

# **“Advances” in Cloud Imager Remote Sensing**

**Andrew Heidinger**

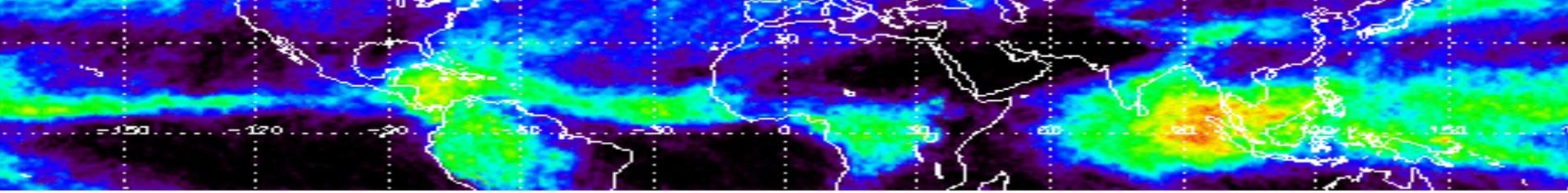
*NOAA/NESDIS/ORR Madison, Wisconsin*

*With material from Mike Pavolonis, Robert Holz, Amato Evan and Fred Nagle*

*STAR Science Symposium November 9, 2007*

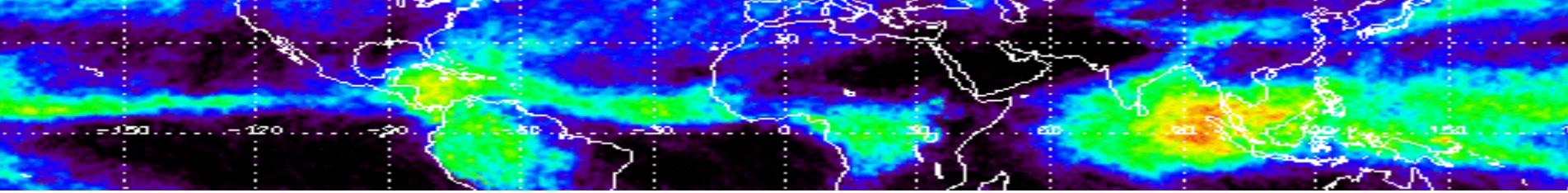
# Goals

- Discuss some of the work we are doing in improving cloud products from imagers. (GOES-R AWG, NPOESS IGS, PSDI, ...).
- Imagers are defined here as the visible/near-infrared/infrared multi-channel satellite instruments such as AVHRR, MODIS, VIIRS, ABI ....
- Highlight our efforts in developing cloud climatologies from imagers.
- Note our future work and the issues we are dealing with.



# Outline

- History of Imager Cloud Remote Sensing in STAR
- Advances in real-time remote sensing
  - Processing Systems
  - Radiative Transfer
  - Use of Spatial Information
  - Consensus approaches for Daytime Cloud Optical / Microphysical Algorithms
  - Improved cloud height from ABI
  - CALIPSO Validation
- Advanced in climate processing
  - Correcting for Orbital Drift
  - Correcting for navigation errors
  - Climate consistency (AVHRR/MODIS)
- Remaining Issues in Cloud Remote Sensing.



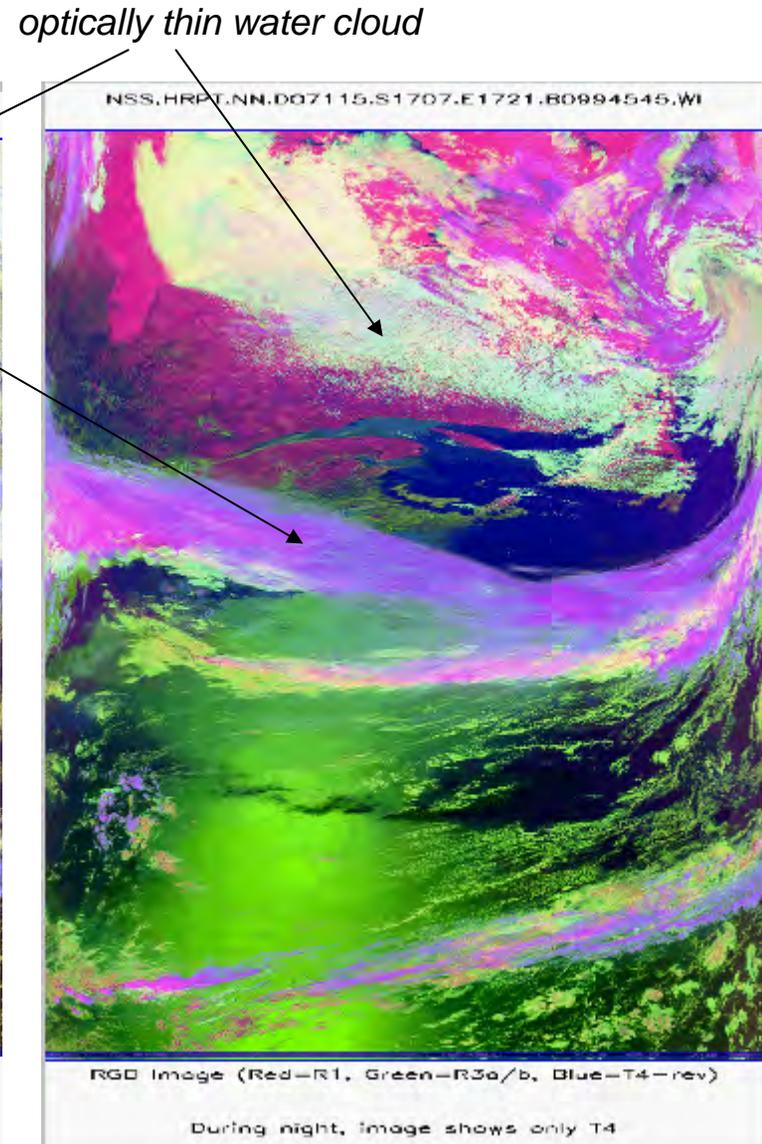
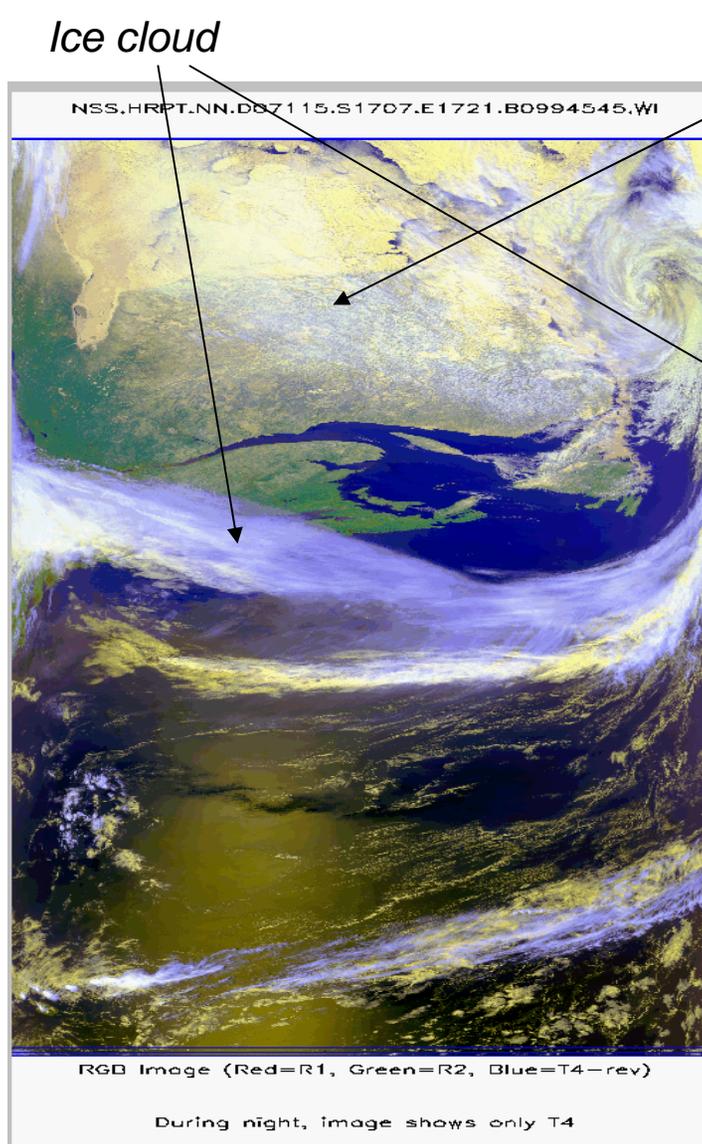
## History of Real-time Imager Cloud Remote Sensing in ORA / STAR

- Larry Stowe led the Clouds from AVHRR project(s) with ORA from 1990 to 2000.
  - CLAVR-1 was a cloud mask.
  - CLAVR-2 consisted of cloud mask and cloud typing algorithm. (Paul Davis)
  - CLAVR-3 provided a dynamic modification of the cloud mask based on clear radiance statistics. (Sastri Vemuri)
  
- Andy Heidinger took over the CLAVR projects after 2000 and merged them into the CLAVR-x project. CLAVR-x generated a full suite of cloud products similar in scope to those produce by MODIS.
  - CLAVR-x cloud mask in the AVHRR preprocessor become operational in 2004.
  - CLAVR-x cloud properties became operational in 2005 and 2007 (METOP).
  
- GOES-NOP saw the development of CO<sub>2</sub> / IR window cloud height algorithm and CSBT
  
- GOES-R cloud application is developing new advanced algorithms for ABI. These improvements are and will continue to impact our operational AVHRR and GOES product systems.
  
- GIMPAP is funding the real-time generation of cloud products from GOES-R algorithms from GOES-NOP.

# A Visual Illustration of an Imager's Cloud ( ie AVHRR) Information Content

From this, we can

1. Detect cloud
2. Determine its top layer type/phase.
3. How optically thick it is.
4. How big its particles are at cloud top.
5. How high it is.



# Processing Systems

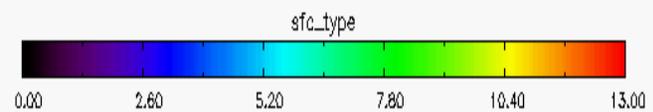
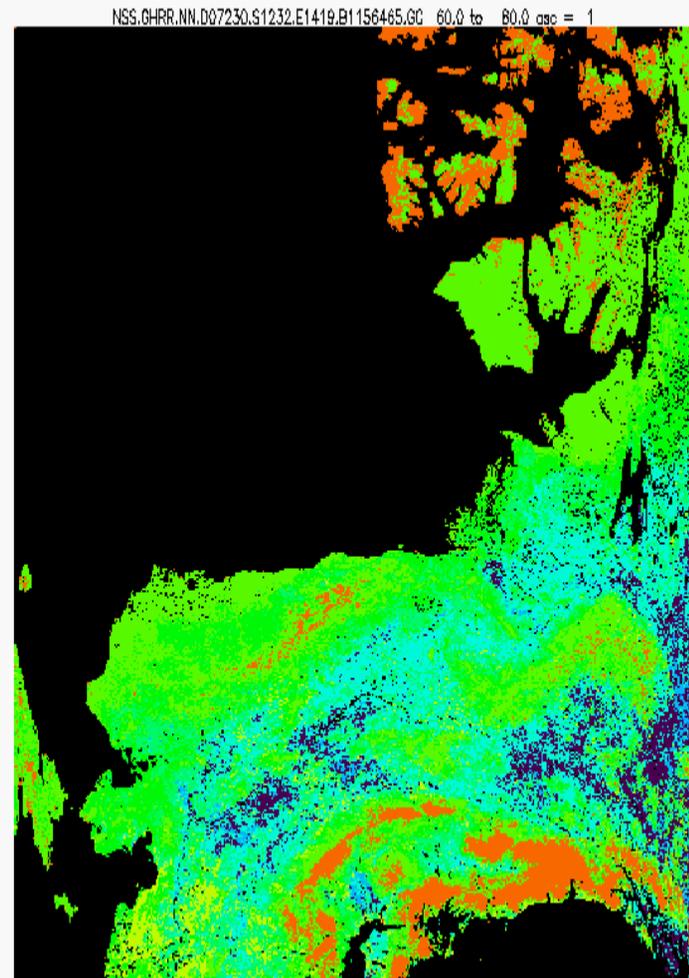
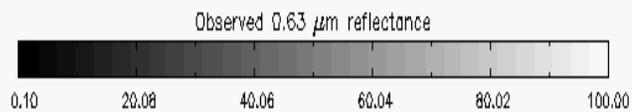
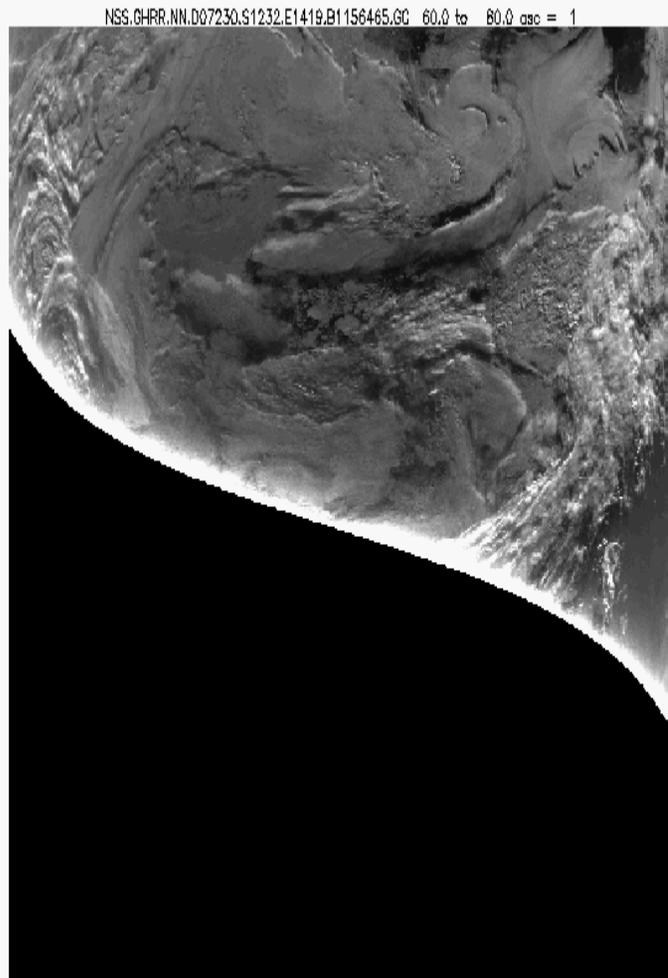
- Cloud retrievals require a lot of ancillary data at high spatial resolution.
- Typically, most algorithms can not be run for a single pixel and require complex processing in the spatial and temporal domains.
- The STAR cloud retrievals have benefited from advanced processing systems.
  - **CLAVR-x** clouds from AVHRR extended - AVHRR only. Provides uniform processing of NWP and RT output to all algorithms through global structures.
  - **GEOCAT\*** Geostationary Cloud Algorithm Test-bed : Processes SEVIRI, GOES-IM, GOES-NOP and MTSAT. Includes all and more RT and NWP capabilities in CLAVR-x and provides a user friendly interface to swap algorithms in and out (including multiple versions of the same algorithm).
  - **LEOCAT\*** - Low Earth Orbiting Cloud Algorithm Test-bed. Similar functionality to GEOCAT but designed for MODIS. Developed under a IPO IGS project.

