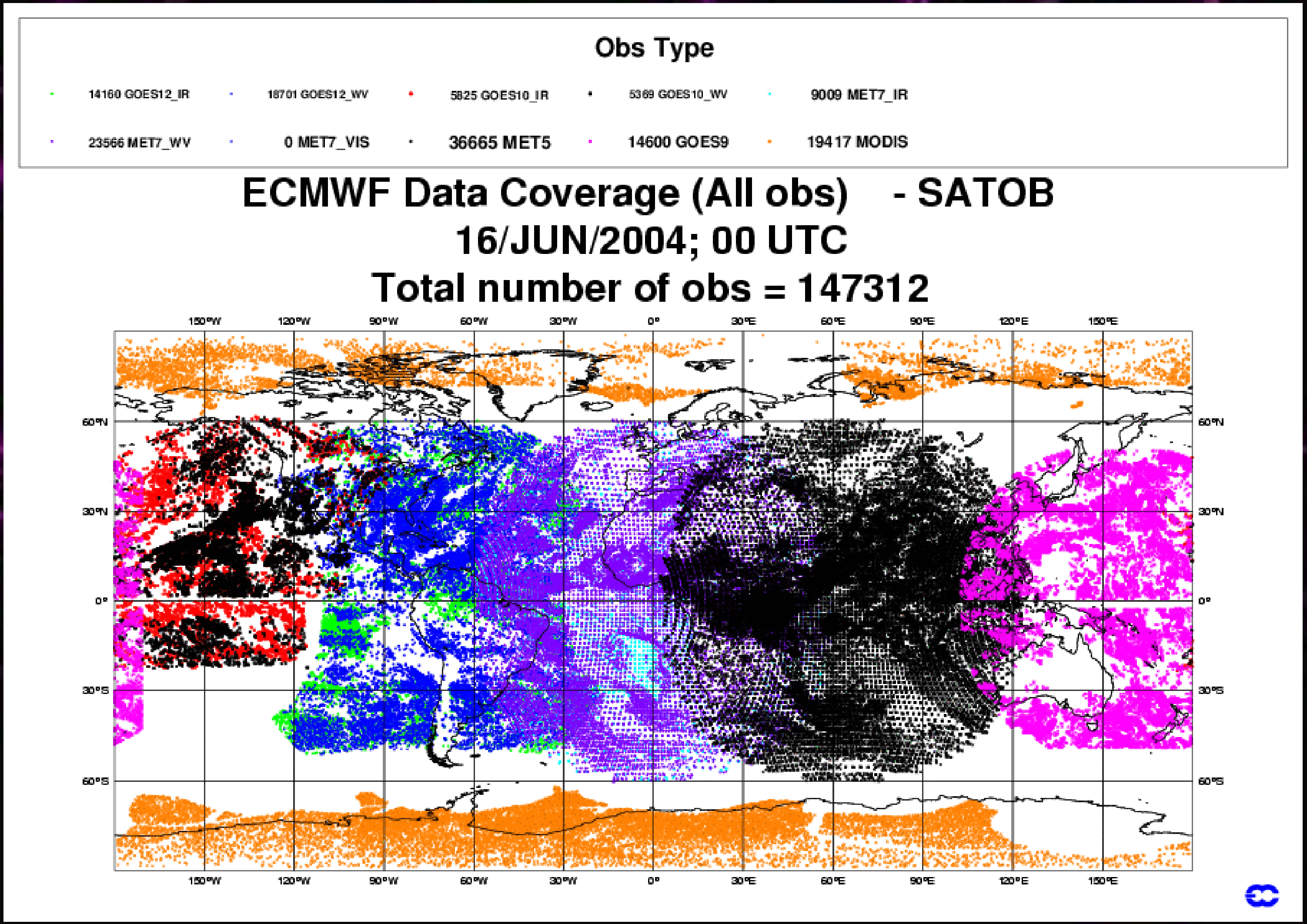
One Day of Arctic Orbits, Terra MODIS



MODIS band 31 (11 µm)

Routine production of MODIS winds began in 2002 with data from the NOAA “bent pipe”.

MODIS Winds Filling Void



Being used operationally at ECMWF since Jan 2003.

What are the issues assimilating satellite-derived AMVs in models?

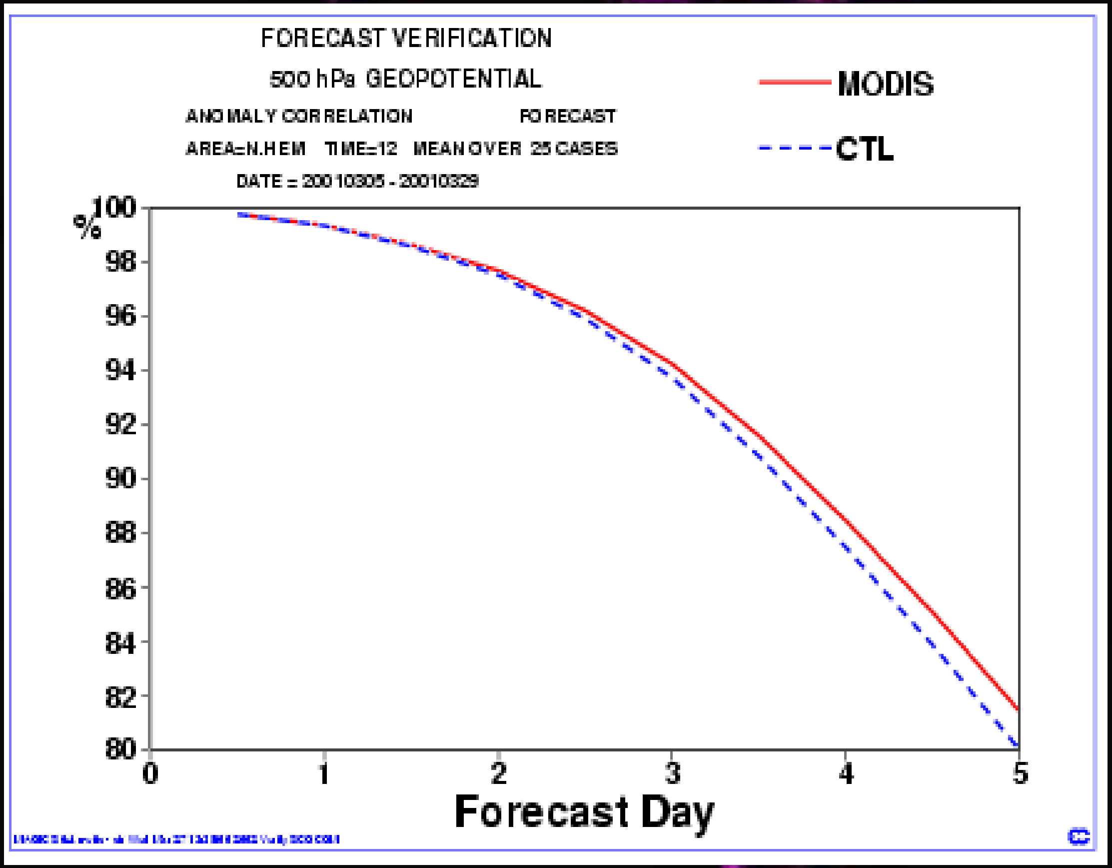
What is the forecast impact of the MODIS AMVs?

Determination of Forecast Improvement

- Anomaly correlation coefficients (ACC) at specific pressure levels with and without the MODIS AMVs. The ACC is the correlation between the predicted and analyzed anomalies (deviation from climatology).
  - Mean over a long time period
  - Daily time-series
- Verification of significant weather event
- Similar impact has been shown from many NWP centers, a few examples follow

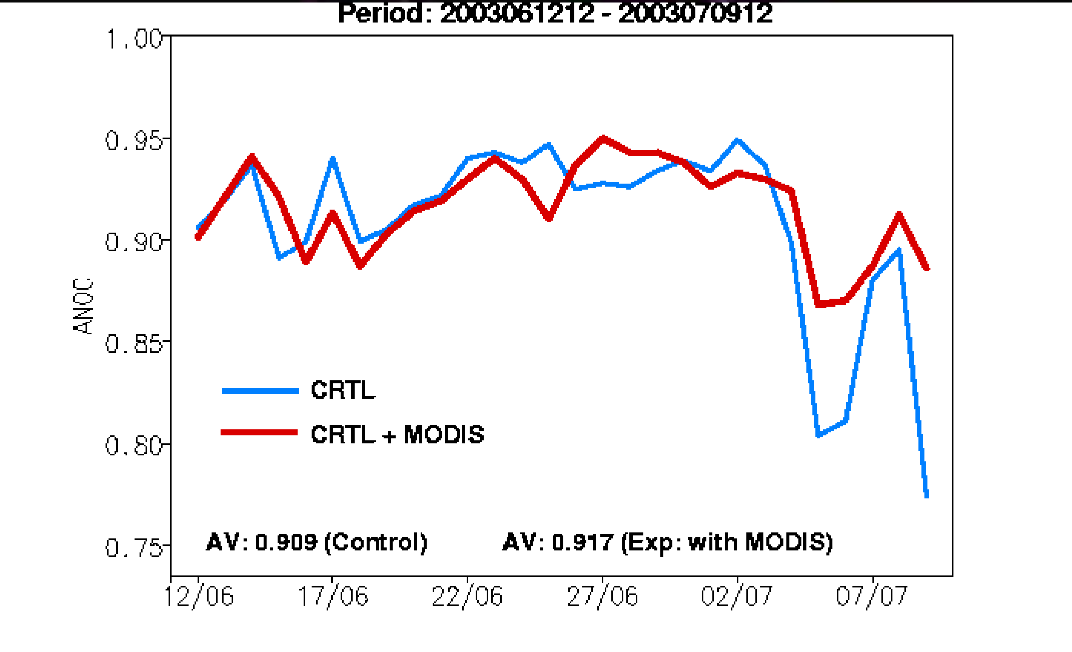
ECMWF Model Impact: N. Hemisphere [2001]

ACC as a function of forecast day for the geopotential at 500 hPa. Study period is 5-29 March 2001. The correlation is between the forecast geopotential height anomalies, with and without the MODIS winds, and their own analyses. This is for the Northern Hemisphere, which is defined as north of 20 degrees latitude.



