Updates on Extending The CERES Cloud Climate Record Using AVHRR, MODIS, and NASA A-Train Data

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Collaborators

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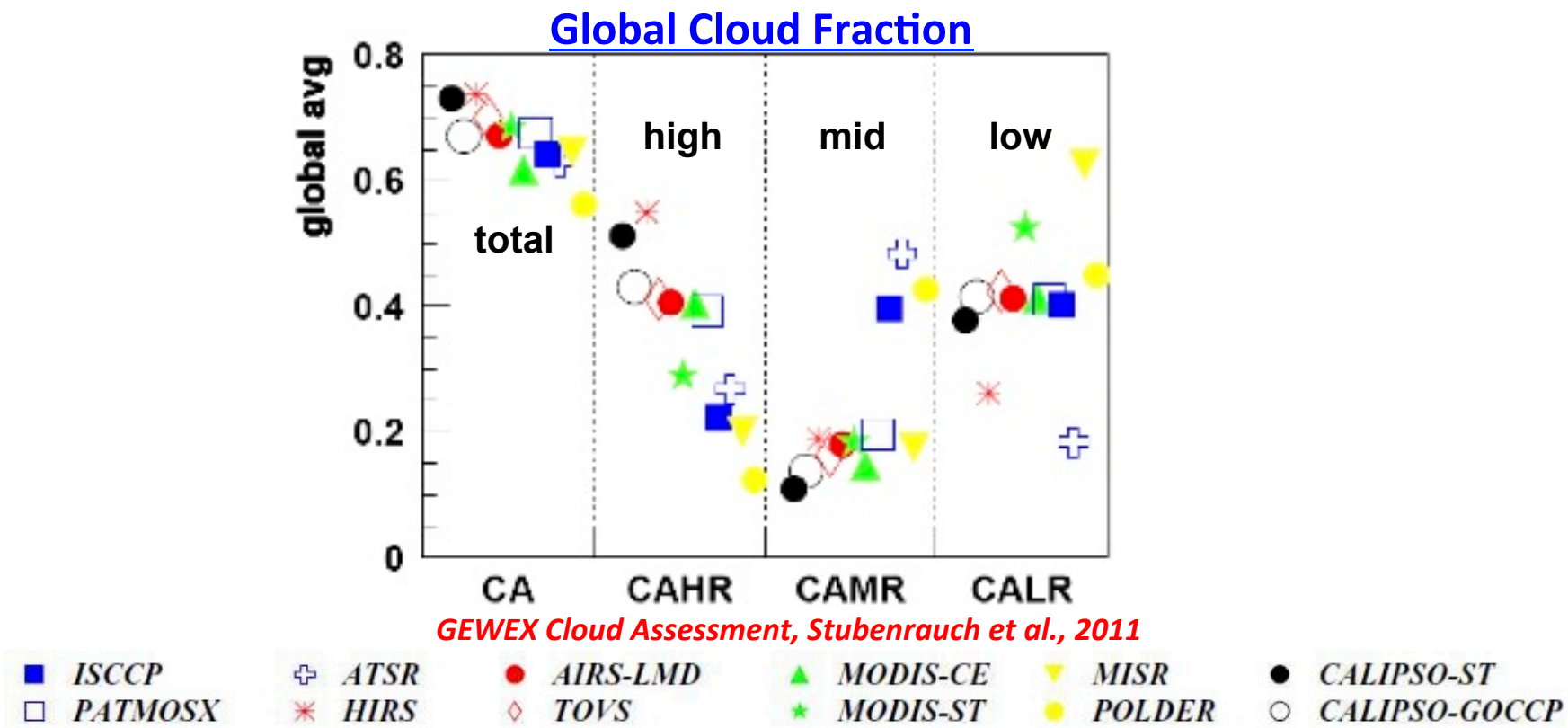
Satellite Cloud Climatology Variability

- **Satellite cloud climatologies vary with sensor and algorithm**
  - ISCCP uses multiple LEO/GEO satellites & a VIS-IR method (Rossow et al)
  - PATMOS-X uses AVHRR with a 4-channel technique (Heidinger et al.)
  - MODIS team uses MODIS with >10 channel method (King et al.)
  - CERES team uses MODIS with 4 and 12 channel technique (Minnis et al.)
  - Different NWP-based input atmosphere analyses (NCEP/NCAR, MERRA, GEOS-5/MOA)
  - Different treatment of surface albedos & emissivities, & calibrations
  - Treatment of pixels (e.g., in blocks or individually)



Motivation

- **Different techniques applied to various instruments yield different answers that tend to reflect the uncertainties in the cloud record**
  - How accurate are the trends? Are they consistent across all techniques?
    - *The more techniques we use, the better we understand the uncertainties as long the methods are reasonable. We can use these uncertainties to constrain/evaluate climate models*

- **CERES is developing a climate data record (CDR) of clouds and radiation fluxes**
  - 2000 (Terra), 2002 (Aqua), 2011 (S-NPP) → 2016 (JPSS) → 20??
  - CERES results reasonable, relatively well validated & understood

- **Can we extend that cloud CDR back in time?**
  - AVHRR has the core channels used by the CERES cloud algorithms

- **GOAL: Develop a cloud CDR from AVHRR data for NOAA NCDC that is consistent (as possible) with CERES, yet extends from ~1978 to the present**
  - Extend CERES clouds back in time using an adaptation of CERES cloud algorithms
  - ERBE has collected broadband radiation measurements from 1984-2003
    - *Make a CERES-like radiation product (led by S. Kato) using AVHRR clouds for NOAA NCDC and NASA MEaSUREs*

Background

- **Goals**
  - Calibrate AVHRR 0.64, 0.87, and 1.6-µm channels
  - Generate CERES-like cloud climatology from AVHRR record

- **Source Data**
  - AVHRR ~4 km Global Area Coverage (GAC) data: 1978 – present
  - SCHIAMACHY hyperspectral data (2004-2009)

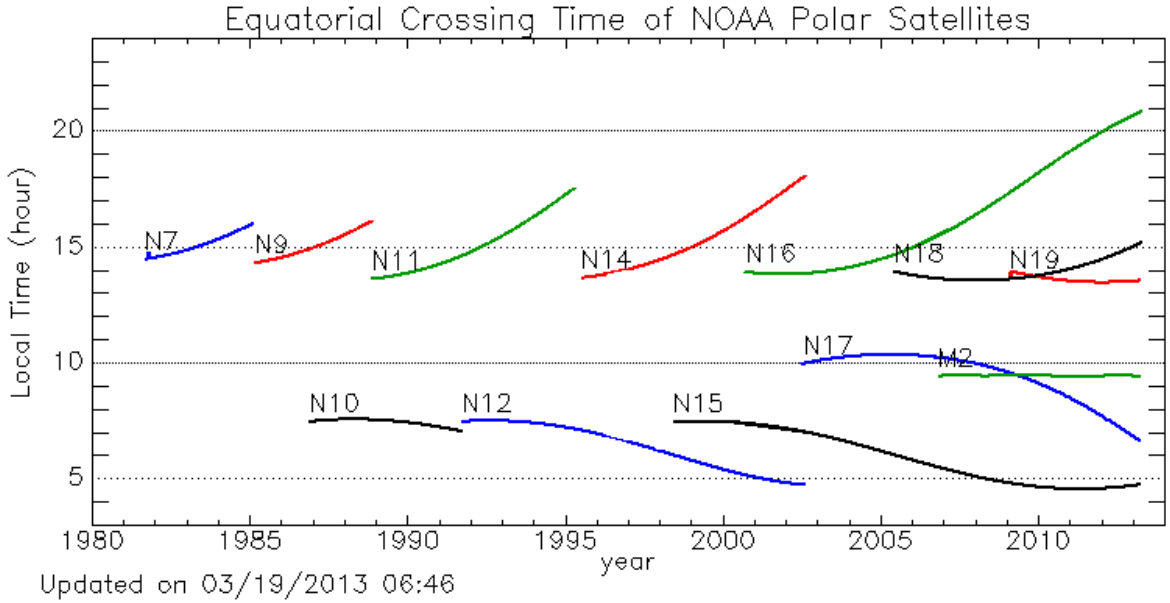
- **Deliverables**
  - **CalibratedAVHRR 0.63, 0.86, and 1.6-µm radiances and calib coefficients**
  - **CDRs of Cloud Mask, Cloud Phase, Cloud Effective T/P/Z, Optical Depth, and Particle Effective Radius**
  - **Other datasets: , Surface Skin Temperature, Broadband SW/LW flux, Cloud Top and Base T/P/Z, Overshooting Convective Cloud Top Detection, Quality Indicators for Mask/Phase/Skin Temp**