# Advances in Radiative Transfer

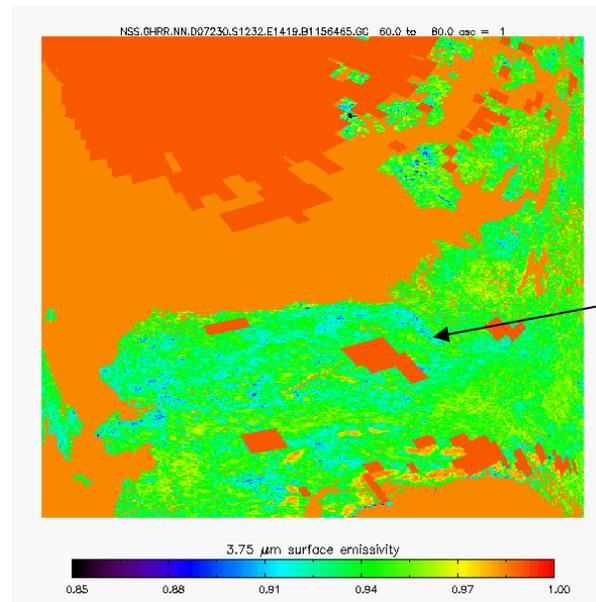
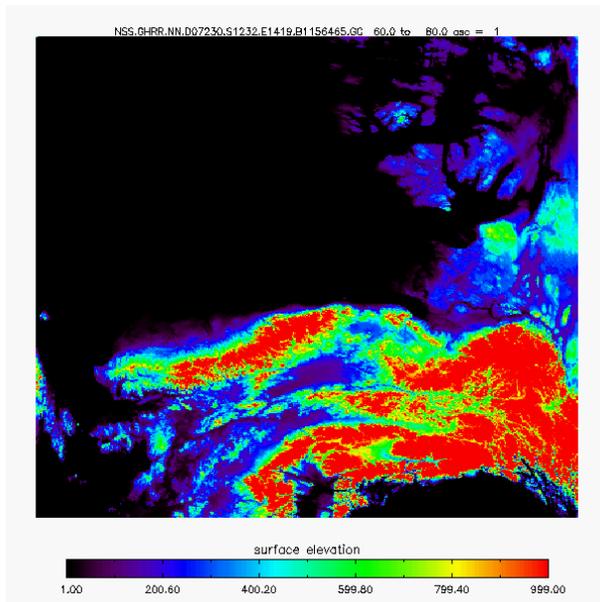
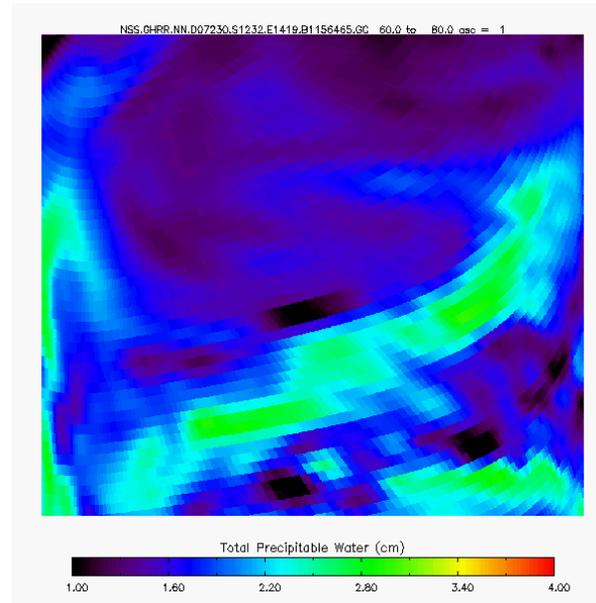
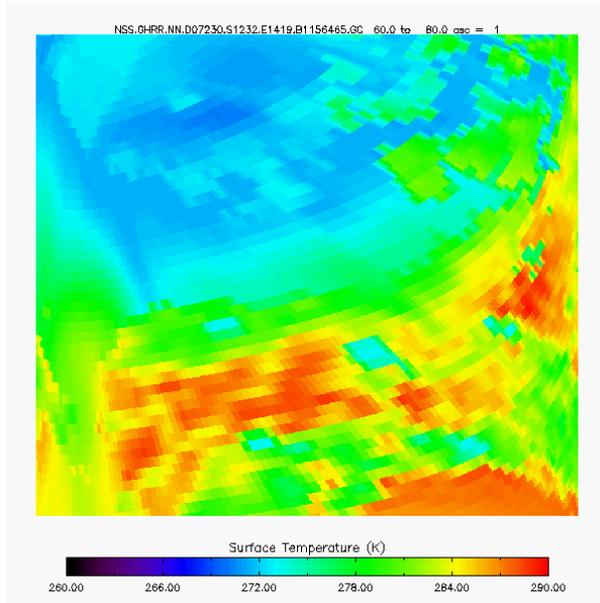
- The cloud algorithms we employ are one dimensional variational retrievals (1DVAR) and require accurate forward models.
- CLAVR employed no radiative transfer models
- For infrared retrievals, ability to model clear-sky radiative transfer is critical. This has been facilitated by the existence of
  - fast clear-sky models (ie CRTM, PFAST)
  - surface emissivity data bases / models from MODIS/AIRS
  - Improving NWP data
- While use of NWP data does build in a reliance, we can't interpret window channel observations fully without knowledge of the clear-sky observations.
- Errors in surface temperatures over land is the major limitation in our use of radiative transfer models.
- In summary, advances in imager cloud remote sensing are absolutely linked to radiative transfer.

# Example Scene to Illustrate the Use of Fast RT models in CLAVR-x

*Alaska in August at sunrise.*

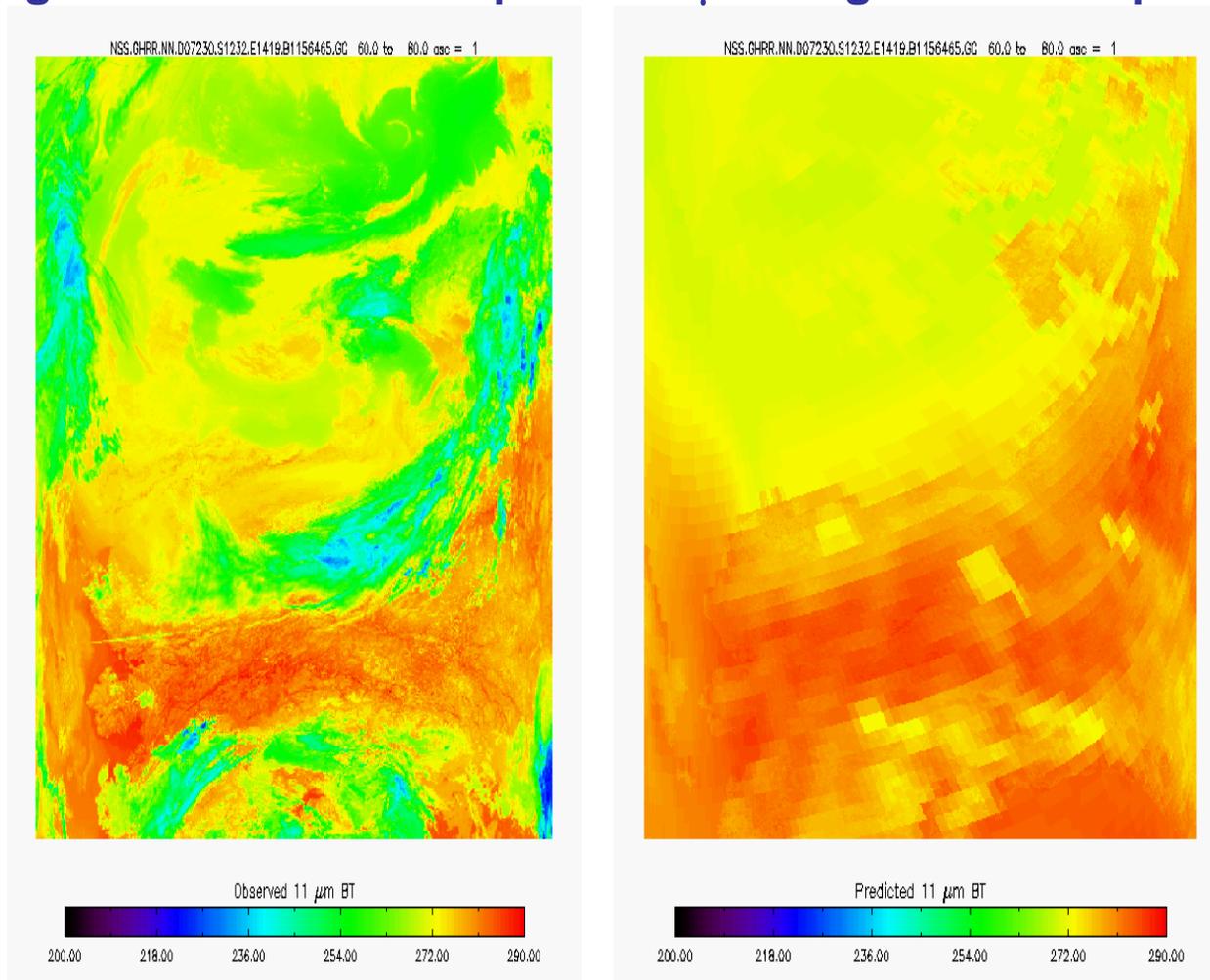


# Some of the fields used to drive the Radiative Transfer Model



*Calculations done at the resolution of the NWP fields - not for each pixel*

# Comparing Observed and Computed 11 $\mu\text{m}$ Brightness Temperature



With NWP and RT, very difficult to use 11  $\mu\text{m}$  channel in polar regions

This method avoids empirical adjustments for angular and water vapor effects.

# Advances in Using Spatial Information

- Computational speeds now allow rapid generation of spatial statistics for each pixel.
- Median filters to reduce noise in observations and products.
- Gradient filters to look for opaque regions of cloud fields to constrain performance of algorithms near cloud edges.
- Generation of local maxima in brightness temperature to serve as tighter thresholds on cloud detection without any assumption of the actual surface temperature.

## Consensus Daytime Optical Depth and Particle Size Retrievals

- Method to estimate optical depth and particle size from visible and near-infrared solar reflectance is well established but ...
  - No consensus on the optimal dimensions of lookup tables. (Fast forward models are still under development for cloudy conditions). One of the GOES-R cloud team's goals is to develop community consensus tables.
  - There is very little consensus on ice cloud scattering models. Large differences in optical thickness and particle size arise from different assumptions on particle shape and habit.
  - Lastly, models are needed that provide spectral consistency. Without spectral consistency we can't utilize vis/nir/ir channels simultaneously.

Example variation in the dimensions of the reflectance lookup tables used by several groups doing SEVIRI processing.

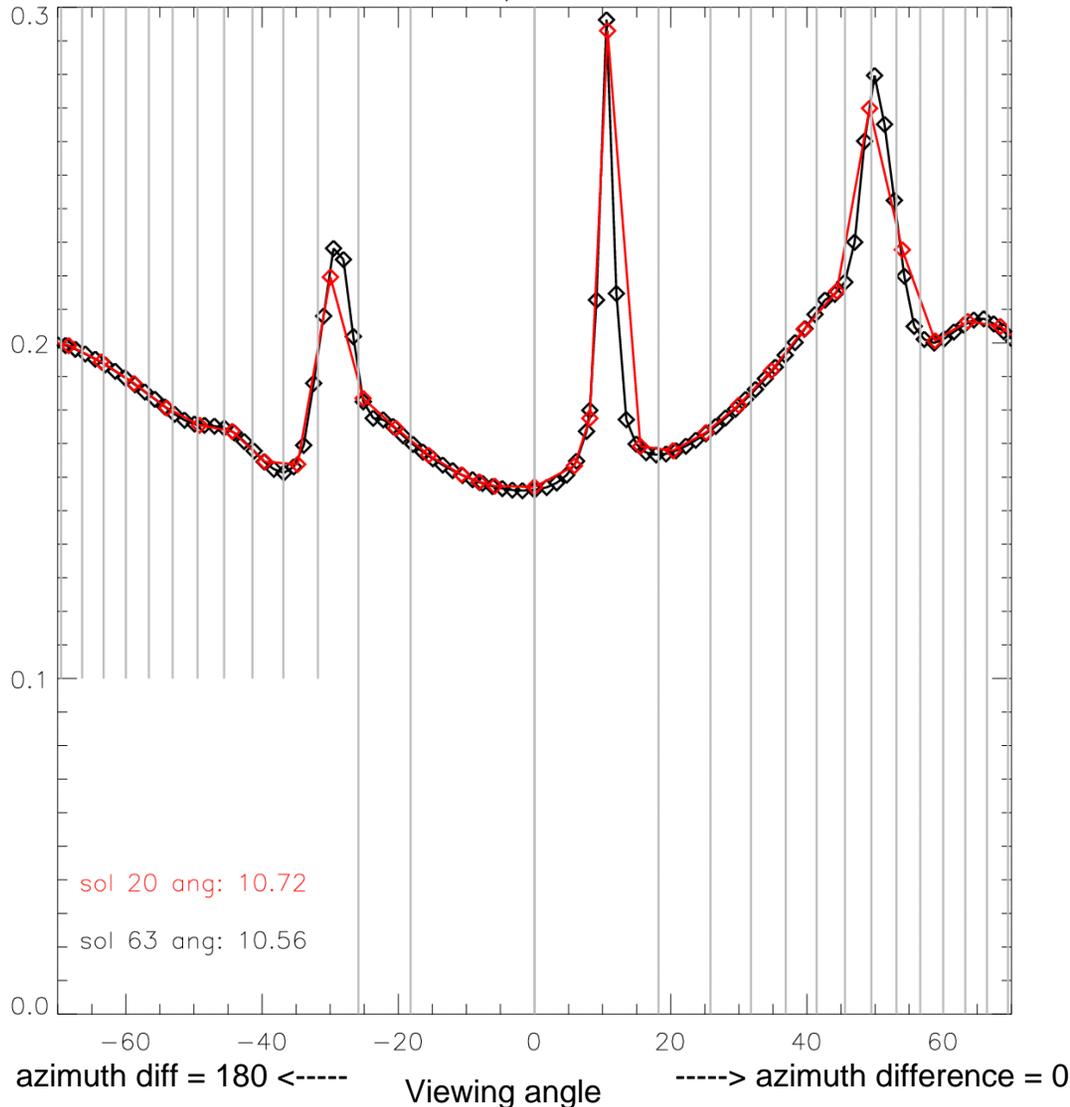
## Number of fix points and range in water LUTs

	Solar zenith [0,zenith]	View zenith	Azimuth	Optical depth	Effective radius	size
KNMI	65 [0,80] ~1.2d	65 [0,80] ~1.2d	91 [0,180] 2 $\square$	22 [0,256] 2 <sup>(n/2)</sup> n=[-4,16]	7 [1,3,5,8,12,16,24]	240MB
FU Berlin	30 [0,88] ~3.13	30 [0,88] ~3.13	15 [0,180] 12.9	14 [0.25,100] log10(0.2)	9 [2.5,100] log10(0.2)	7 MB
CIMSS	45 [0,88] 2.	45 [0,88] 2.	37 [0,180] 5 $\square$	14 [0.25,100] log10(0.2)	9 [2.5,100] log10(0.2) $\square$	38 MB
TEXAS A&M	18 [0,81] Cos	15 [0,66] $\square$ cos	31 [0,180] 5 , 2d(170+)	60 [0,100] 1 (<50),10	15 [8,120] 4	8 MB

# How does the number of LUT entrees affect the accuracy?

Solar angle 10 deg-thin cloud

ref: 15.84 $\mu$ m tau: 04



Red- $\square$  20 viewing angles  
(20 with azimuth difference=0deg and 20 with 180 deg)

Black- 63 viewing angles

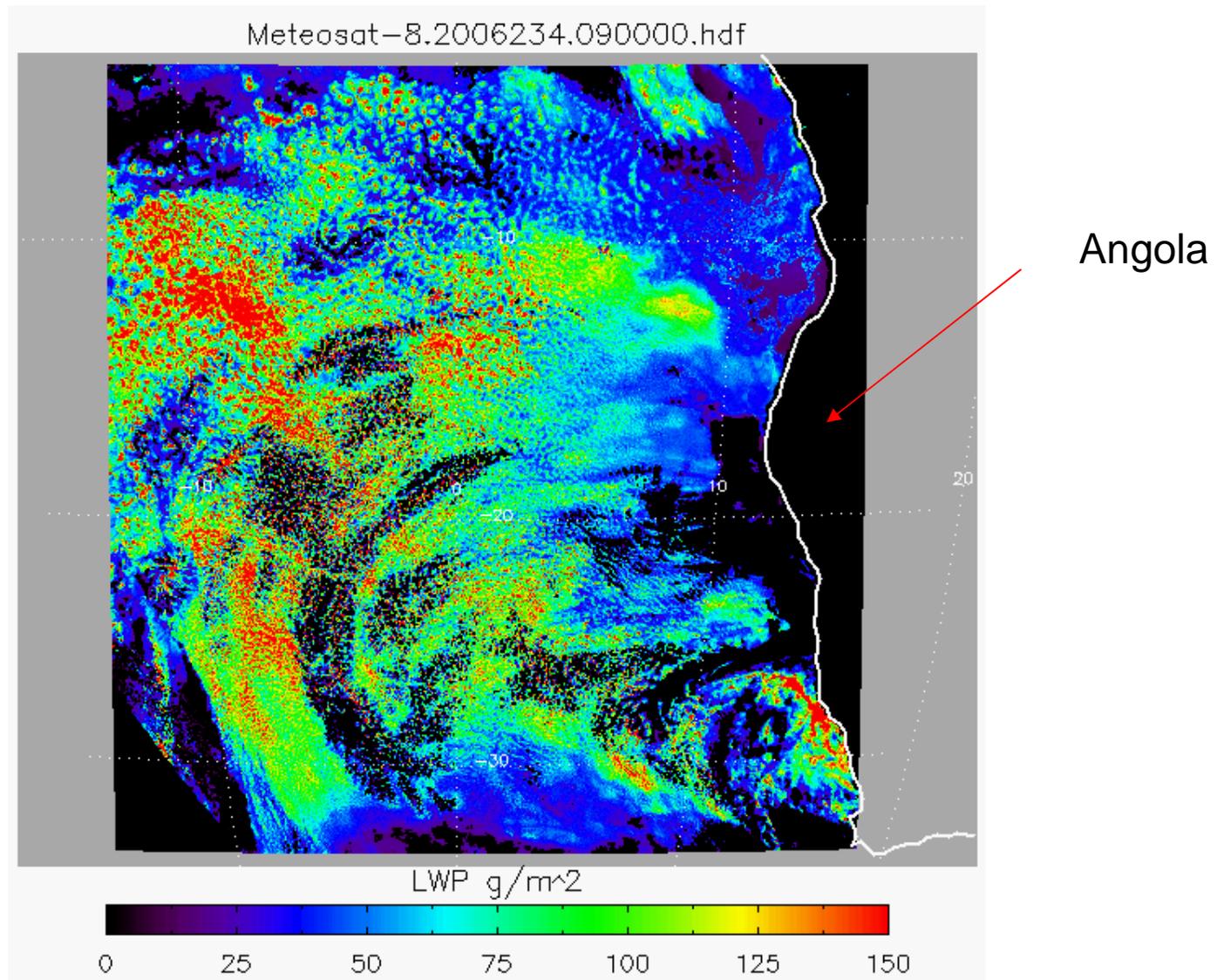
Gray lines- 14 cos spaced angles -would not see the rainbow peaks at low viewing angles.