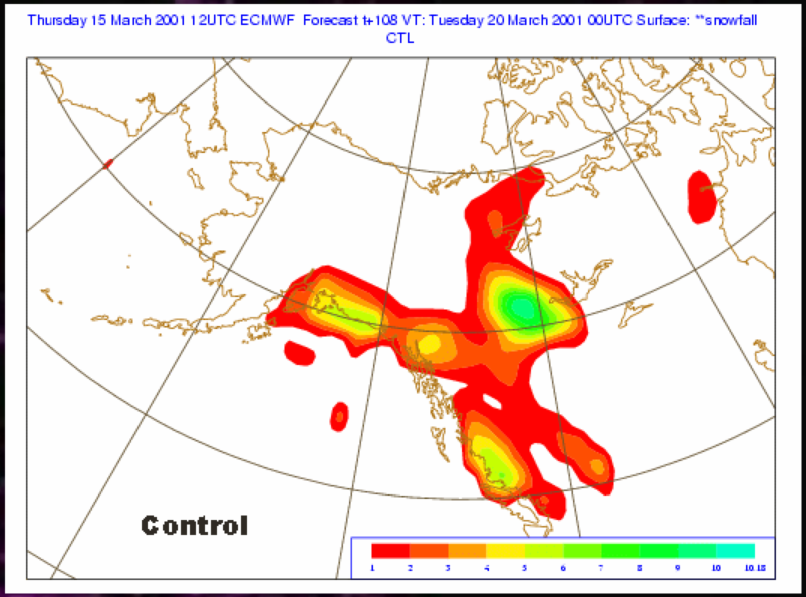
DWD Model Impact: Daily ACC [2001]

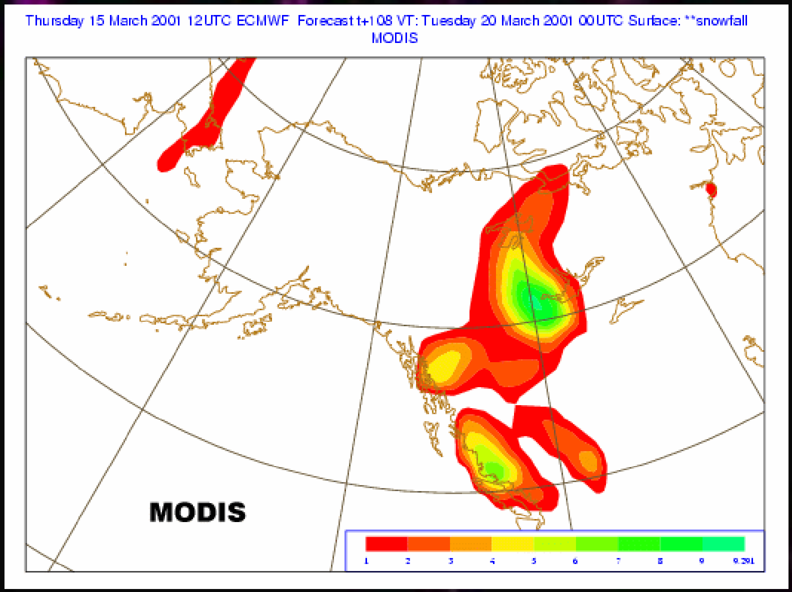
ACC as a function of day for the 60-hour forecast of the geopotential at 500 hPa. Study period is 12 June to 9 July 2003. Forecast scores are the correlation between the forecast geopotential height anomalies, with and without the MODIS winds, and their own analyses. This is for the Northern Hemisphere.



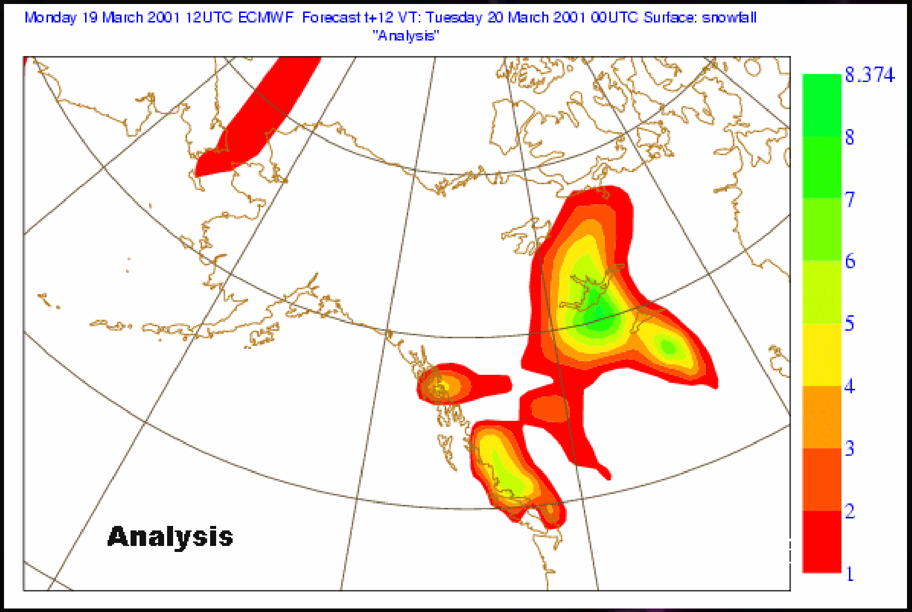
From Alexander Cress at the 7th Int. Winds Workshop

Propagation to Lower Latitudes: Snowfall





Accumulated snowfall forecasts (mm water equivalent) over Alaska for 20 March 2001. Inclusion of MODIS winds in the analysis can produce a more accurate forecast. Top-left is the snowfall from the 5-day Control forecast (no MODIS winds); top-right is the snowfall from the 5-day forecast that included the MODIS winds in the analysis; below right is the snowfall from a 12-hr forecast for verification ("truth"). From ECMWF.



Hurricane Track Forecasts [2004]

Average hurricane track errors (nm)

13.2	66.5	102.8	301.1	Cntrl
11.4	60.4	89.0	252.0	Cntrl + MODIS
74	64	52	34	Cases (#)
00-h	24-h	48-h	120-h	Time

In both tables, the forecast time is the bottom row. The control run (Cntrl) did not assimilate the MODIS winds.

Frequency of superior hurricane performance

48.9	44.8	39.6	29.4	Cntrl
51.1	55.2	60.4	70.6	Cntrl + MODIS
74	64	52	34	Cases (#)
00-h	24-h	48-h	120-h	Time

Percent of cases where the specified run had a more accurate hurricane position than the other run. Note: These cases are for hurricanes in the subtropics during 2004.

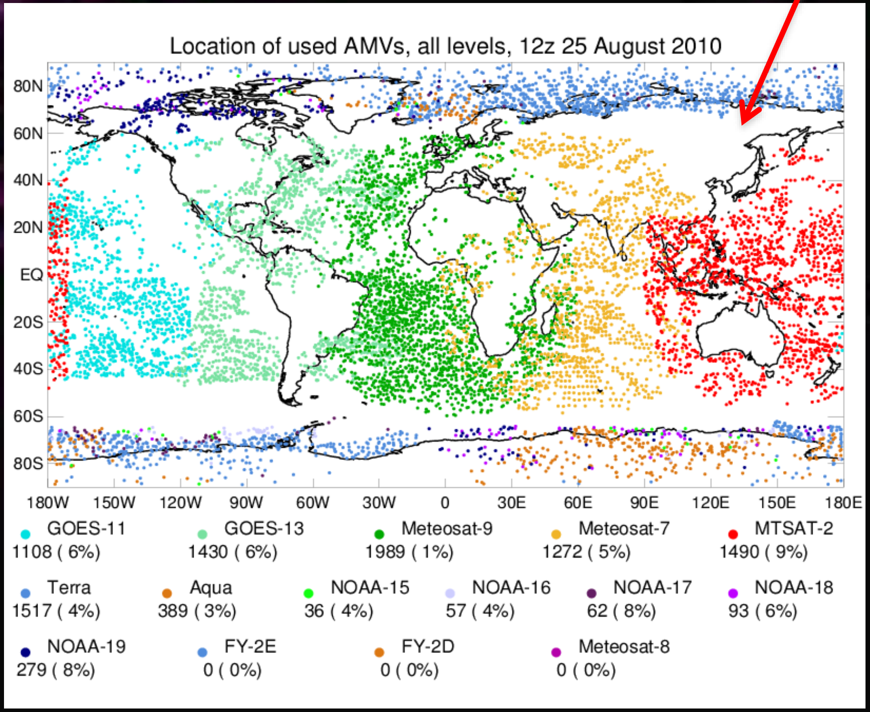
(Courtesy of JCSDA)

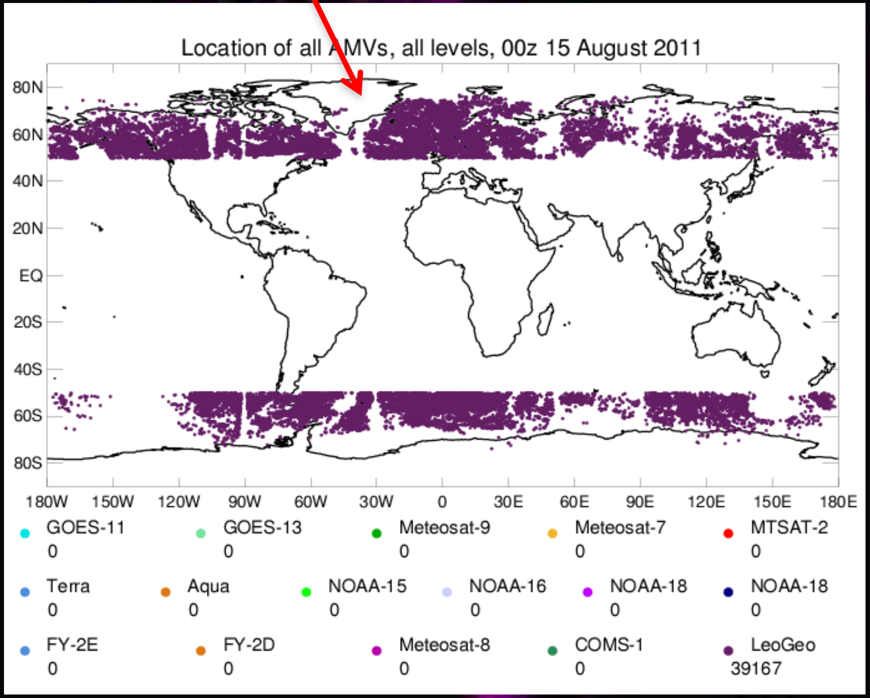
Assimilation and forecast impact of the Leo/Geo AMVs in the high-latitude data-gap corridor [2010]

Geostationary and Polar-orbiting Atmospheric Motion Vectors

Missing winds – gap in coverage

- NWP centers: the polar jet stream can be located in this gap; improper model initialization can lead to errors in the forecasts.
- CIMSS research: the addition of the wind information is important in this region.