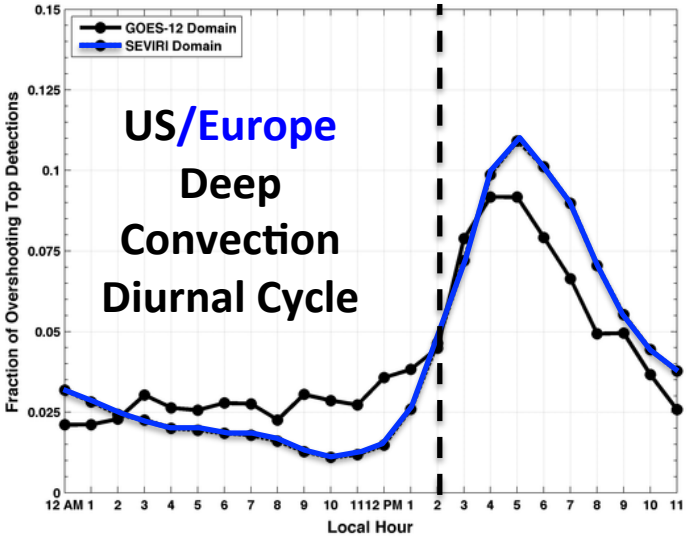
Advanced Very High Resolution Radiometer (AVHRR) Instrument Background

- **AVHRR is a 5-channel imager aboard NOAA POES and NOAA/EUMETSAT IJPS satellites, the first of which launched in 1978**
  - **Core AVHRR spectral channels: 0.63, 0.86, 3.74, 10.8, and 12.0 µm**
  - **Latest AVHRRs provide 1.61 µm data during the day instead of 3.74 µm**

- **Four "classes" of AVHRRs, creates challenges for algorithm development**
  - **NOAA-15 to present: Core channels**
  - **NOAA-7,-9,-11,-14: Core channels but 3.74 µm channel has differing calibration and relatively poor data quality**
  - **NOAA-16 (2 years) and -17, MetOp-A and –B: 1.61/3.74 µm daytime switching**
  - **TIROS-N, NOAA-6, -8, and -10: No 12.0 µm channel**

- **Orbit drift throughout instrument lifetime can be substantial**





AVHRR Cloud and Clear-Sky Property CDR: Development Approach

- **Re-navigate, calibrate, and noise filter (pre-NOAA-15 3.7 µm channel) AVHRR observations**

- **Adapt CERES Ed4 mask and retrieval logic to operate upon AVHRR**

  - **Test & tune based on NOAA-18 using comparisons with CERES Aqua MODIS and CALIPSO**

    - *Test using scenes across diverse regions, surface types, and seasons*

  - **Compare zonal and monthly average results with CERES MODIS, GSFC MODIS, EUMETSAT CMSAF, ISSCP, PATMOS-X (if available), and CALIPSO**

    - *Also, compare results from AVHRRs operating in same month, assess impact of varying solar illumination*

  - **Derive AVHRR pixel-level product validation via comparison with A-Train, NOAA OISST, and ground-based datasets**

  - **Process AVHRR data record from 1978-present**

- **Produce CF-compliant NetCDF files with all AVHRR products at the pixel scale (170 Mb / ~2 hrs of orbit time)**

Solar Channel Calibration Methodology

- **3 Calibration Methods, all independently referenced to Aqua-MODIS**
  1) **Simultaneous Nadir Overpasses (SNO)**

  2) **Deep Convective Cloud Technique** (DCC; Doelling et al. 2013)

  3) **Invariant-site Approach** (Libya-4, Dome-C, etc.; Bhatt et al. 2013)

  * SCIAMACHY hyperspectral sensor used to account for spectral band differences for the visible channels for all 3 methods above (Doelling et al. 2013)

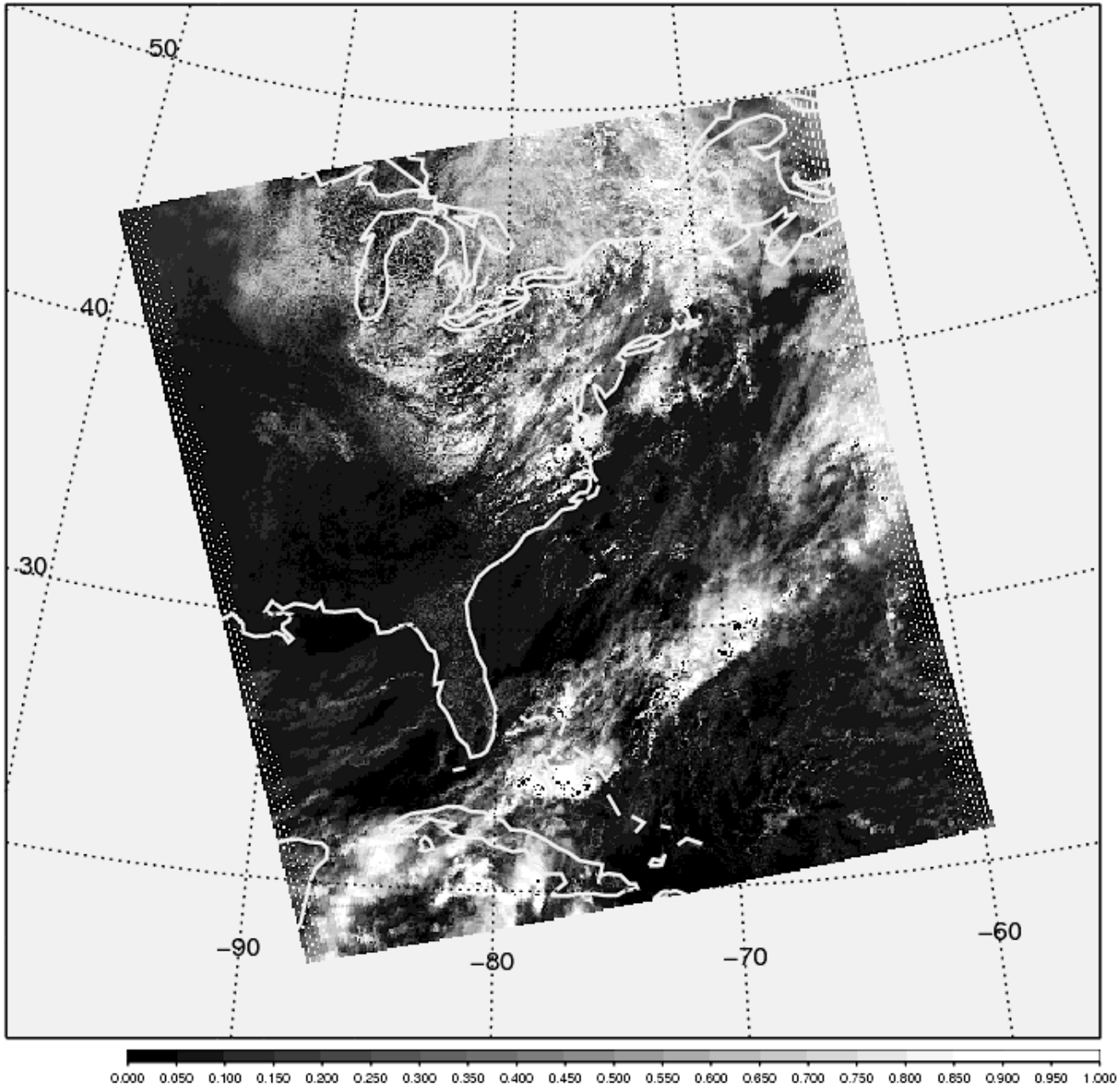
- **Calibration of NOAA AVHRR sensors**
  - **During MODIS timeframe**
    - SNO comparisons with MODIS establish standard gain trend
    - Invariant-site and DCC techniques validated by SNO method during AVHRR-MODIS overlap period