## Conclusions:

**Linear spaced**

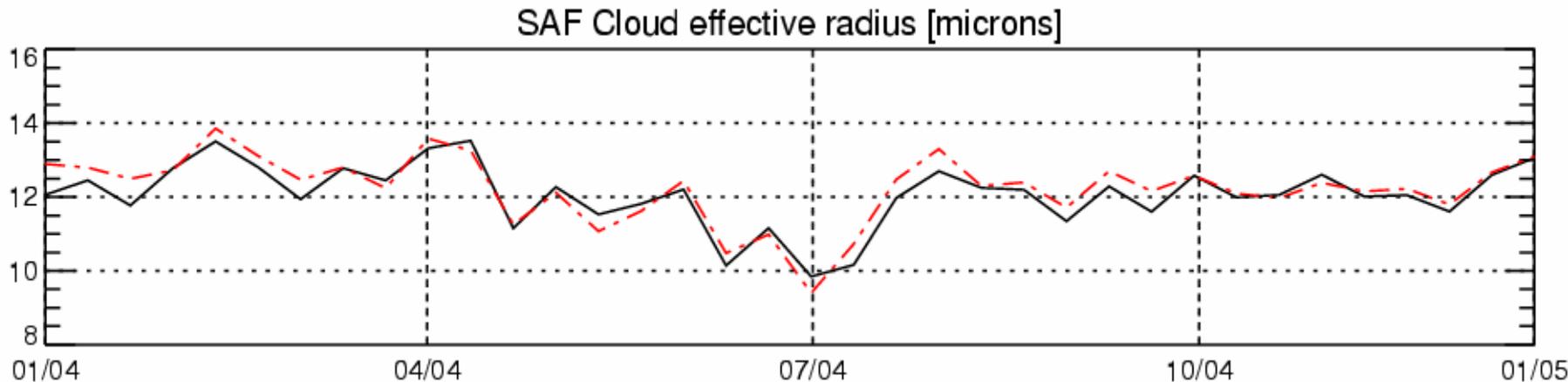
**20-40 entrees are adequate**

## Example of SEVIRI LWP (Derived from optical depth and particle size)



Questions - Is it temporally stable and does it exhibit realistic diurnal variations?<sup>15</sup>

## A goal of this work is make algorithms that are consistent across different platforms



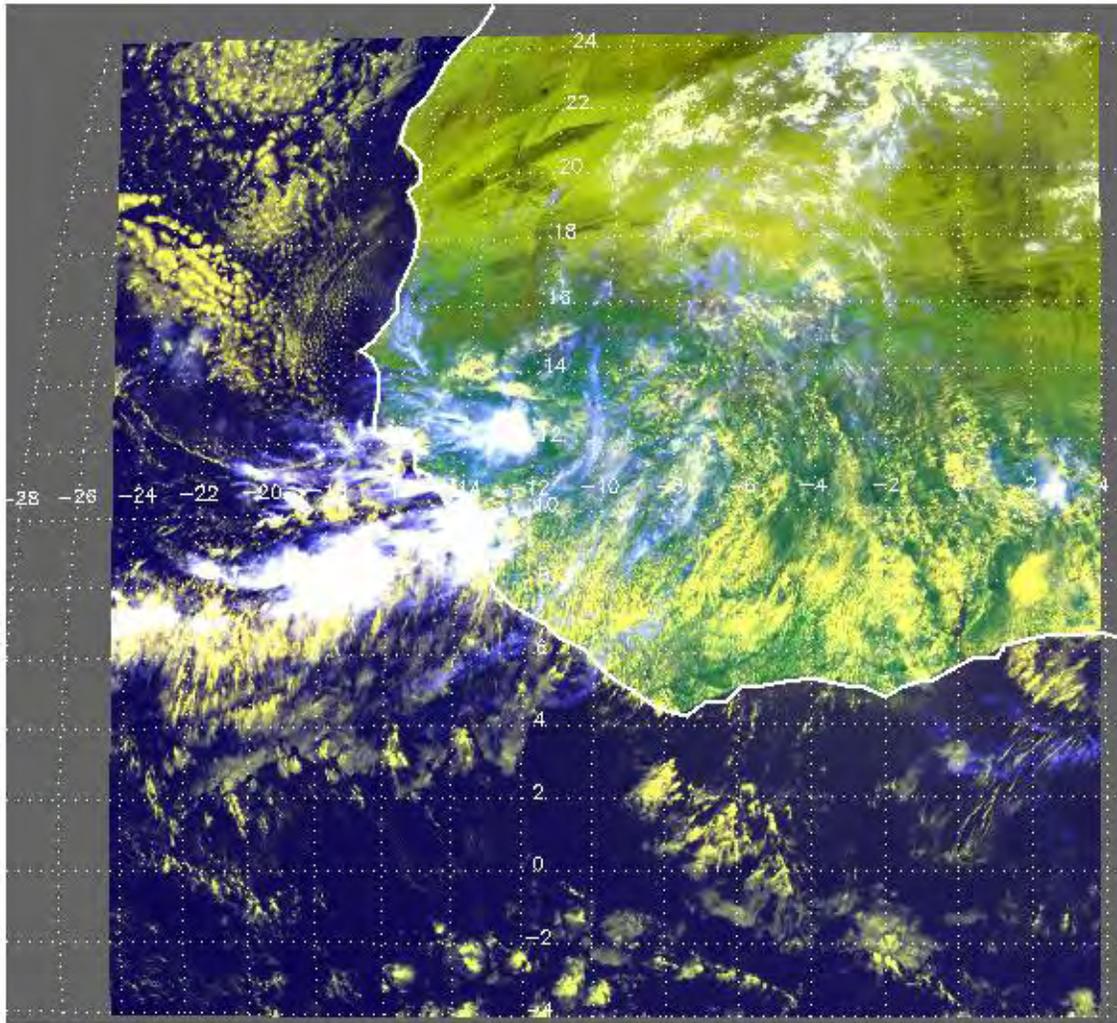
The image shows a NOAA-16/AVHRR vs AQUA/MODIS comparison of liquid water cloud effective radius for one year in a region near South Africa. (Plot provided by Ralf Bennartz, UW/AOS, Madison, WI)

The GOES-R Cloud Application Team has representation of most of the operational imager cloud products from NOAA and NASA and achieving consistency is one of the benefits from our collaboration.

# Cloud Height Estimation from ABI - Challenges

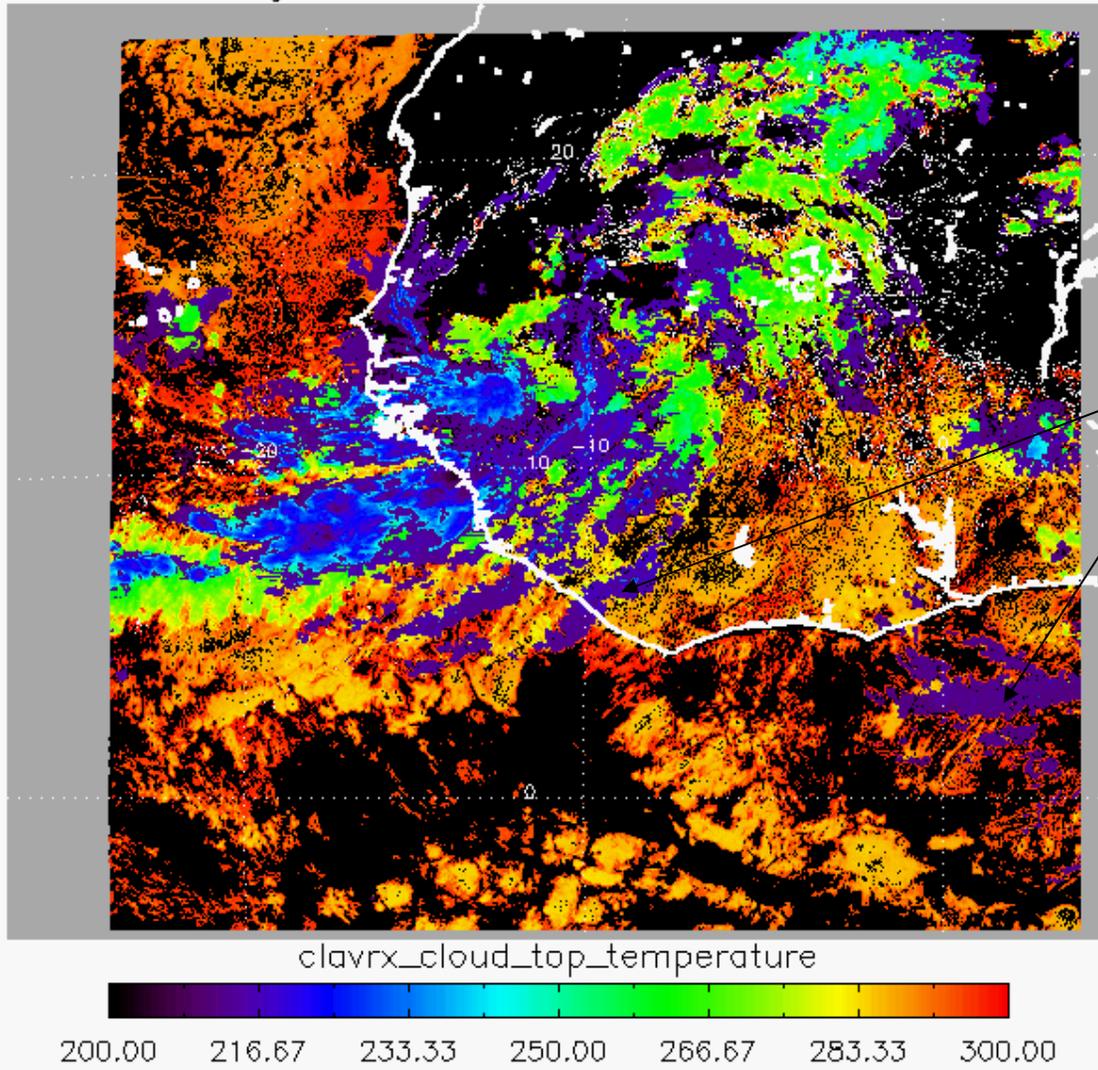
- Without HES, estimating of cloud height from GOES-R is difficult.
- The 13.3  $\mu\text{m}$   $\text{CO}_2$  channel is relatively weak and offers reduced sensitivity to cloud height relative to other  $\text{CO}_2$  channels such as found on MODIS.
- The difference in cloud emissivity between 11 and 13.3 microns also complicates the estimation height.
- For ABI, we can utilize multiple windows to simultaneously estimate the spectral variation of emissivity and cloud height.
- The spectral variation of emissivity is a fundamental measure of cloud microphysics - another GOES-R cloud product.
- To increase the sensitivity to cloud height for thin clouds (cirrus), we need to employ the water vapor bands.
- ***Our main work is to optimize the use of the water vapor bands and to exploit spatial information to improve performance near cloud edges.***