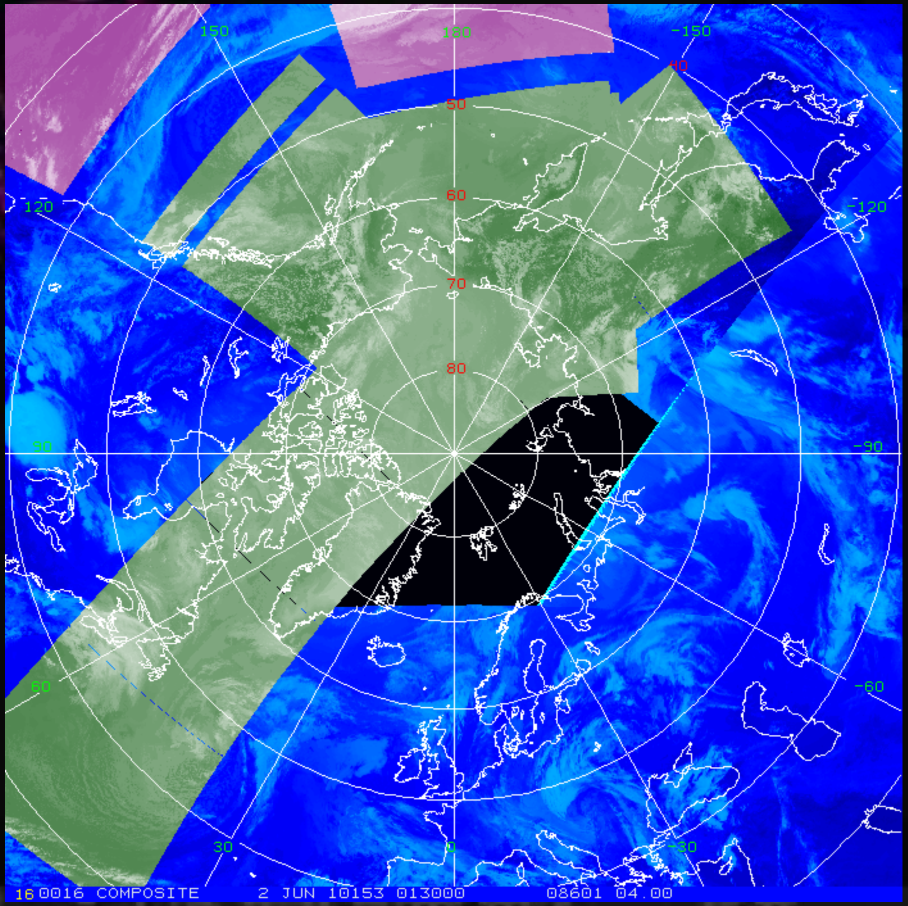


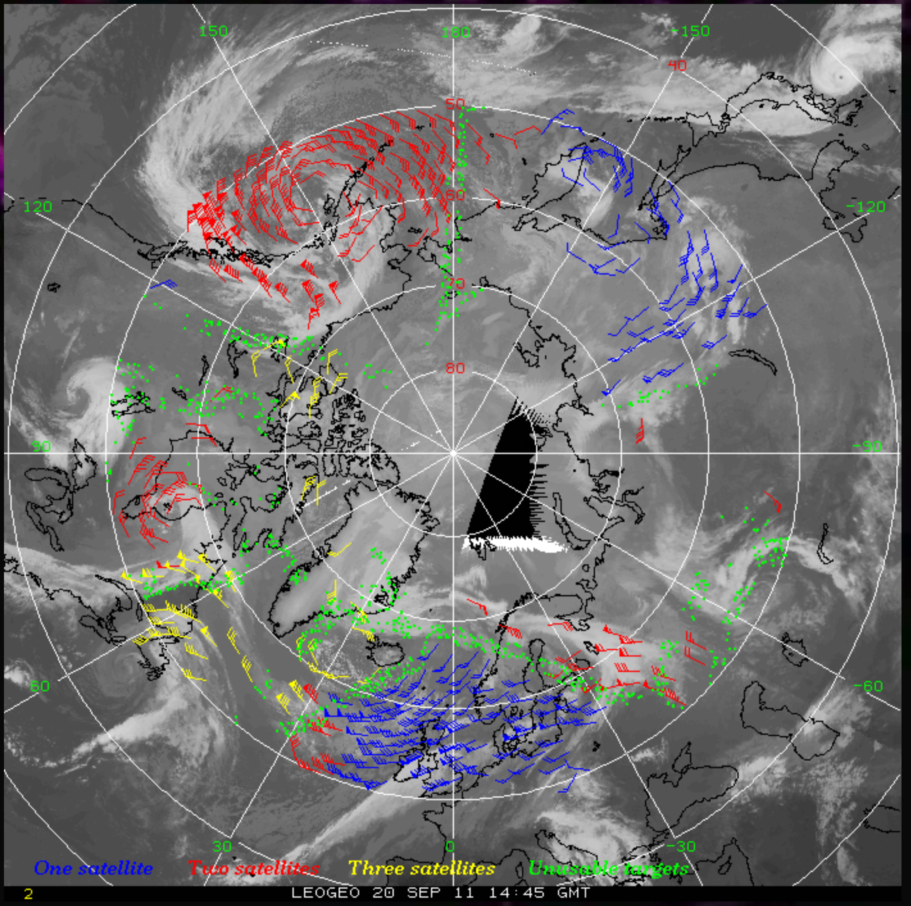


UK Met Office monitoring plot: 25 August 2010

Vectors are generated from either **single** satellite or by mixing **two** or **three** satellites.

Tracking can use data from different satellites in the 3 images (accounts for time and parallax at each pixel)