  - **Prior to MODIS, use combination of invariant-site and DCC techniques referenced to Aqua-MODIS to determine AVHRR gain trend**

NASA LaRC AVHRR Cloud and Clear-Sky Property CDR: Ancillary Inputs

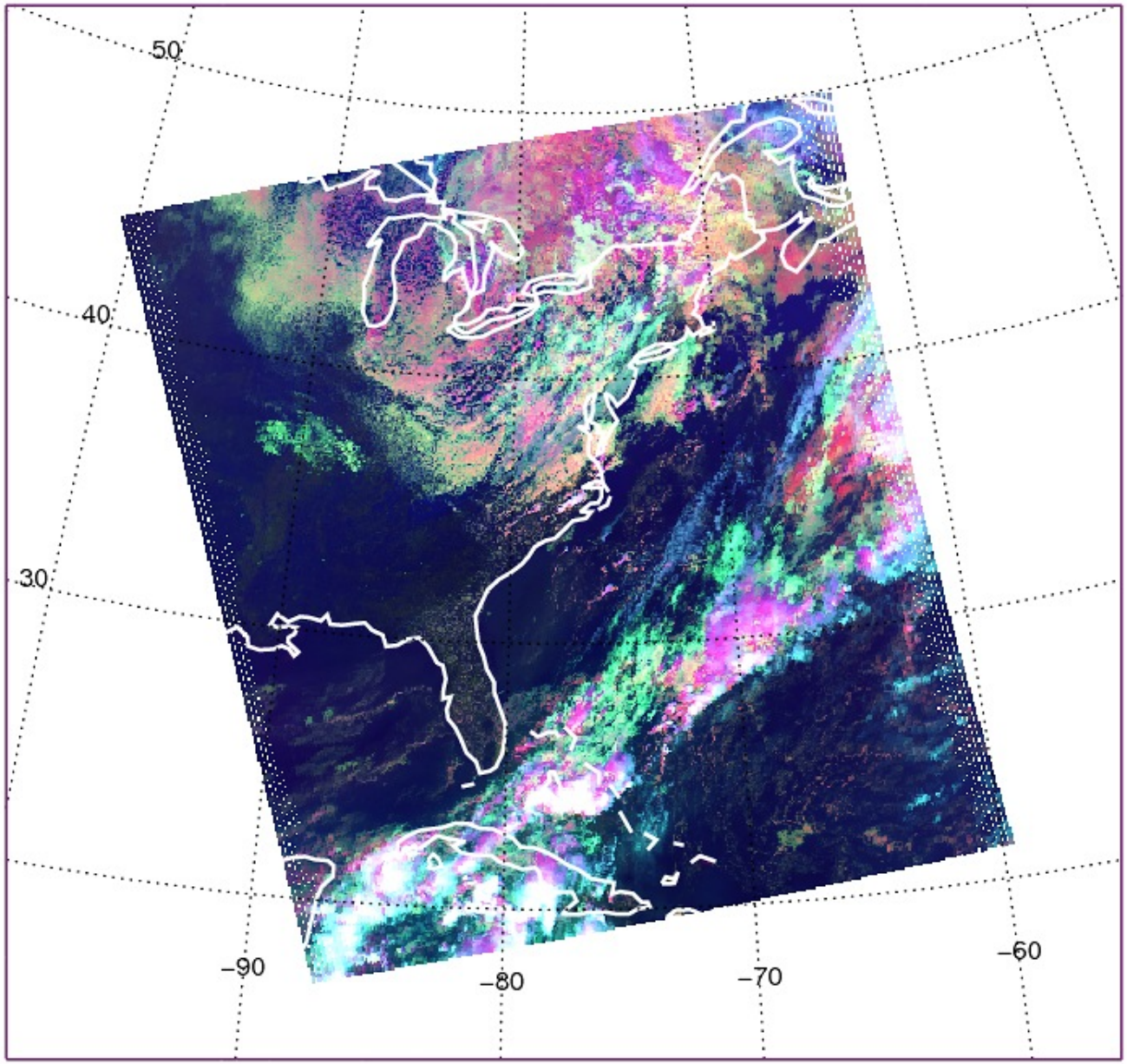
- **NASA Modern Era Retrospective Analysis for Research and Applications (MERRA) 3-D thermodynamic and ozone profiles, surface fields, and snow/ice cover maps**
  - 0.5 x 0.66° spatial resolution, 42 vertical levels, 6-hourly profiles, hourly surface data
- **10-minute spatial resolution land surface elevation, water percentage, IGBP ecosystem, surface emissivity, and many others from the CERES MODIS framework**
- **Dynamically generated clear sky overhead albedo maps based on CERES Ed4 logic and clear-sky AVHRR observations**
- **Cloud microphysical models for spherical water droplets and roughened ice crystals from P. Yang and G. Hong**
- **Directional and bi-directional surface reflectance models for each IGBP land surface type with and without ice- or snow-cover**
- **and many more….**

NOAA Climate Data Record of AVHRR 0.63 Micron Channel Reflectance 2008275 S1812 E2007 UTC