## A Scene to Illustrate various cloud height algorithms



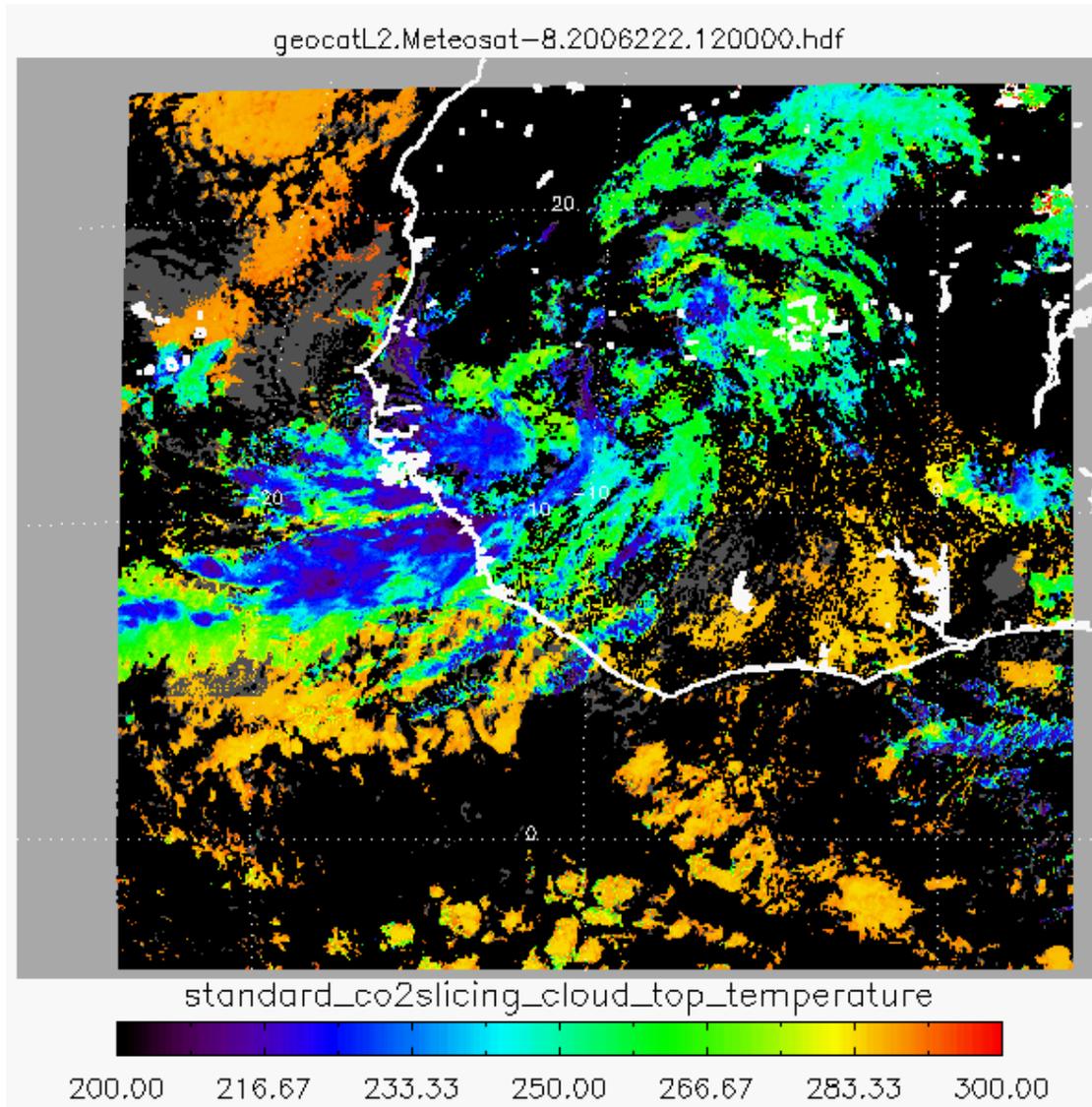
# POES AVHRR: 11 and 12 microns

geocatL2.Meteosat-8.2006222.120000.hdf



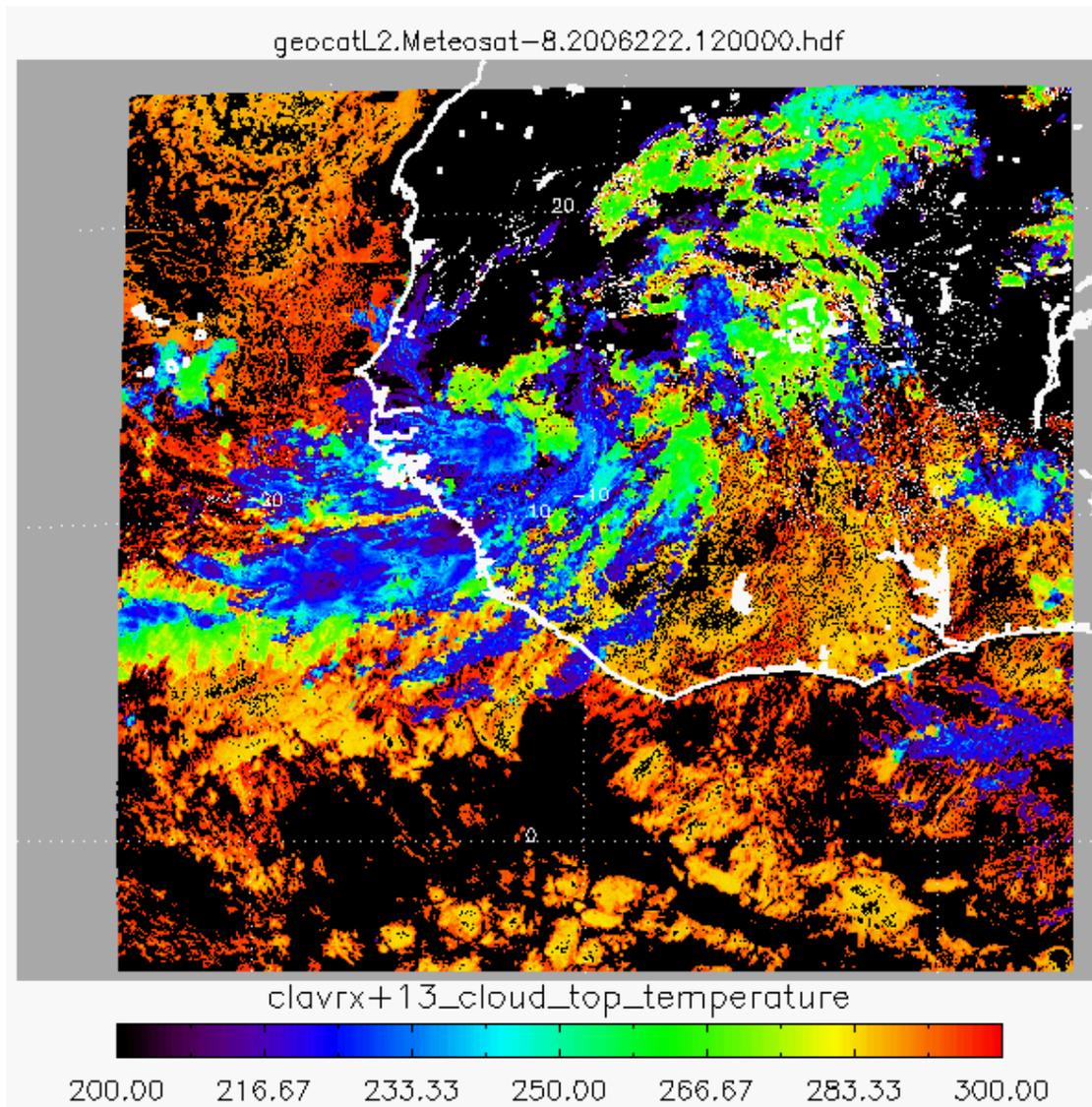
Tendency  
to go to  
first guess  
for thin  
cirrus

# GOES-NOP: 11 and 13.3 microns



\* - Jim Jung has new version for GEOCAT that is true to the GOES-NOP code<sup>20</sup>

## Experimental SEVIRI: 11, 12 and 13.3 microns



*The benefit of more channels is the ability to estimate cloud  $\mu$ -physics.*

# Intercomparison of CALIOP and Aqua Data

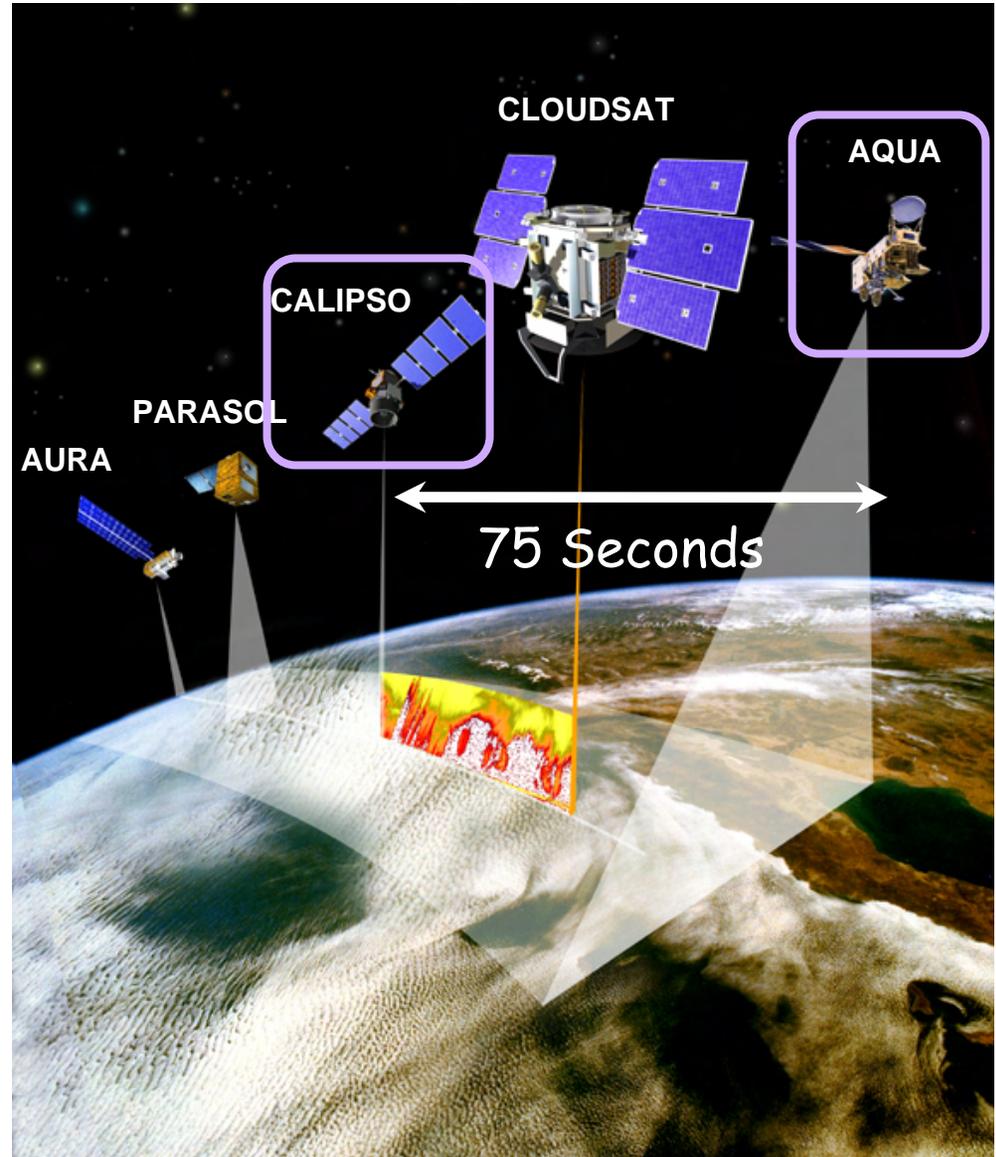
CALIOP data: about 80 m resolution

MODIS cloud products at both 1 & 5 km

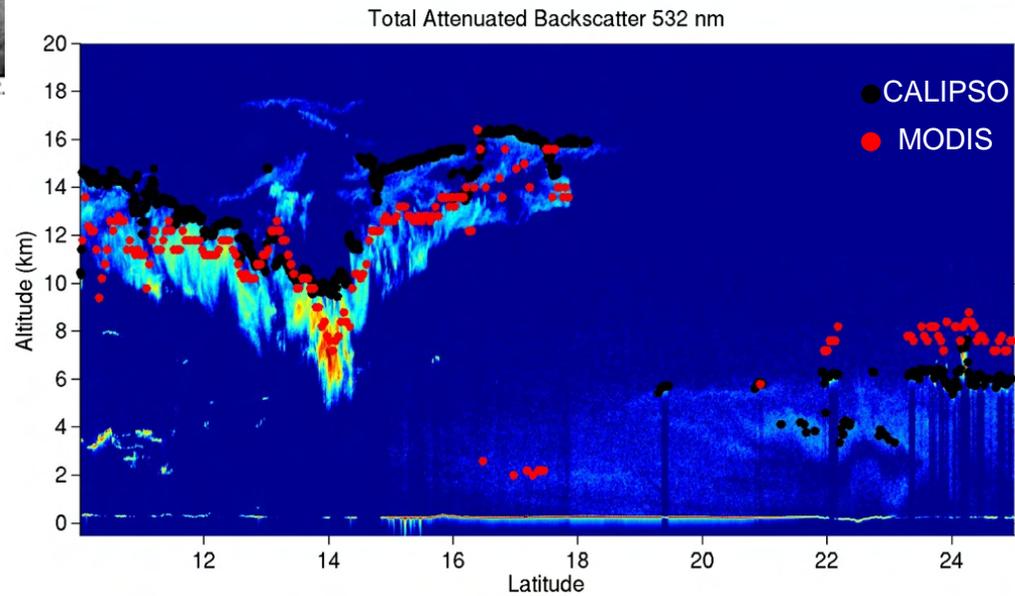
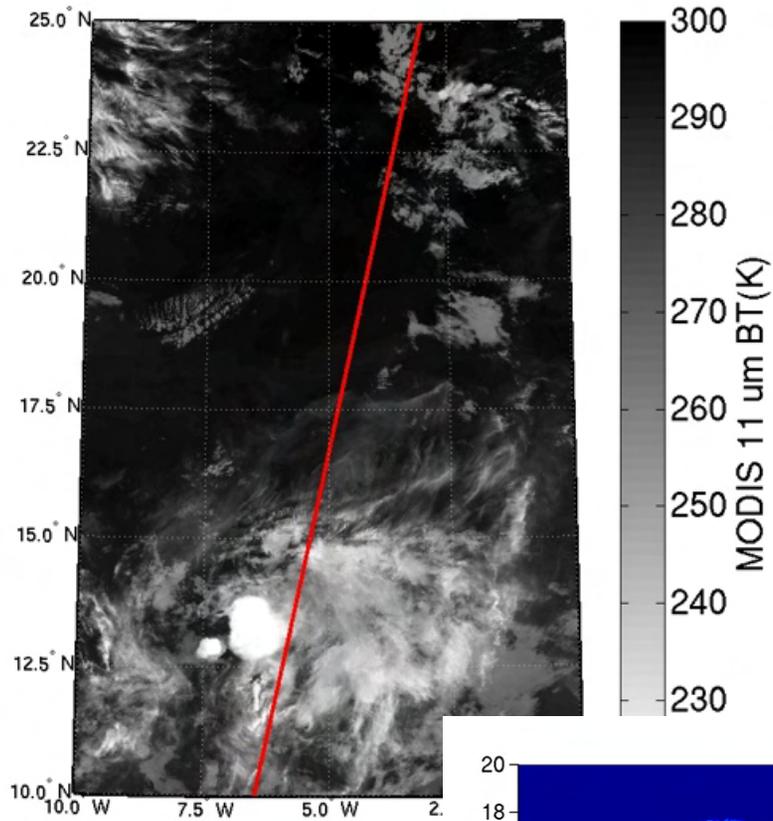
Process goes like this:

- Determine mechanics of how to link observations from two different spaceborne platforms (i.e., Aqua and CALIPSO)
- Link viewing geometry to obtain correspondence between observations
- Strip out the appropriate data products (may mean multiple granules)
- Perform intercomparison\*

\* Assumes understanding of the data, retrieval algorithms, and data products

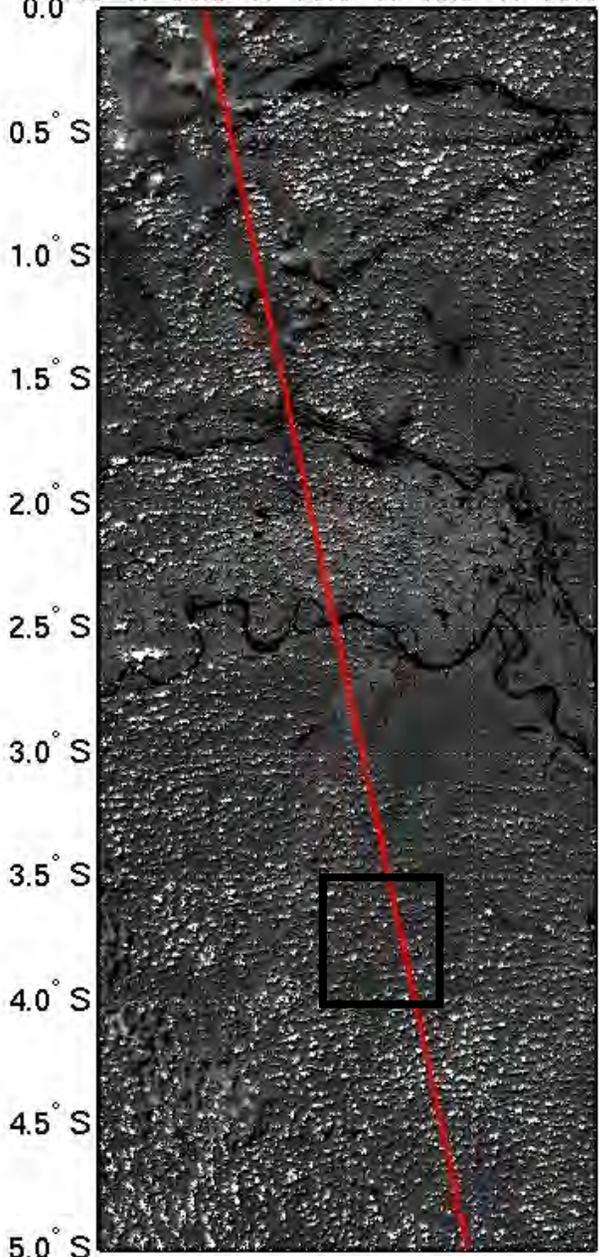


# CALIPSO COMPARISON ILLUSTRATION (Provided by Bob Holz)

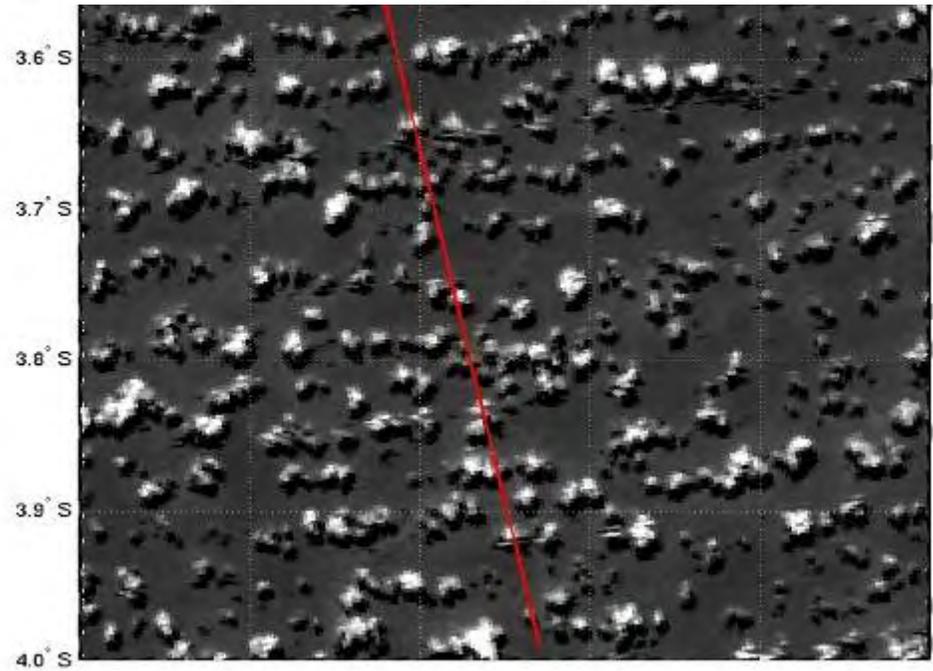
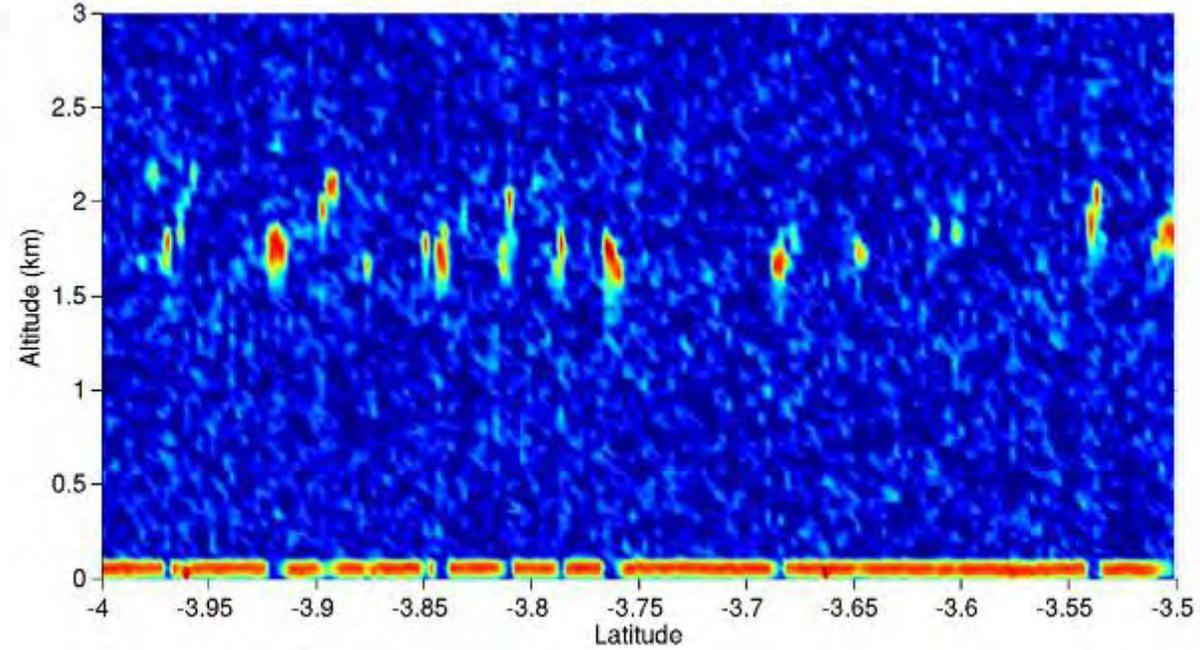


