

Polar Winds from Satellite Imagers for Numerical Weather Prediction and Climate Applications

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with lots of help from:

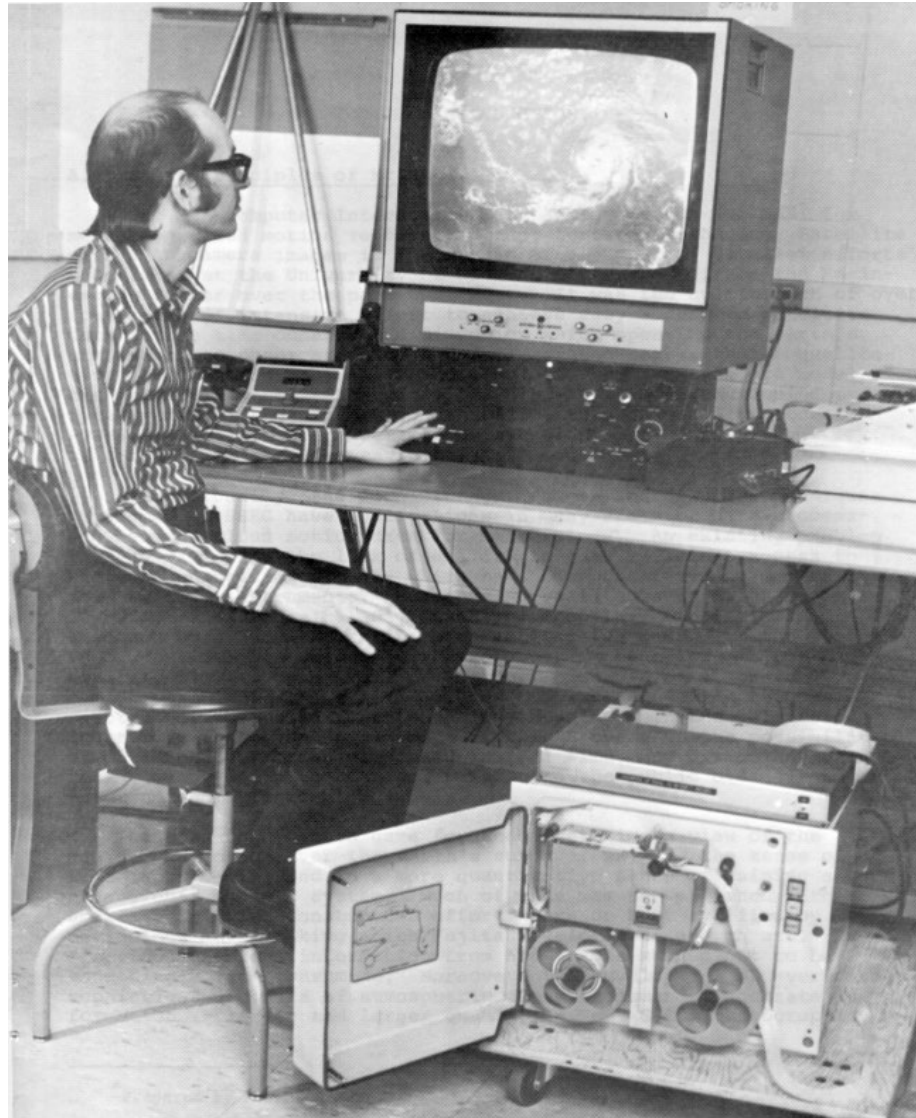
Dave Santek, Chris Velden, Matthew Lazzara, William Straka

Space Science and Engineering Center, University of Wisconsin
Madison, Wisconsin USA



Satellite-Derived Winds Heritage

The polar winds work is building on the long history of geostationary wind retrieval, which began around 1970 when the first geostationary satellites were launched.

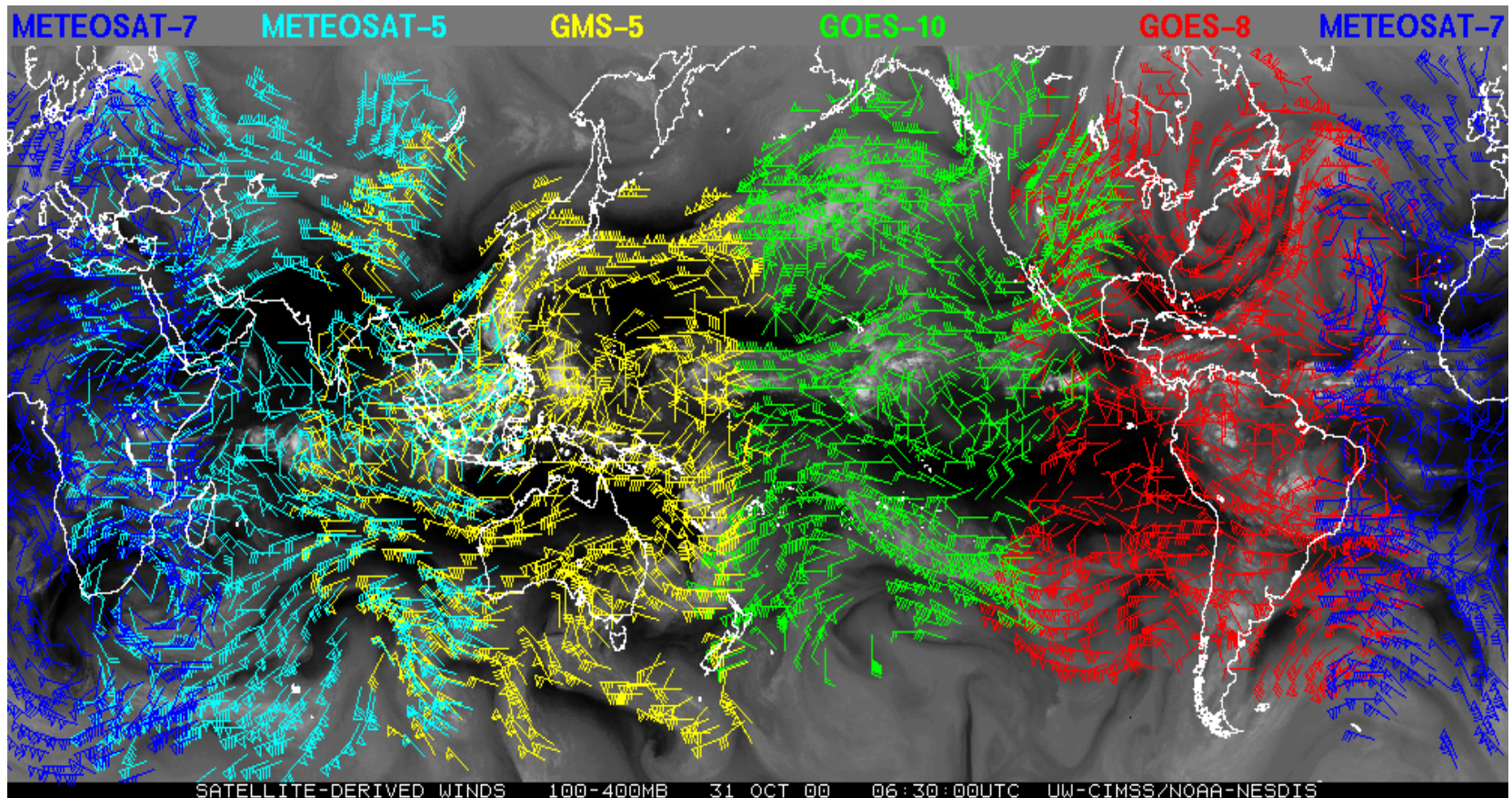


Automated Wind Retrieval Methodology

- Targeting
 - - clouds in the IR window channel 11 μm
 - - water vapor features in 6.7 μm
- Tracking
 - - cross-correlation technique
 - - model winds used as first guess
 - - image triplets (rather than pairs) used for consistency check
- Wind height assignment: IR window, CO₂-slicing, or H₂O-intercept

Geostationary Cloud Motion Vectors

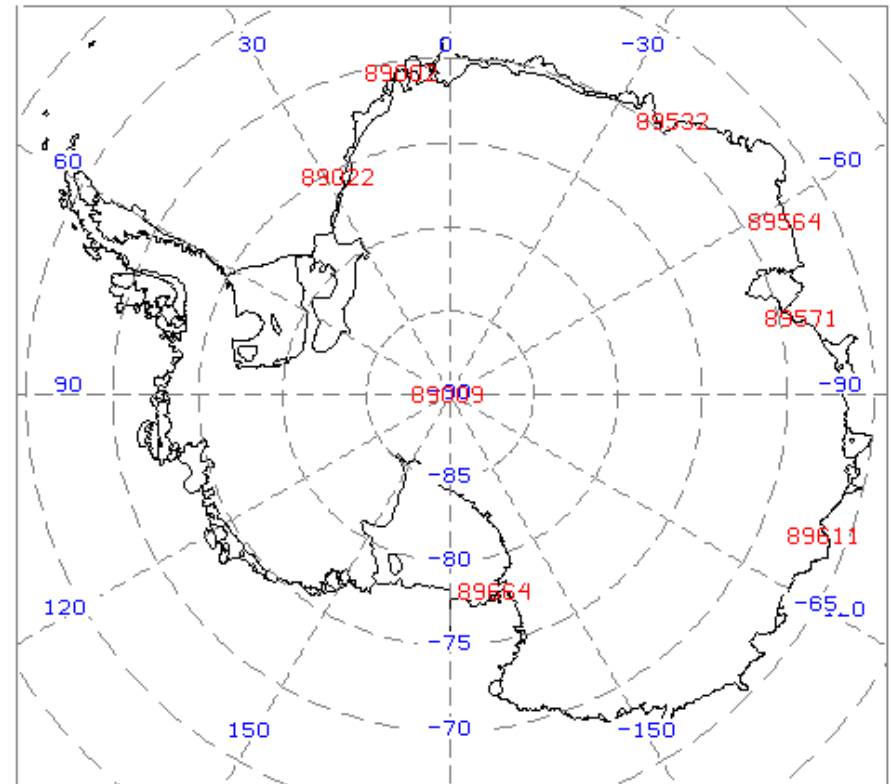
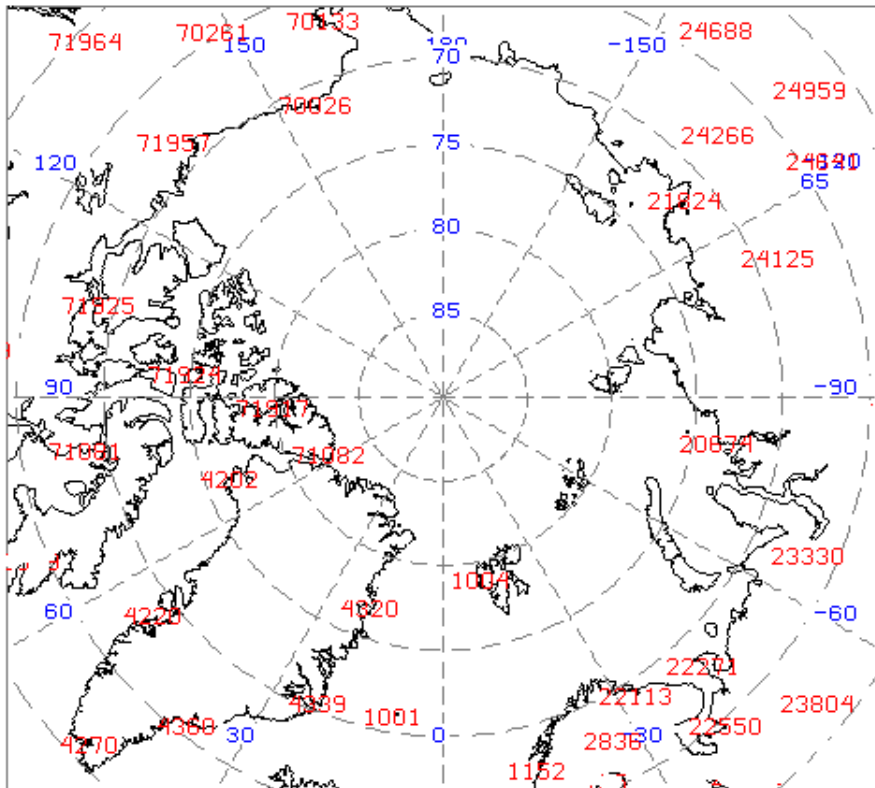
Five geos provide coverage for winds in the tropics and mid-latitudes. However, the total number of wind vectors drops off steadily beyond a 30 degree view angle, with a sharp drop off beyond 60 degrees. The success rate (#vectors/total possible) drops off beyond 50 degrees.



Justification

Sparse Observation Network

Arctic and Antarctic Rawinsonde Distribution



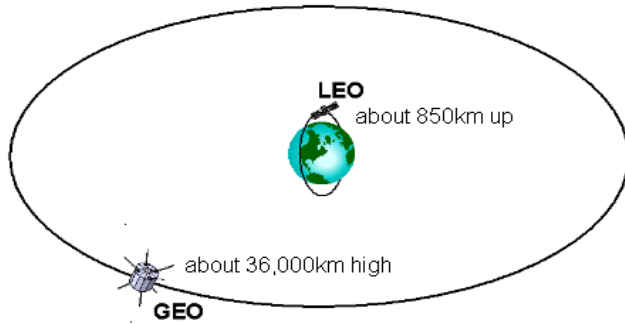
Raob locations are indicated by their WMO station numbers.

New Challenges

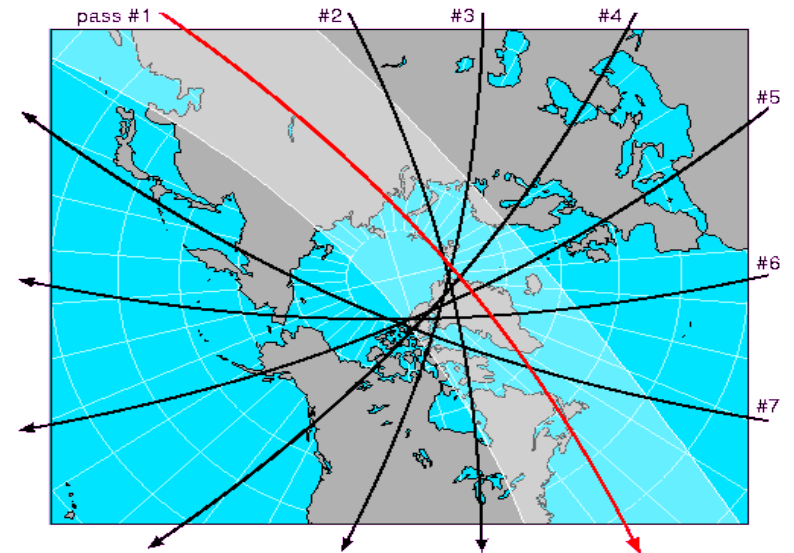
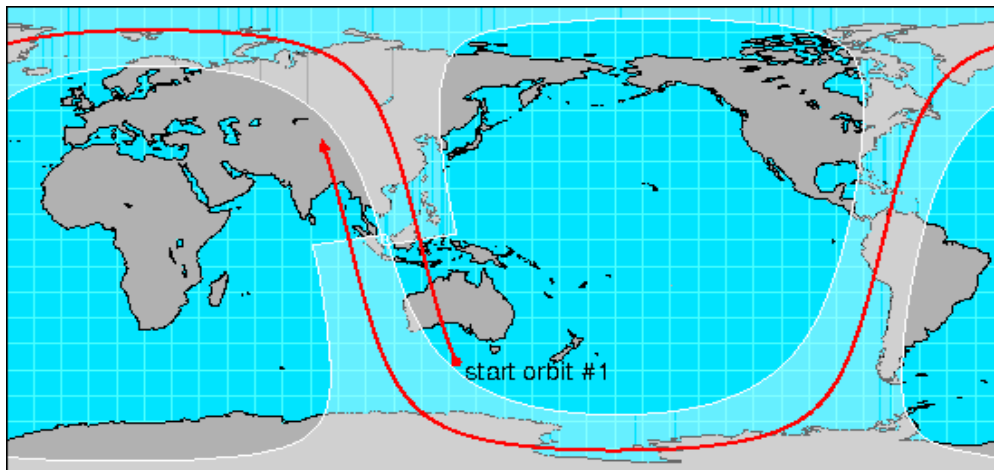
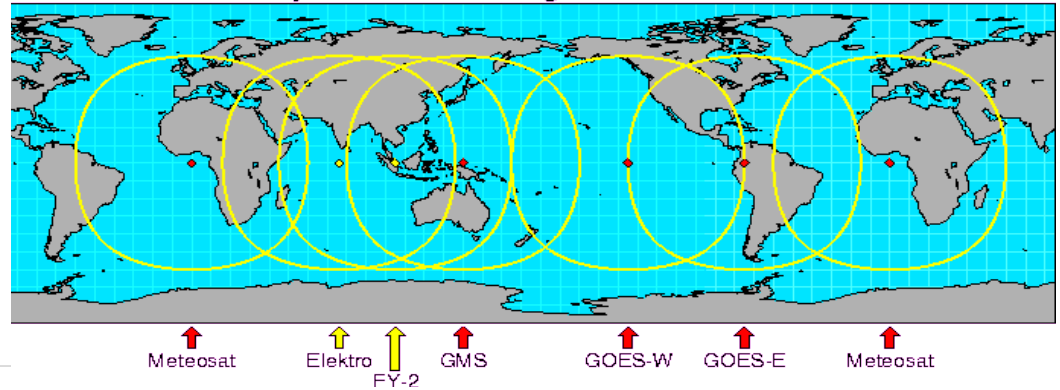
- Reduced temporal sampling compared to GOES
- Parallax
- Height assignment issues
 - low-level inversion
 - isothermal layers
 - warm, thin clouds over cold surface
 - low water vapor amounts
- Additional spectral channels are available. Are they useful?
- Validation

Orbits

LEO and GEO orbit elevations



Global Geostationary Satellite Coverage



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

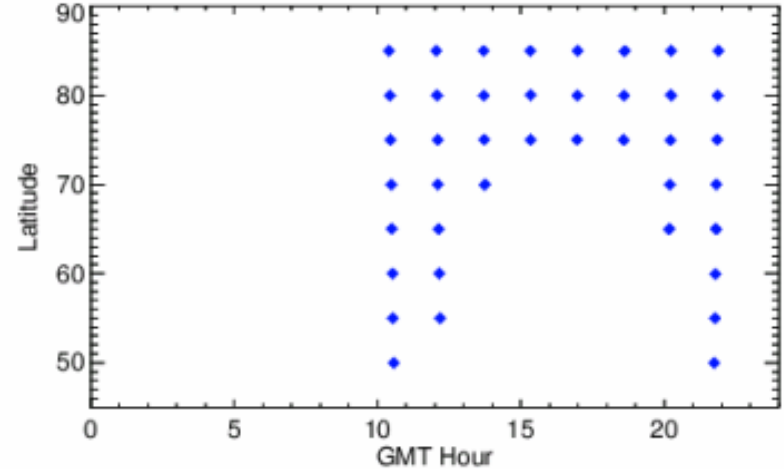
Overpass Frequency

The figure at right shows the time of successive overpasses at a given latitude-longitude point on a single day with only the Terra satellite. The figure at the upper right shows the frequency of "looks" by two satellites: Terra and (the future) Aqua. The figure at the lower right shows the temporal sampling with five satellites.