NASA LaRC

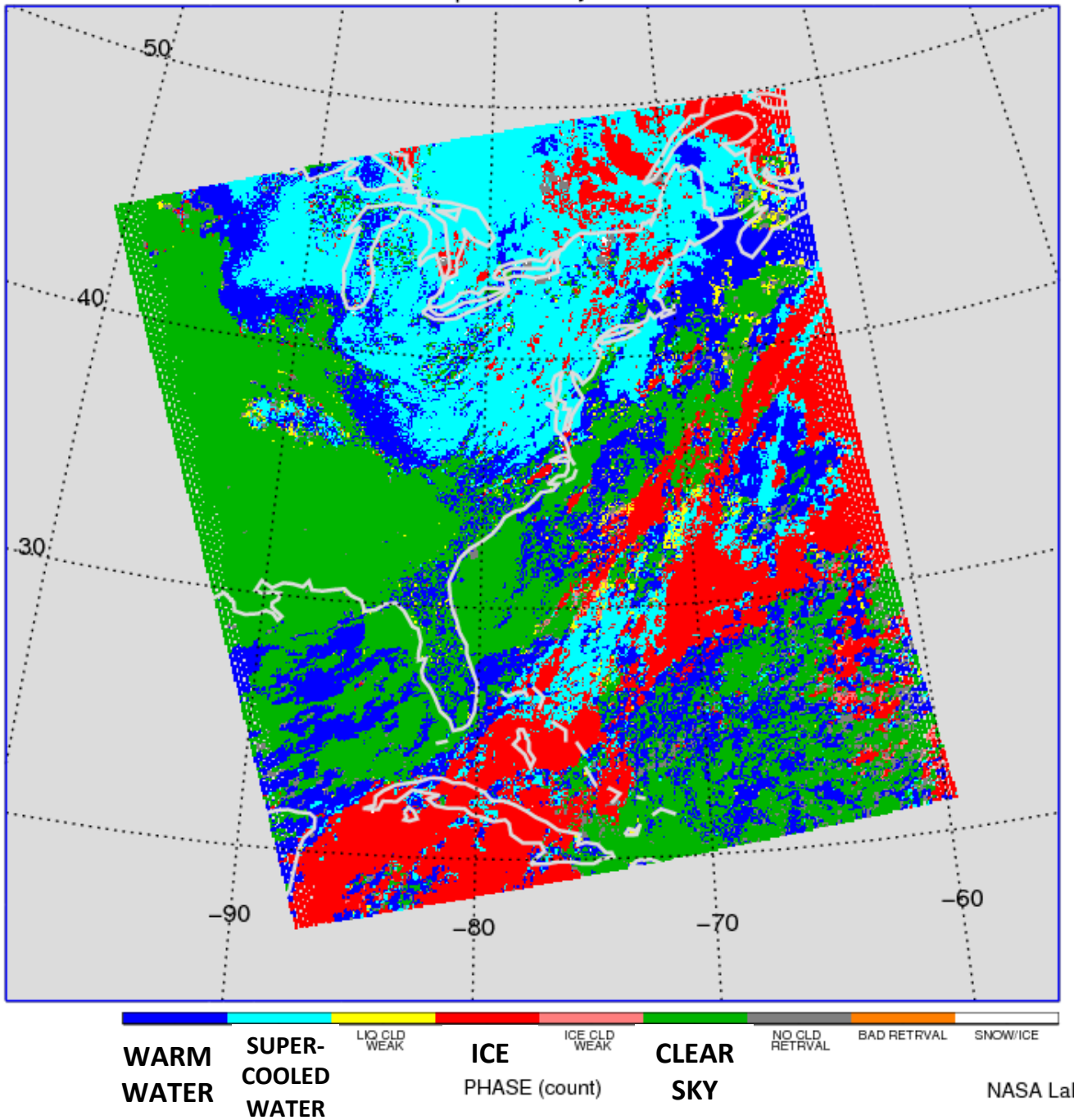
Multichannel–RGB 2008275 S1812 E2007 UTC