MODIS 841 - 876 um 10-Aug-2006 18:05:07

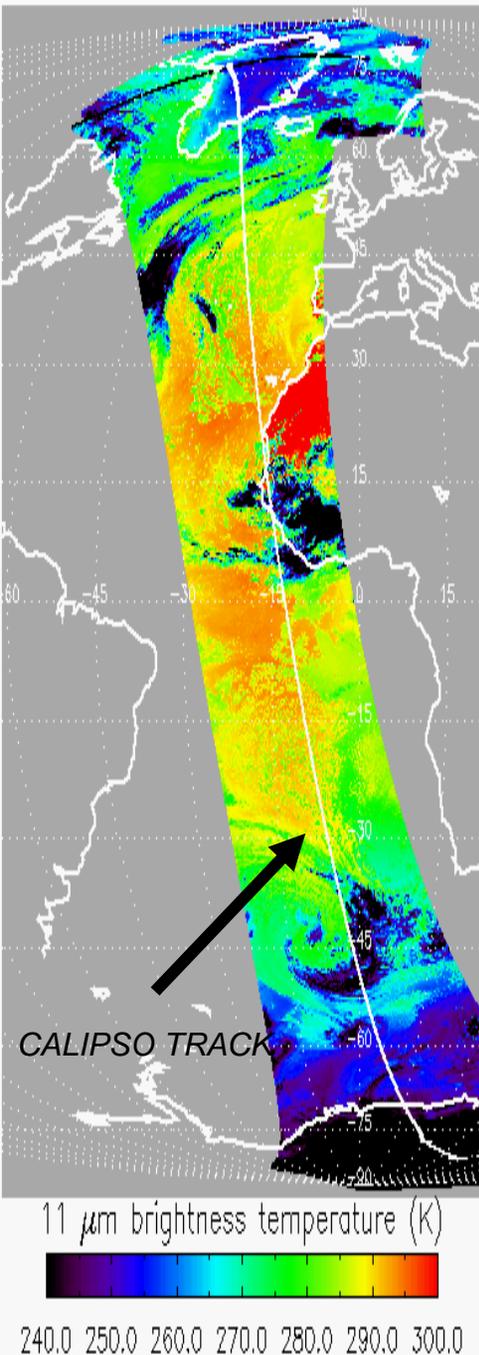
67.0 W 66.5 W 66.0 W 65.5 W 65.0 W



Total Attenuated Backscatter 532 nm

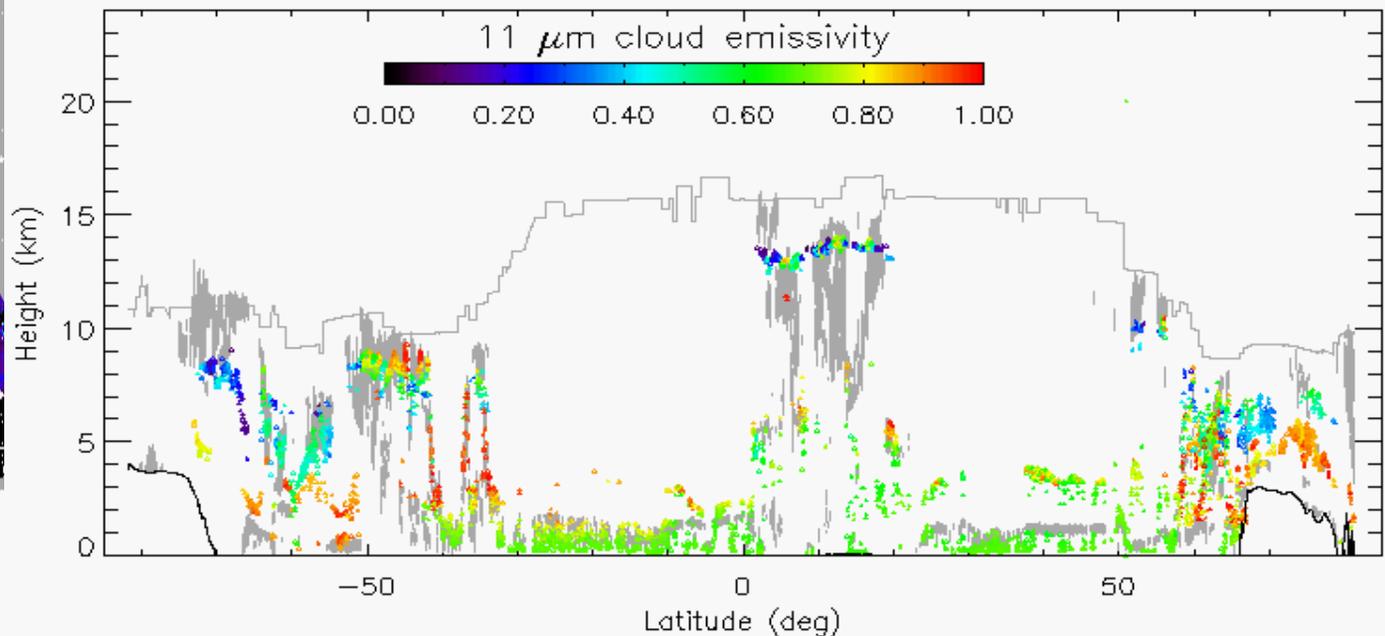


## Daytime Scene



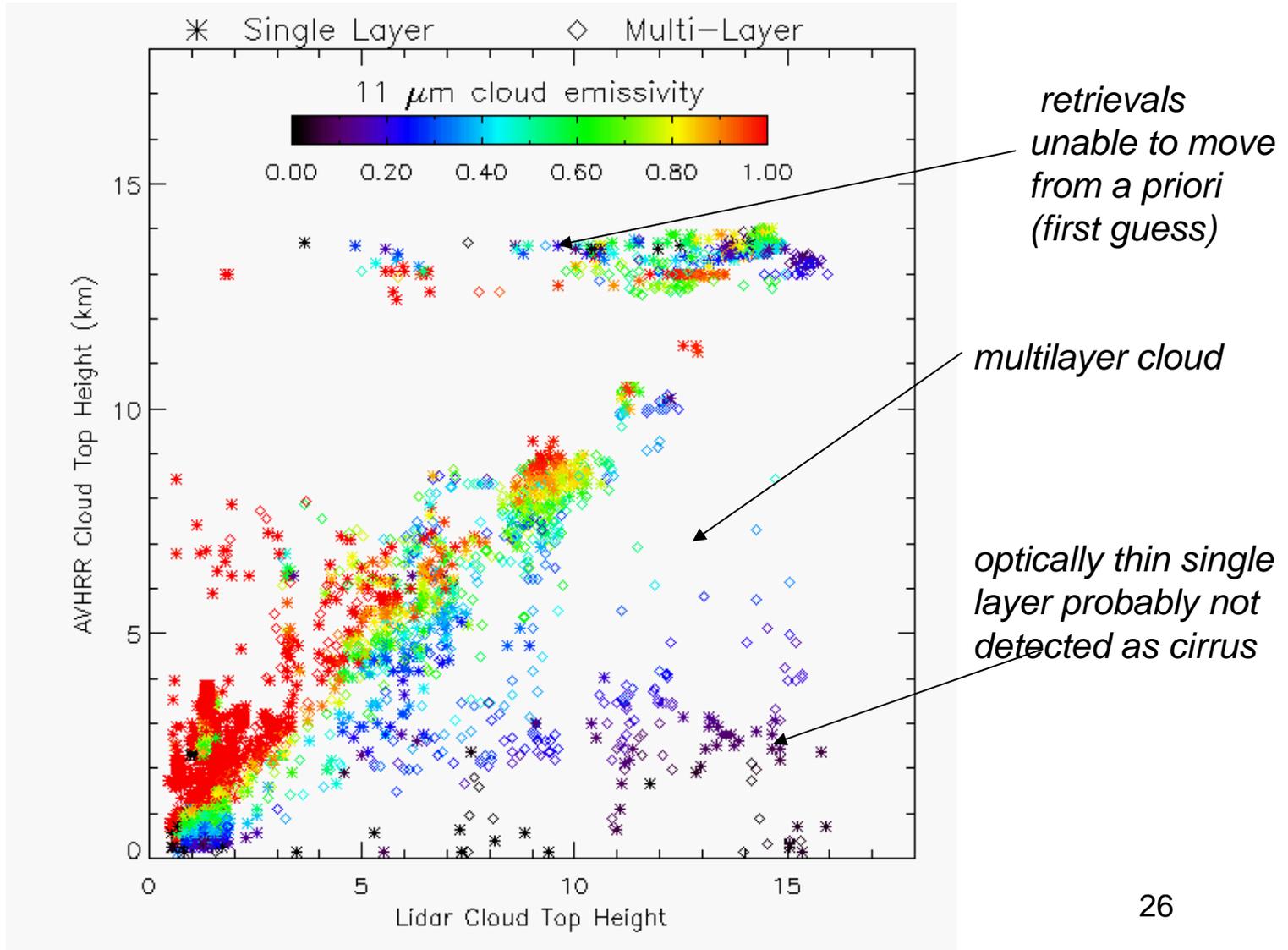
## Comparison of CLAVR-x Cloud Temperature-Heights-Emissivities

- CLAVR-x cloud heights are available operationally and the image shows their values overlaid on a CALIPSO cross section
- Results show expected lack sensitivity of the AVHRR to the height of optically thin cirrus. (split-window approach)
- Also some issues with low clouds (*likely inversion related*).



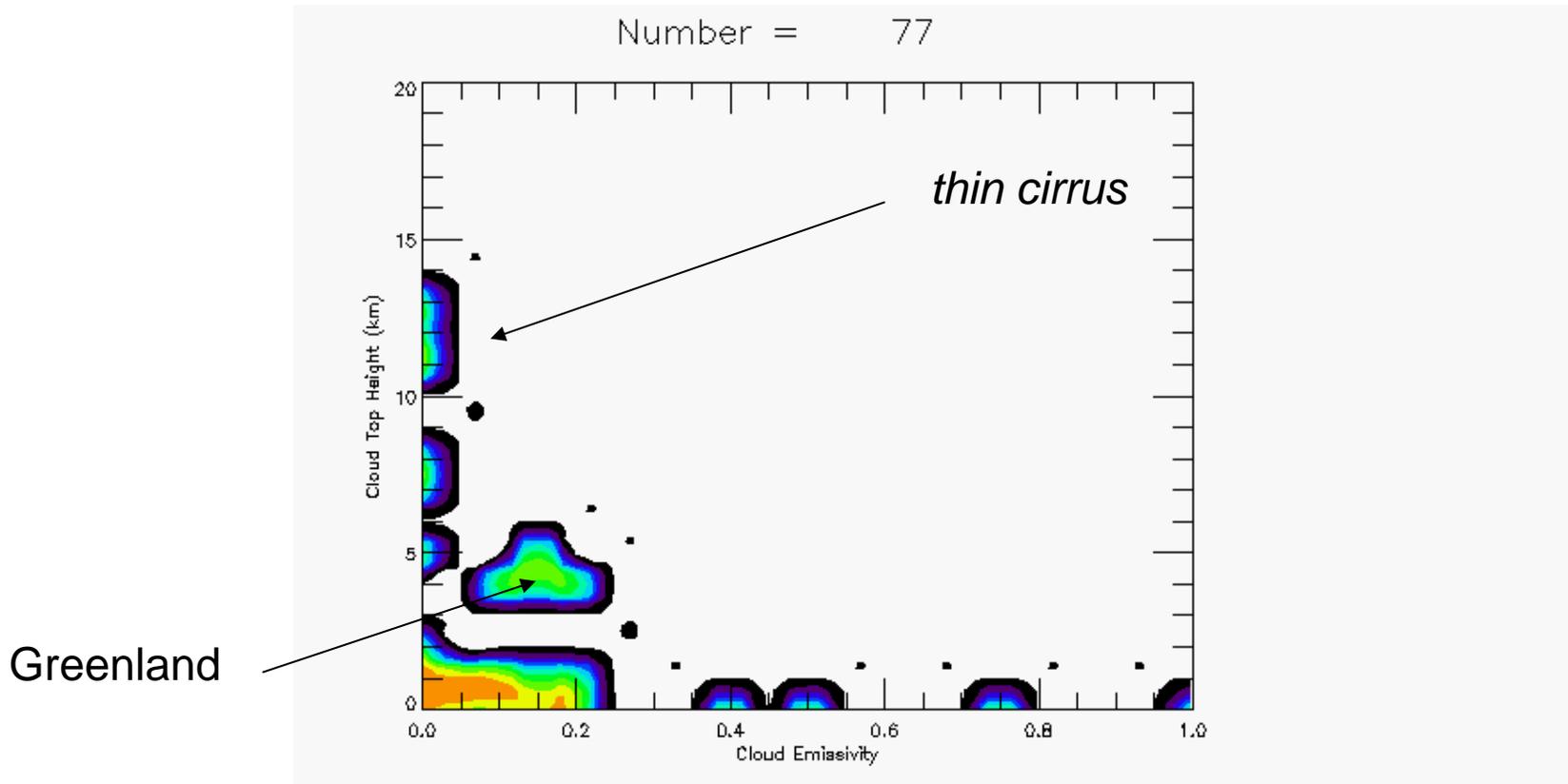
# Interrogation of CALIPSO and AVHRR cloud height comparisons

We are exploring using CALIPSO to isolate algorithmic weaknesses.



## Other Ways to Use CALIPSO Data (Cloud Detection Performance)

What is the height and emissivity distribution of clouds missed by CLAVR-x?