Satellite Overpasses by Latitude on 30 March 2003

One Satellite: Terra

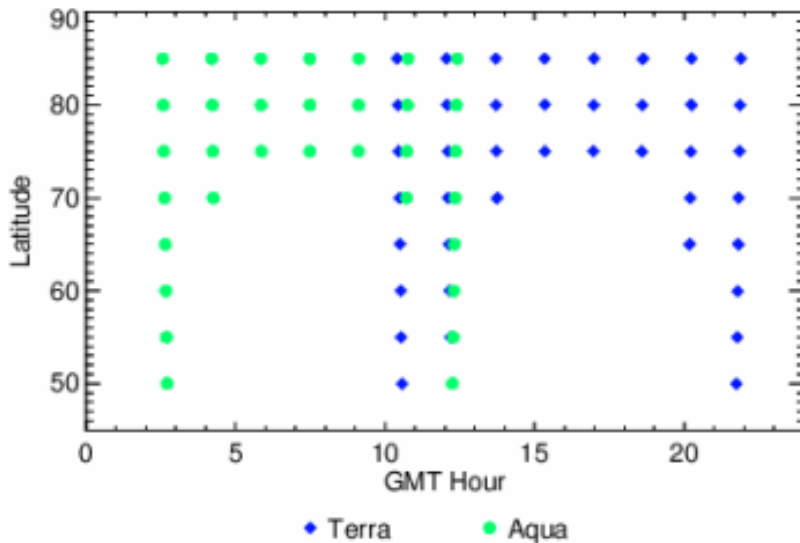
Longitude: 0; Maximum scan angle: 50 degrees



Satellite Overpasses by Latitude on 30 March 2003

Two Satellites: Terra and Aqua

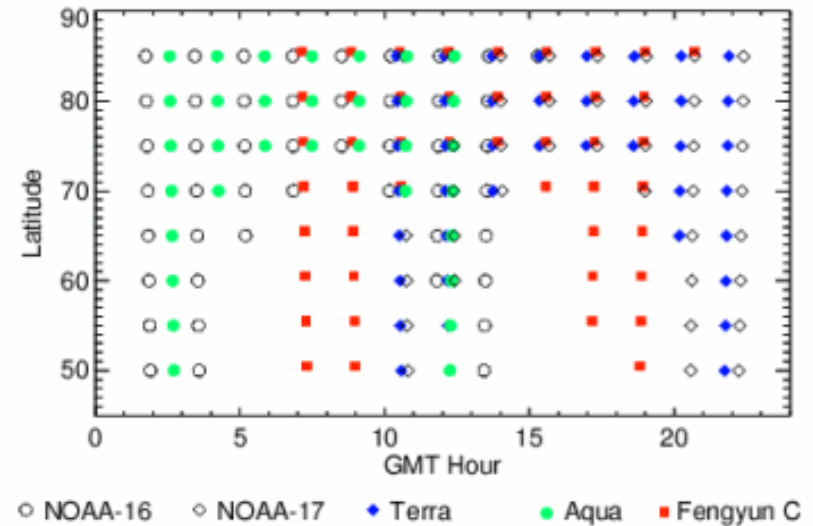
Longitude: 0; Maximum scan angle: 50 degrees



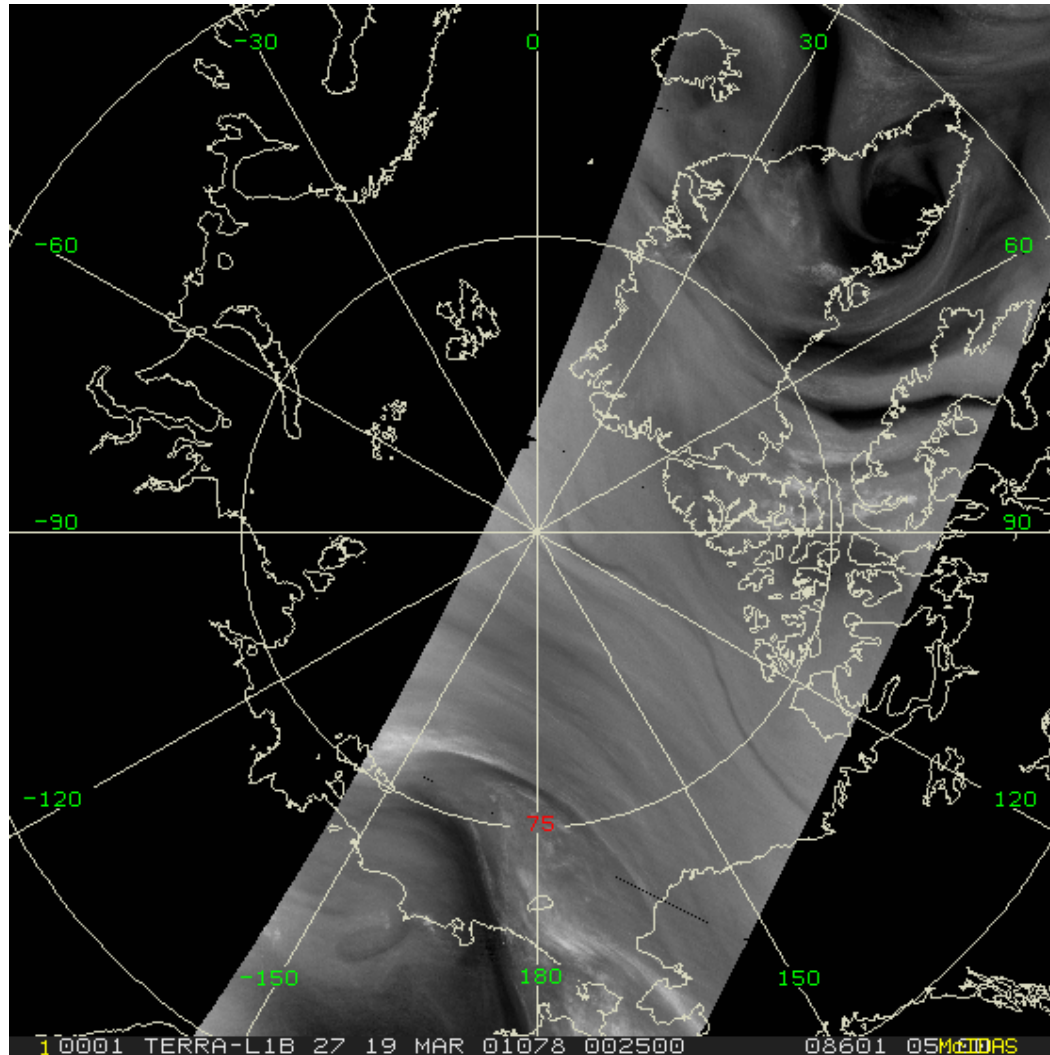
Satellite Overpasses by Latitude on 30 March 2003

NOAA-16, NOAA-17, Fengyun C, Terra, and Aqua

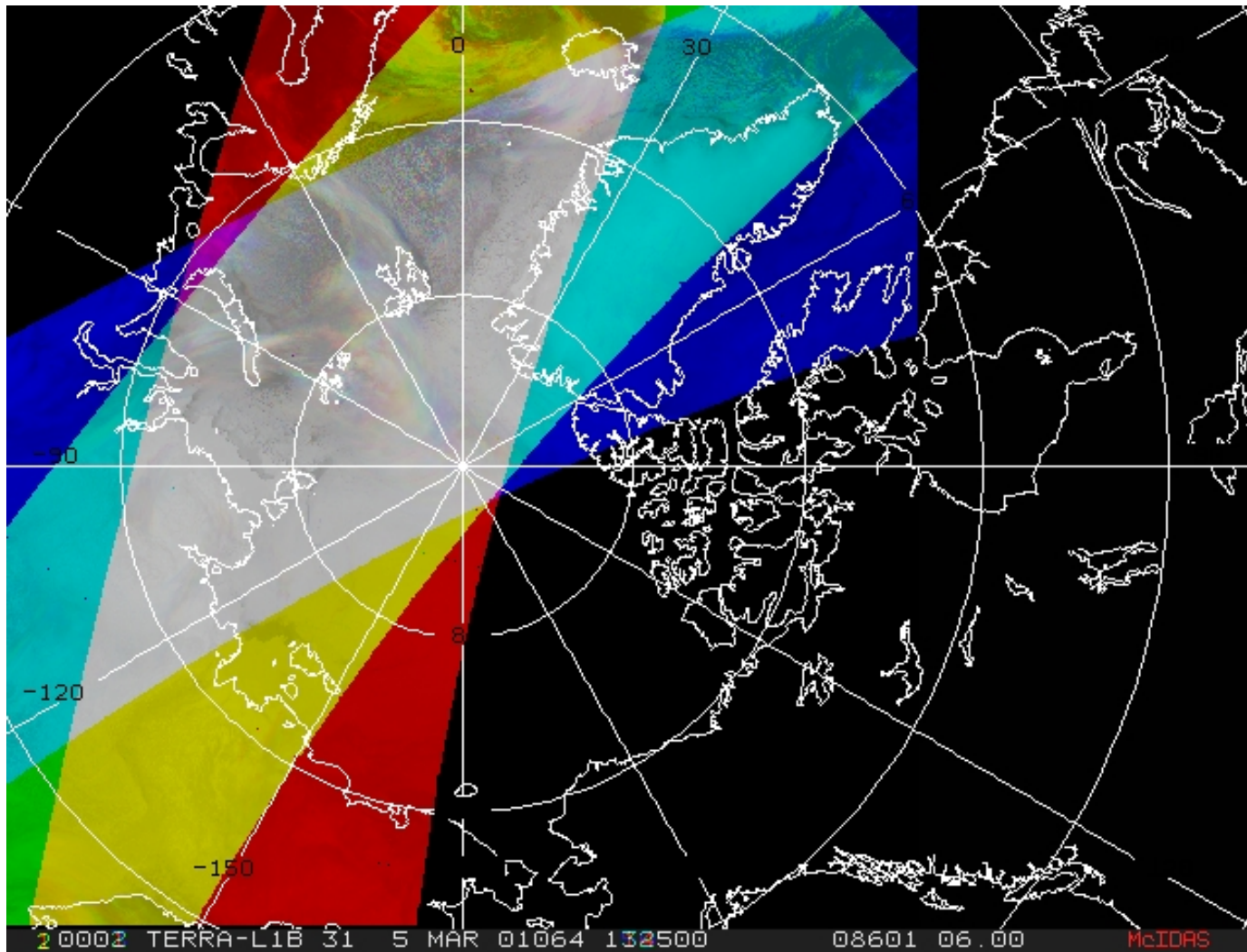
Longitude: 0; Maximum scan angle: 50 degrees



One Day of Arctic Orbits, Terra MODIS

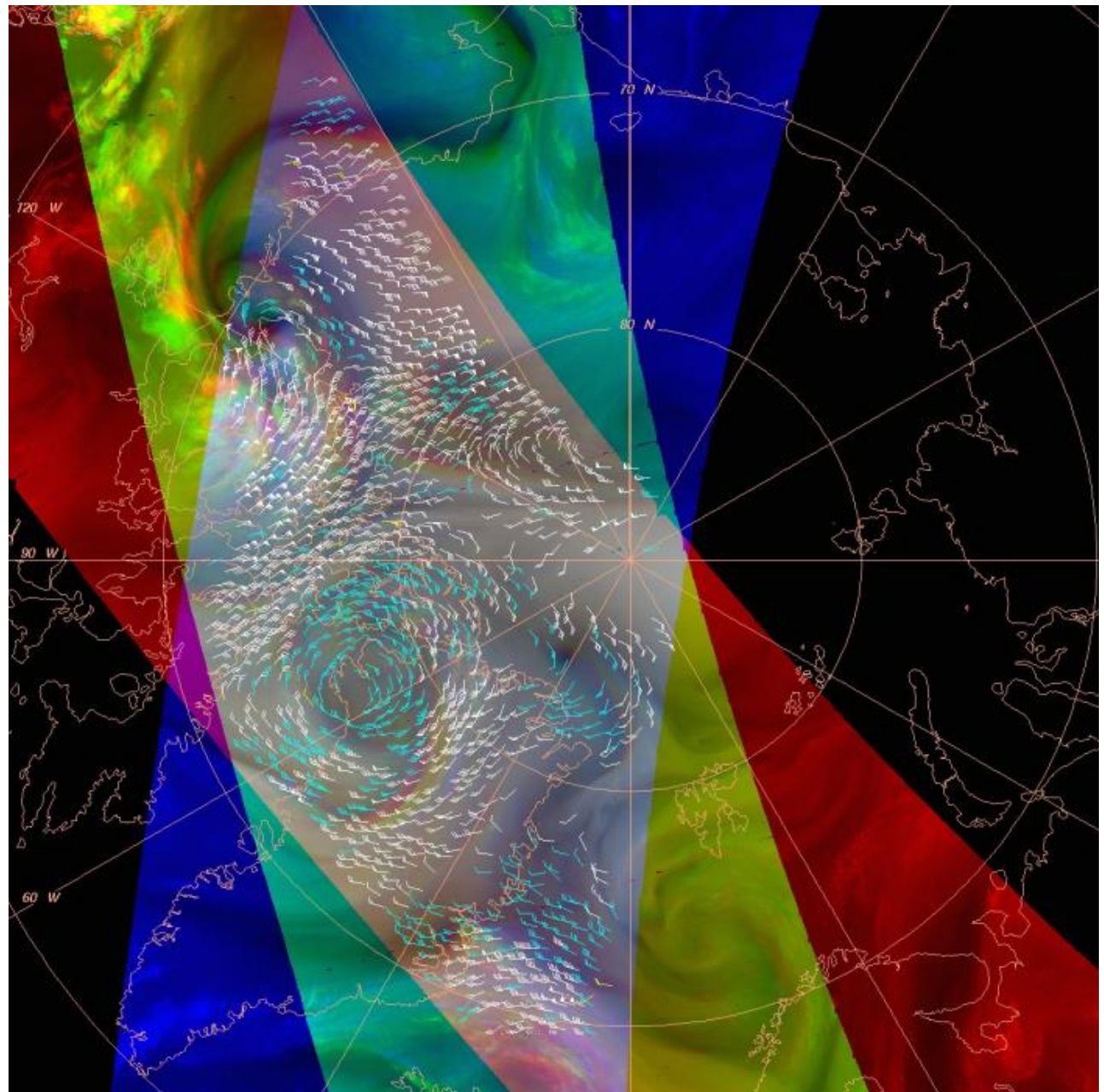


MODIS band 27 (water vapor at 6.7 μm)



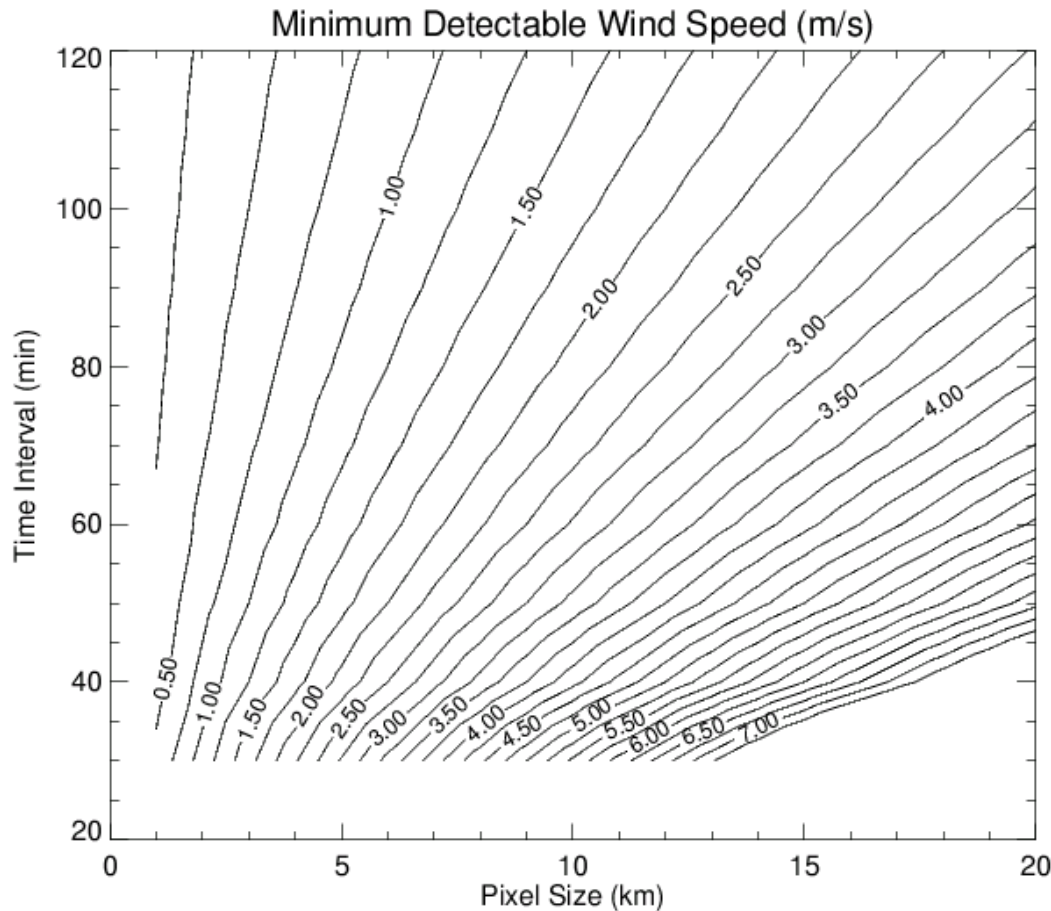
Unlike geostationary satellites at lower latitudes, it is not possible to obtain complete polar coverage at a snapshot in time with one or two polar-orbiters. Instead, winds must be derived for areas that are covered by two or three successive orbits, an example of which is shown here. The whitish area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

Unlike geostationary satellites at lower latitudes, it is not 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.

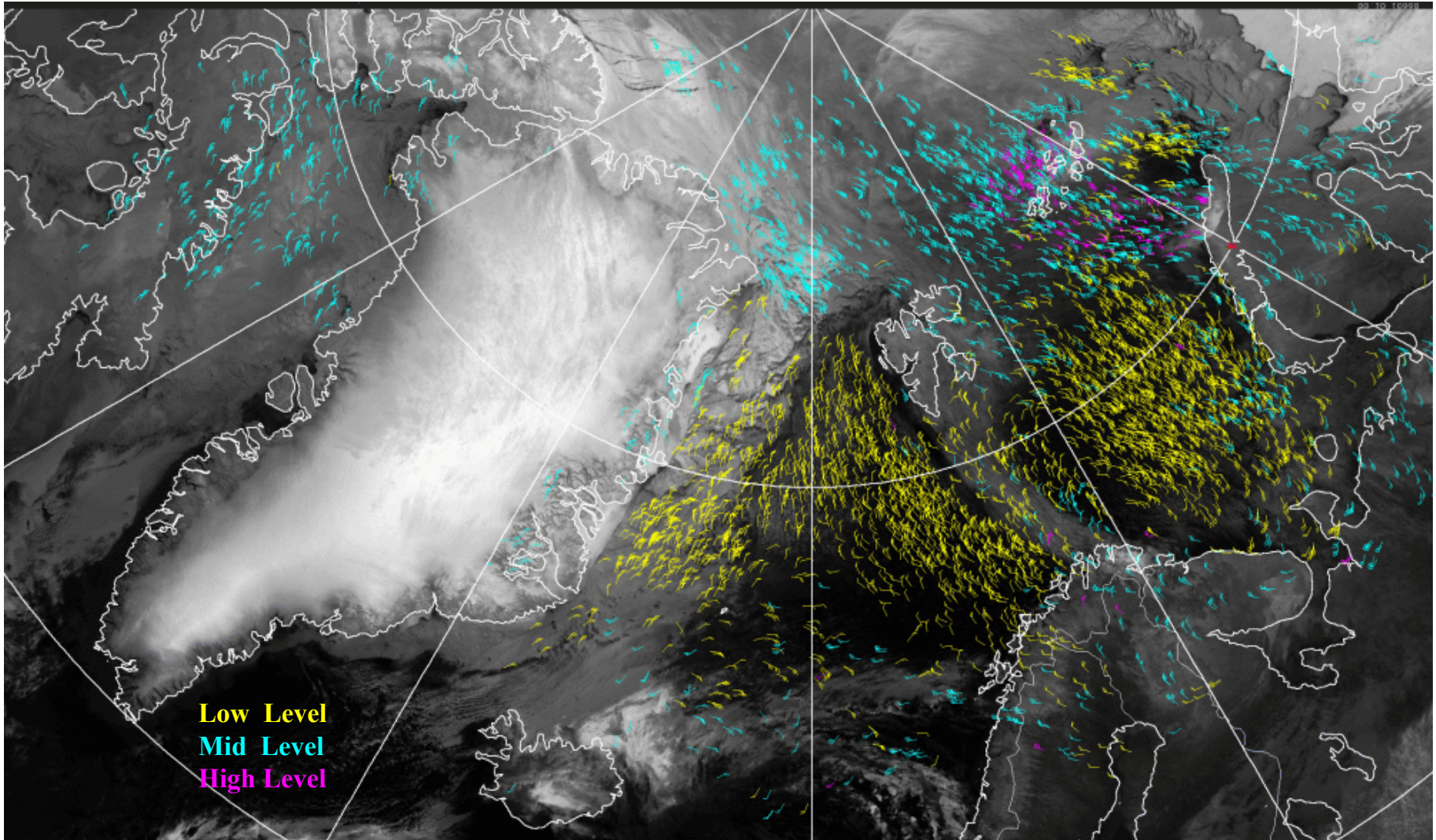
Spatial and Temporal Resolution Relationships



The minimum detectable wind speed as a function of pixel size and time interval, calculated as the pixel size divided by the time interval. For example, with a 4 km pixel and a sampling frequency of 60 minutes, we won't be able to detect speeds less than 1.1 m/s. This could also be viewed as the precision of the measurement; e.g., we will only measure wind speeds in increments of 1.1 m/s at these time and space resolutions.