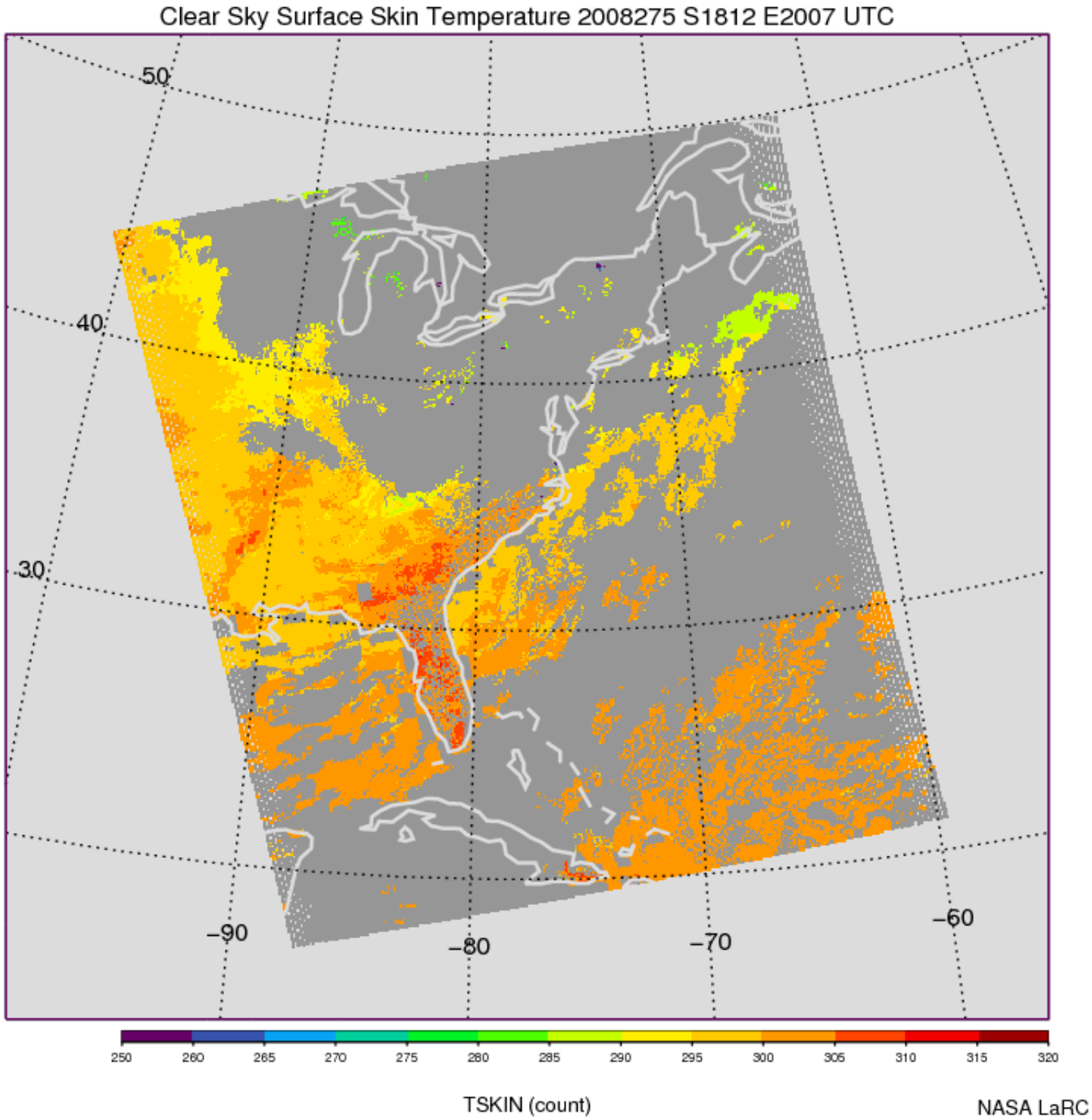


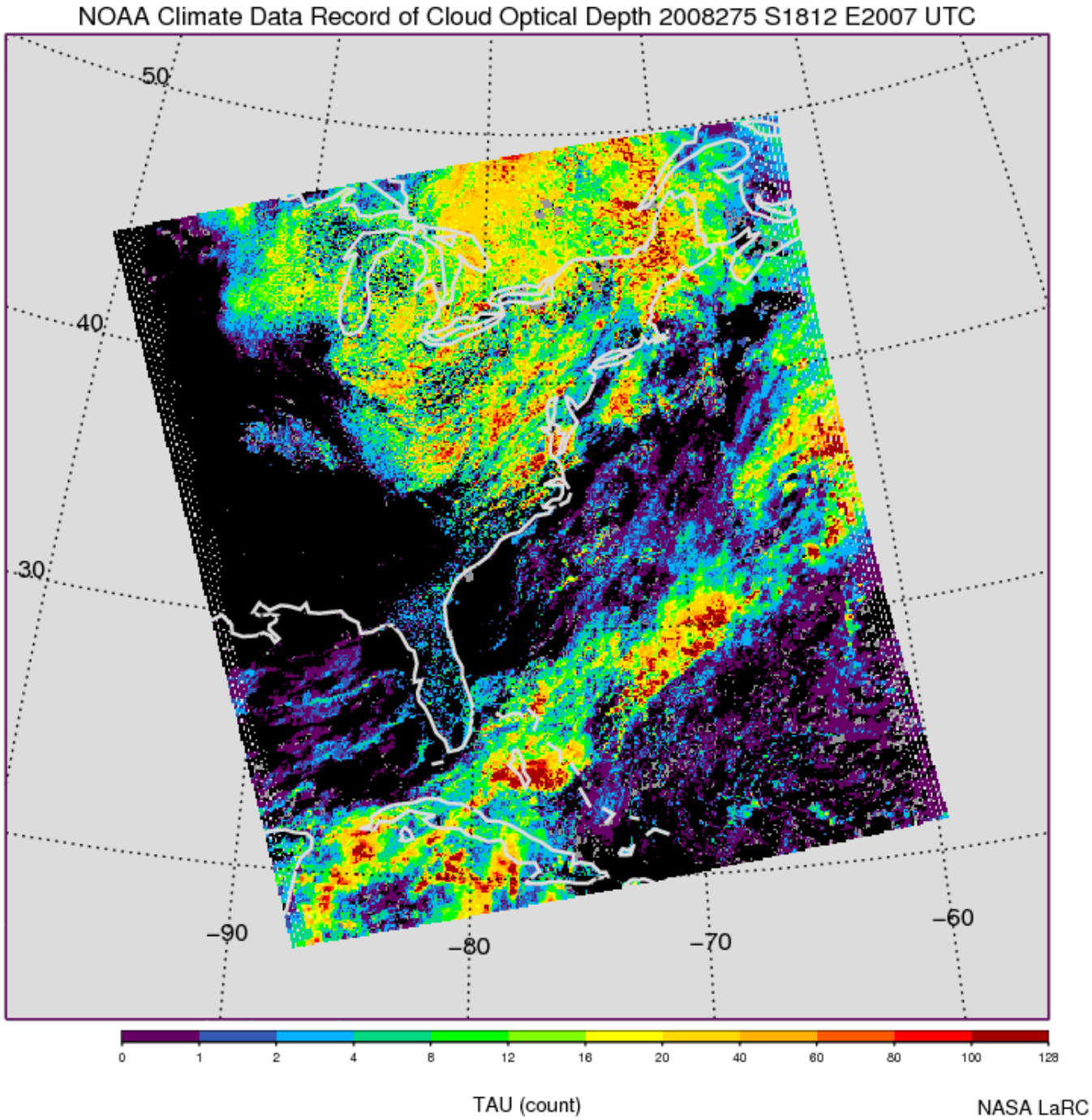
RED=R6.5 GRN=T3.7–11 BLUE=T11

NASA LaRC

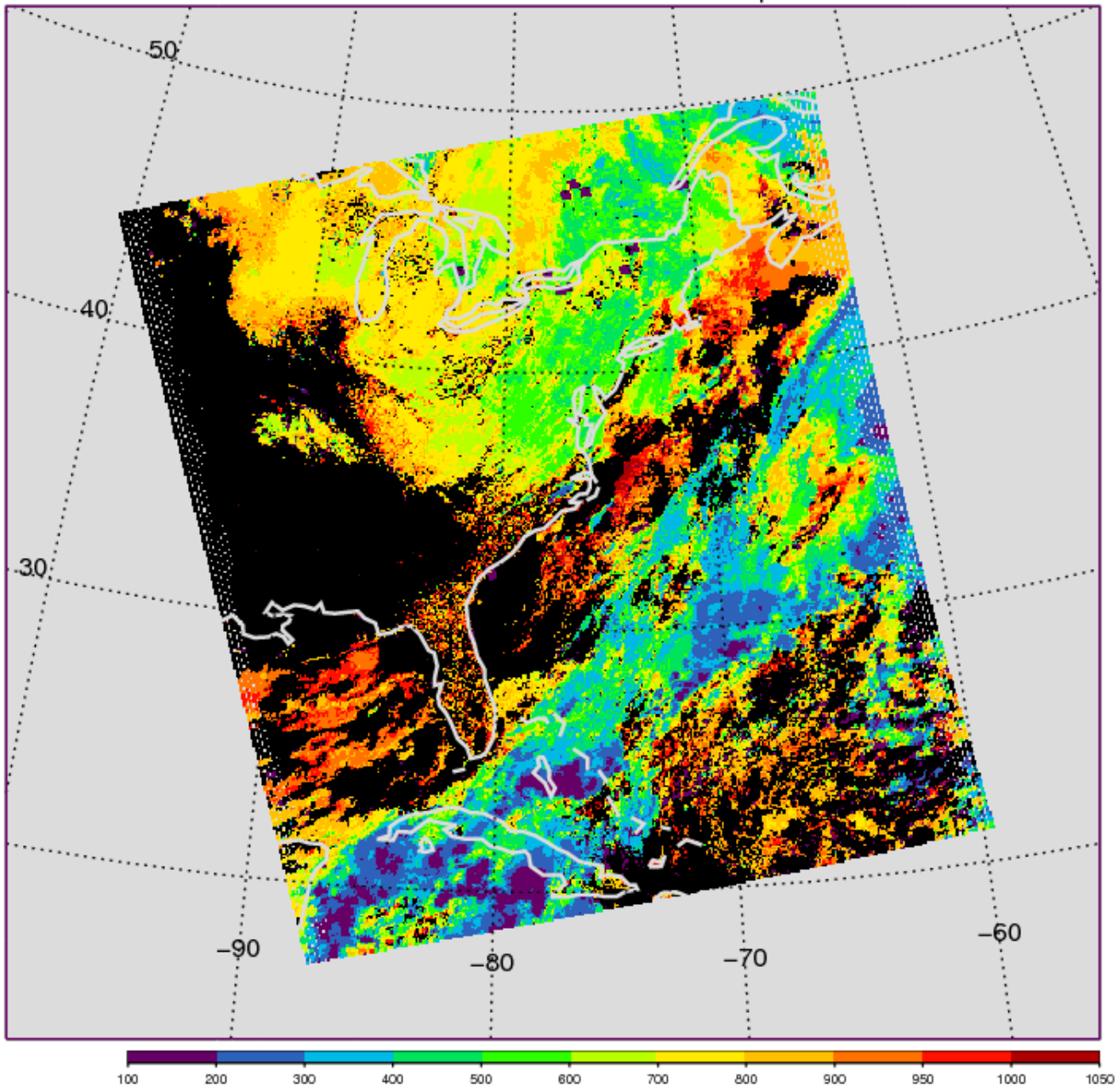
NOAA Climate Data Record of Cloud Top Thermodynamic Phase 2008275 S1812 E2007 UTC