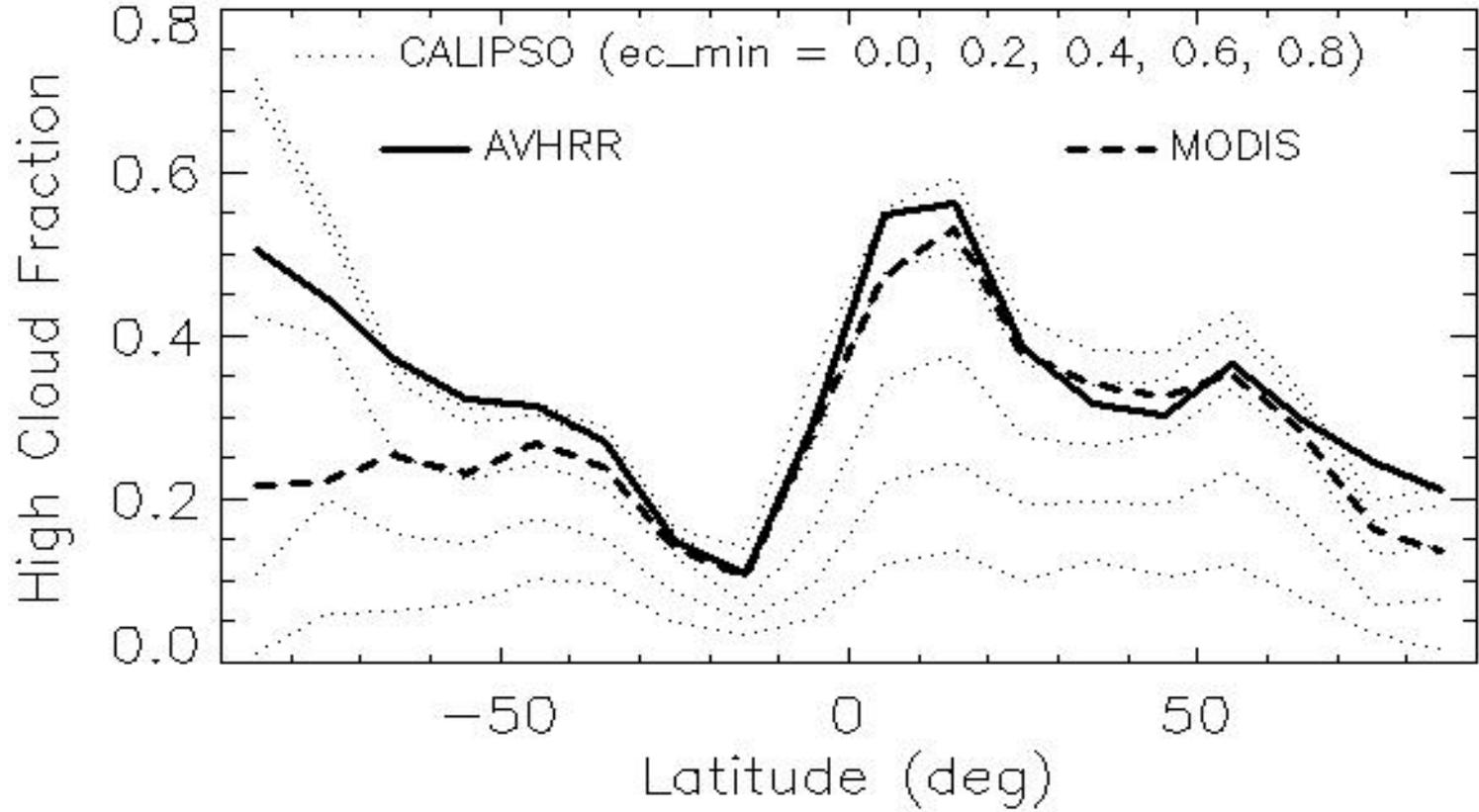


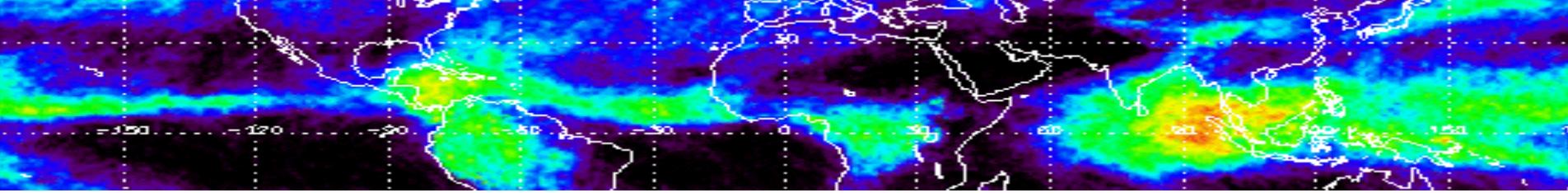
CLAVR-x missed 77 cloudy pixels out of 3012 total for this orbital segment

# Using CALIPSO to Compare High Cloud Amounts from Different Imagers

However, the faults in cloud height assignment do not destroy our high cloud amounts as this comparison with MODIS and CALIPSO shows.

Because you can derive a CALIPSO emissivity value, you can throw away clouds with emissivities below a threshold and see the effect on the cloud distribution. AVHRR and MODIS tend to follow the 0.2 line.





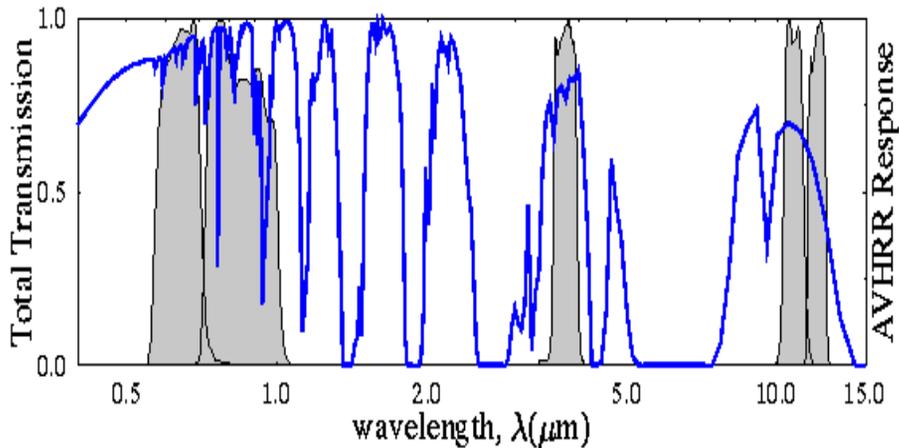
## Advances in Generation of Imager Cloud Climate Records

- The improvements in algorithms and processing are also relevant to our climate processing system (PATMOS-x).
- PATMOS-x uses AVHRR data from 1981 to the present to make cloud climate records.
- PATMOS-x uses the CLAVR-x code but run with navigation, calibration improvements and with Reanalysis data (not forecasts).
- PATMOS-x also helps our GOES-R/NPOESS development efforts by testing algorithmic concepts on long time series.
- Exploring how best to make consistent records from AVHRR/MODIS/VIIRS.
- PATMOS-x data from 1981 to 2006 is available online for free.

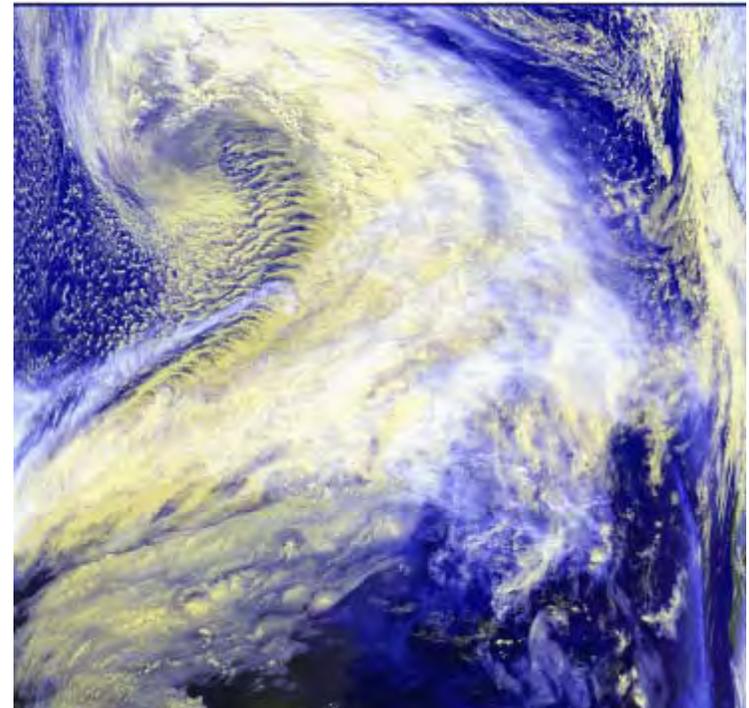
# The Advanced Very High Resolution Radiometer (AVHRR)

The Advanced Very High Resolution Radiometer (AVHRR) was launched in the 1979 for non-quantitative cloud imagery and SST. It flies on the NOAA Polar Orbiting Satellites (POES)

1. AVHRR provides enough spectral information with sufficient calibration for multiple quantitative applications (0.63, 0.86, 1.6/3.75, 10.8 and 12.0  $\mu\text{m}$ )



2. The spatial resolution (4 or 1 km) is sufficient to resolve many cloud features.

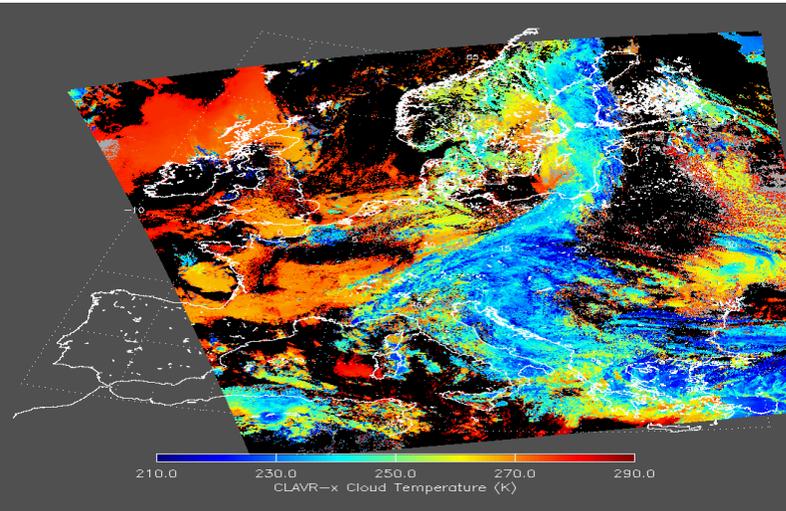


3. Its long data record (1981-2016) makes the AVHRR data-set very important for decadal climate studies in addition to being relevant for real-time work.

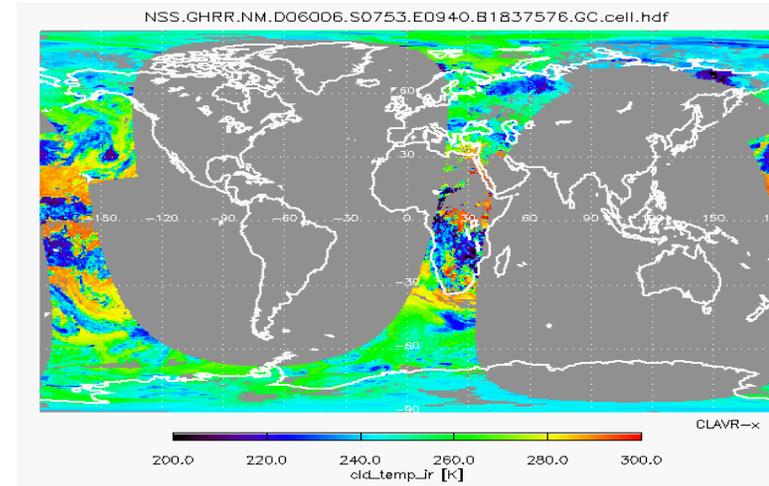
# Temporal / Spatial Resolution of Products from PATMOS-x

*Capturing meaningful information in Level-3 maps is tricky.*

Pixel Level (1 or 4km)



Mapped Orbital (55km)



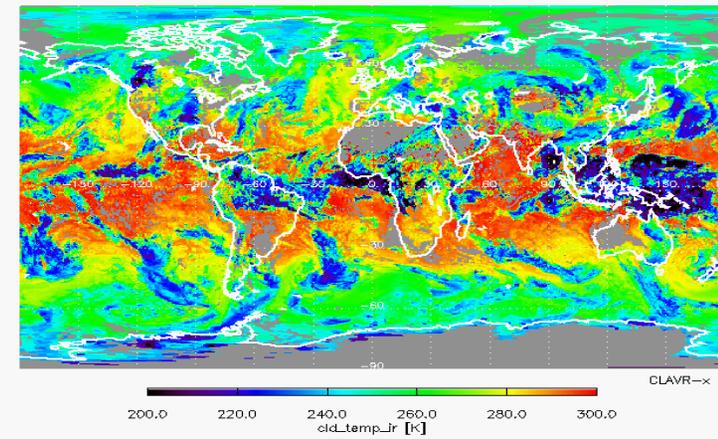
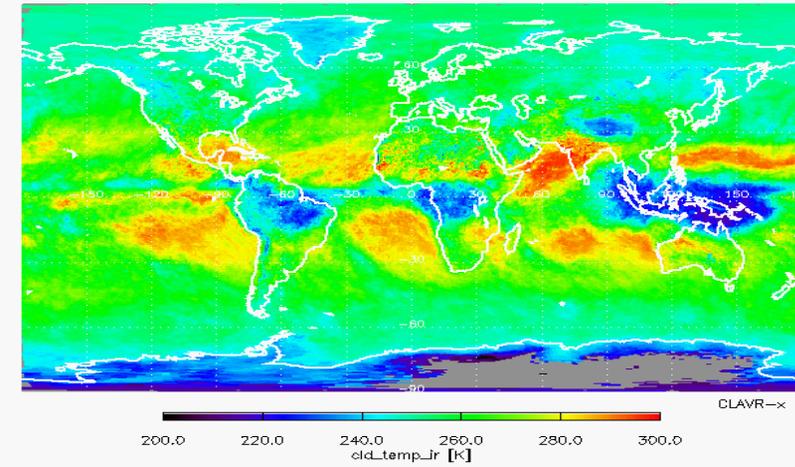
Monthly Averages

*(Images are of cloud temperature)*

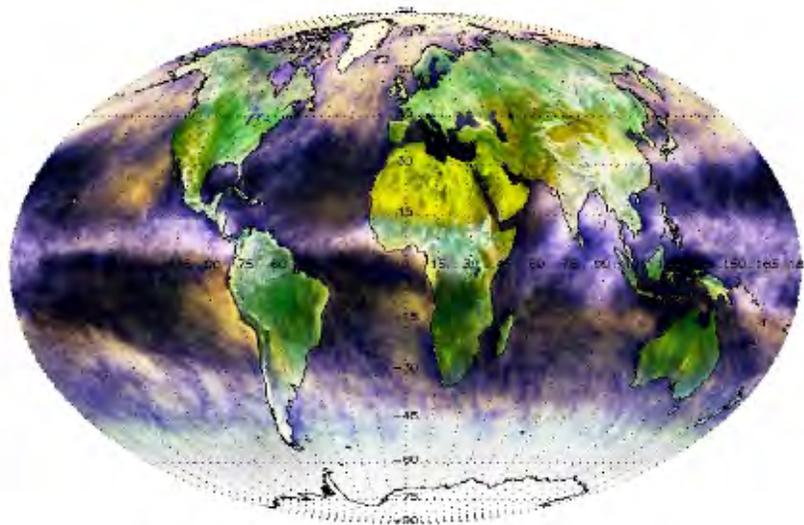
Daily Ascending/Descending

clavrx\_n18\_asc\_05\_D\_2006\_091to120.cell.hdf

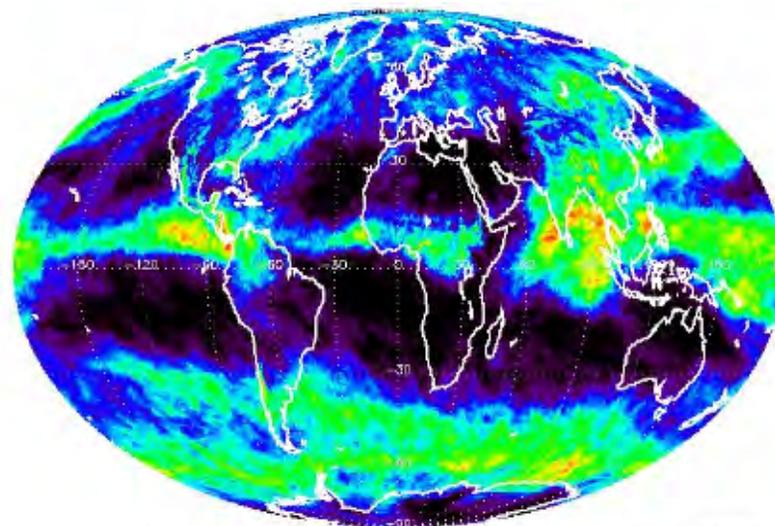
clavrx\_n18\_asc\_05\_D\_2006\_118.cell.hdf