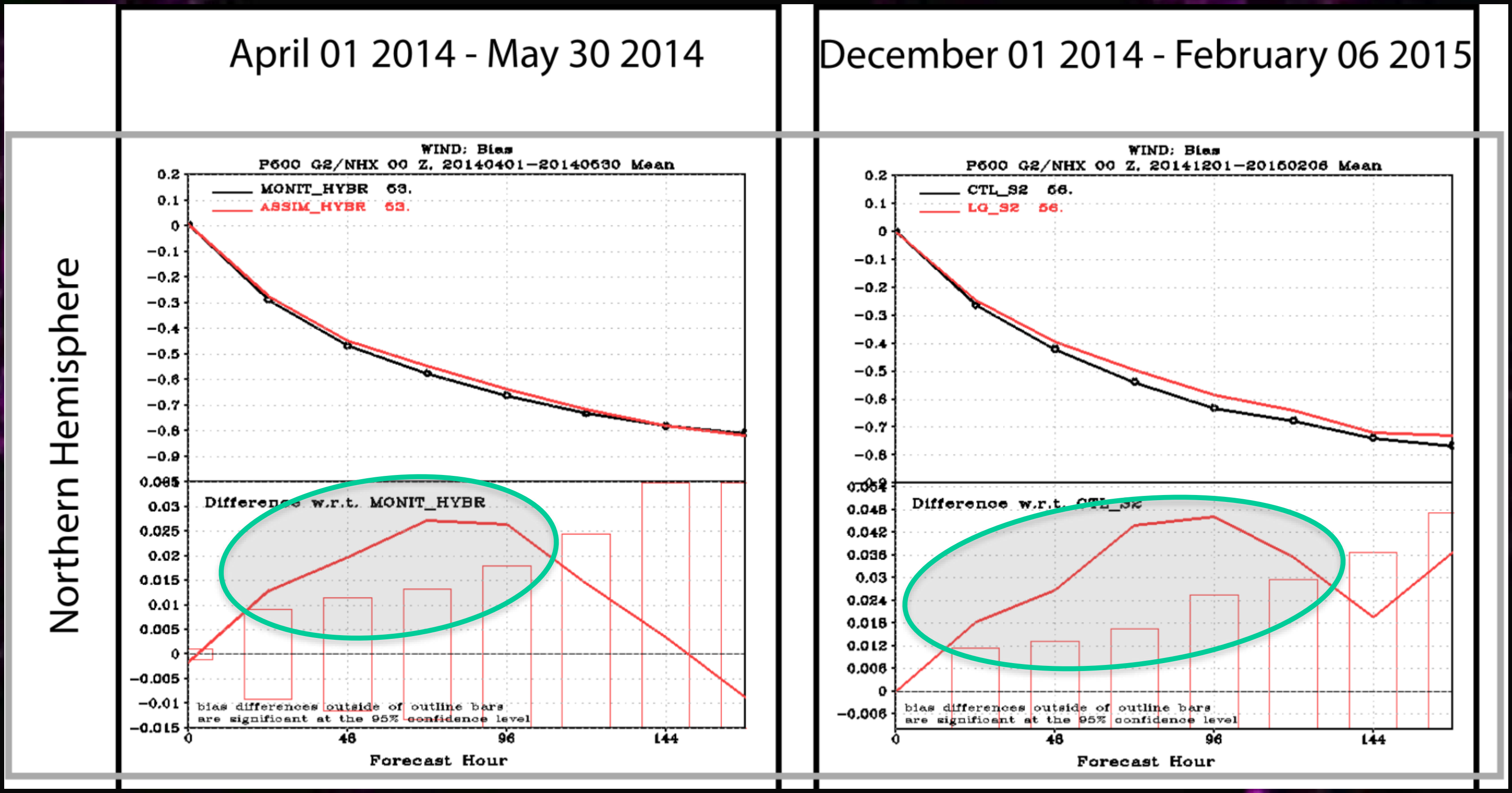




Target/search box in each individual image must be from a single satellite

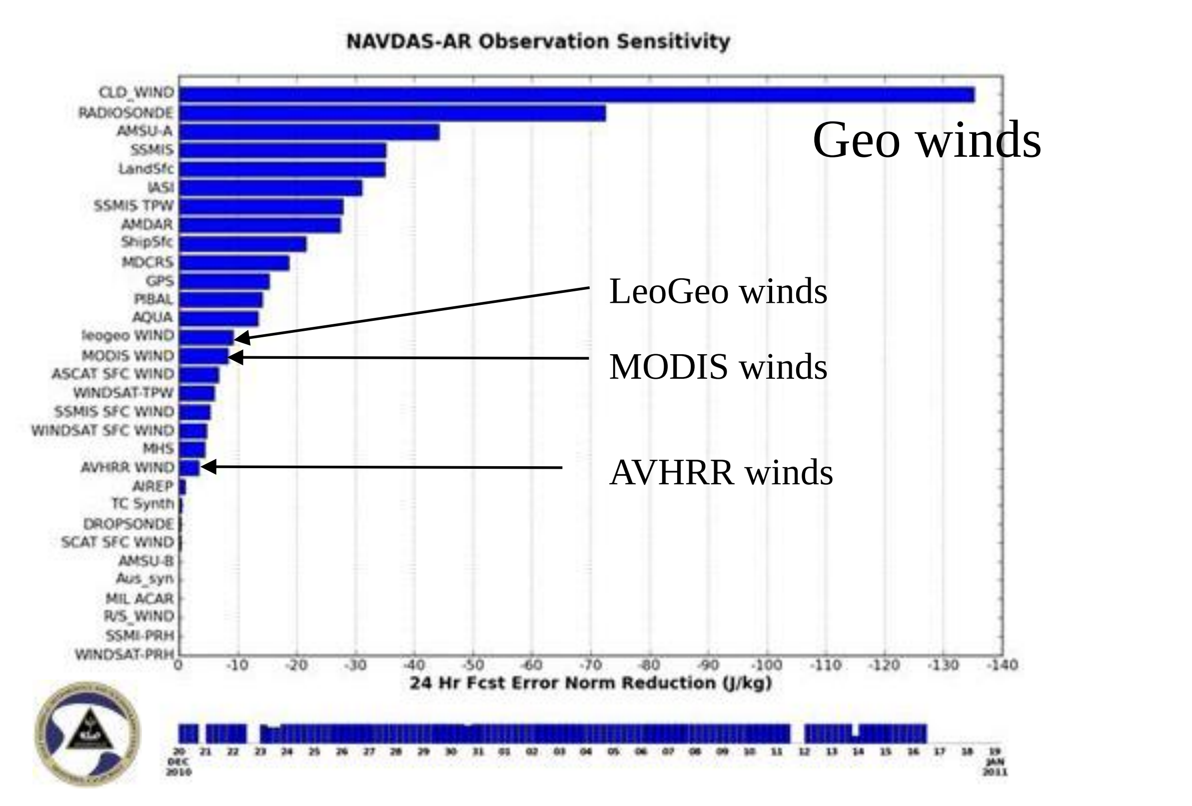
Potential targets that **cannot** be tracked (mixed satellites within target or search box)

Northern Hemispheric Score
500 hPa Wind Speed Bias



Forecast improvements are statistically significant for the:
Spring season 24-96 hours
Winter season 24-120 hours

Leo/Geo Winds in Operations: US Navy NAVDAS



The US Navy has demonstrated positive observation sensitivity of
Leo/Geo winds similar to MODIS AMVs

Satellite-derived Cloud Motion Winds in the North Polar Region of Mars

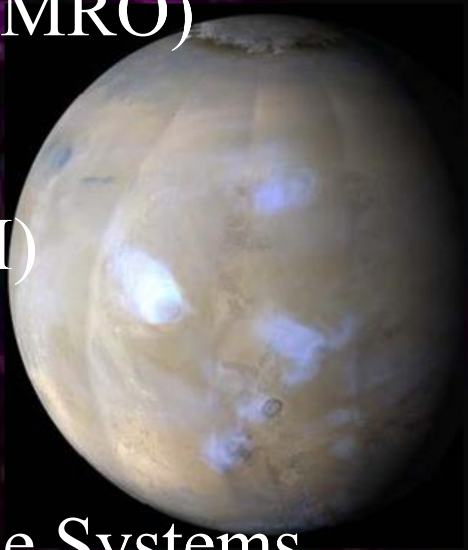
Motivation

Using an automated procedure, produce a ‘high’ density winds dataset in the north polar region of Mars to:

- Provide as input to global models
- Lend insight into behavior and life cycle of developing baroclinic waves and cyclones

The Data

- Satellite: Mars Reconnaissance Orbiter (MRO)
  - Polar orbiting satellite
  - 112 minute orbit
- Instrument: Mars Color Imager (MARCI)
  - 5 visible and 2 ultraviolet wavelengths
  - 1 km resolution at nadir



- Images processed at Malin Space Science Systems (MSSS)
  - Reprojected to polar stereographic; centered on north pole
  - 1 km resolution (sampled to 2 km for cloud tracking)
  - Northern hemisphere summer, 2006 ($Ls = 111.9^\circ$ to 210.6°)