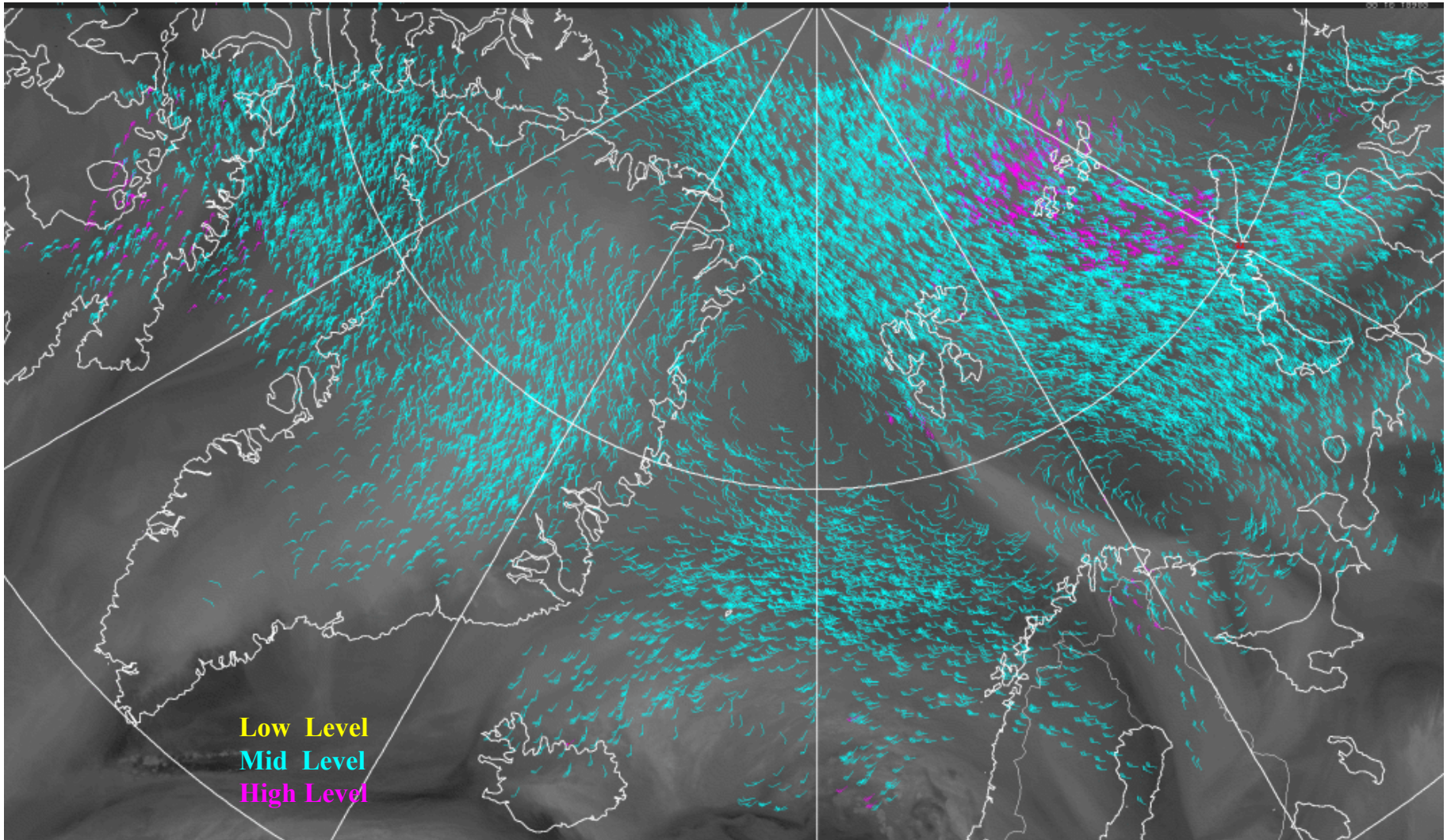
This does not take into account the evolution of tracking features over time, or the increase in spatial variability as pixel size decreases.

Infrared Winds



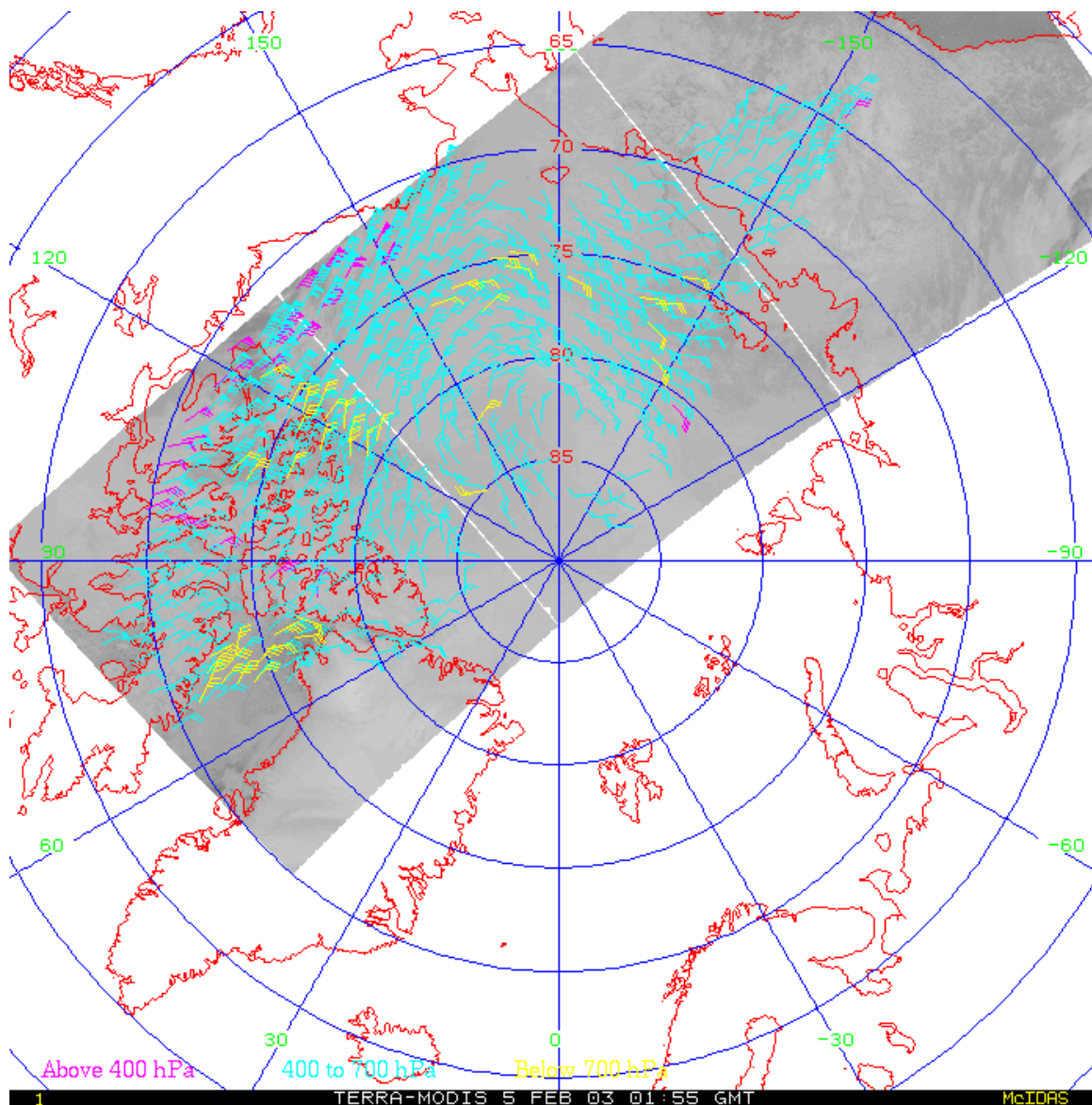
05 March 2001: Daily composite of 11 micron MODIS data over half of the Arctic region. Winds were derived over a period of 12 hours. There are about 4,500 vectors in the image. Vector colors indicate pressure level - yellow: below 700 hPa, cyan: 400-700 hPa, purple: above 400 hPa.

Water Vapor Winds



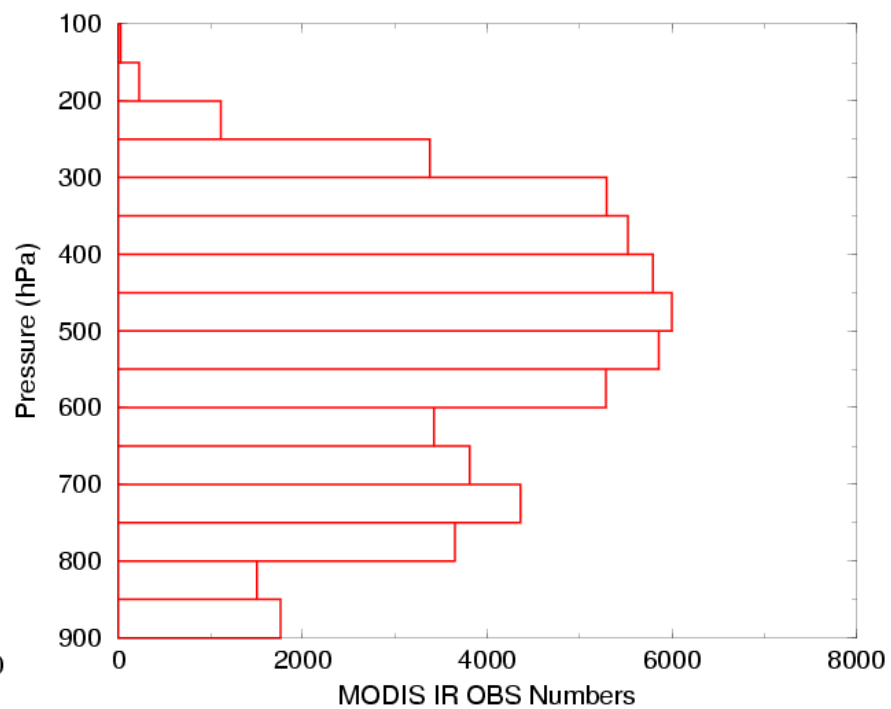
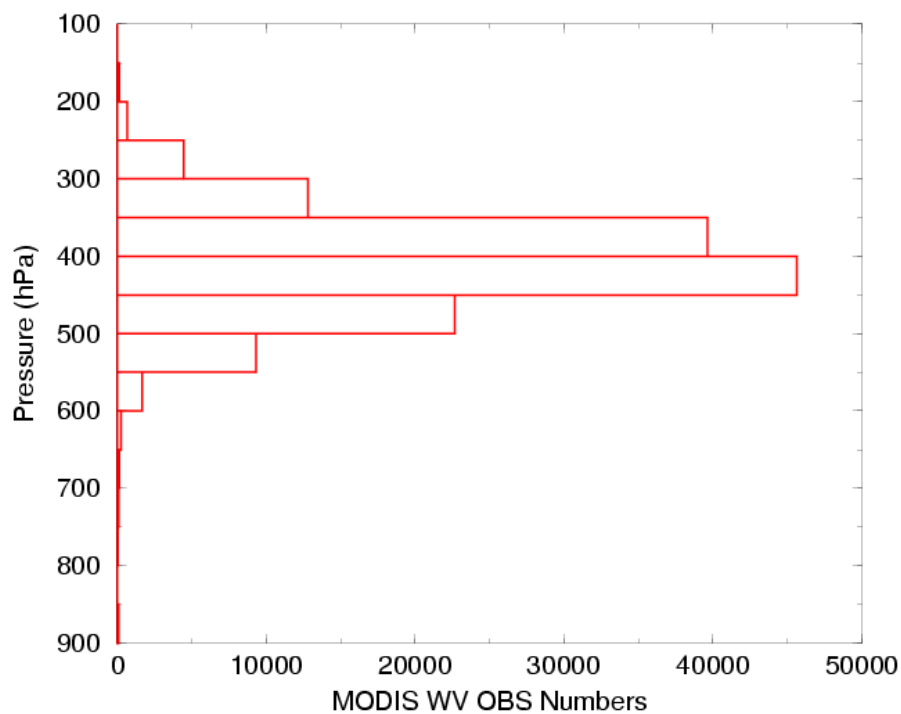
05 March 2001: Daily composite of 6.7 micron MODIS data over half of the Arctic region. Winds were derived over a period of 12 hours. There are about 13,000 vectors in the image. Vector colors indicate pressure level - yellow: below 700 hPa, cyan: 400-700 hPa, purple: above 400 hPa.

One Day of Arctic Orbits, Terra MODIS



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

Frequency of Water Vapor and IR Winds

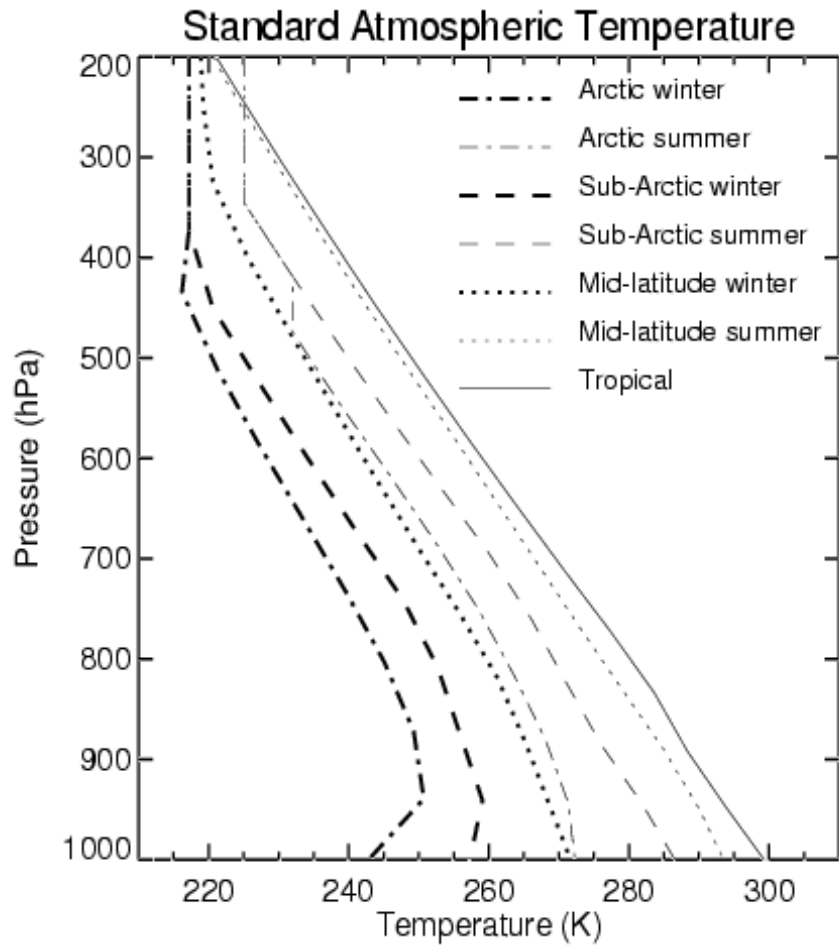


Height Assignment

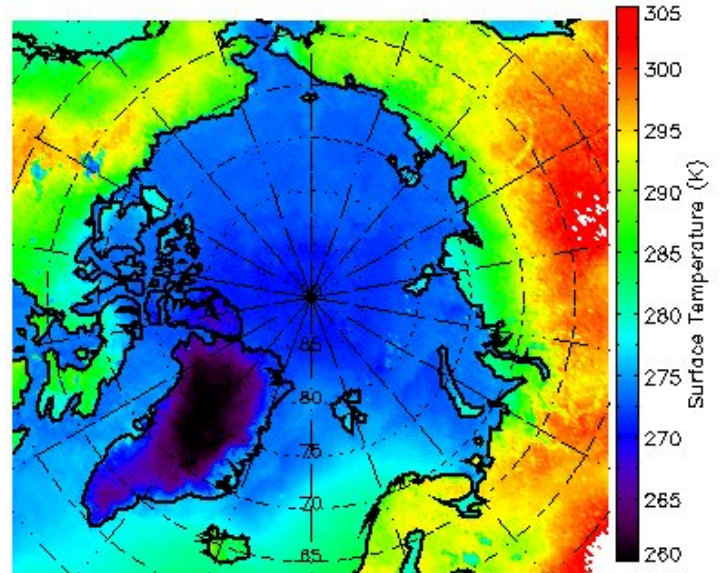
Three primary height assignment methods:

- CO₂ slicing - Problems occur when the clear-cloudy radiance difference is small. Cloud pressures greater than 700 mb (lower in altitude) are generally not retrievable with this method.
- H₂O intercept - In practice the method is generally not useful for cloud pressures greater than 600-700 mb.
- IR Window - This approach assumes the cloud is opaque so that the IR brightness temperature is also the cloud temperature. Ideally, an adjustment for surface emission would be used with thin clouds, which means optical depth must be calculated.