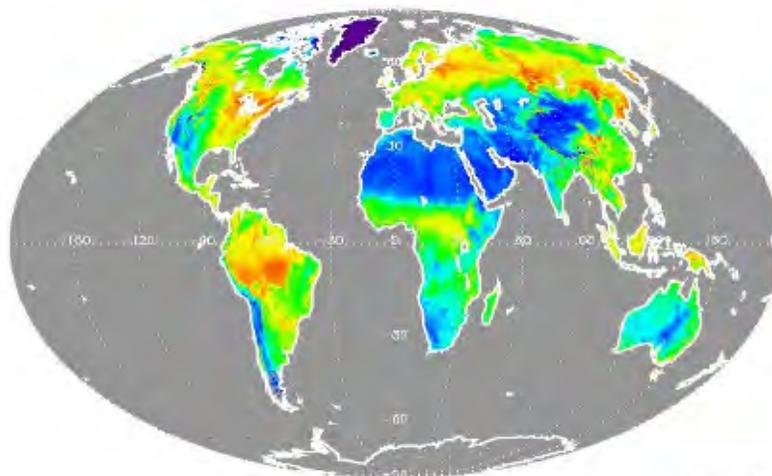
# Some Examples of PATMOS-x fields



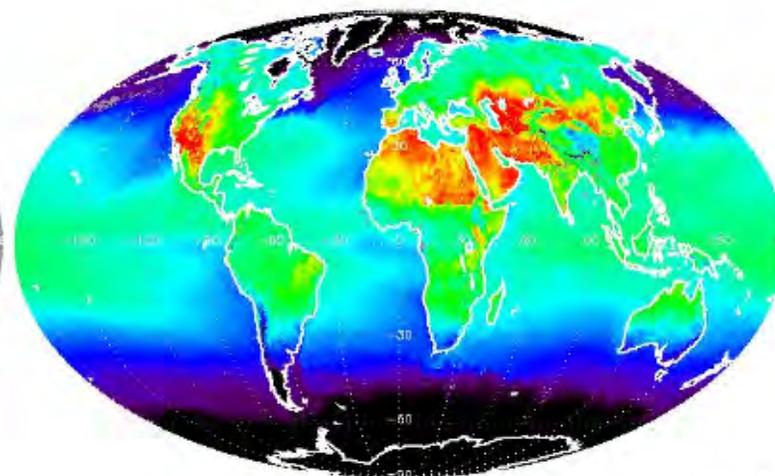
**False Color Composite**



**Ice Cloud Fraction**



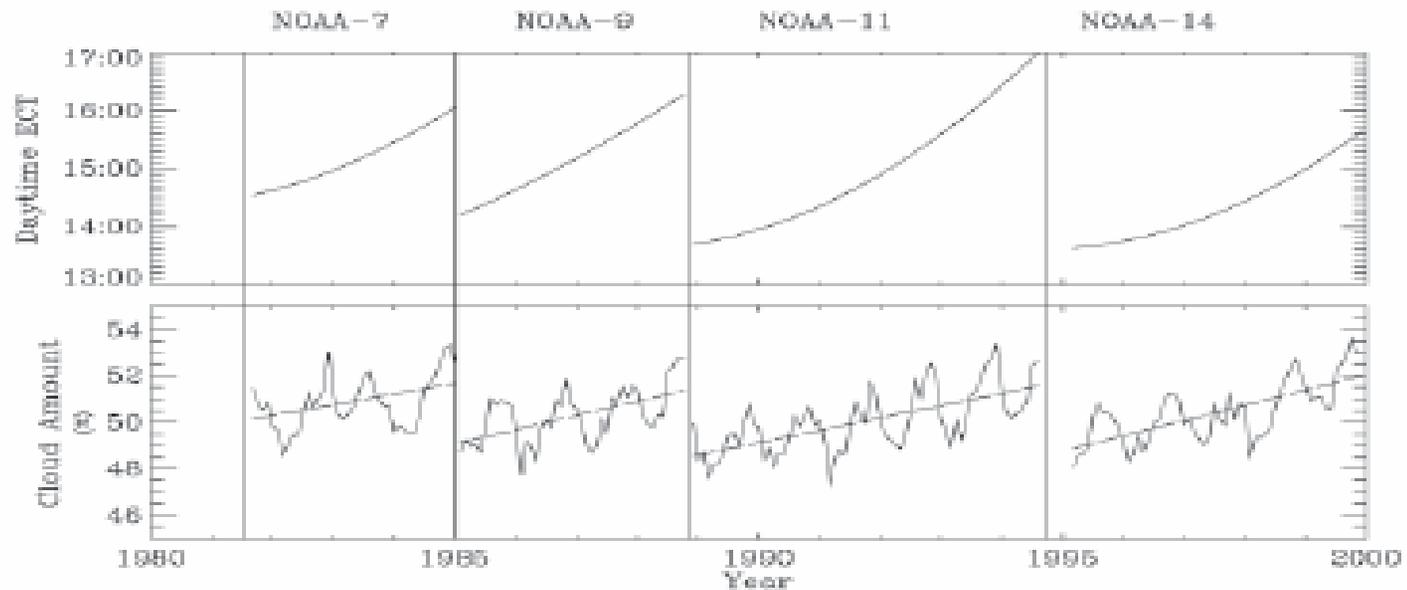
**Atmospherically Corrected NDVI**



**Surface Temperature**

# Correcting for Orbital Drift

The POES satellites provide 4 times per day sampling but the times varied through the life of each satellite. This can cause difficulties in interpreting long term time-series.

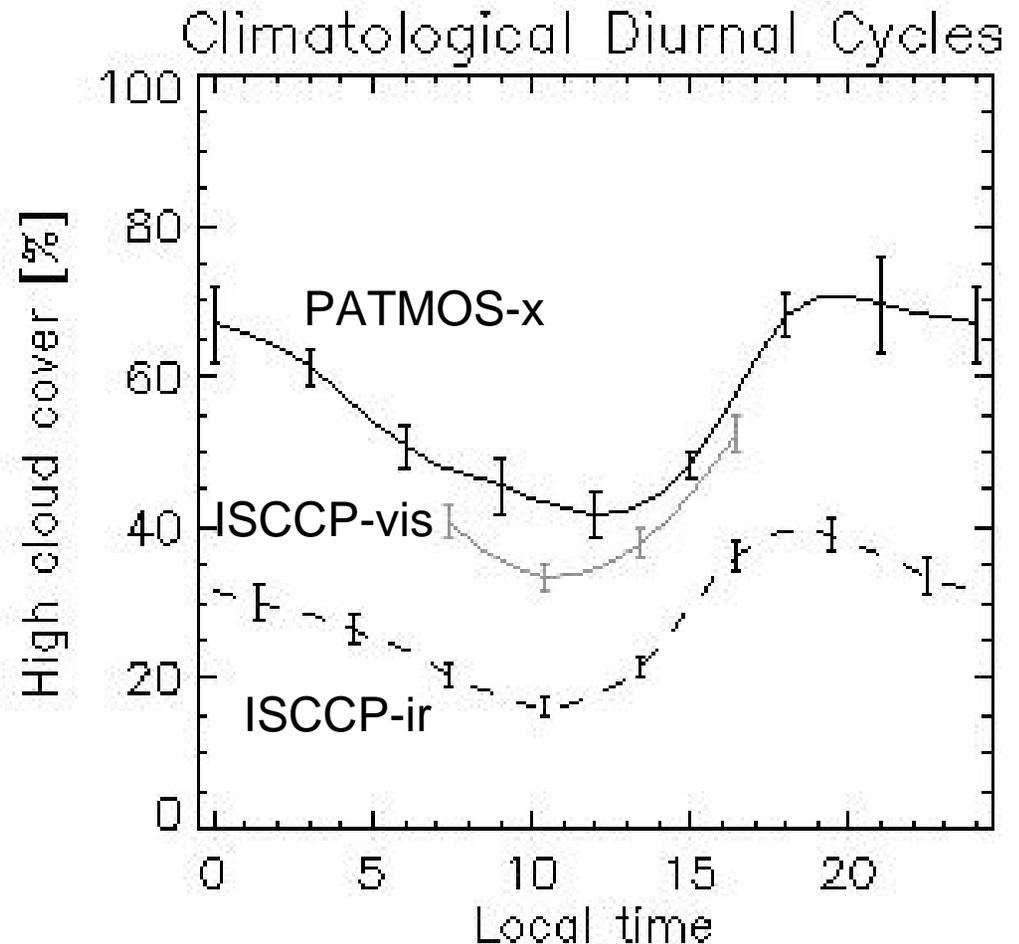


**FIG. 1. (a) Time series of the ECT for the four NOAA polar-orbiting satellites comprising the PATMOS dataset. (b) Time series of tropical ( $20^{\circ}\text{N}$ – $20^{\circ}\text{S}$ ) day–night average monthly mean PATMOS cloud amount (%) for Sep 1981 through Dec 1999.**

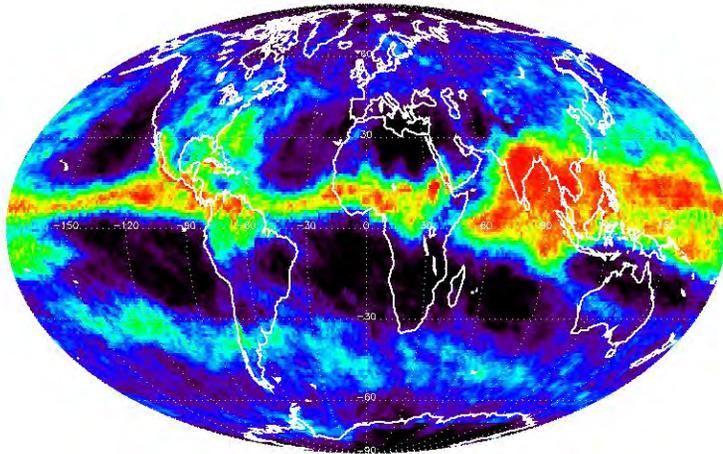
*This is a PATMOS result - not PATMOS-x*

# Correcting for Orbital Drift

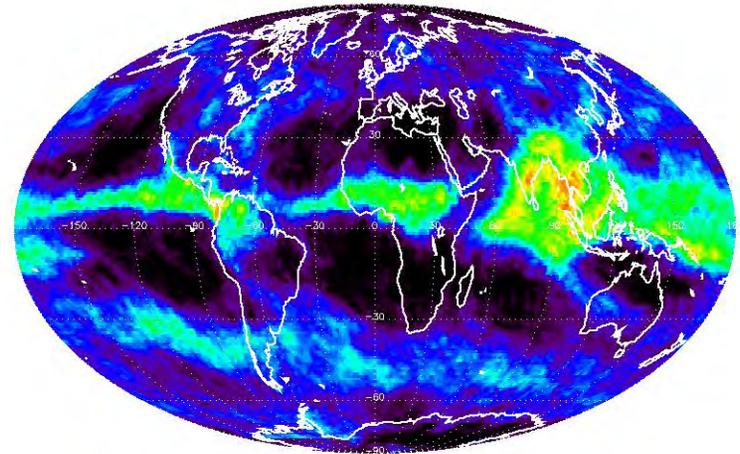
- One way to handle this is to derive climatological diurnal cycles using the data from all satellites over the whole record.
- This CDC can be used to produce data at uniform observation times given the limited values (4x per day or 2x day) at non-uniform observation times.
- The image on the right shows an example of a PATMOS-x derived CDC compared to the diurnal cycle in ISCCP.
- Work done by Amato Evan and we have paper submitted on this.



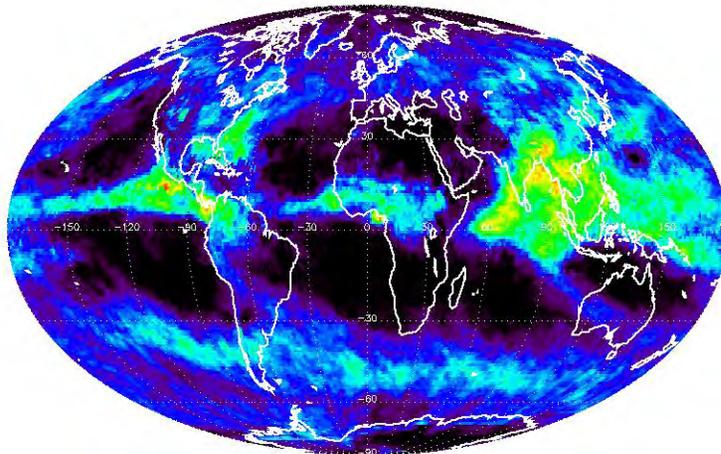
# Diurnal Cycle of High Cloud for July 2004 produced at 0, 6, 12, and 18 local time.



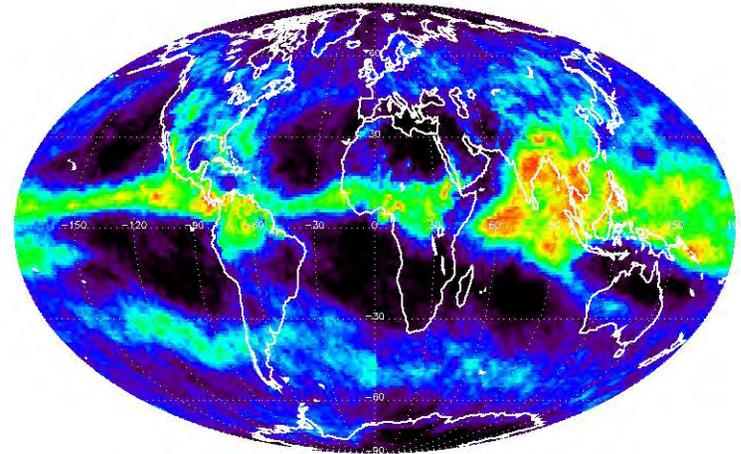
0.0 20.0 40.0 60.0 80.0 100.0  
2004 high cloud cover @ 0 local time