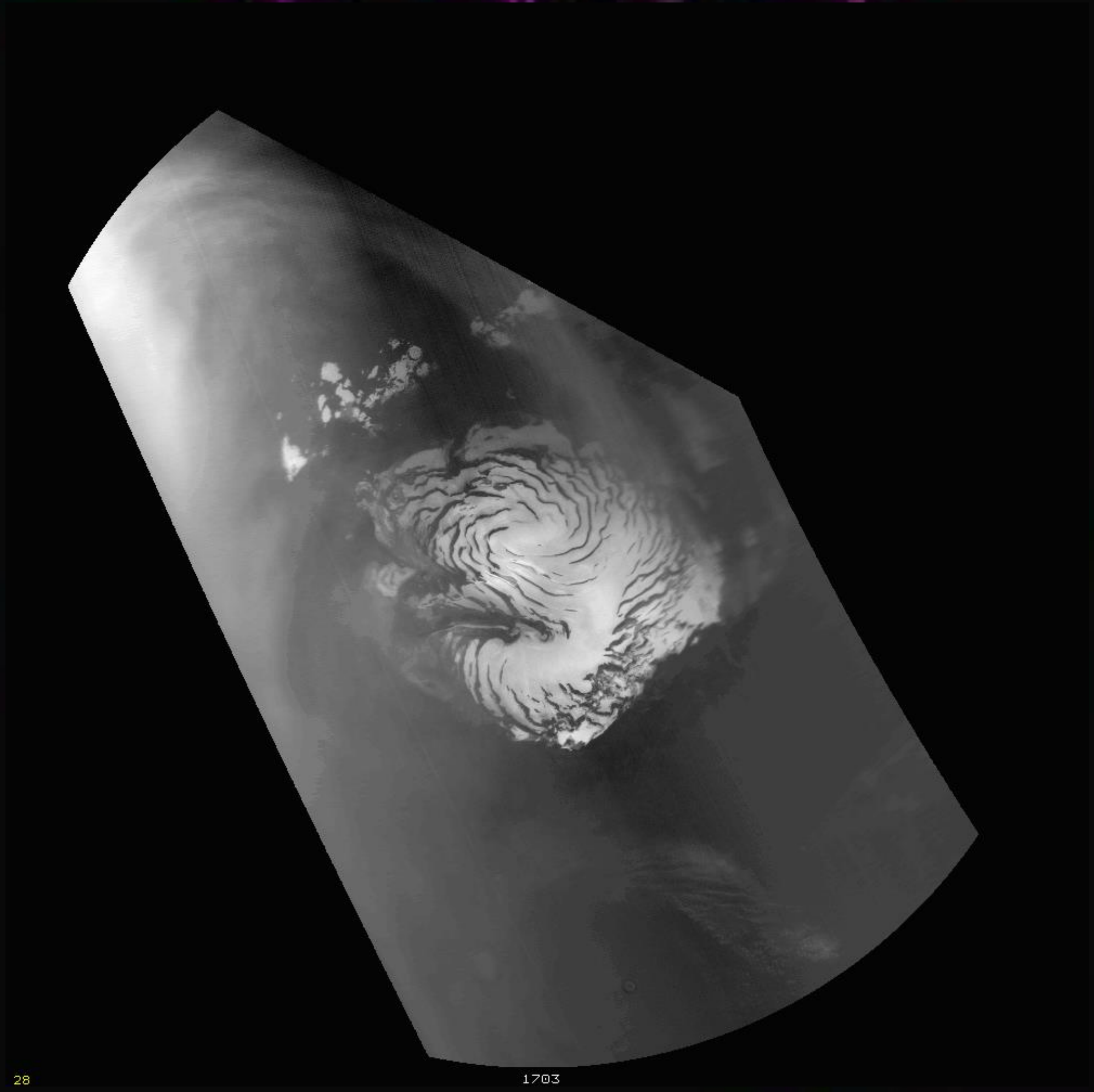
The Data

One day of MRO MARCI images

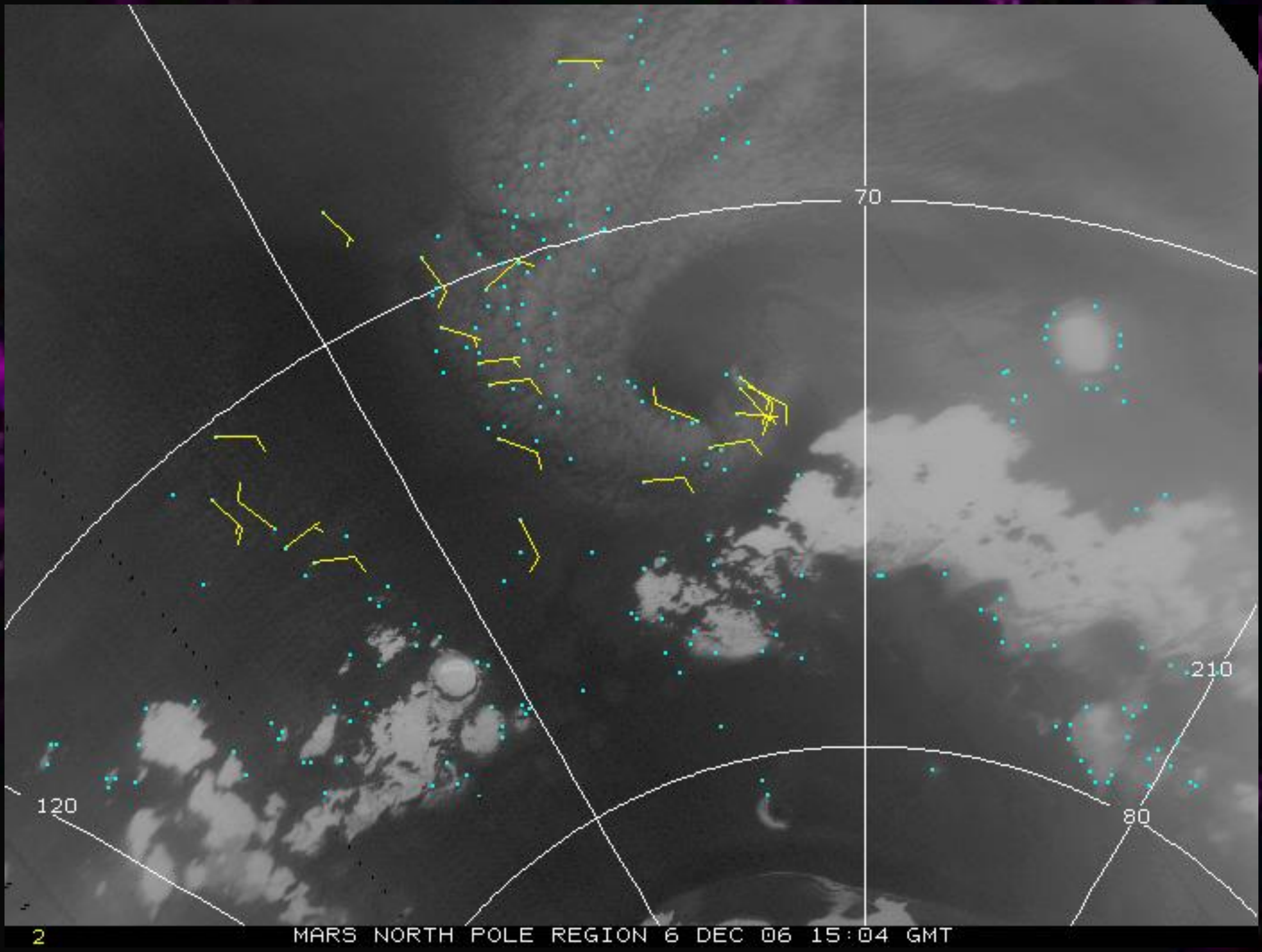
Orbits 1703 to 1716

Blue filter: Band 1 (425 nm)

View from pole to 60 deg. north latitude



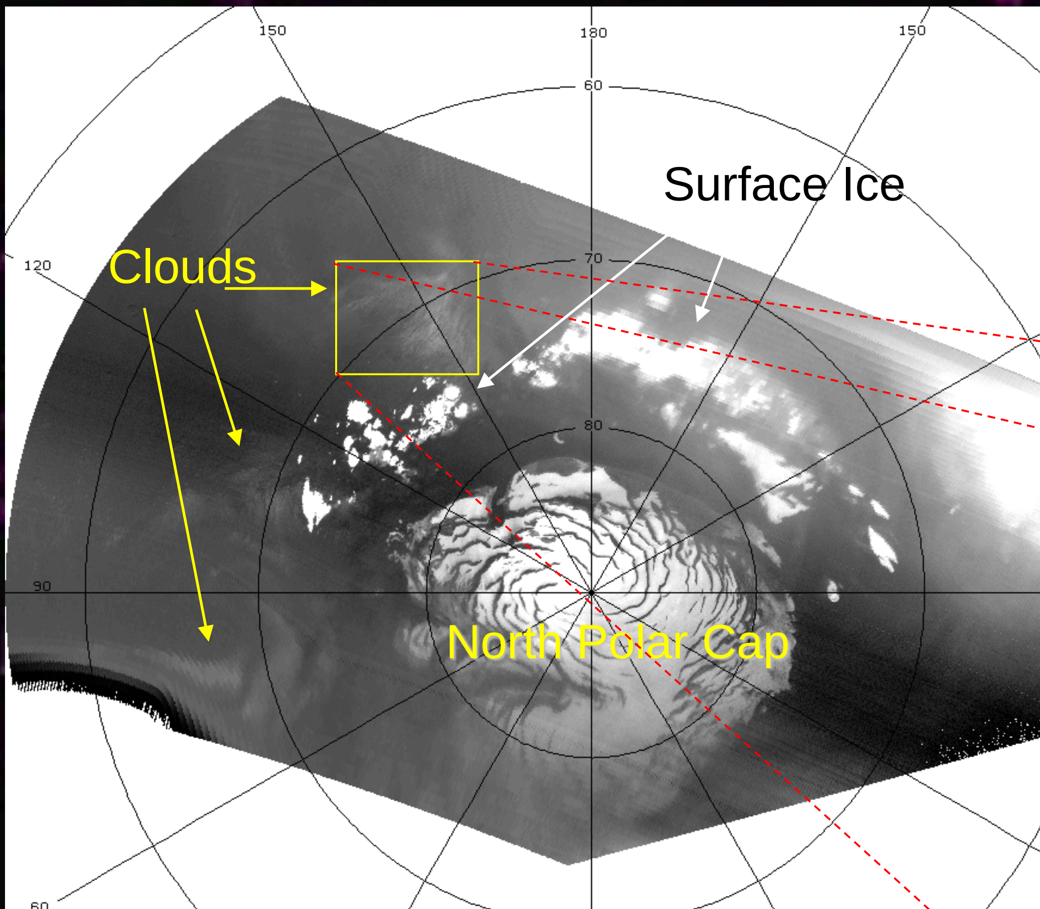
Cloud Tracking Methodology



Targets: cyan dots

Winds: yellow wind barbs

High latitude winds on Mars



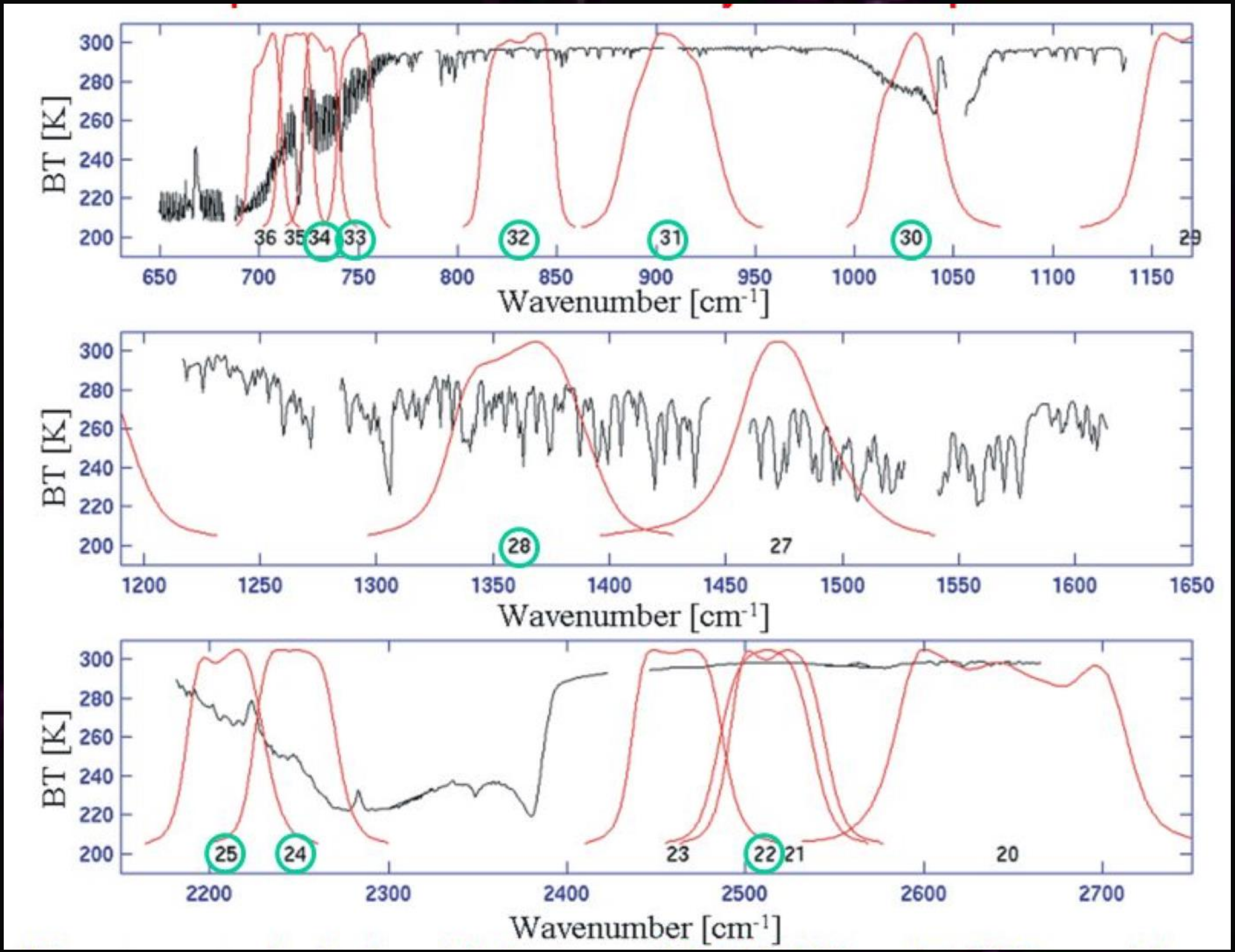
- Wind speeds up to about 7 ms^{-1} in this example.
- Winds slower than 3 ms^{-1} are discarded (geolocation errors)