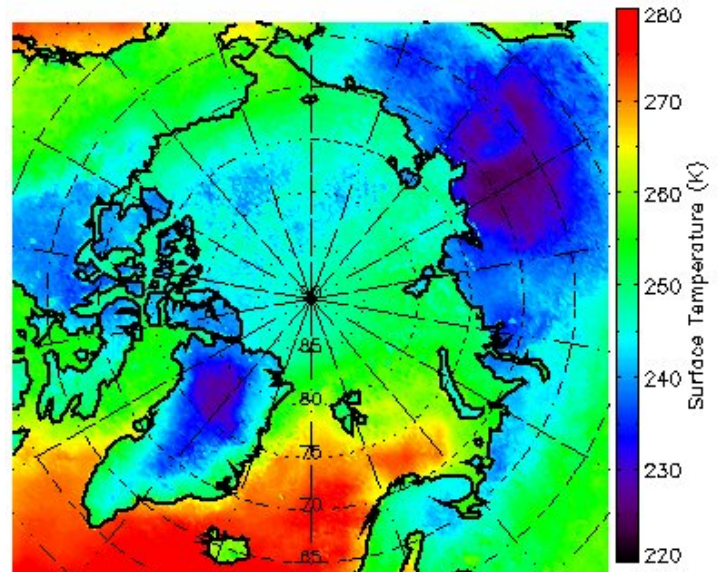
Temperature



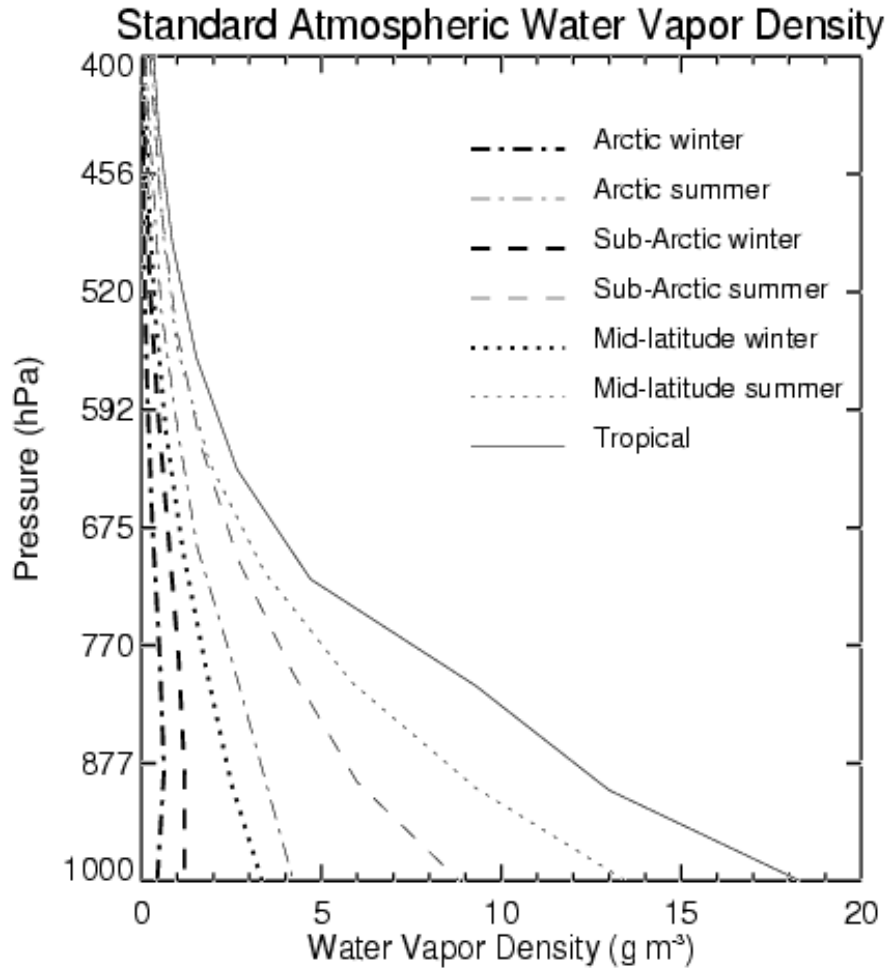
Surface Temperature
June



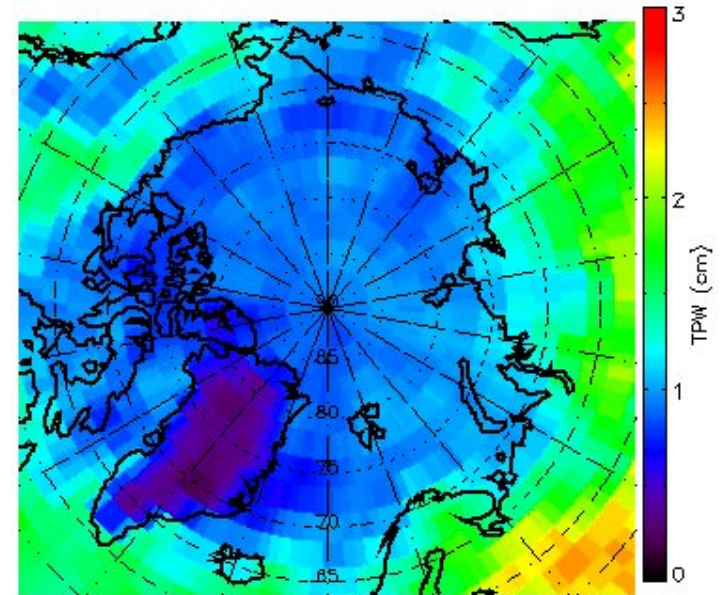
Surface Temperature
January



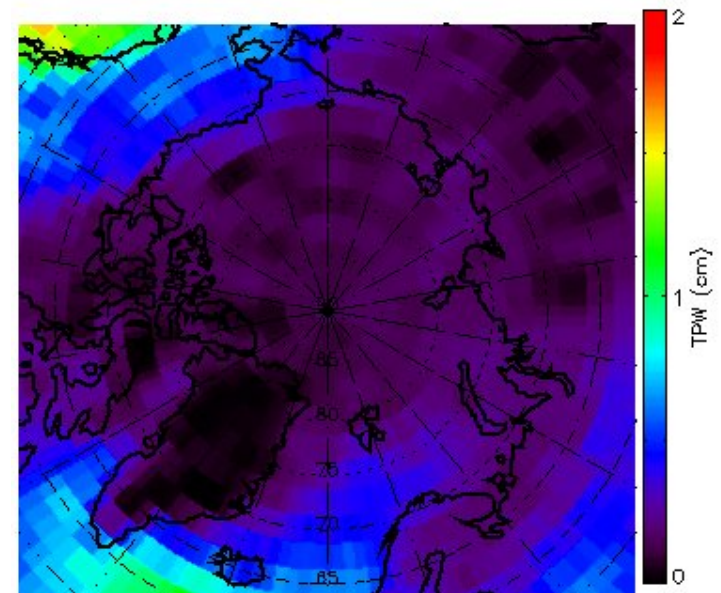
Water Vapor



Total Precipitable Water (NCEP)
June



Total Precipitable Water (NCEP)
January



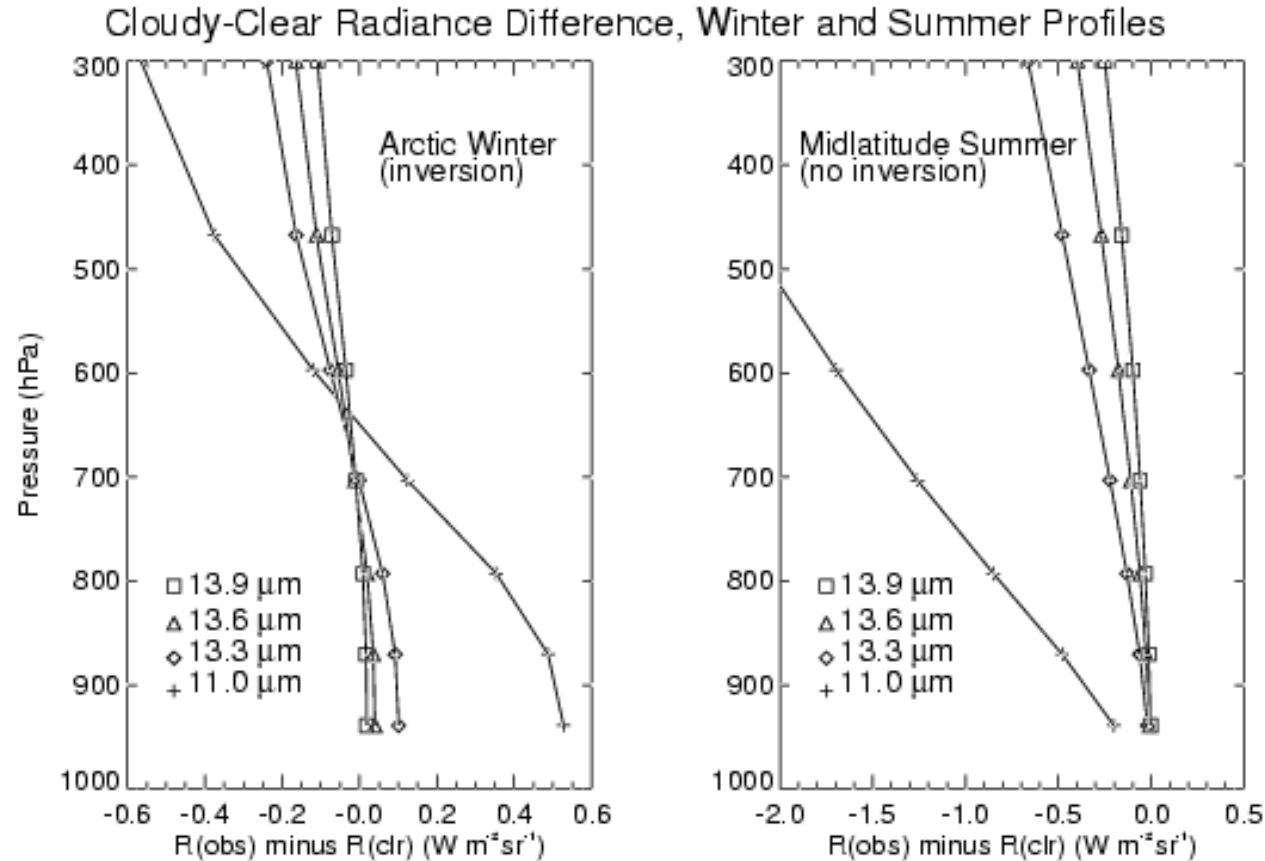
Height Assignment

CO2-Slicing

$$\frac{R(CO_2) - R_{CL}(CO_2)}{R(IRW) - R_{CL}(IRW)} = \frac{nE(CO_2)[R_{BCD}(CO_2, P_c) - R_{CL}(CO_2)]}{nE(IRW)[R_{BCD}(IRW, P_c) - R_{CL}(IRW)]}$$

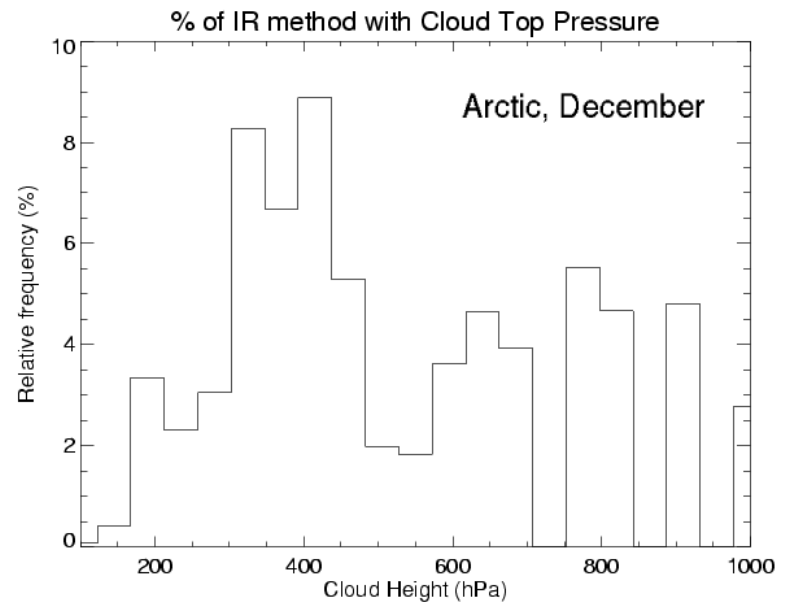
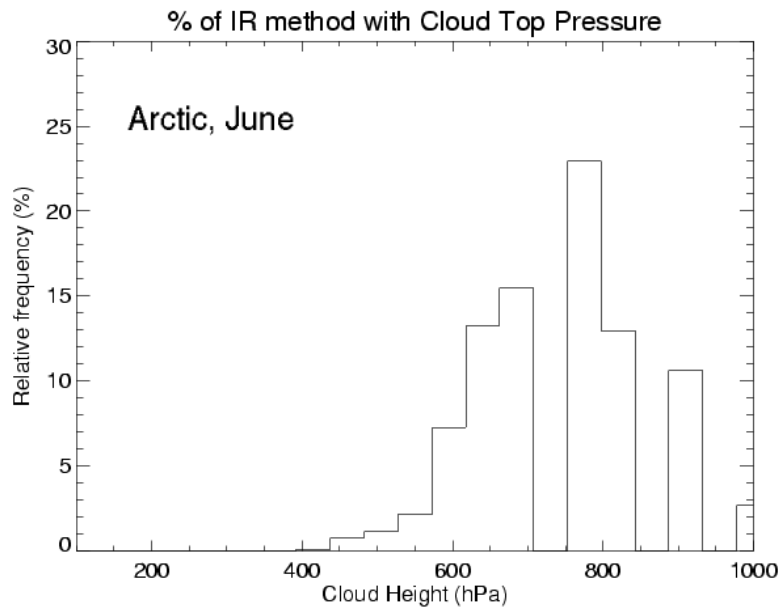
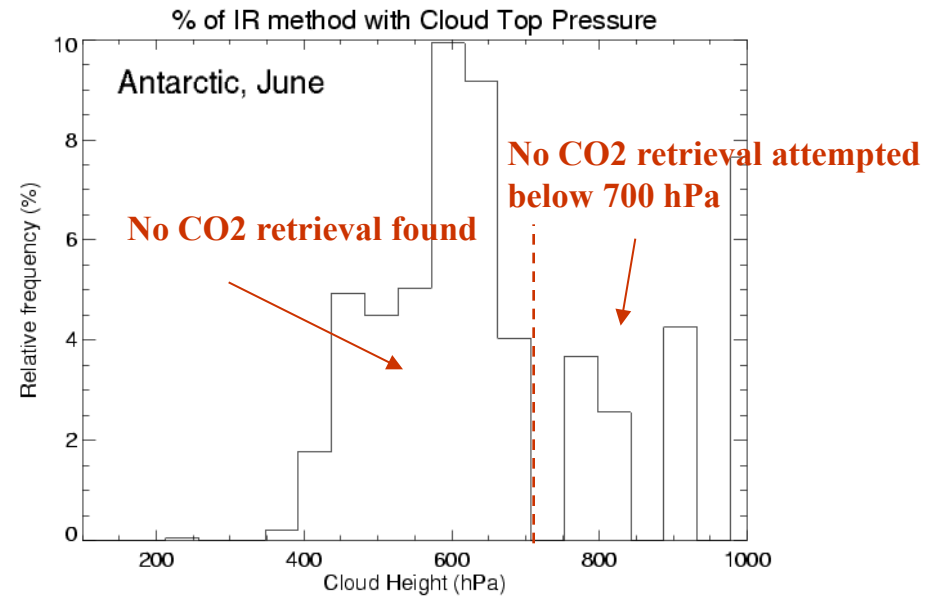
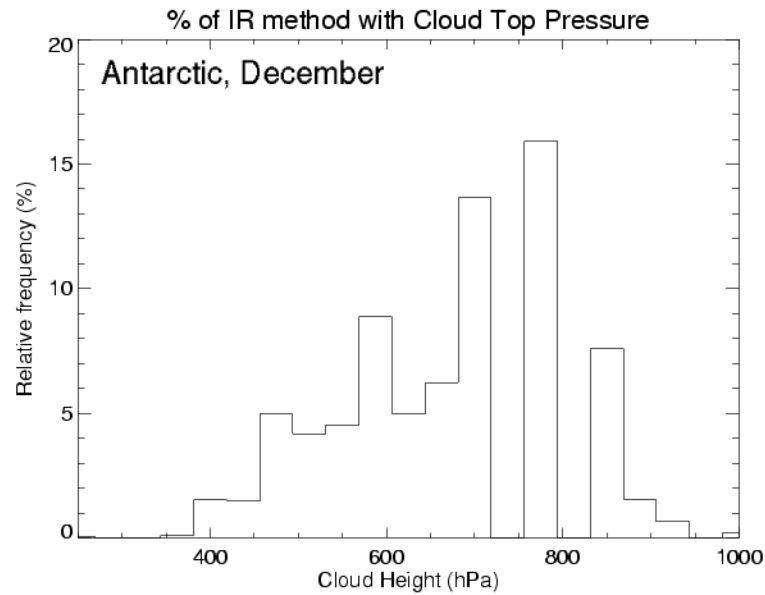
Problems occur when the clear-cloudy radiance difference is small.

Cloud pressures greater than 700 hPa (lower in altitude) are generally not retrievable with this method.



Note difference in horizontal scales.

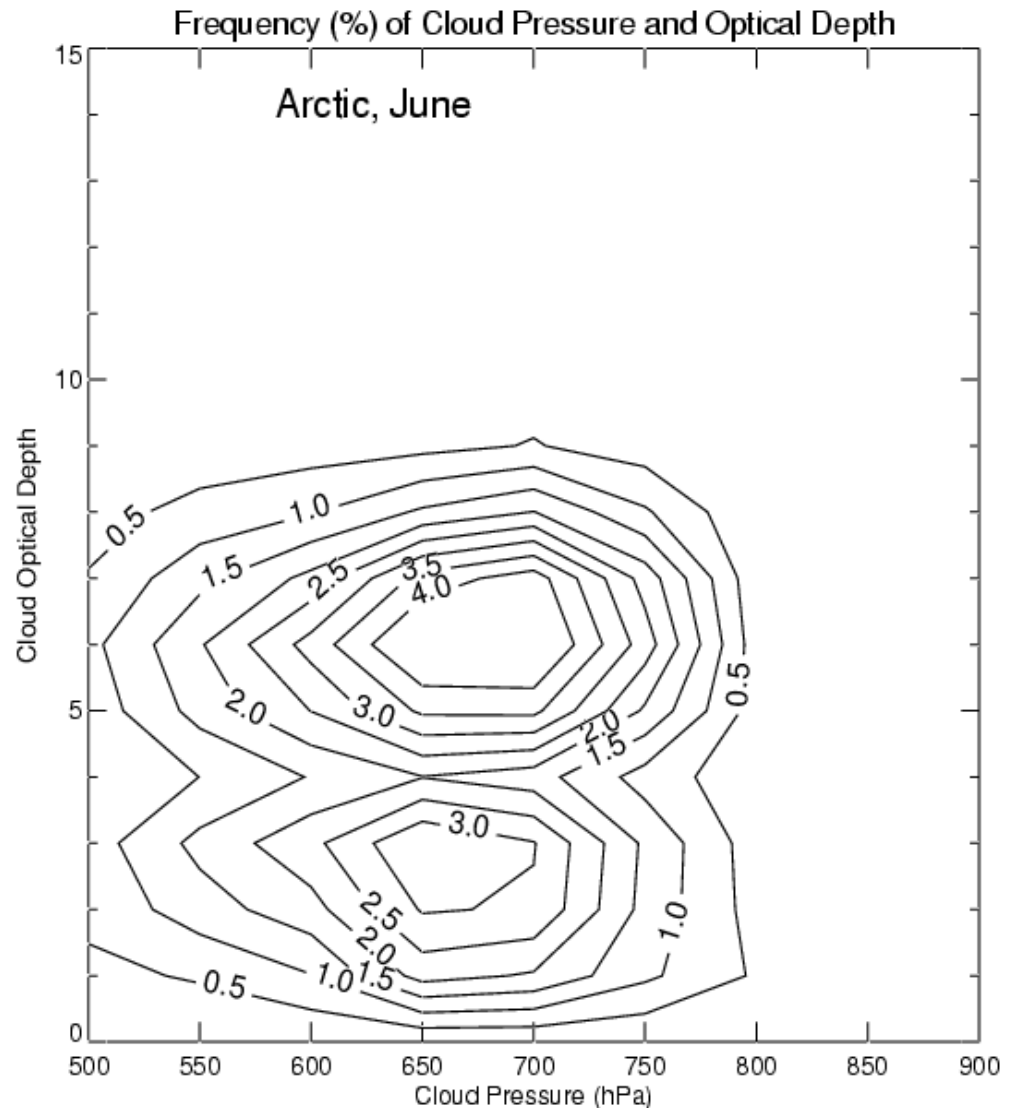
MODIS CO2-Slicing "Failure" Rate in the Polar Regions



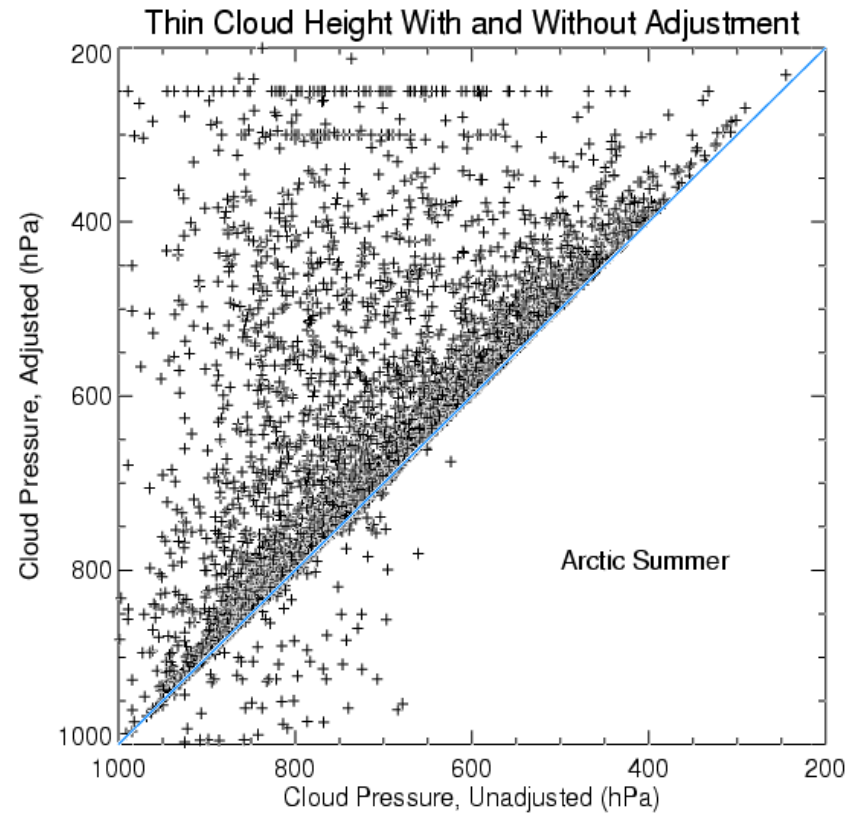
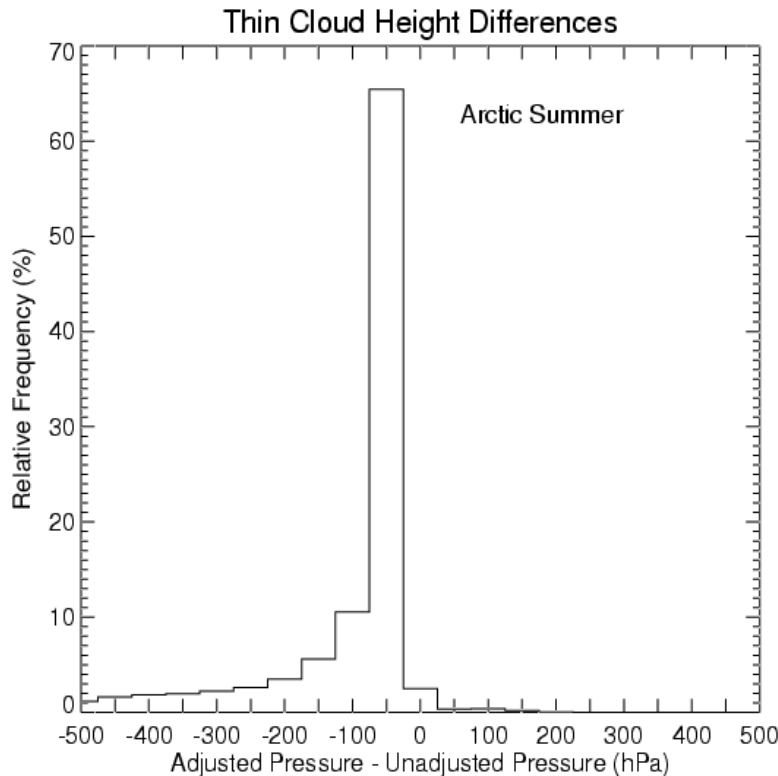
IR Window

Currently, this approach assumes the cloud is opaque so that the IR brightness temperature is also the cloud temperature. Find the temperature in the profile to get the height.