0.0 20.0 40.0 60.0 80.0 100.0  
2004 high cloud cover @ 6 local time



0.0 20.0 40.0 60.0 80.0 100.0  
2004 high cloud cover @ 12 local time

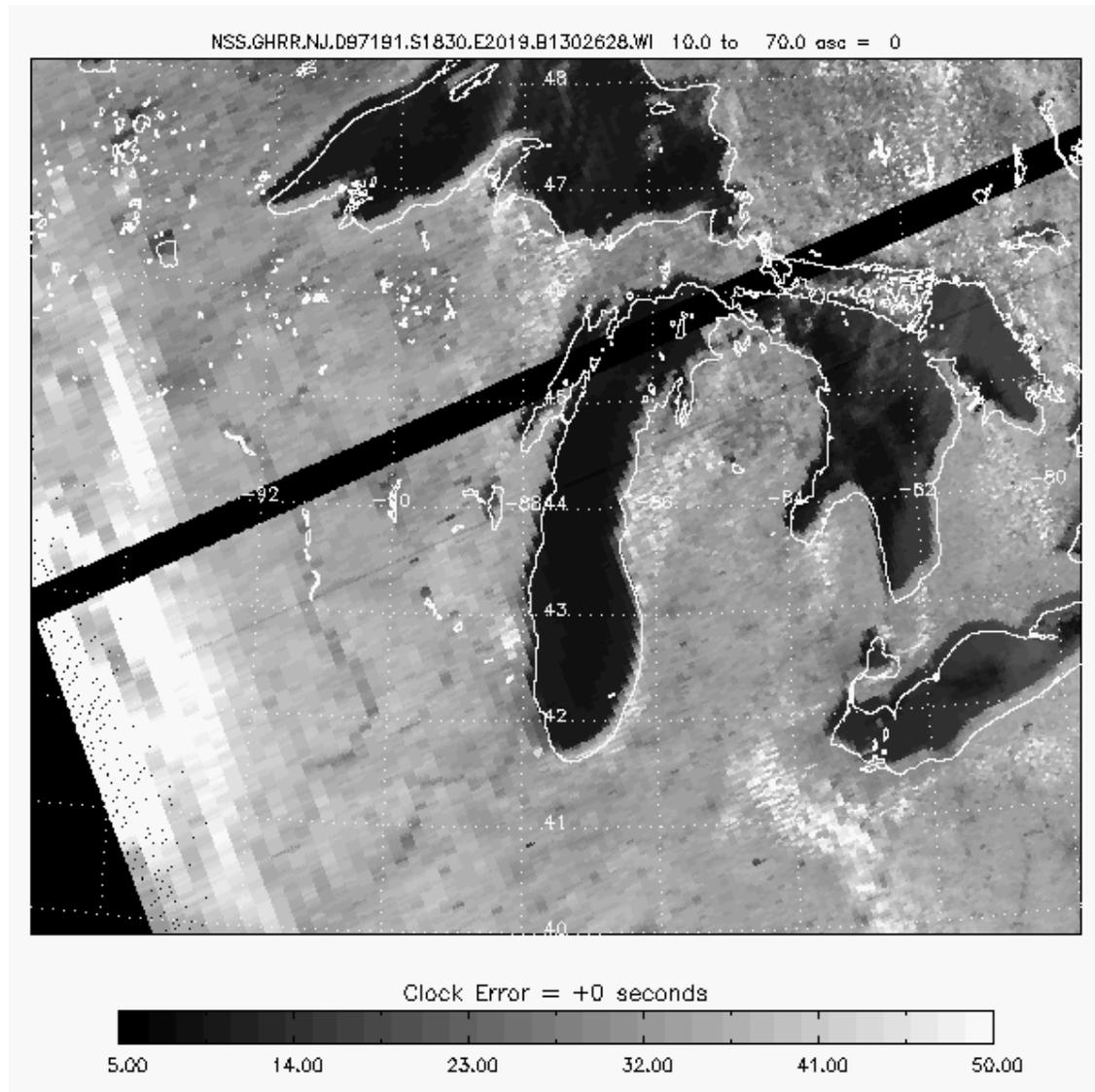


0.0 20.0 40.0 60.0 80.0 100.0  
2004 high cloud cover @ 18 local time

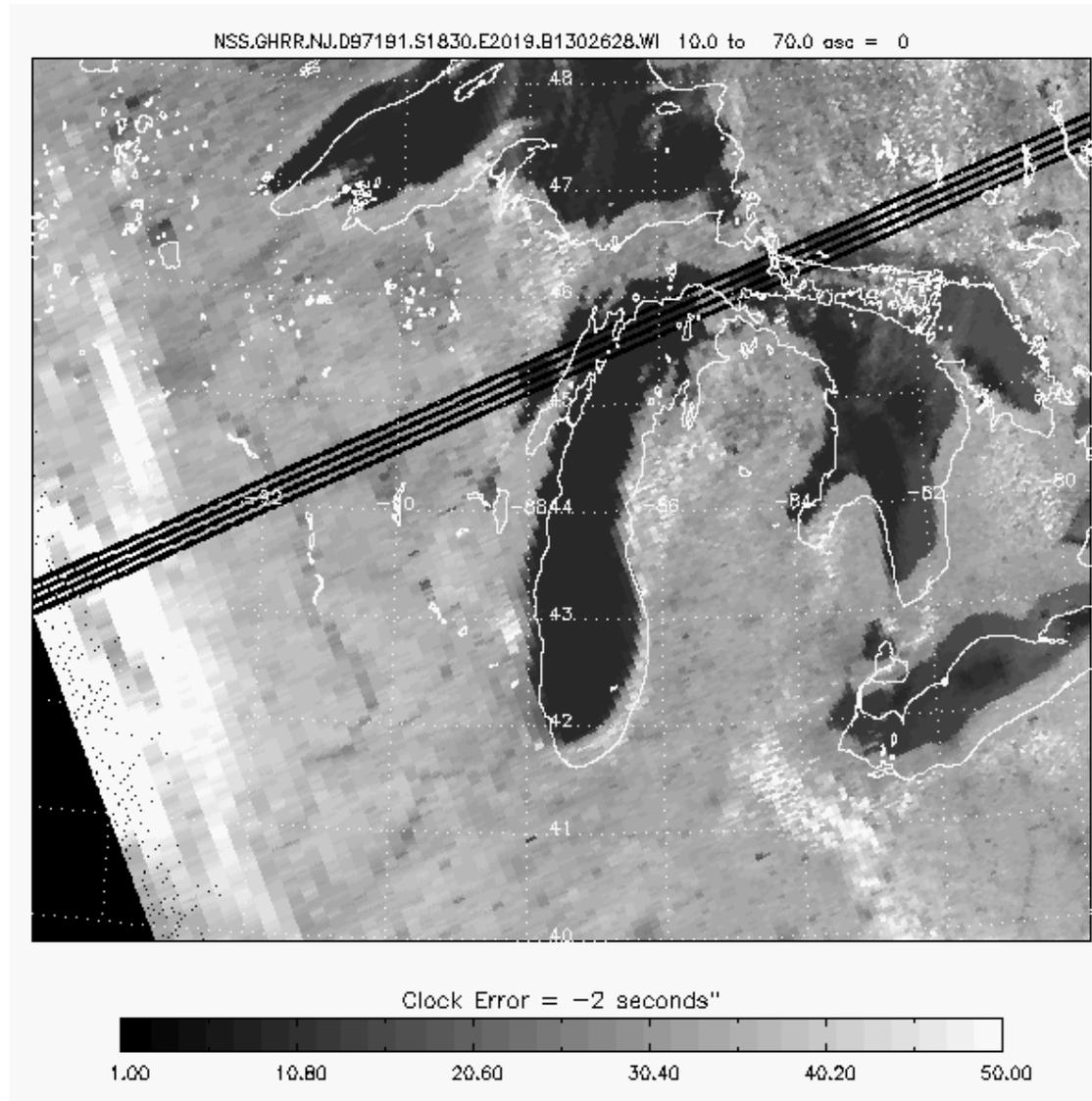
# Navigation Improvements

*Example AVHRR scene with a noticeable clock error*

- The AVHRR on-board clock had errors of roughly +/- 1 second which equates to +/- 10 km.
- This error varied between times when the clock was corrected.
- These errors are large enough to impact our cloud climatologies (ie. coastal cloudiness)
- Clock corrections have been tabulated by the AVHRR Pathfinder Oceans.
- Aleksander Jelenak has written a renavigation tool called CLEVERNAV.
- Fred Nagle was also written a routine to correct for clock errors directly (no renavigation).



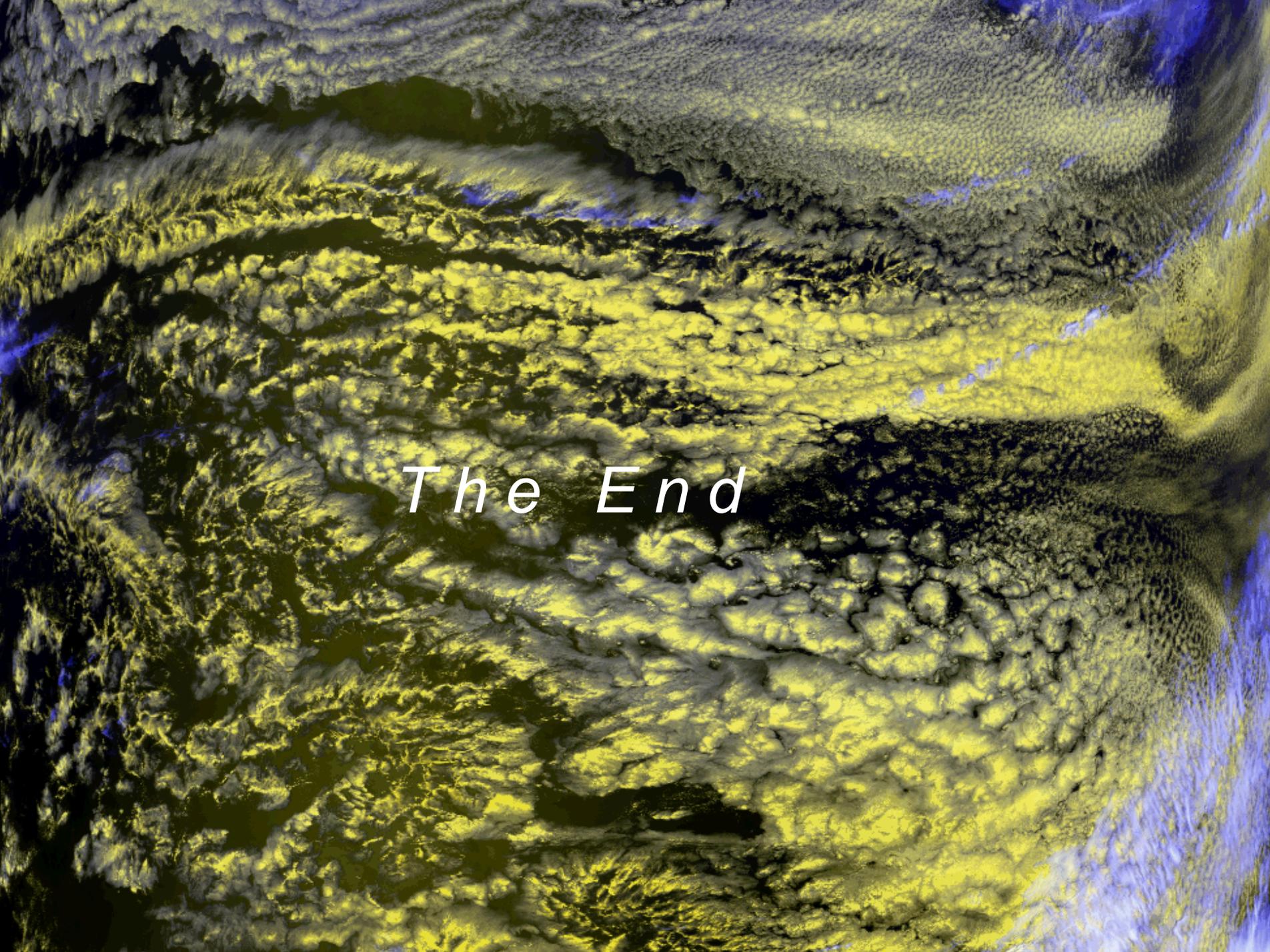
# Demonstration of Fred Nagle's Lat, Lon adjustments for various clock errors



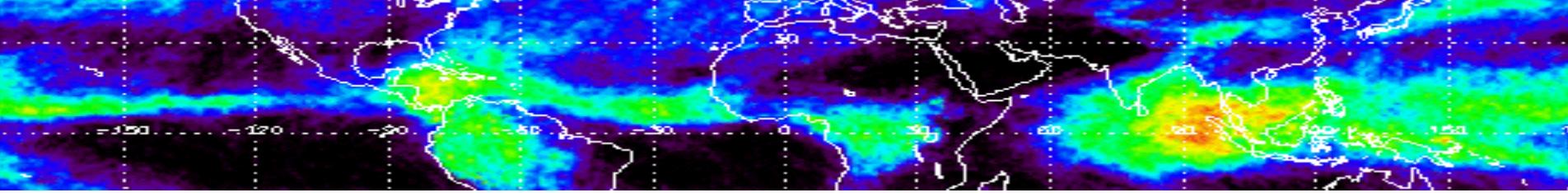
*Measured clock error for this period was 1.75 seconds  
(note visual agreement at Clock Error = +2 seconds).*

# Conclusions

- Imager cloud remote sensing is very active in STAR. Every algorithm is being scrutinized and improved from GOES-R.
- We are relying heavily on NWP and RT models and assuming they are improving with time.
- We employ complex physical algorithms and are pushing the limits of our knowledge of cloudy radiative transfer.
- Our climate work is an integral part of our remote sensing efforts and improves our real-time products.
- The GOES-R Cloud Application Teams welcomes any collaboration on these issues.

An aerial photograph of a volcanic crater, possibly Mount Fuji, showing a complex network of ridges and valleys. The terrain is illuminated with a mix of yellow and blue light, creating a dramatic, high-contrast scene. The central part of the image is dominated by a large, circular depression, likely the main crater, surrounded by several smaller, concentric ridges. The lighting highlights the textures of the volcanic rock and the intricate patterns of the landscape.

*The End*



## History of Climate Imager Cloud Remote Sensing in ORA/STAR

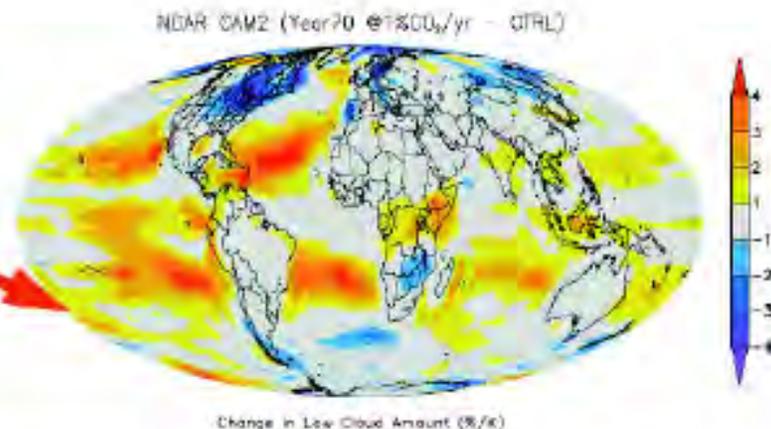
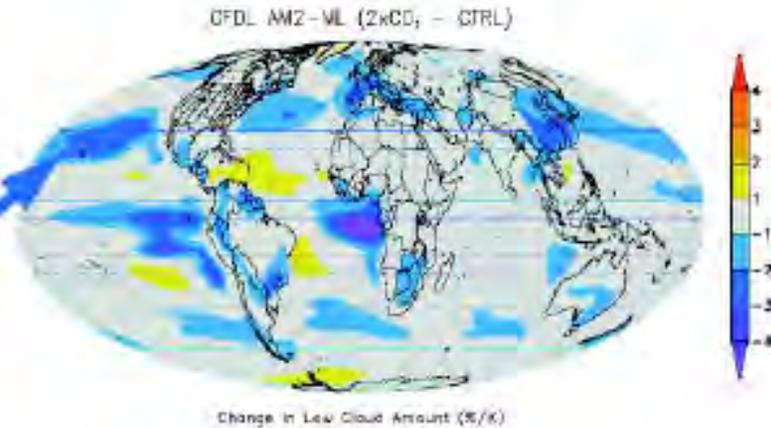
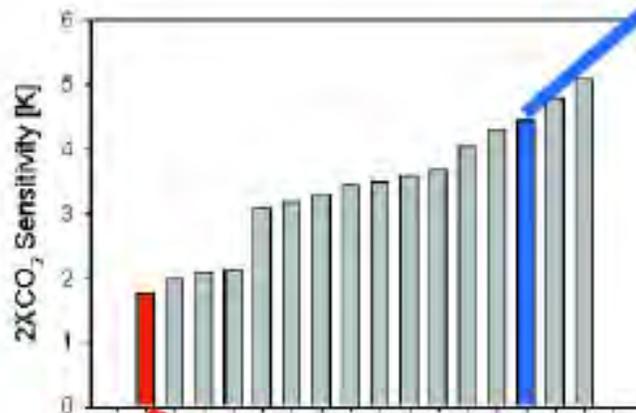
- PATMOS was a program funded by NOAA and NASA from 1990 – 1997). It applied the CLAVR-1 cloud mask to the entire AVHRR/2 afternoon GAC record and only produced total cloud amount (no other cloud products).
- PATMOS-x is the AVHRR Pathfinder Atmospheres Extended. It is based on the operational NESDIS AVHRR processing system (CLAVR-x - Cloud from AVHRR Extended).
- PATMOS-x started in 2003 as an internal NOAA/NESDIS/ORA project to demonstrate the feasibility of doing AVHRR GAC reprocessing. PATMOS-x was one of several projects funded for this purpose.
- PATMOS-x continues to evolve along with our cloud remote sensing efforts for NPOESS and GOES-R.

# Why Do This with the AVHRR?

Stephens et al, 2005

## Cloud Amount Changes due to CO<sub>2</sub> Doubling

Two models with differing 2XCO<sub>2</sub> sensitivities also exhibit differences in cloudiness.



**We should be able to see a 4% change over 20 years**

FIG. 1. The response of a number of present-day climate models forced by a 1% yr<sup>-1</sup> increase of CO<sub>2</sub>. Shown is the difference of the 20-yr average of the simulation with fixed and increasing CO<sub>2</sub>. The averages are over years 1961–80; corresponding broadly to the time of a CO<sub>2</sub> doubling. To the right are the changes to low clouds averaged over this same period for two models that fall on either end of the projected warming range (courtesy of B. Soden).

# Goals – Why are we doing this?

Stephens et al, 2005

- Climate Variability is key NOAA mission. It supports our mission for real-time cloud remote sensing.
- Clouds are major uncertainty in climate models. Satellite records are now long enough to begin to offer some relevant constraints if they are credible.
- The scientific relevance of the cloud climate records from EOS and NPOESS will be much larger if we can extend selected time series back in time using the AVHRR data. (*Ralf and I submitted a proposal to this effect*).

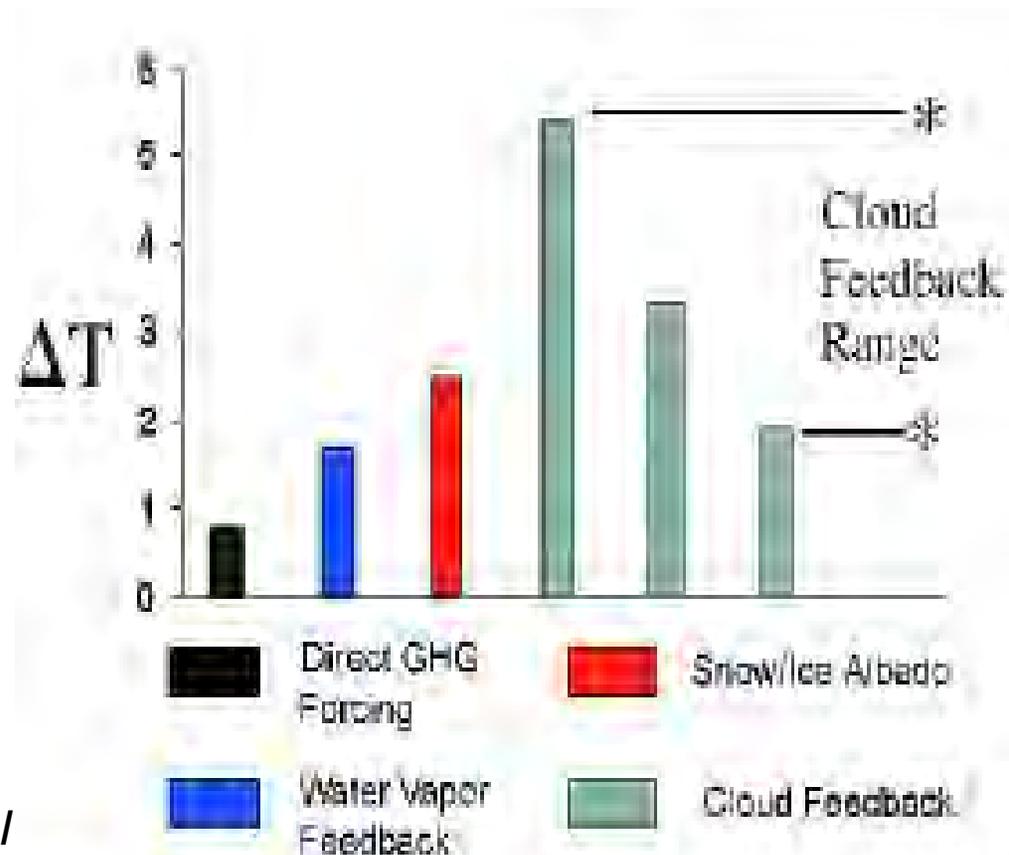


FIG. 13. The response of a single climate model to an imposed doubling of  $\text{CO}_2$  as different feedbacks are systematically added in the model (adapted from Senior and Mitchell 1993). Different treatments of cloud processes in the model produce a large spread in predicted surface temperature due to  $\text{CO}_2$  doubling.