Clear Sky Surface Skin Temperature 2008275 S1812 E2007 UTC
50
40
30
−90
−80
−70
−60
250
260
265
270
275
280
285
290
295
300
305
310
315
320
TSKIN (count)
NASA LaRC

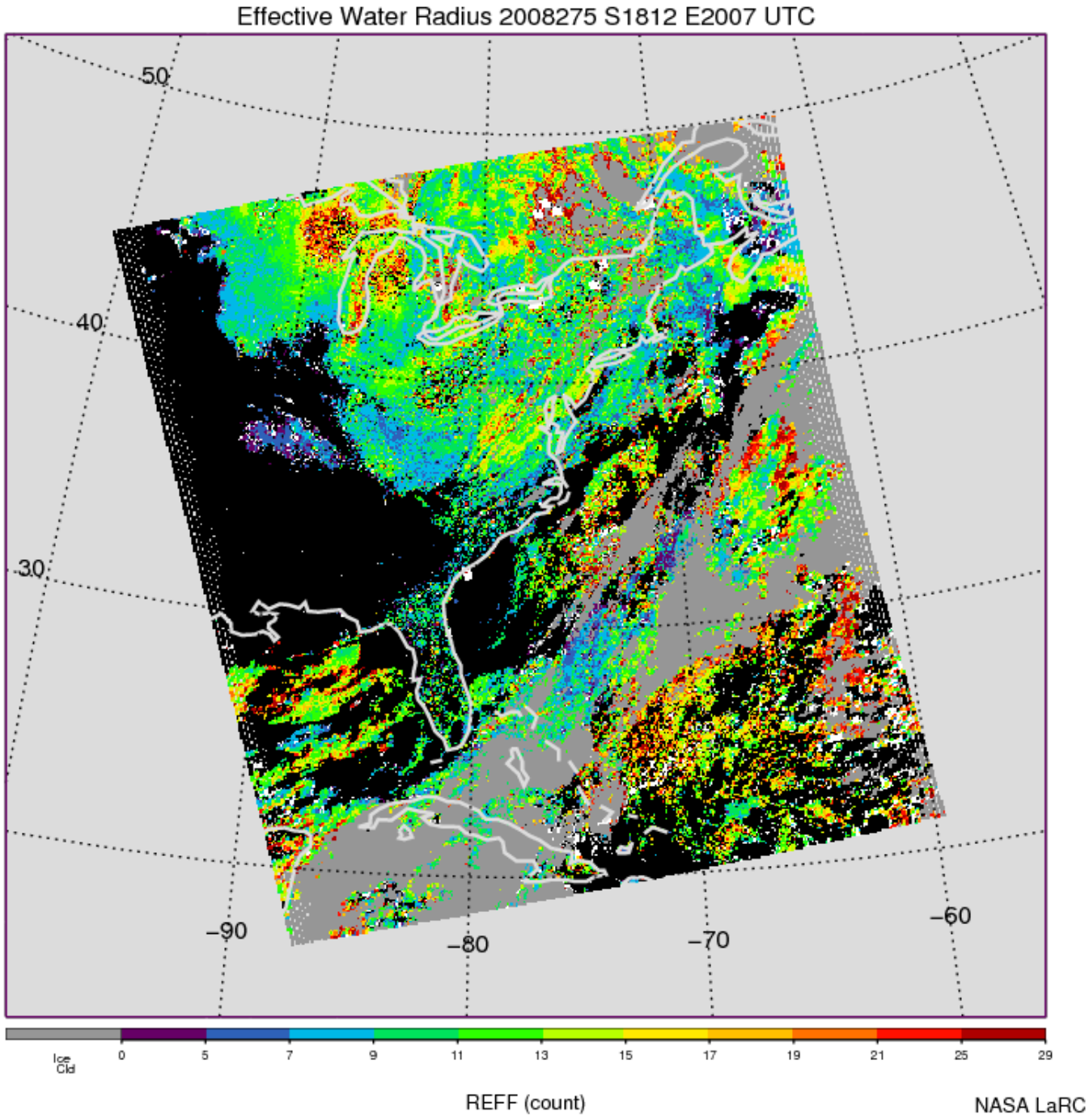

NOAA Climate Data Record of Cloud Optical Depth 2008275 S1812 E2007 UTC
50
40
30
−90
−80
−70
−60
0
1
2
4
8
12
16
20
40
60
80
100
128
TAU (count)
NASA LaRC

NOAA Climate Data Record of Air Pressure At Effective Cloud Top 2008275 S1812 E2007 UTC



PEFF (count)