An adjustment for surface emission should be used with thin clouds, which means optical depth must be calculated. The ISCCP and CASPR methods adjust cloud temperature if the IR optical depth is less than 4.6 ($> 1\%$ transmission), which is a larger visible optical depth for water clouds but somewhat smaller for ice clouds.



Converting the cloud temperature to a cloud pressure (lookup in the profile), the adjustment in summer will generally increase the cloud altitude. In winter the direction of change may be mixed due to inversions.



The point-by-point retrievals, with and without the adjustment for optical depth, are shown above for one summer image. Only clouds with visible optical depths less than 5 are shown.

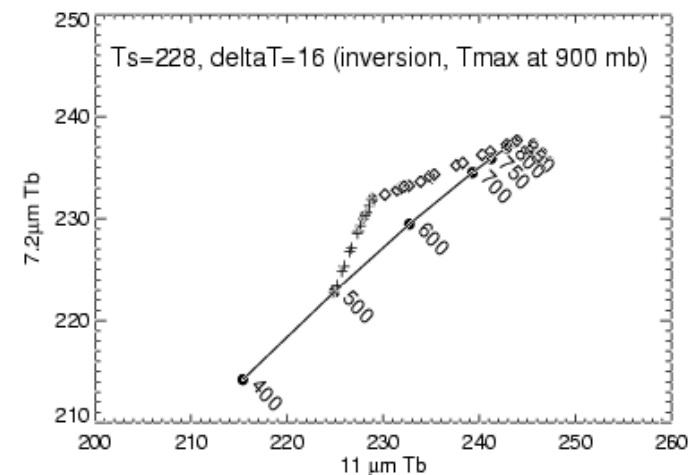
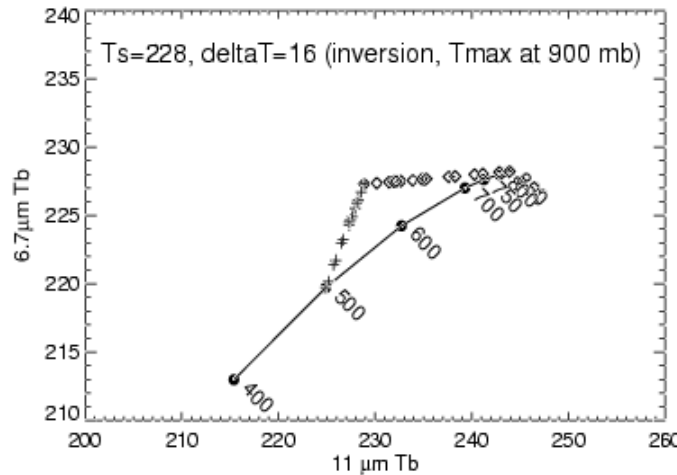
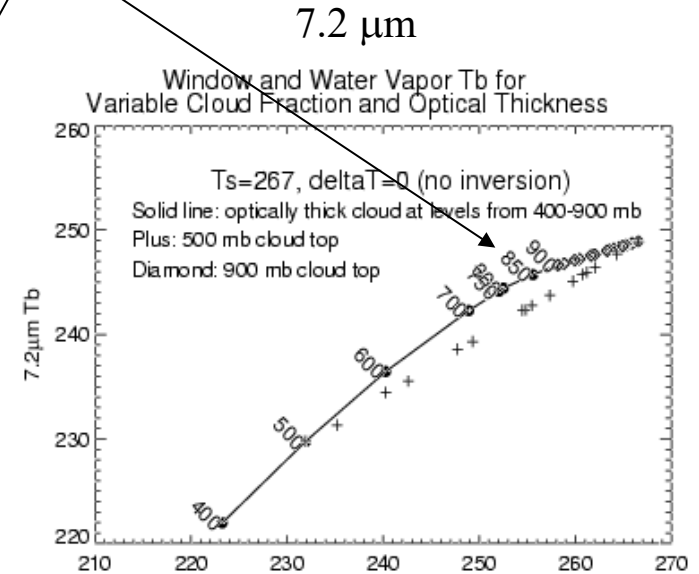
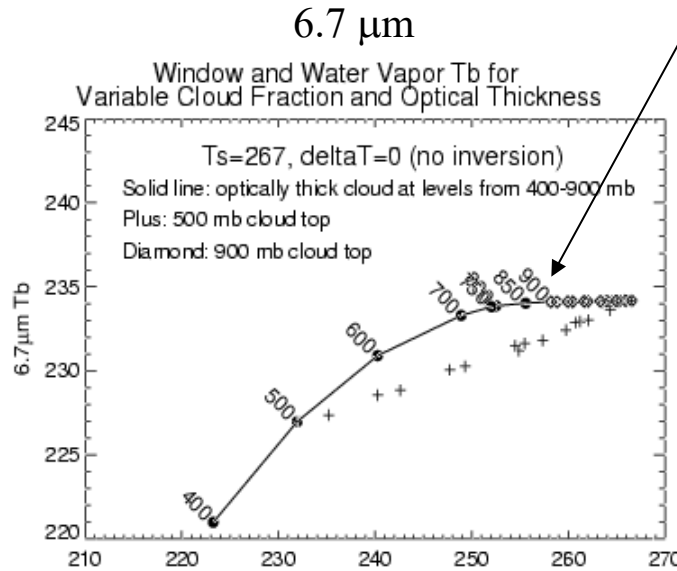
The relative frequency of the pressure differences is shown at left.

H2O-Intercept

Problem: 6.7 μm band is insensitive to low clouds. In theory the 7.2 μm band, which peaks in the lower troposphere, would be better.

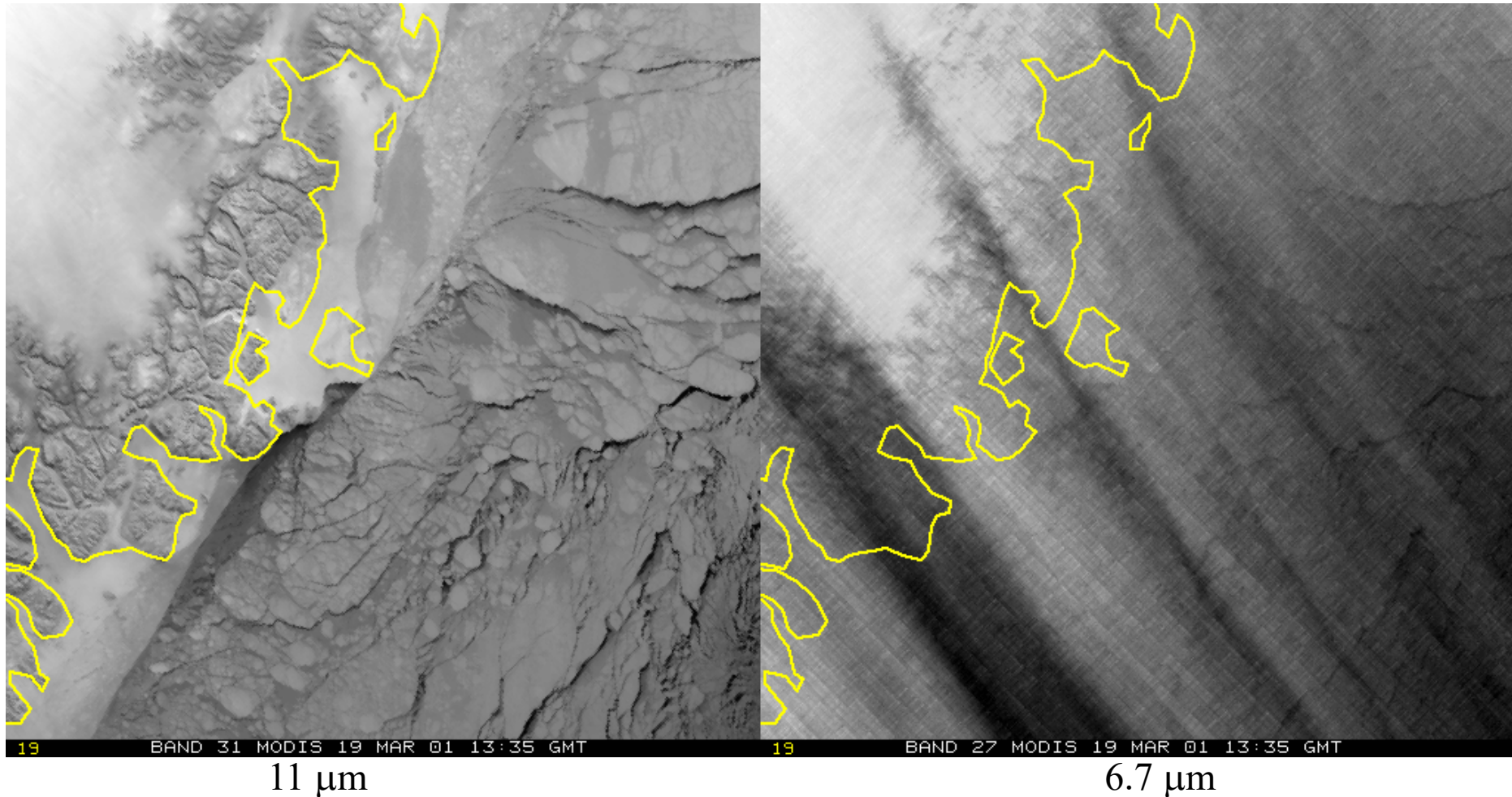
In practice the method is generally not useful for cloud pressures greater than 600 mb for 6.7 μm and 750 hPa for 7.2 μm .

Note slope differences for low clouds

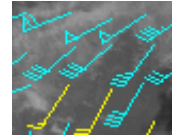


Can the 6.7 μm band see the surface? (cont.)

This is a MODIS image covering part of the Arctic (SE Greenland) on 19 March 2001. Surface features are clearly seen in the IR window band (left), but **are also apparent in the water vapor band (right)**.



The MODIS Winds Product

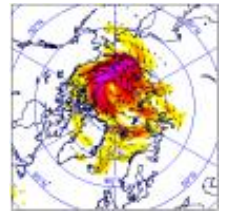


There is an official NOAA/NESDIS operational MODIS polar winds product, but there is no official NASA product, e.g., no MODxx.

The current products are:

1. Near real-time (2-4 hr delay) MODIS winds for the Arctic and Antarctic, distributed by NESDIS and by CIMSS/UWisconsin.
2. Real-time winds from the McMurdo, Antarctica direct broadcast site. Soon to come: Tromsø DB winds!
3. Historical Arctic and Antarctic AVHRR winds, 1981-2002, for use in reanalysis projects.

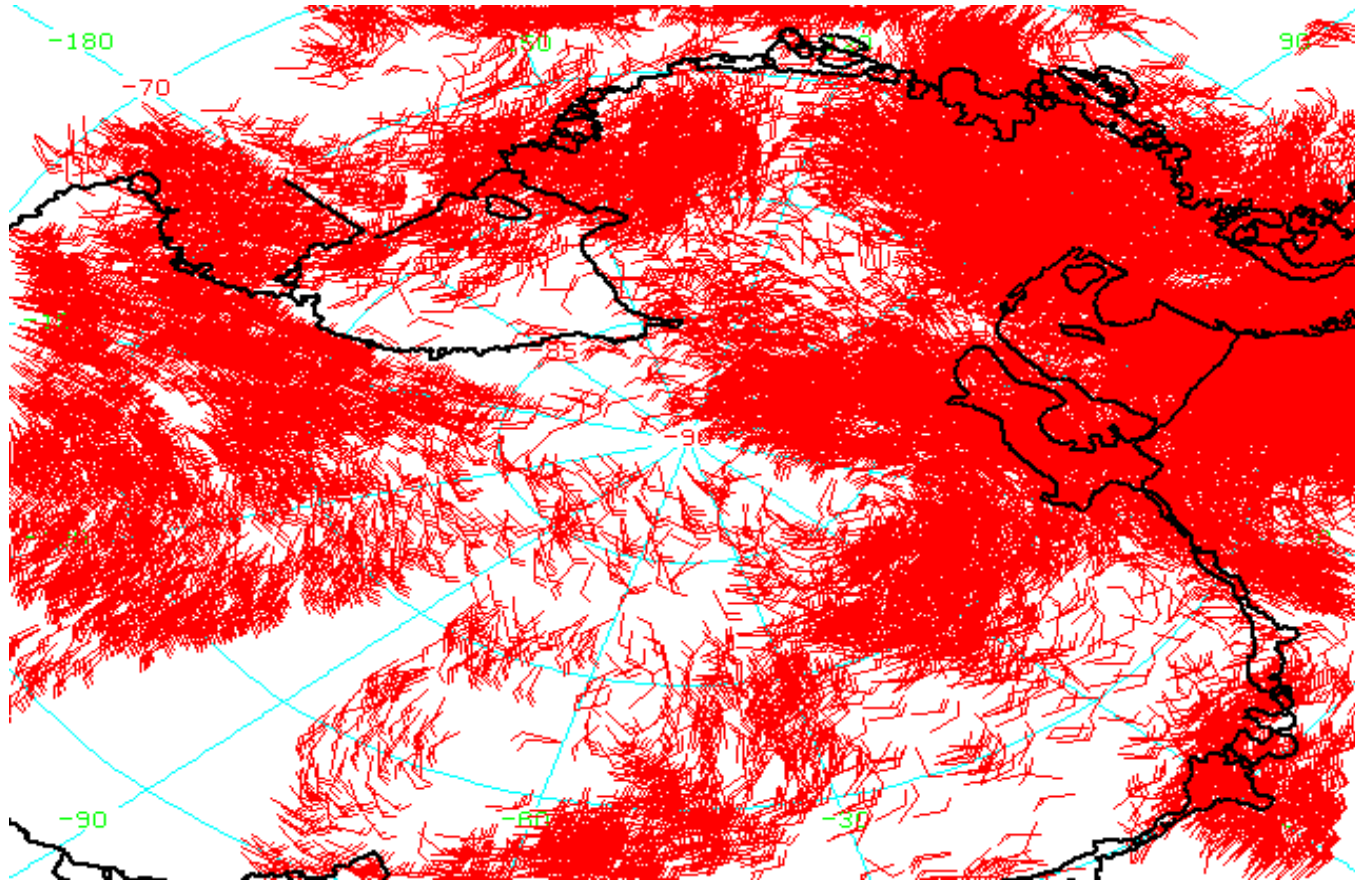
MODIS Winds in NWP



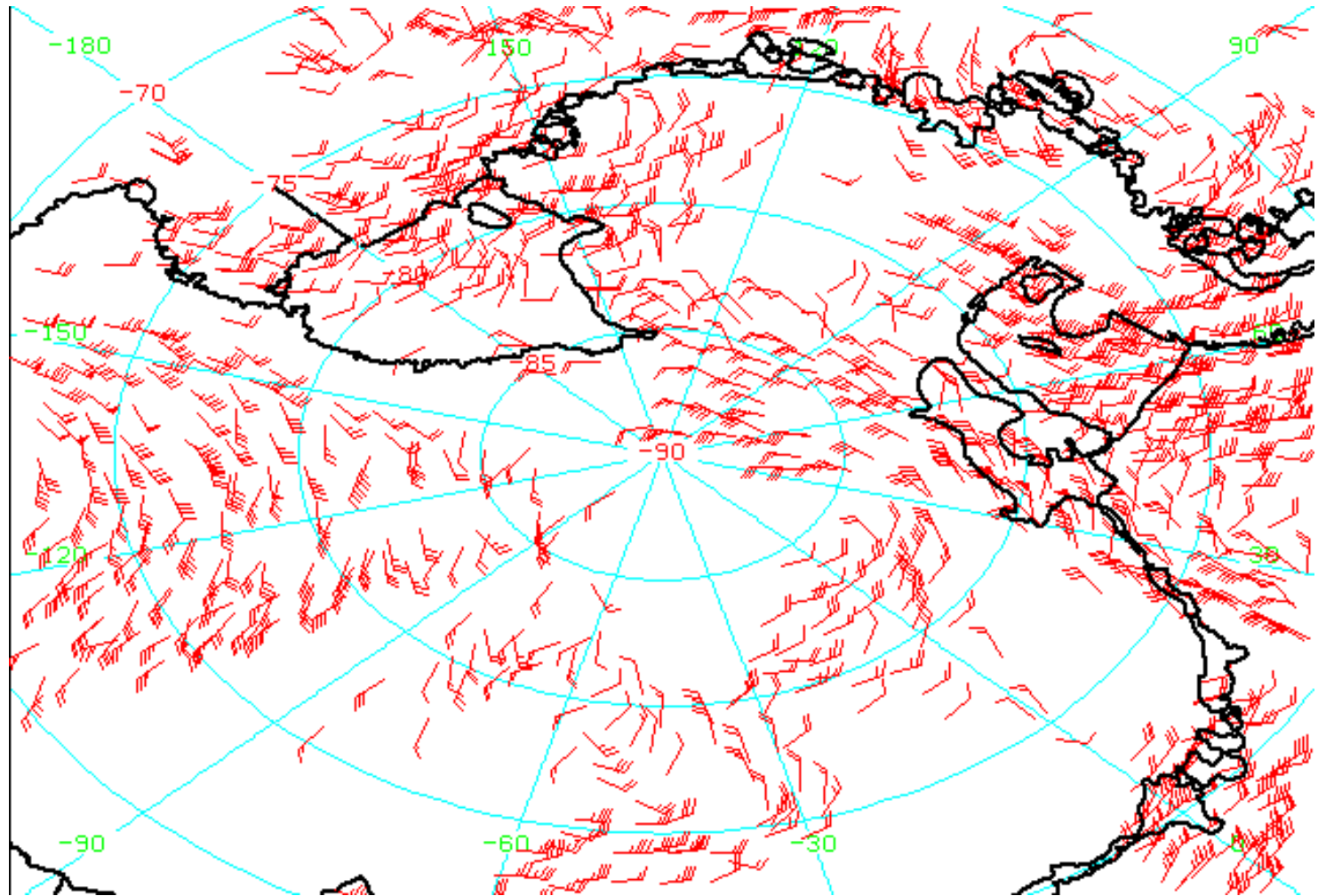
Using Winds in Operational Forecast Systems:

- European Centre for Medium-Range Weather Forecasts (ECMWF)
- NASA Global Modeling and Assimilation Office (GMAO)
- Japan Meteorological Agency (JMA)
- Canadian Meteorological Centre (CMC)
- US Navy, Fleet Numerical Meteorology and Oceanography Center (FNMOC)
- UK Met Office
- National Centers for Environmental Prediction (NCEP/EMC & JCSDA)
- Deutscher Wetterdienst (DWD)
- NCAR Antarctic Mesoscale Model (AMPS)

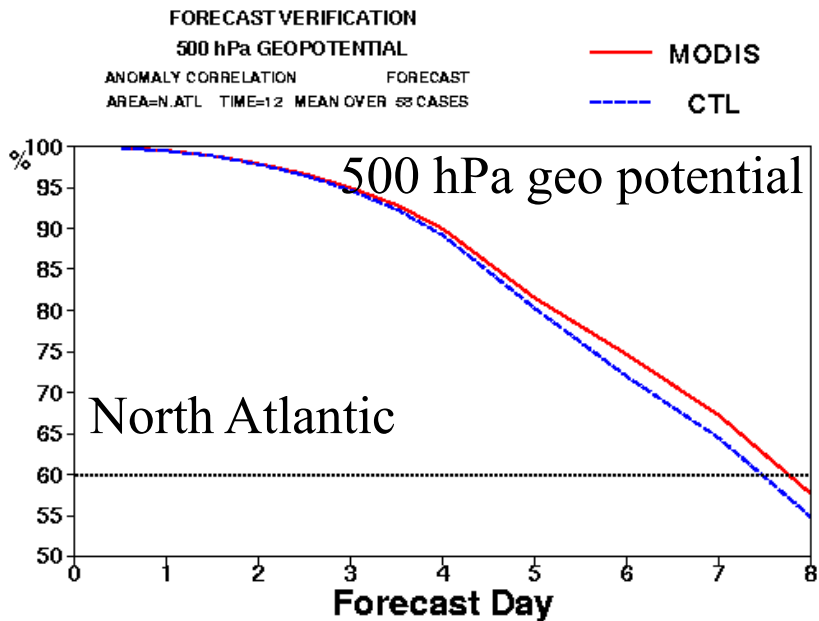
Thinning demonstration:



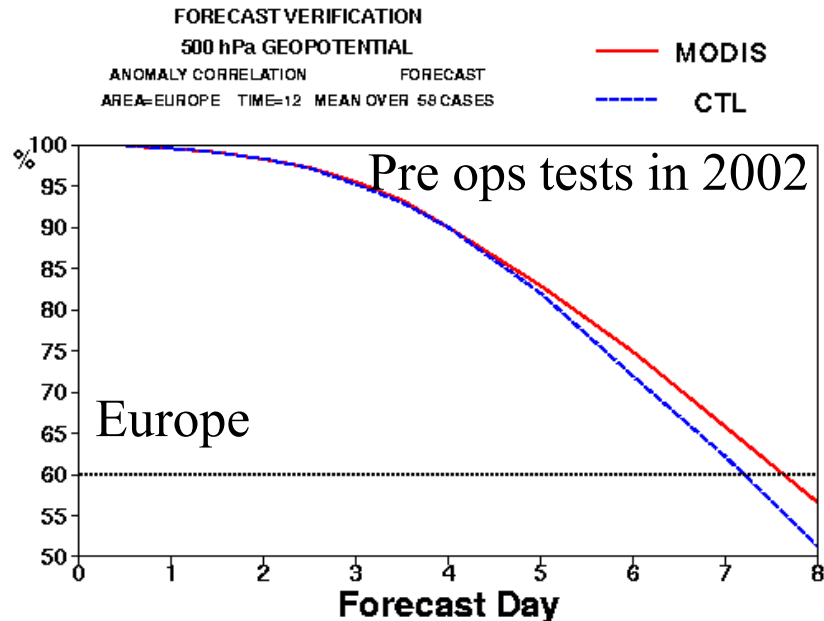
Thinning demonstration:



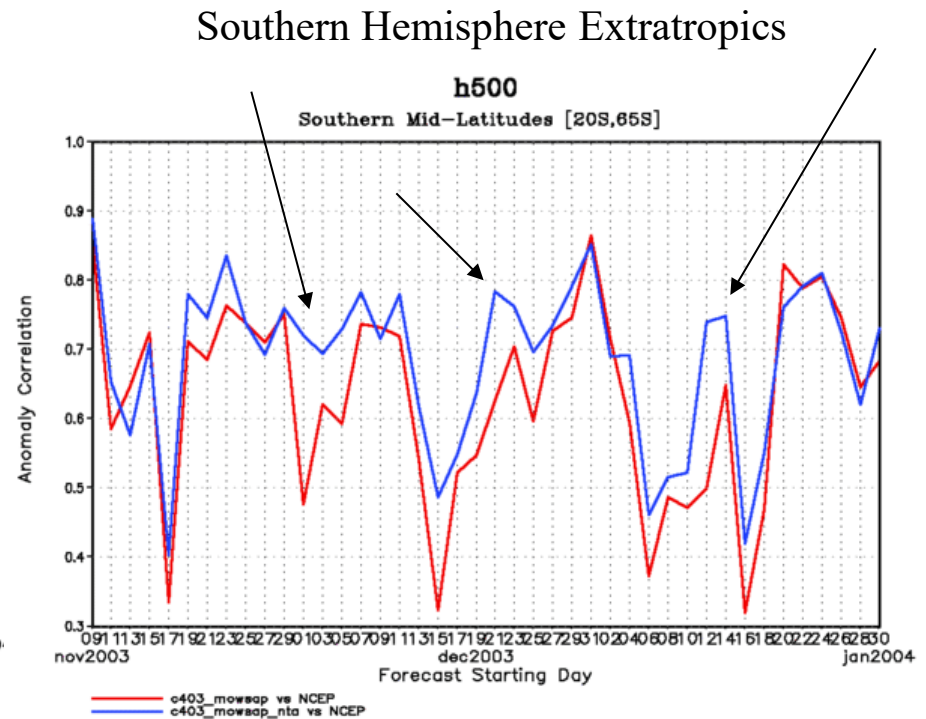
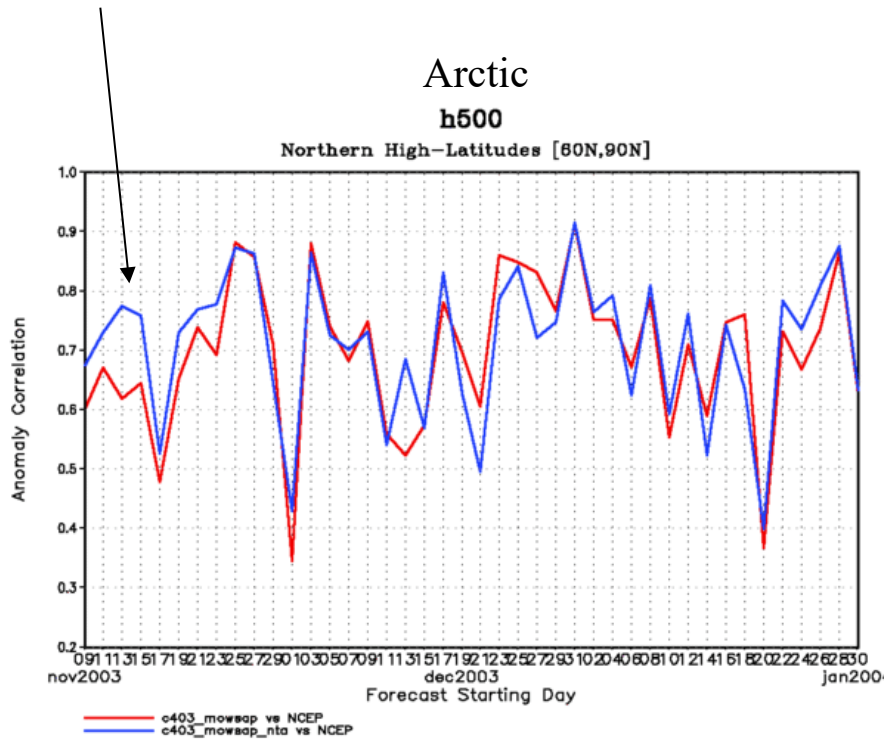
Positive Impact on Weather Forecasts Demonstrated By ECMWF, NASA GMAO, and others



ECMWF
Impacts



Forecast Busts (GMAO)



Blue is forecast with MODIS winds; red is control run

Impact of MODIS Winds in the Tropics and on Hurricane Track Forecasts (JCSDA)

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

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.

MODIS winds filling observing system void

Being used operationally since Jan 2003

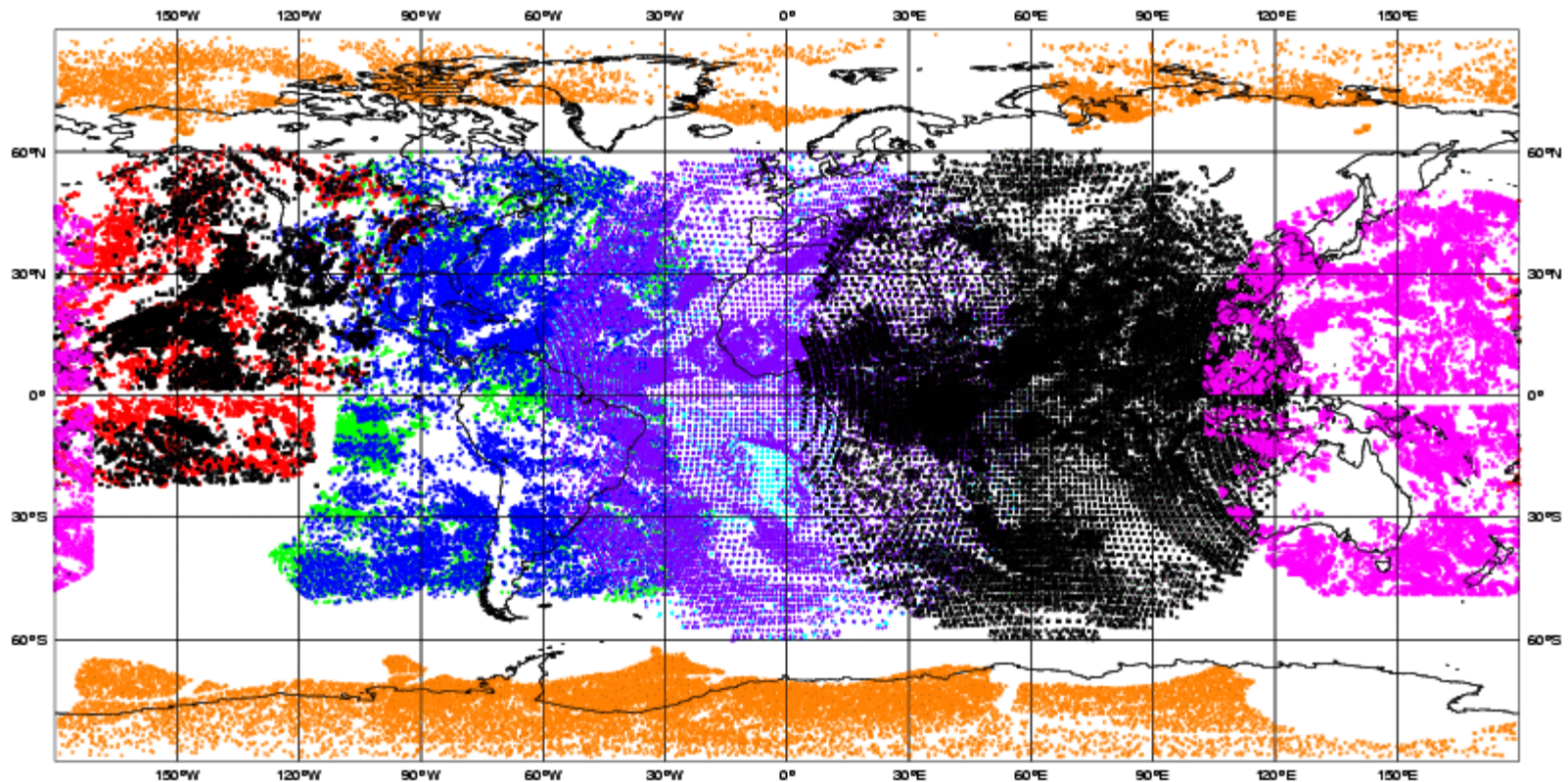
Obs Type

- | | | | | |
|-------------------|-------------------|------------------|------------------|----------------|
| • 14160 GOES12_IR | • 18701 GOES12_WV | • 5825 GOES10_IR | • 5389 GOES10_WV | • 9009 MET7_IR |
| • 23566 MET7_WV | • 0 MET7_VIS | • 36665 MET5 | • 14600 GOES9 | • 19417 MODIS |

ECMWF Data Coverage (All obs) - SATOB

16/JUN/2004; 00 UTC

Total number of obs = 147312



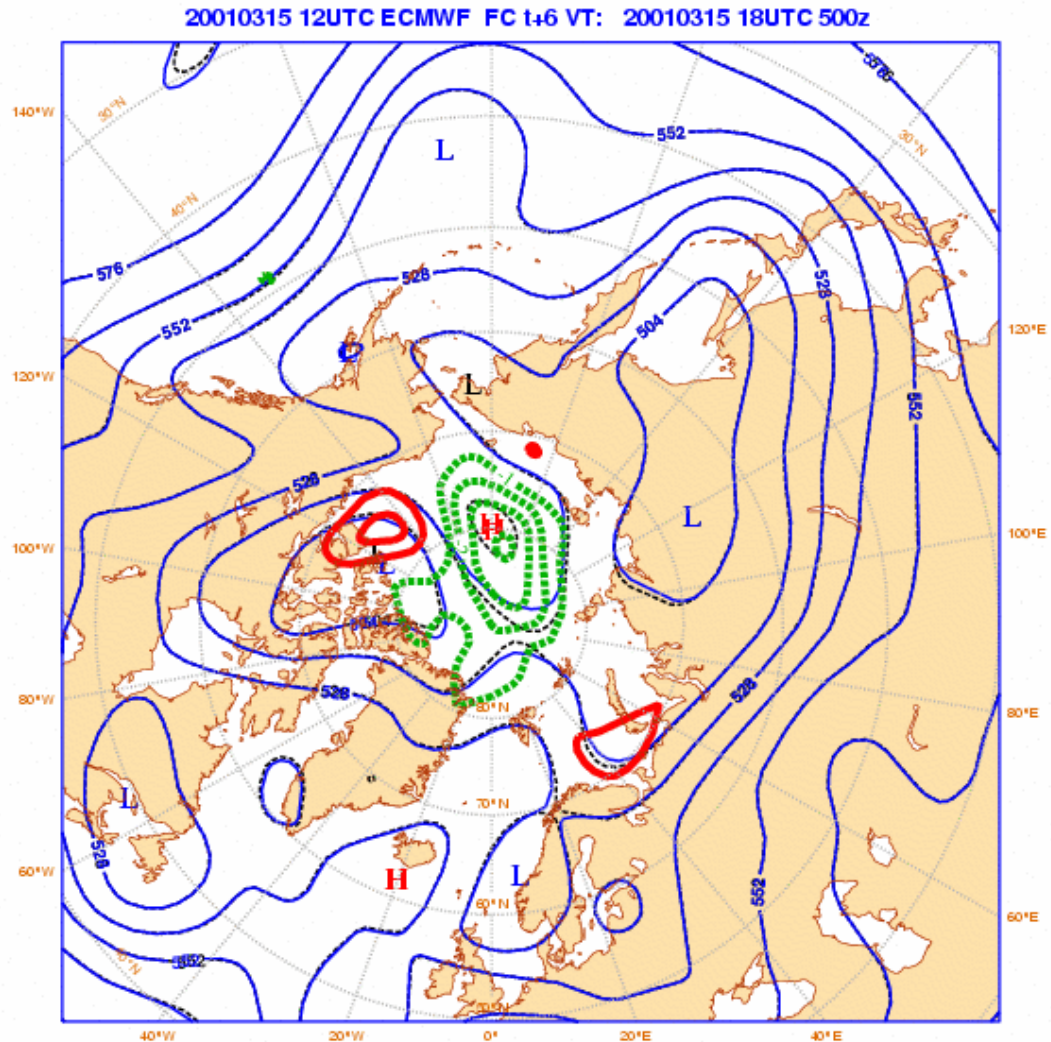
ECMWF: Error Propagation to the Midlatitudes

This animation illustrates the propagation of analysis errors from the poles to the midlatitudes for one case study. Each frame shows the 500 hPa geopotential height for forecasts from 1 to 5 days in 1 day increments. The **solid blue line** is the geopotential from the experiment that included MODIS winds; the **dashed black line** is the control (CTL) experiment without MODIS winds. **Solid red lines** show positive differences in the geopotential height (MODIS minus CTL), and **thick dashed green lines** show negative differences.

The area of large positive differences near the Beaufort Sea (north of Alaska) moves southward over the 5-day period. The CTL run is forming a deeper trough over central Alaska and then over the Pacific south of Alaska than the MODIS run.

The 5-day MODIS forecast verifies better against the subsequent analysis (not shown), so the initial analysis for this MODIS forecast was closer to the “truth” than the CTL (positive impact on forecast). The propagation of differences is therefore also a propagation of analysis errors in the CTL forecast.

Better observations over the poles should improve forecasts in the midlatitudes.

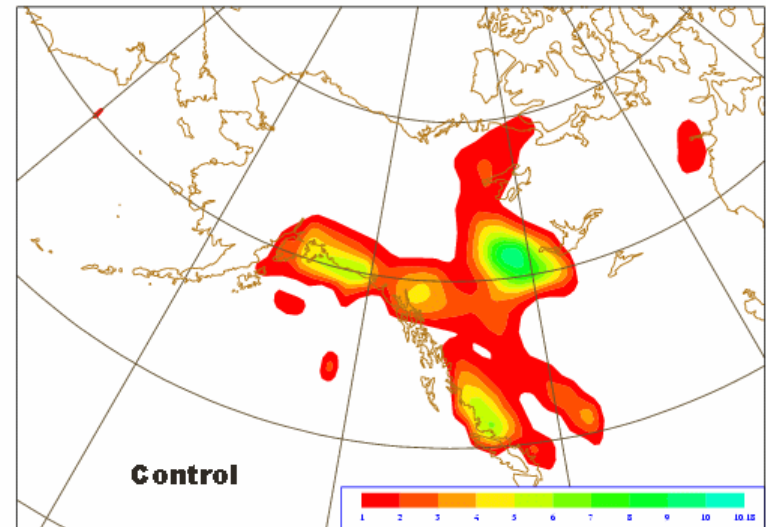


Error Propagation to the Midlatitudes: Snowfall

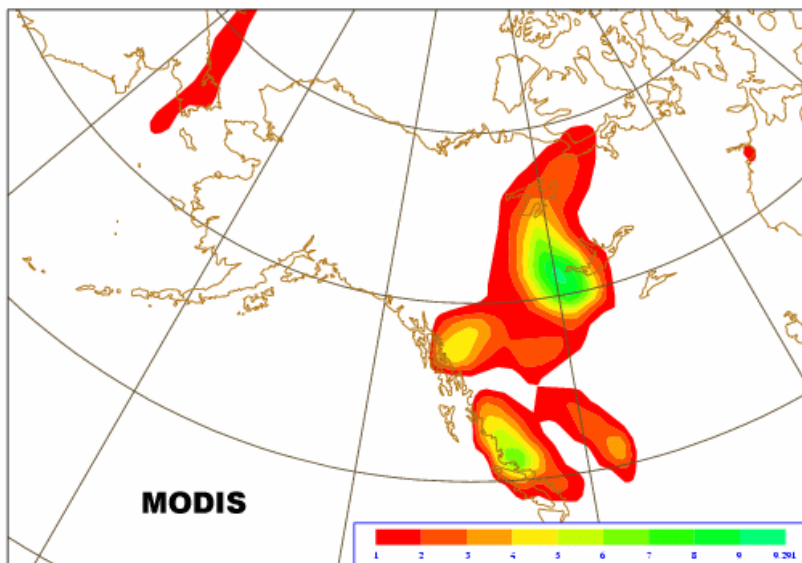
Accumulated snowfall forecasts (mm water equivalent) over Alaska for 20 March 2001.

Inclusion of MODIS winds in the analysis can produce a more accurate forecast. At right is the snowfall from the 5-day Control forecast (no MODIS winds); below left 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”).