NASA Grant: NNX09AI41G

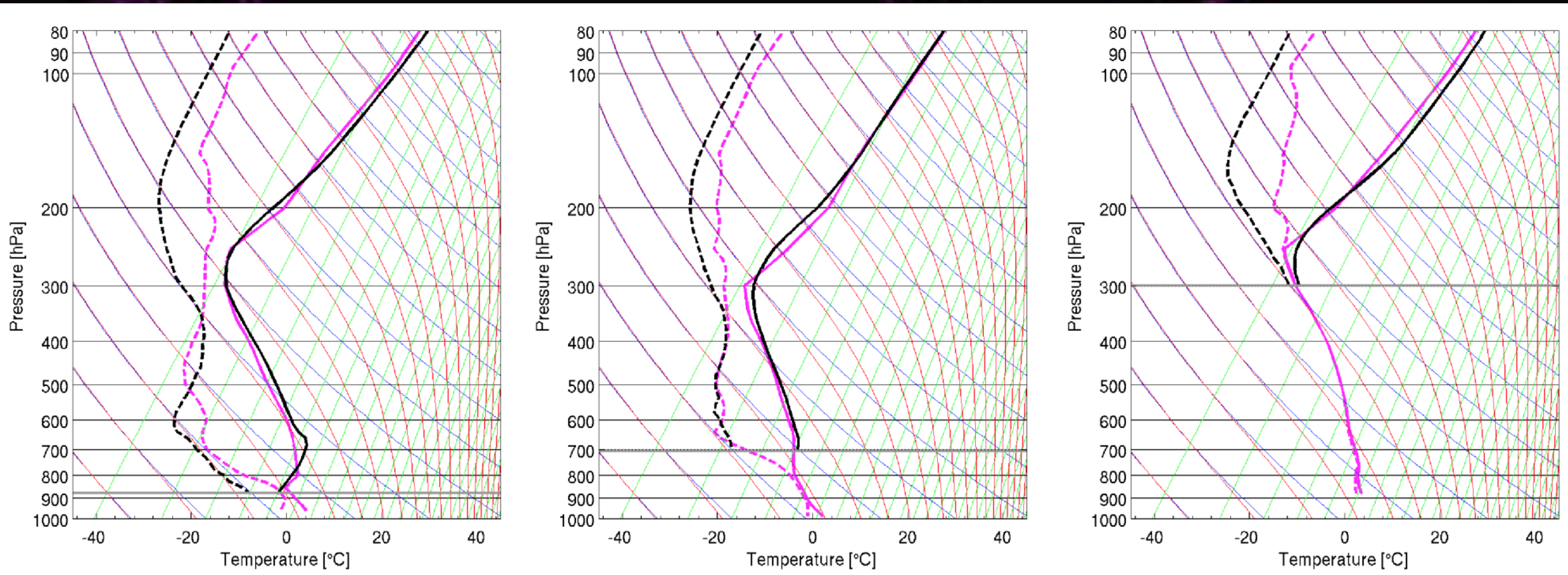
Feature-tracked 3D Winds from Satellite Sounders: Derivation and Impact in Global Models
[2010s]

Hyperspectral sounder vs. Imager

- Hyperspectral sounder: Atmospheric Infrared Sounder (AIRS) on Aqua
- 2378 channels in the IR band vs. 36 MODIS bands



Retrieved profiles of temperature and humidity

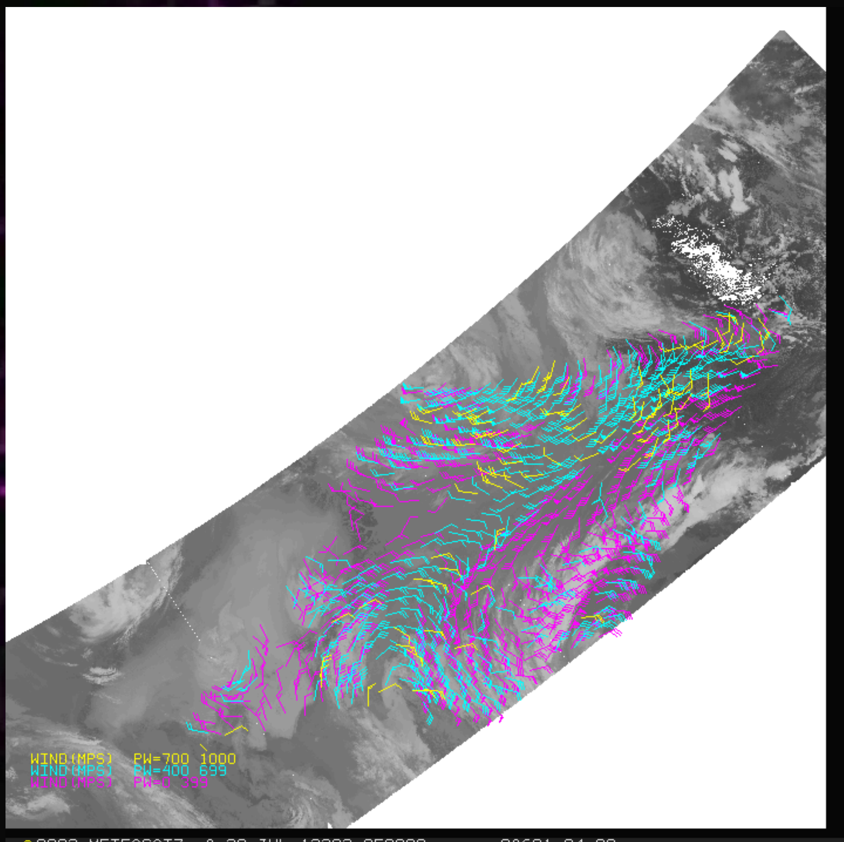


Example of temperature and dewpoint profiles for clear sky (left), low cloud (middle), high cloud (right). Retrievals (black) and NCEP/GFS (magenta).

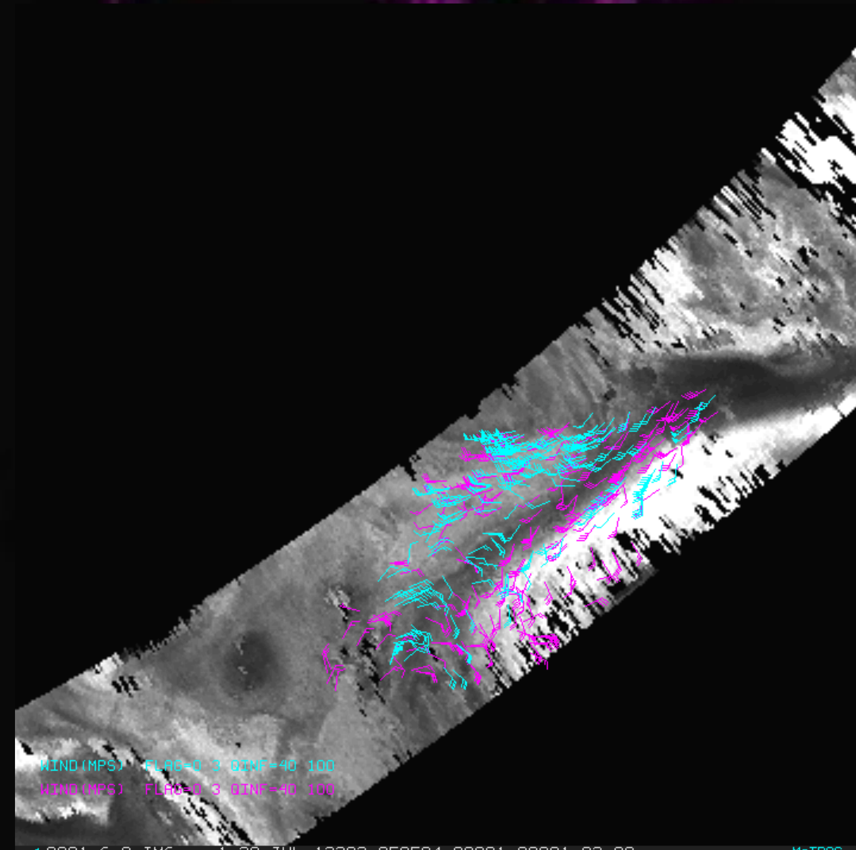
What are 3D winds from satellite sounders?

- Create images horizontal fields of humidity
- Track humidity 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

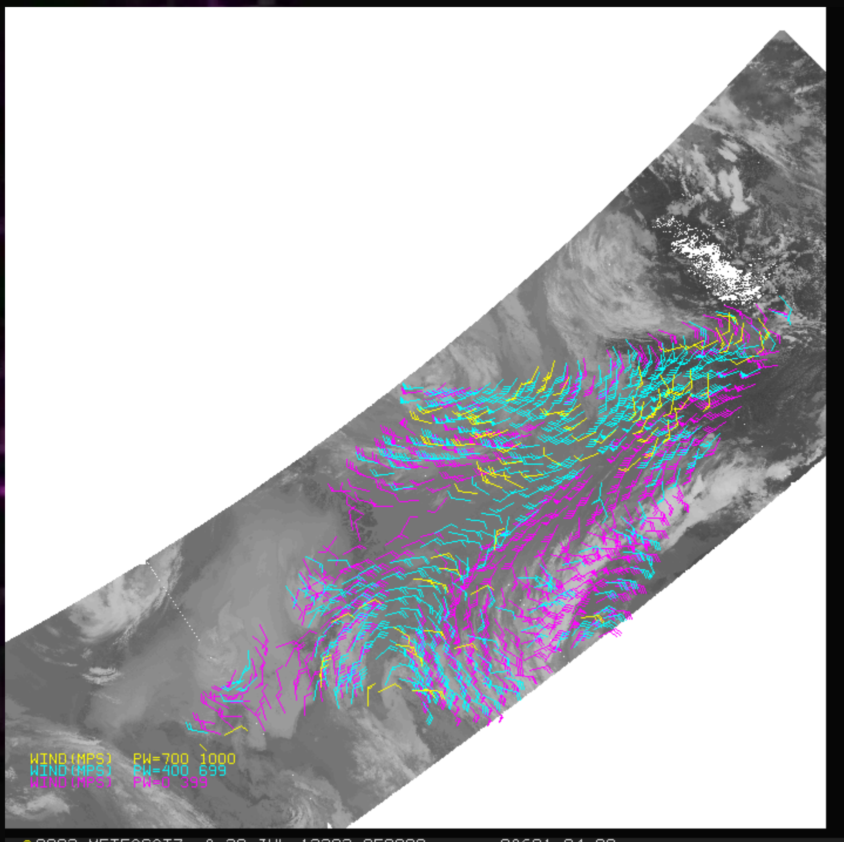


MODIS 20 July 2012 0551 UTC
Infrared and Water Vapor
(including clear sky)