NASA LaRC


Effective Water Radius 2008275 S1812 E2007 UTC
50
40
30
−90
−80
−70
−60
Ice
Cld
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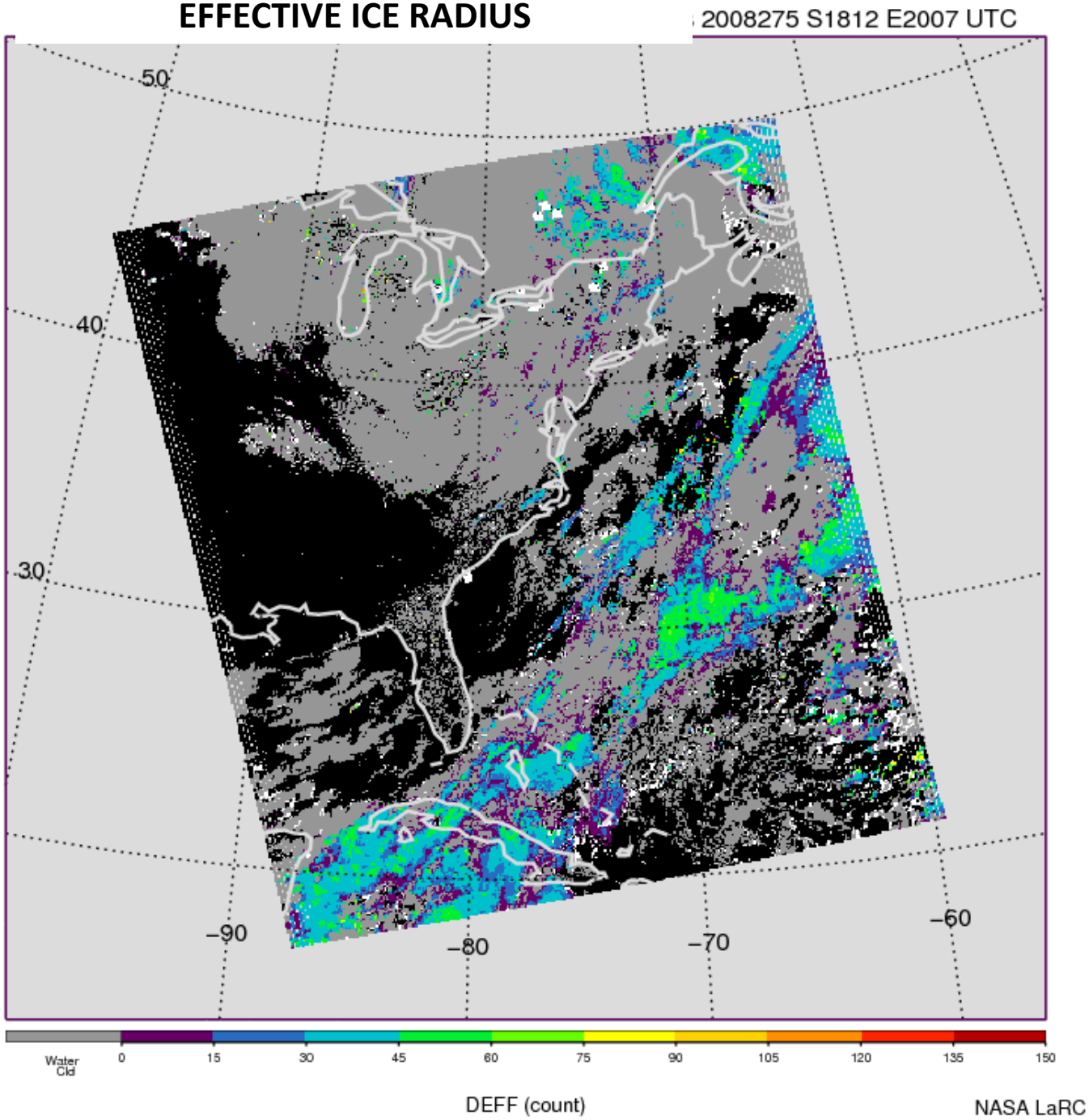
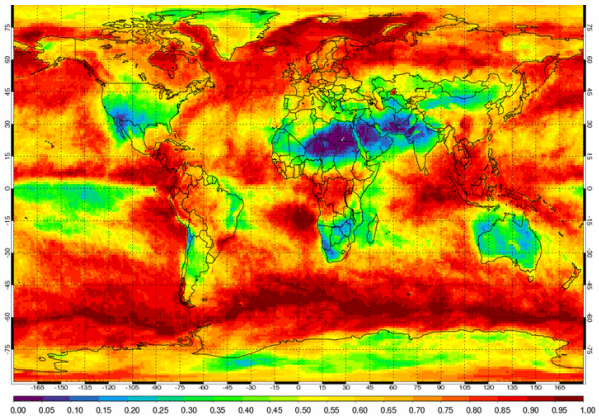
7
9
11
13
15
17
19
21
25
29
REFF (count)
NASA LaRC