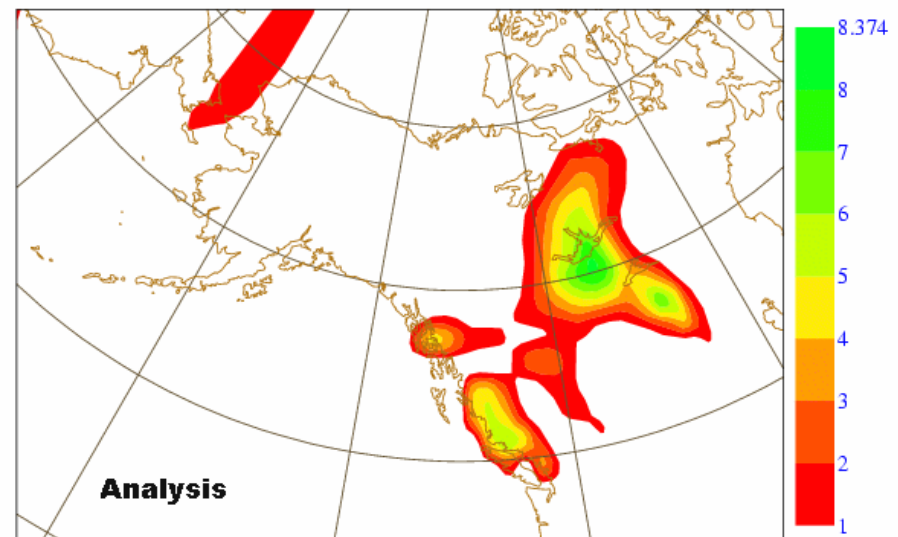
Thursday 15 March 2001 12UTC ECMWF Forecast t+108 VT: Tuesday 20 March 2001 00UTC Surface: **snowfall CTL



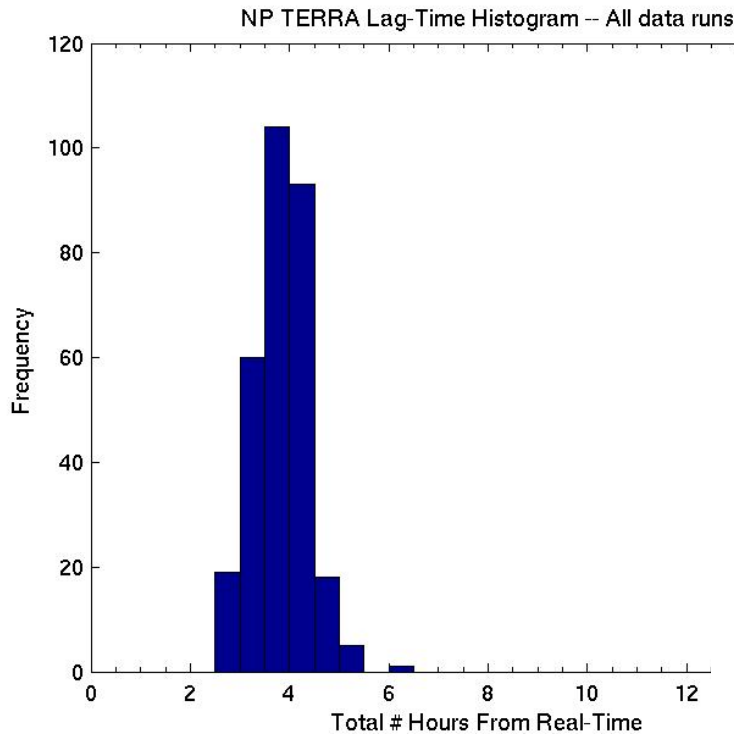
Thursday 15 March 2001 12UTC ECMWF Forecast t+108 VT: Tuesday 20 March 2001 00UTC Surface: **snowfall MODIS



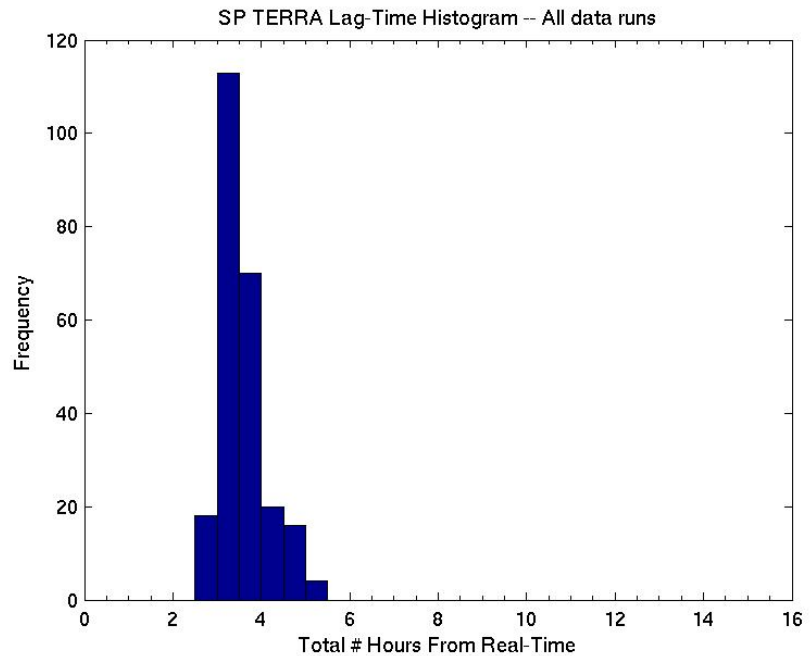
Monday 19 March 2001 12UTC ECMWF Forecast t+12 VT: Tuesday 20 March 2001 00UTC Surface: snowfall "Analysis"

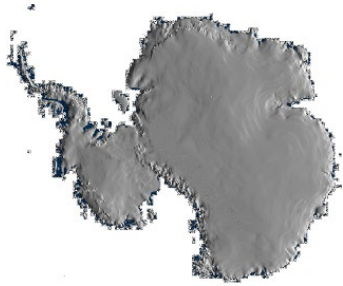


MODIS Polar Winds Real-Time Processing Delays - Frequency of Delays in Wind Retrievals



With an average delay of 3-5 hours, MODIS winds do not meet the 3-hr cutoff for regional/limited area data assimilation systems. Possible solution: Generate winds with direct broadcast data, either on- or off-site.





X-band Satellite System at McMurdo Station, Antarctica

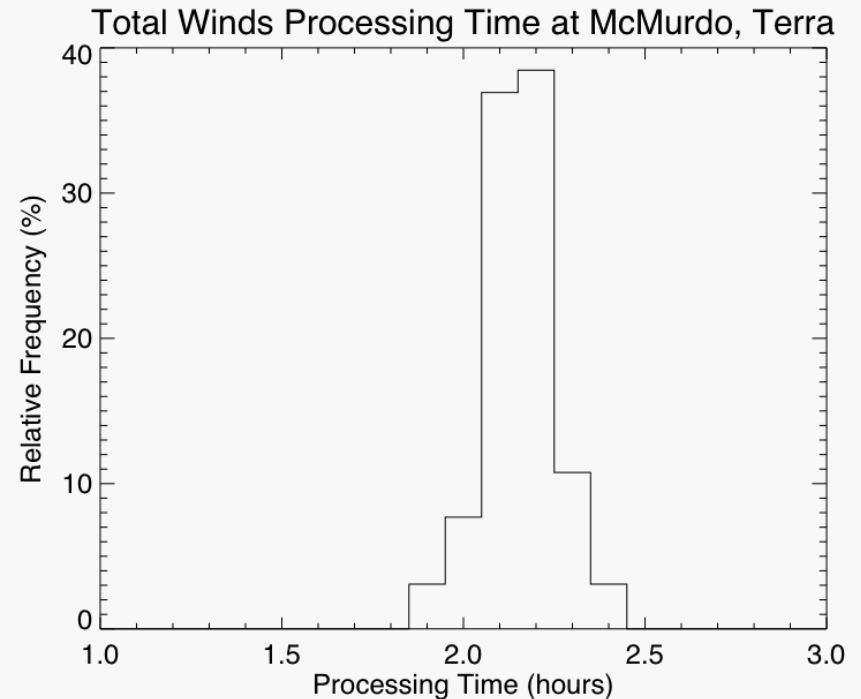
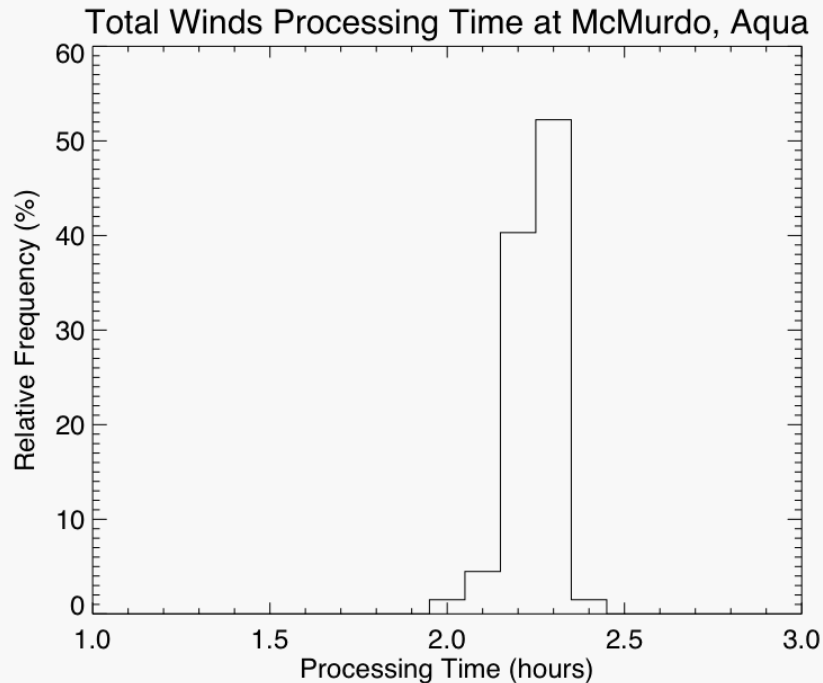
An L/S/X-band ground station was installed at McMurdo station in January 2005.

- The system is a SeaSpace design with a 2.4 meter dish, three computing systems with powerful processing capability.
- McMurdo station now has the capability to capture and process AQUA and TERRA satellite data.
- The system is also one of the first to be able to capture all telemetries available: L-band NOAA, S-band DMSP and X-Band AQUA/TERRA.
- The system supports Antarctic flight and field operations.

(Photographer and date unknown)



MODIS Polar Winds Real-Time Processing Time - Direct Broadcast MODIS Data at McMurdo



Processing times are for the middle image in a 3-orbit triplet. Actually processing time from image acquisition to availability of wind vectors is 100 minutes (1.67 hrs) less than shown. MODIS images are available (image acquisition to level 1b) in 20-30 minutes. Winds processing takes an additional 10-15 minutes.

Current Products at McMurdo

(all MODIS):

Winds

Cloud mask*

Cloud pressure*

Cloud phase*

Total precipitable water*

Inversion strength

Inversion depth

Ice/snow surface temperature

Ice/snow albedo

Planned products:

Ice motion (MODIS + AMSR-E)

Ice age

Cloud optical properties

* *IMAPP/MODIS Science Team products*

<http://stratus.ssec.wisc.edu/db/mcmurdo>

Mozilla Firefox Beta 1

http://stratus.ssec.wisc.edu/cgi-bin/db_main?site=mcm

SSEC webmail Netscape Mail Unisys MeteoStar CIMSS Weather Yahoo News BBC News

http://stratus.s...in?site=mcmurdo

NESDIS/STAR/ASPT Home Products Projects Scenes Links CIMSS

Real-Time MODIS Products from McMurdo

A number of MODIS products are generated on-site at McMurdo, Antarctica, using data from the National Science Foundation's direct broadcast system. Here are the most recent images for each product. **Click on the product links at left for more images of a specific product.** The purpose of this direct broadcast real-time system is two-fold: (1) to generate polar wind and other information more quickly than is done with our current system, so that numerical weather prediction centers can assimilate more polar data in their model runs, and (2) to provide an additional source of information, primarily winds, for weather forecasters in Antarctica.

AQUA:

 Winds Day 269, 12:22 UTC	 Cloud Mask Day 269, 14:01 UTC	 Cloud Pressure Day 269, 14:01 UTC
 Cloud Phase Day 269, 14:01 UTC	 Inversion Strength Day 269, 14:01 UTC	 Inversion Depth Day 269, 14:01 UTC
 Precipitable Water Day 269, 14:01 UTC	 Surface Temperature Day 269, 14:01 UTC	 Surface Albedo Day 269, 14:01 UTC

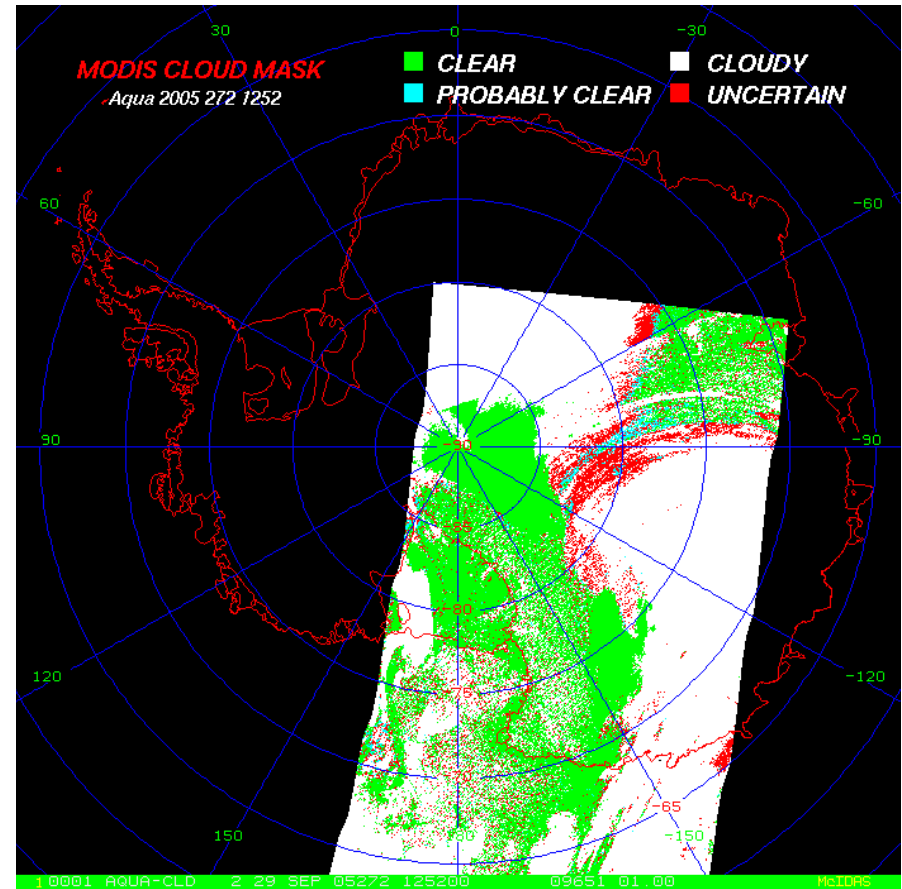
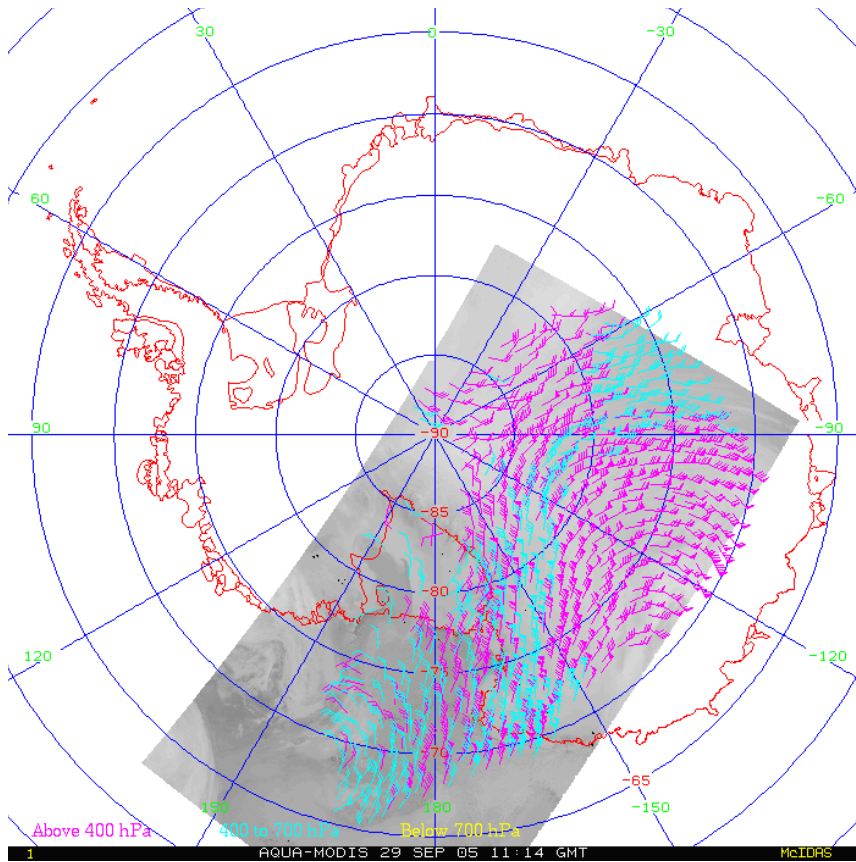
TERRA:

Note: The McMurdo system is currently experiencing a problem with Terra MODIS acquisition.

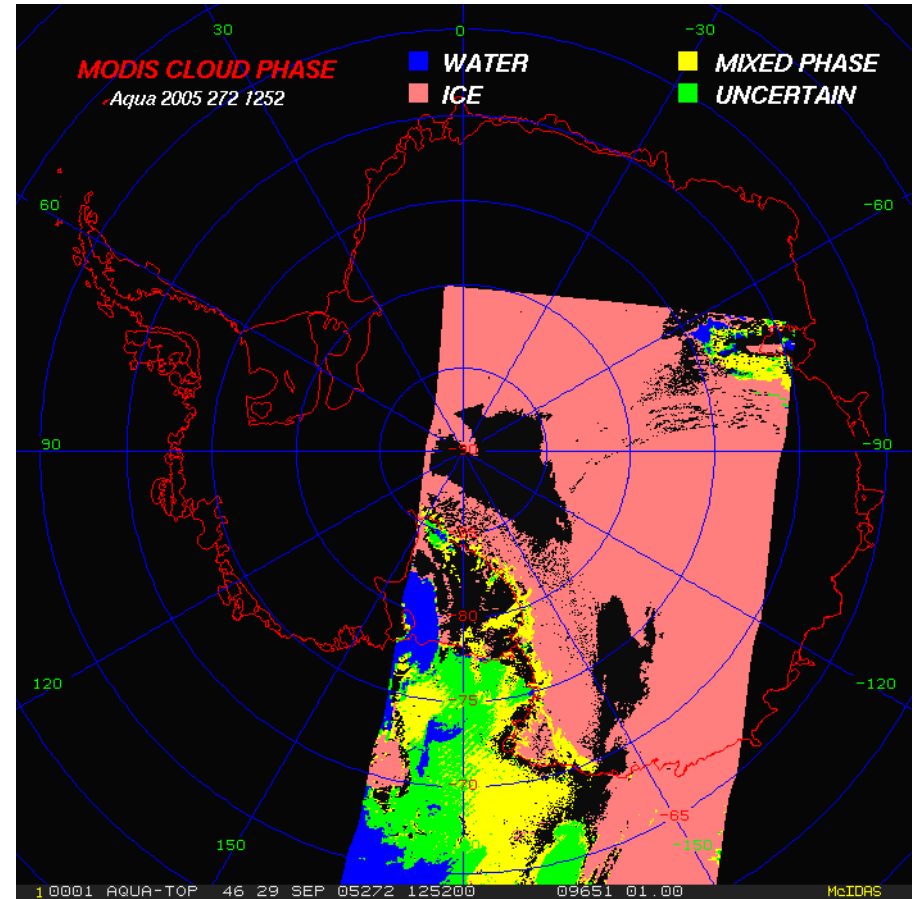
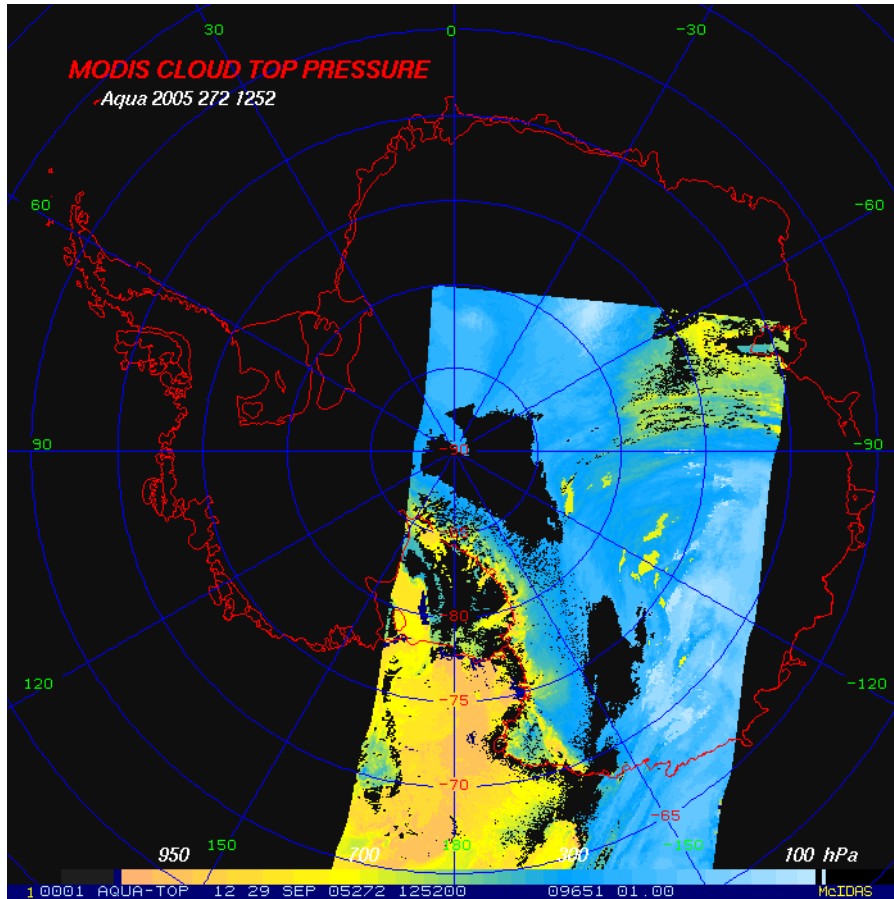
Winds Cloud Mask Cloud Pressure