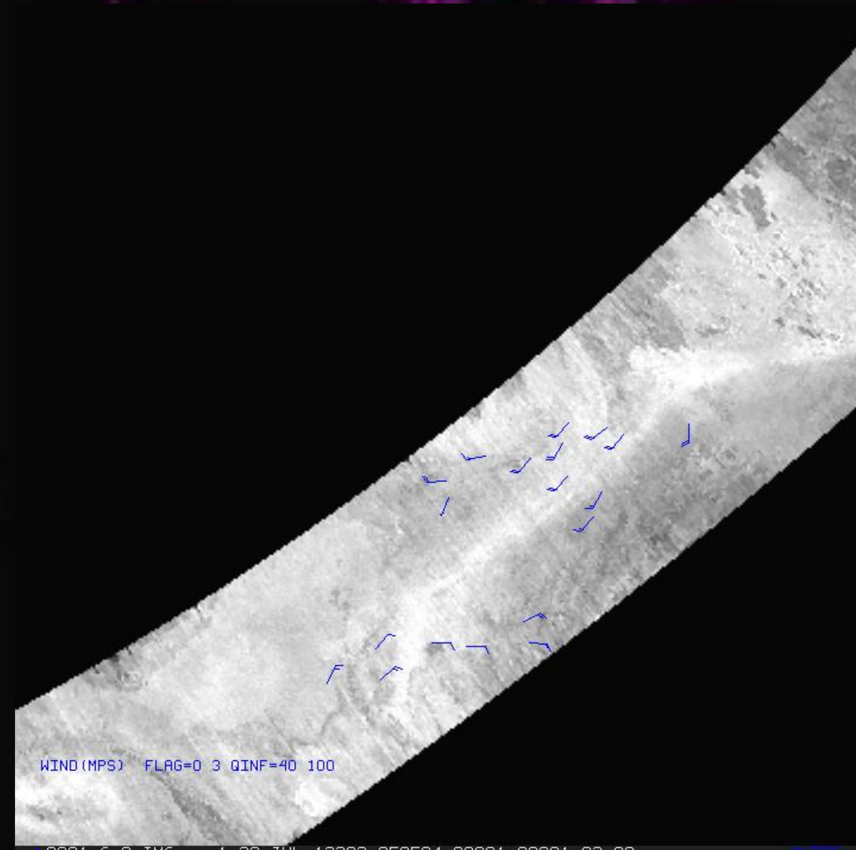


AIRS 20 July 2012 0505 UTC
Ozone: 103 to 201 hPa Moisture:
359 to 616 hPa

Aqua MODIS AMVs
AIRS Retrieval AMVs at All Levels

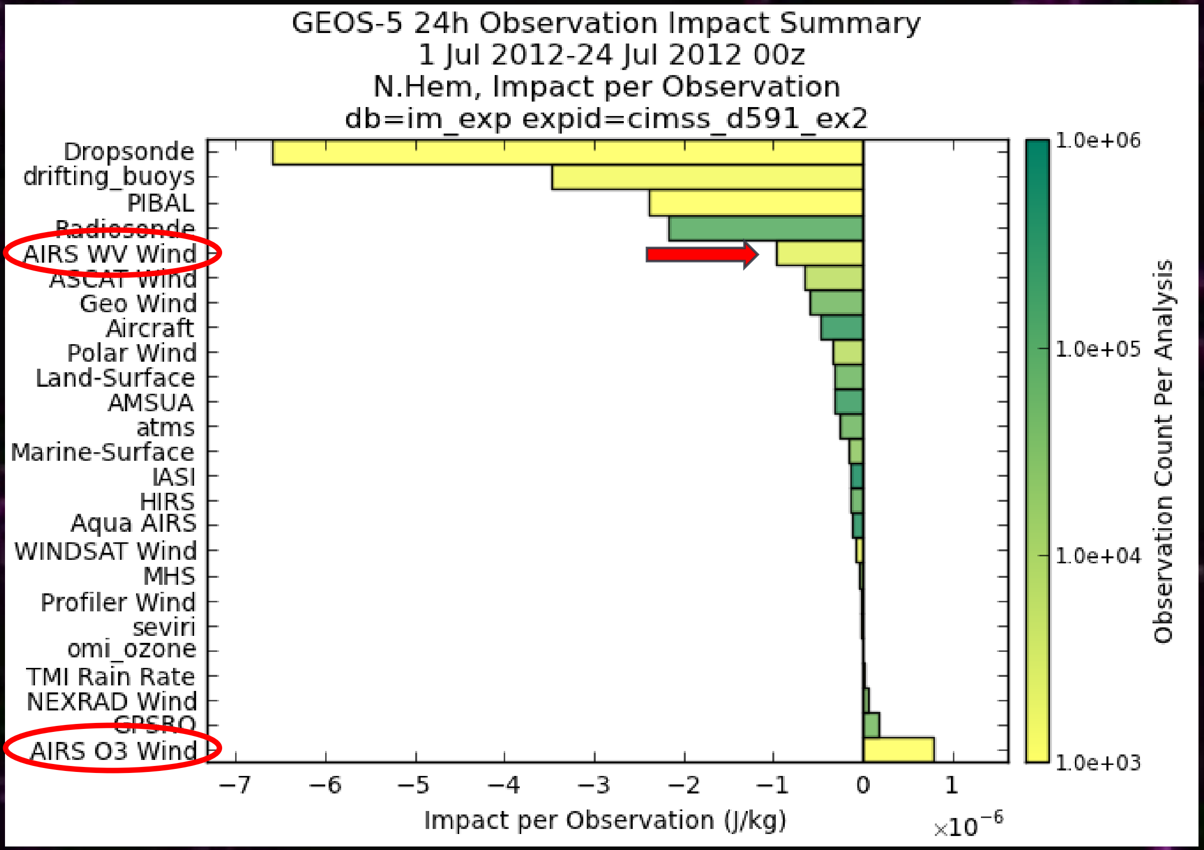


MODIS 20 July 2012 0551 UTC
Infrared and Water Vapor
(including clear sky)



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

Impact per observation



1 – 24 July 2012 00 UTC

GEOS-5 Forecast Impact: ACC

Two experiments

Control in black.

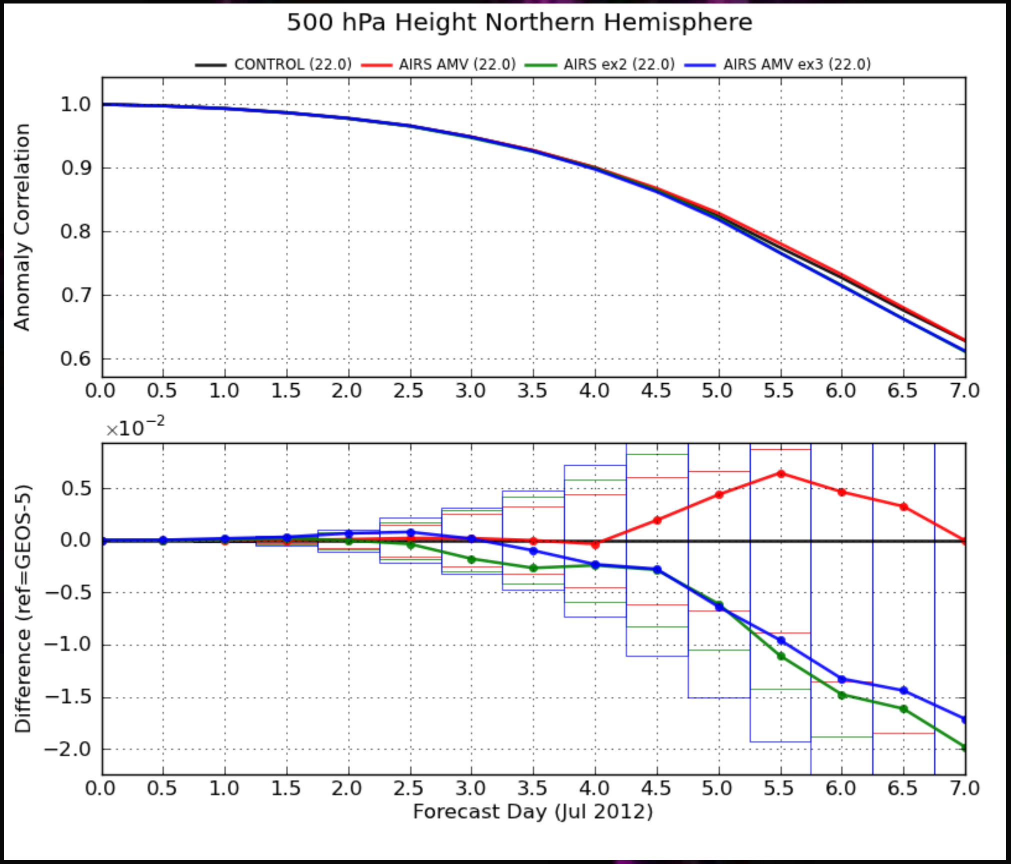
Red: Addition of AIRS AMVs. Slight improvement after Day 4 (not statistically significant).

Blue: Removal of the MODIS AMVs decreases ACC score:

- AIRS AMVs can not offset loss of MODIS AMVs

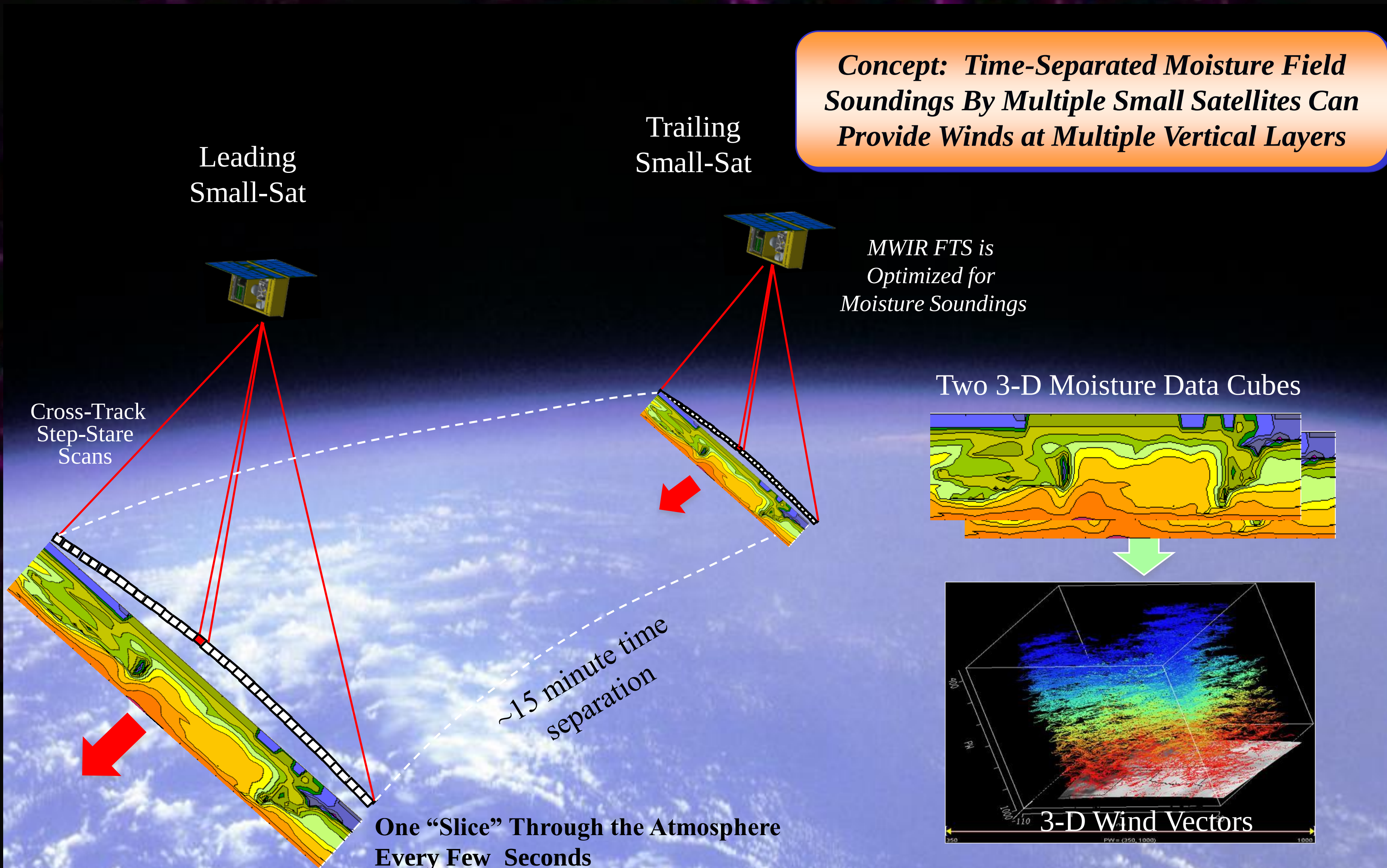
AIRS AMVs complement the MODIS AMVs

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

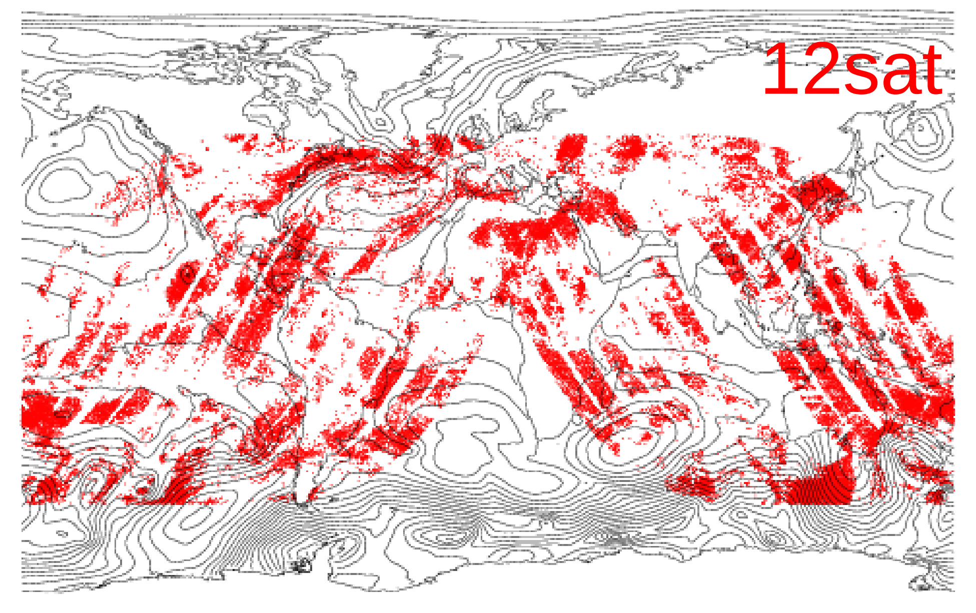


500 hPa Northern Hemisphere
1 – 24 July 2012 00 UTC

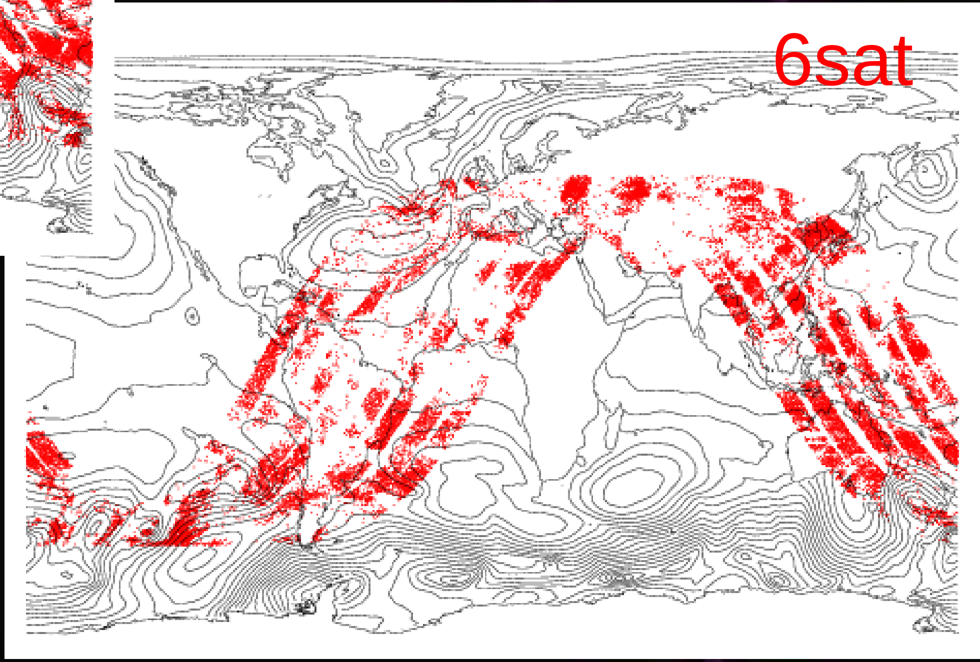
Future: 3D Wind Measurements Using Constellation of Small-Sats



Simulated Observations (12- and 6- satellite constellations)



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

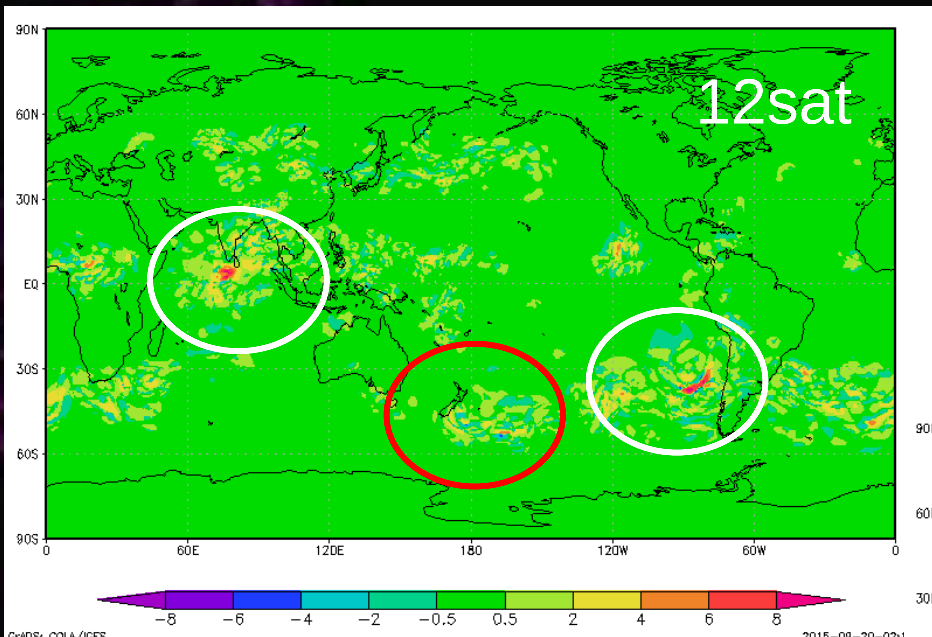


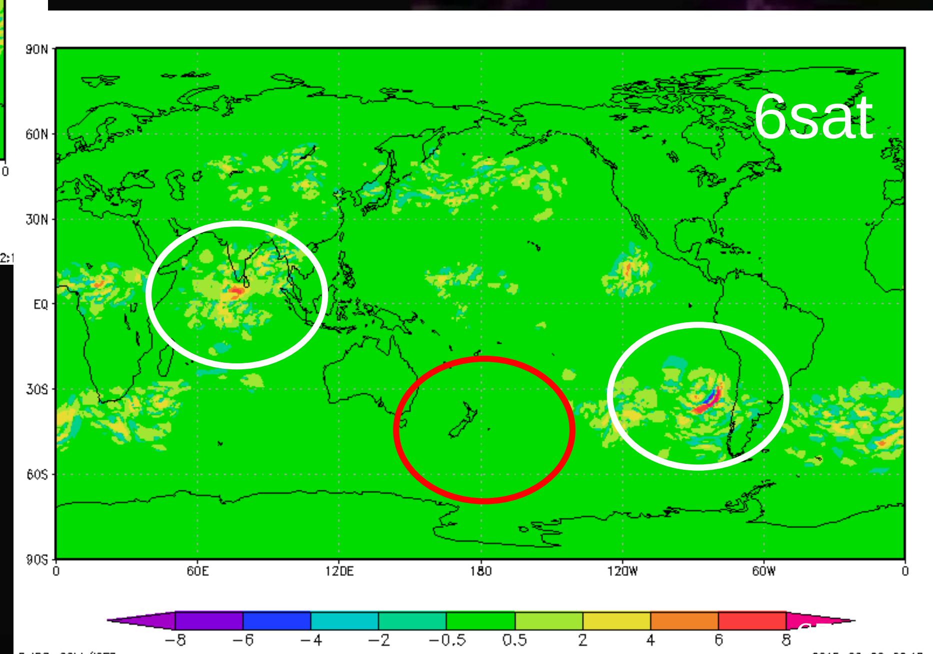
Simulated AMVs valid for 6-hour assimilation window

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 of Satellite-derived Winds

- History and future (1970s to the 2020s)
- AMVs from geostationary satellites (automated in the 1990s)
- AMVs from polar satellites (early 2000s)
- Tracking clouds from LEO/GEO composites.
- Tracking clouds on Mars
- AMVs from hyperspectral sounders (2010s and beyond)

Questions?