Done Disabled

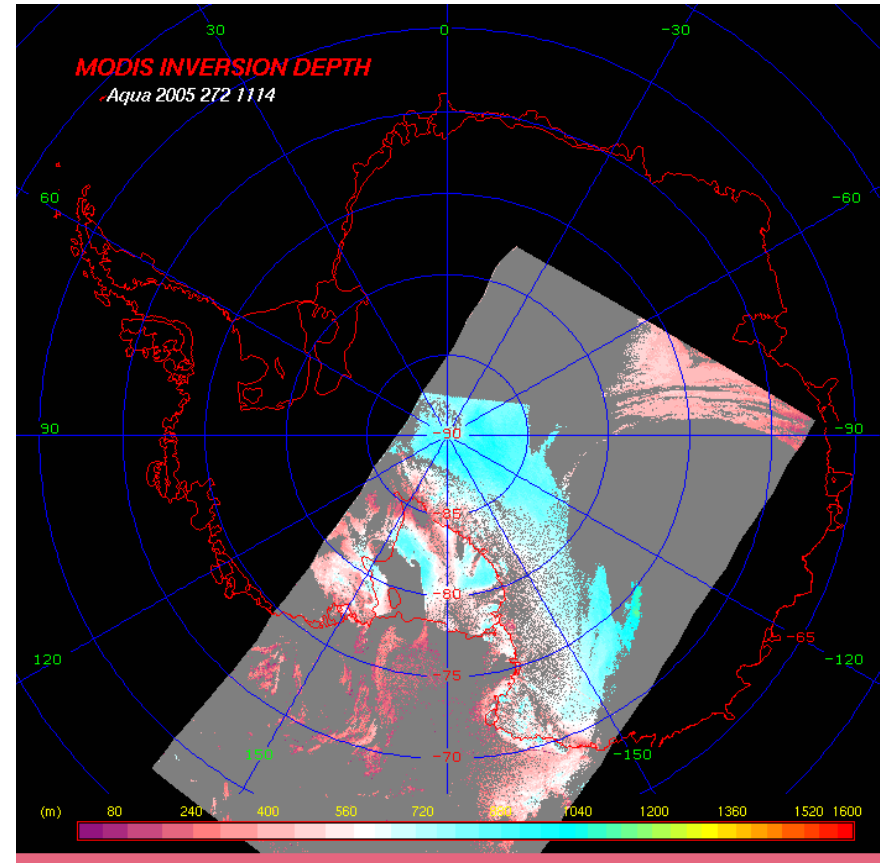
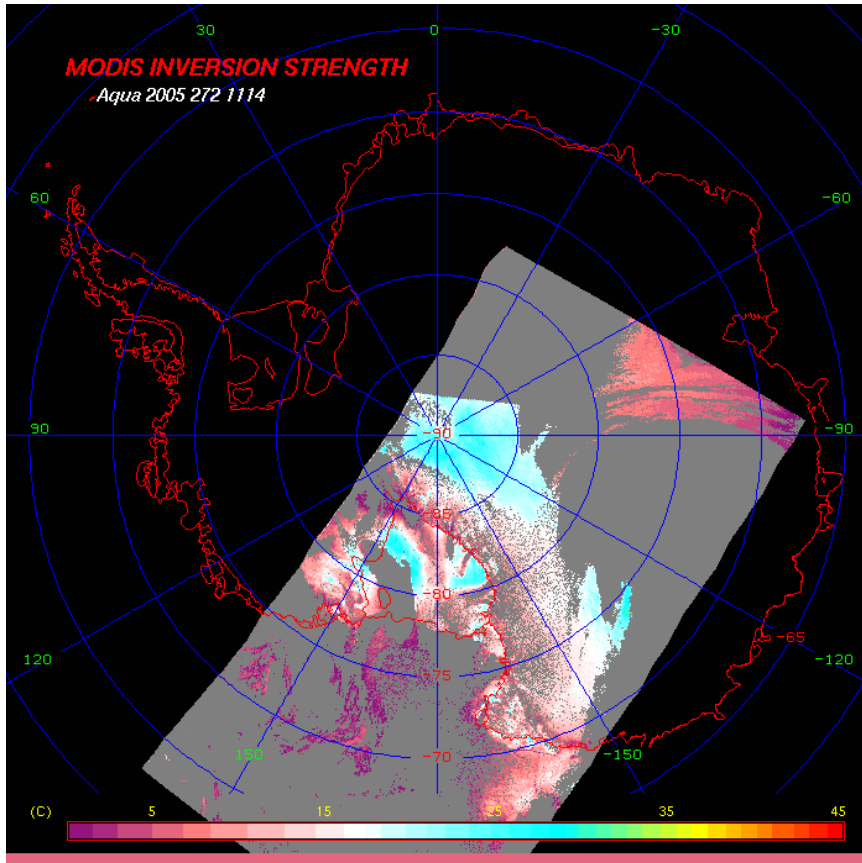
Examples of McMurdo DB MODIS Products



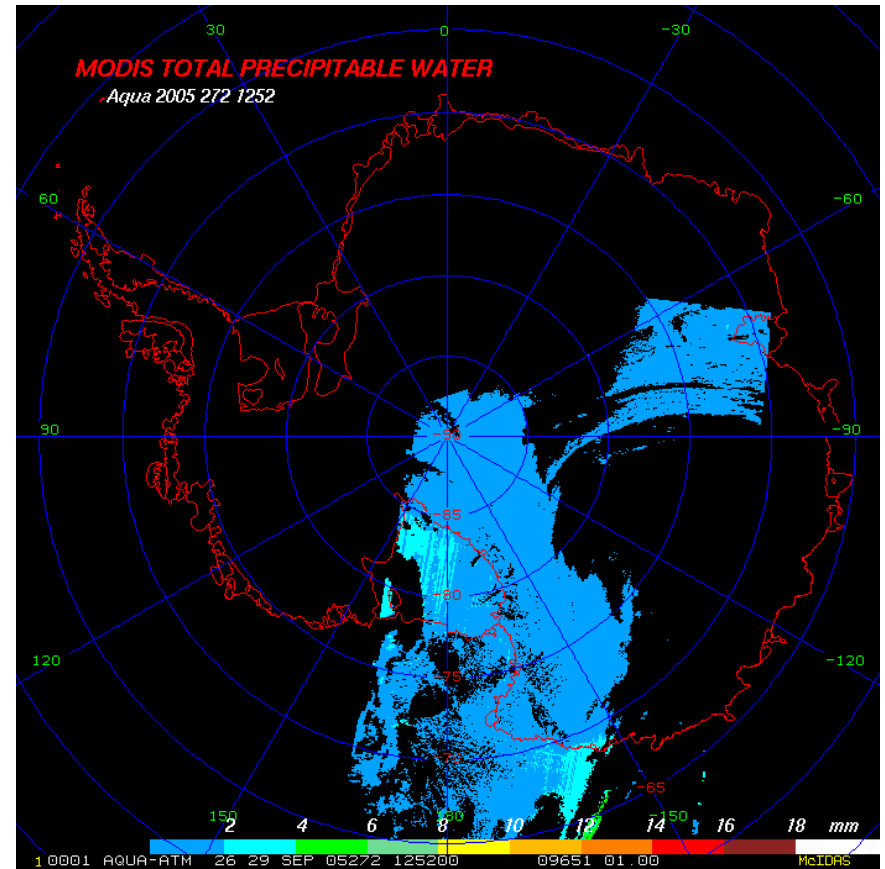
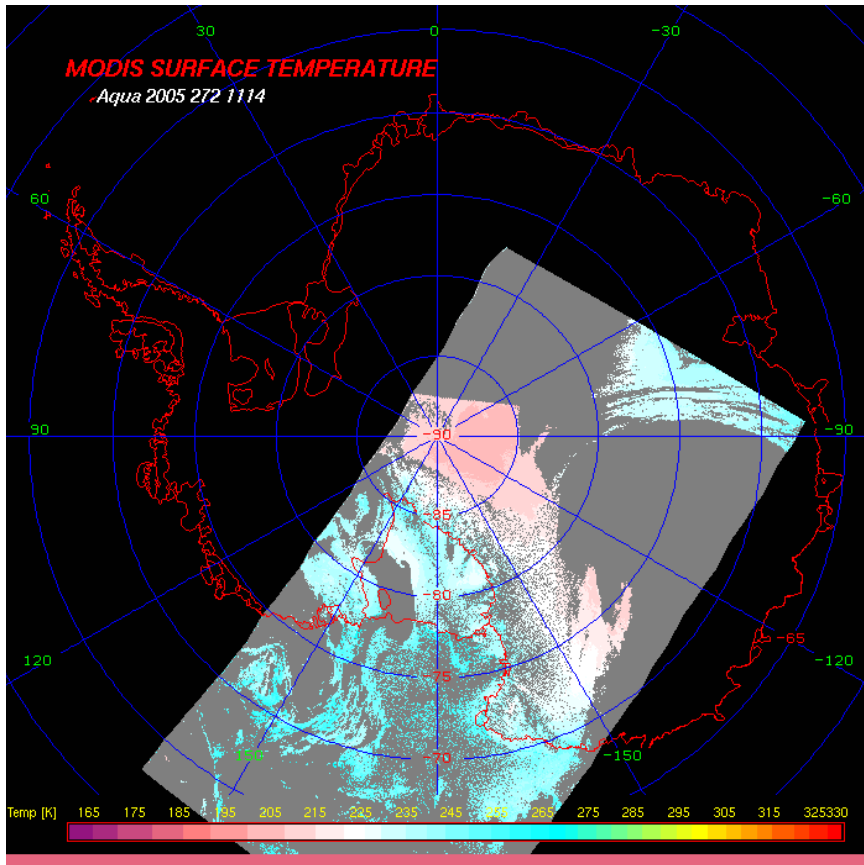
Examples of McMurdo DB MODIS Products



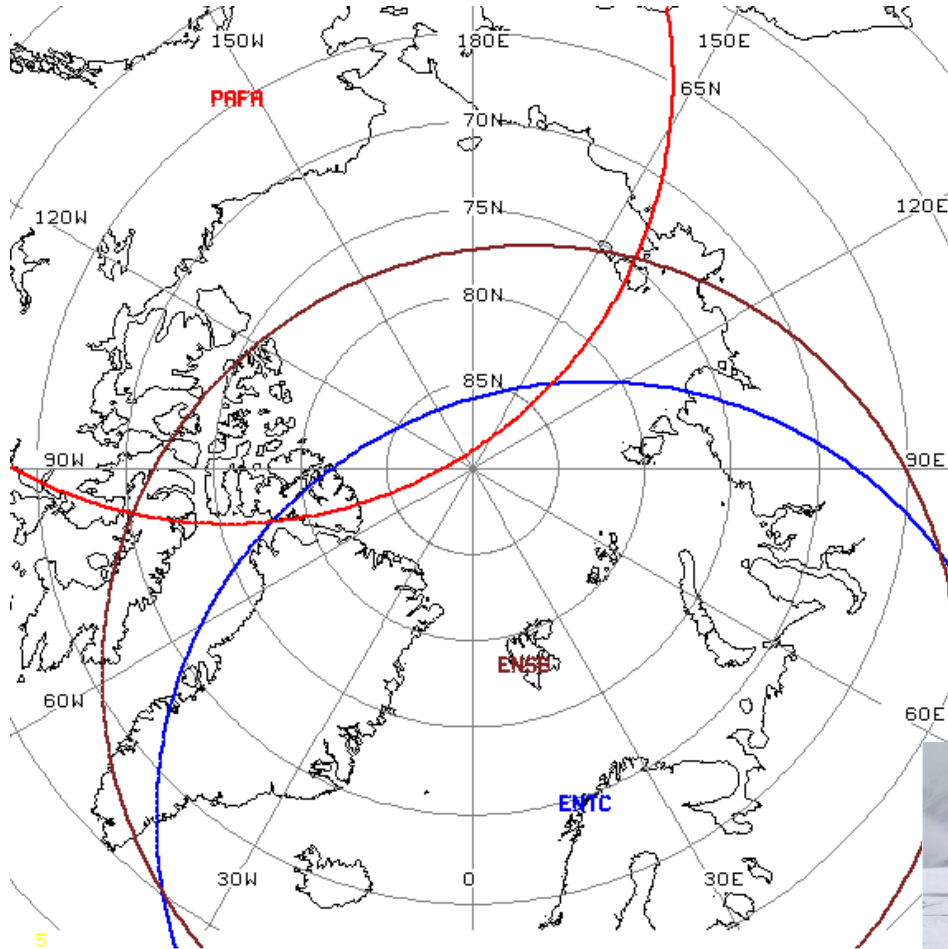
Examples of McMurdo DB MODIS Products



Examples of McMurdo DB MODIS Products



Next Steps: Arctic Direct Broadcast Sites



- Station masks for
- Fairbanks, Alaska
 - Tromsø, Norway
 - Svalbard



Another Potential Antarctic Site: Troll

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Troll (Norway)

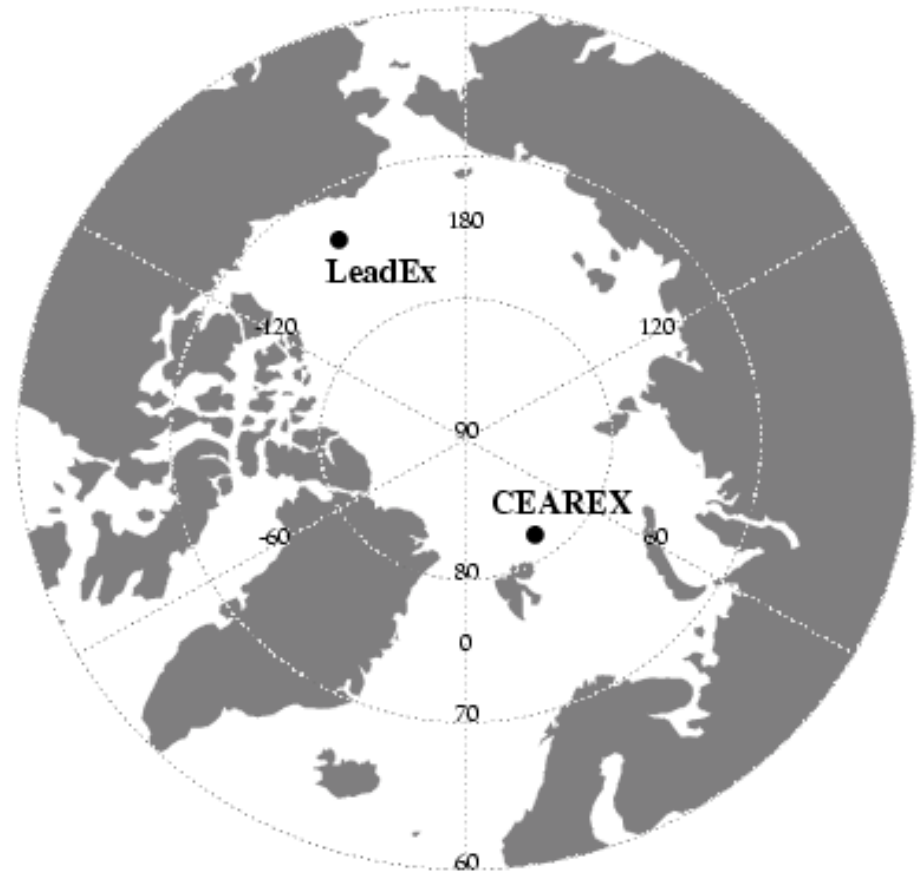


Climate Application: Reanalysis

Model Wind Errors:

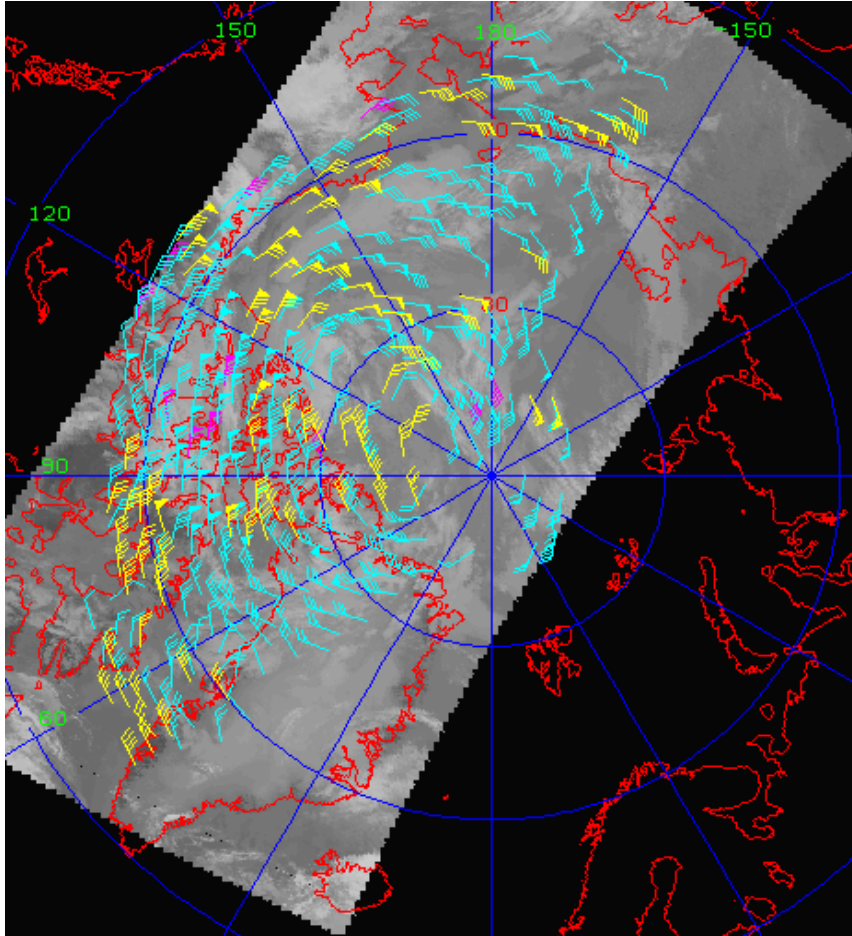
Francis, 2002 (GRL) examined differences between NCEP/NCAR and ECMWF Reanalysis winds and raob winds for raobs that were not assimilated in the reanalysis, from the LeadEx (1992) and CEAREX (1988) experiments.

It was found that both reanalyses exhibit large biases in zonal and meridional wind components, being too westerly and too northerly. Winds are too strong by 25-65%.

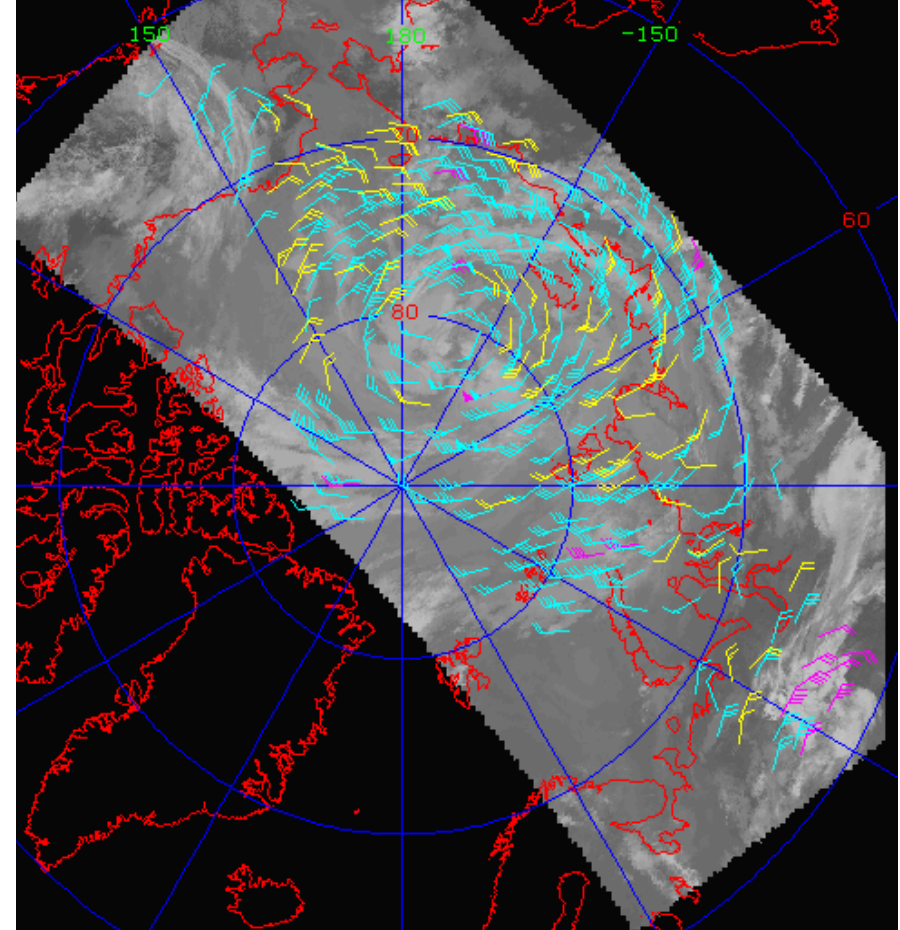


Historical AVHRR Polar Winds Project 1981-2002

Yellow: Below 700 hPa
Light Blue: 400-700 hPa
Magenta: Above 400 hPa



NOAA-11 August 5, 1993 1800 UTC



NOAA-14 August 14, 1995 2300 UTC