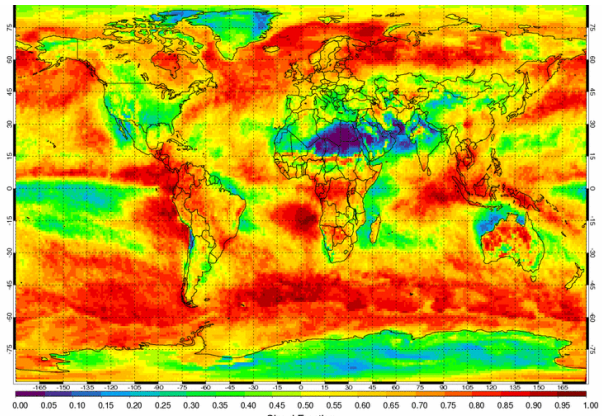
EFFECTIVE ICE RADIUS



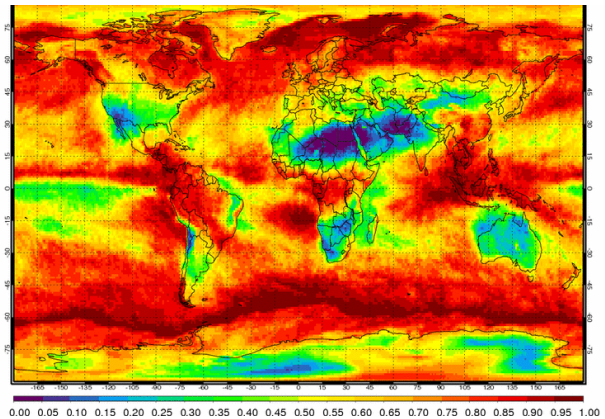
LaRC NOAA-18



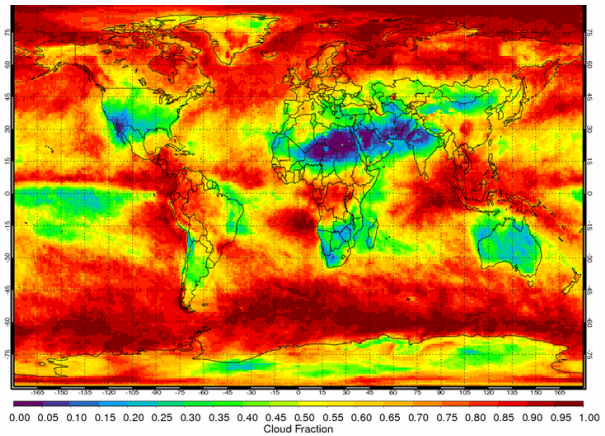
EUMETSAT CMSAF NOAA-18



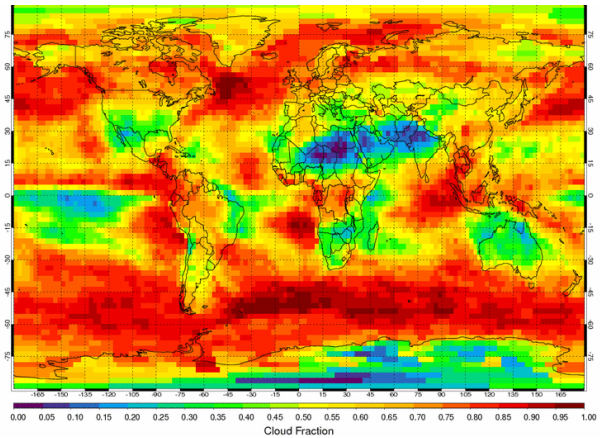
GSFC Aqua MODIS Col. 5



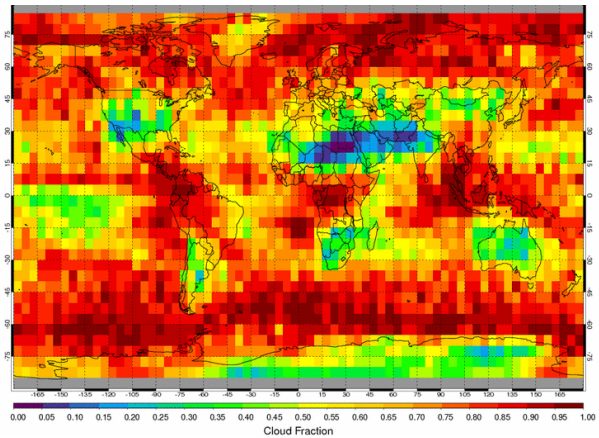
CERES Aqua



ISCCP



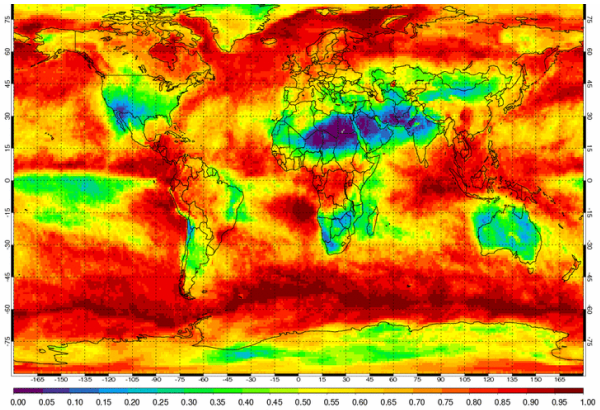
CALIPSO



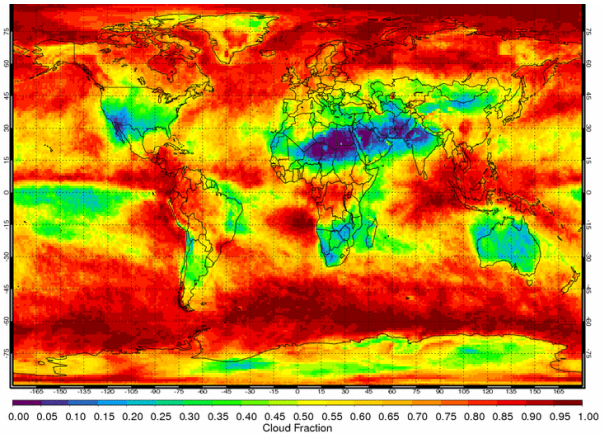
Cloud Fraction October 2008

	LaRC AVHRR	CERES Aqua MODIS	EUMETSAT CMSAF	GSFC Aqua MODIS	ISCCP	CALIPSO
GLOBAL CLOUD FRACTION	0.678	0.671	0.623	0.684	0.649	0.666

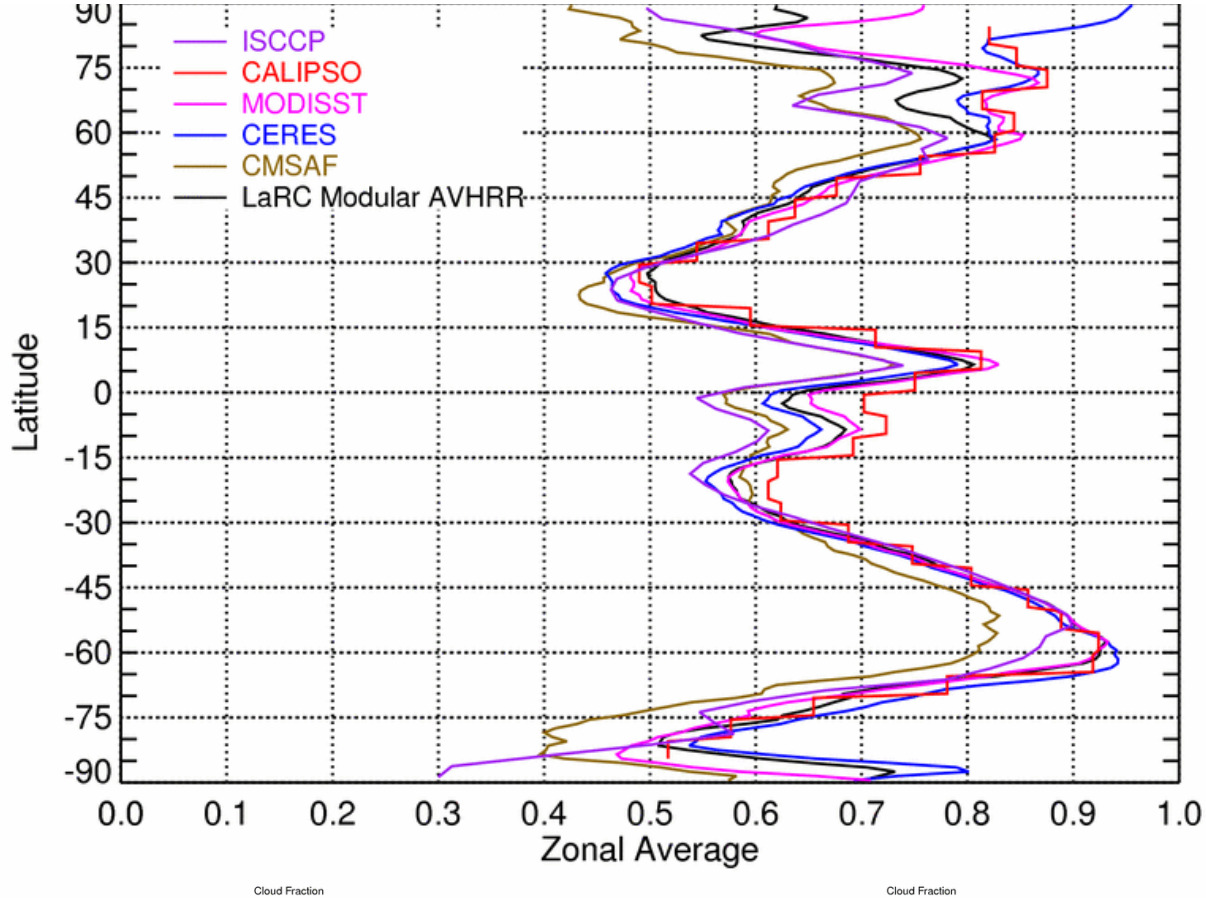
LaRC NOAA-18



CERES Aqua



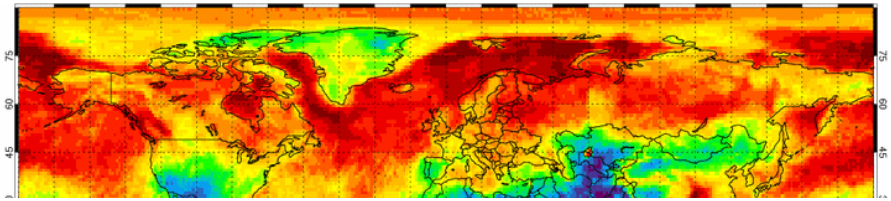
October 2008 Zonal Average Cloud Fraction: Day and Night



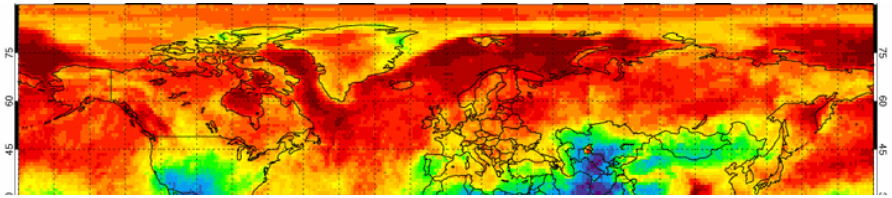
Cloud Fraction October 2008

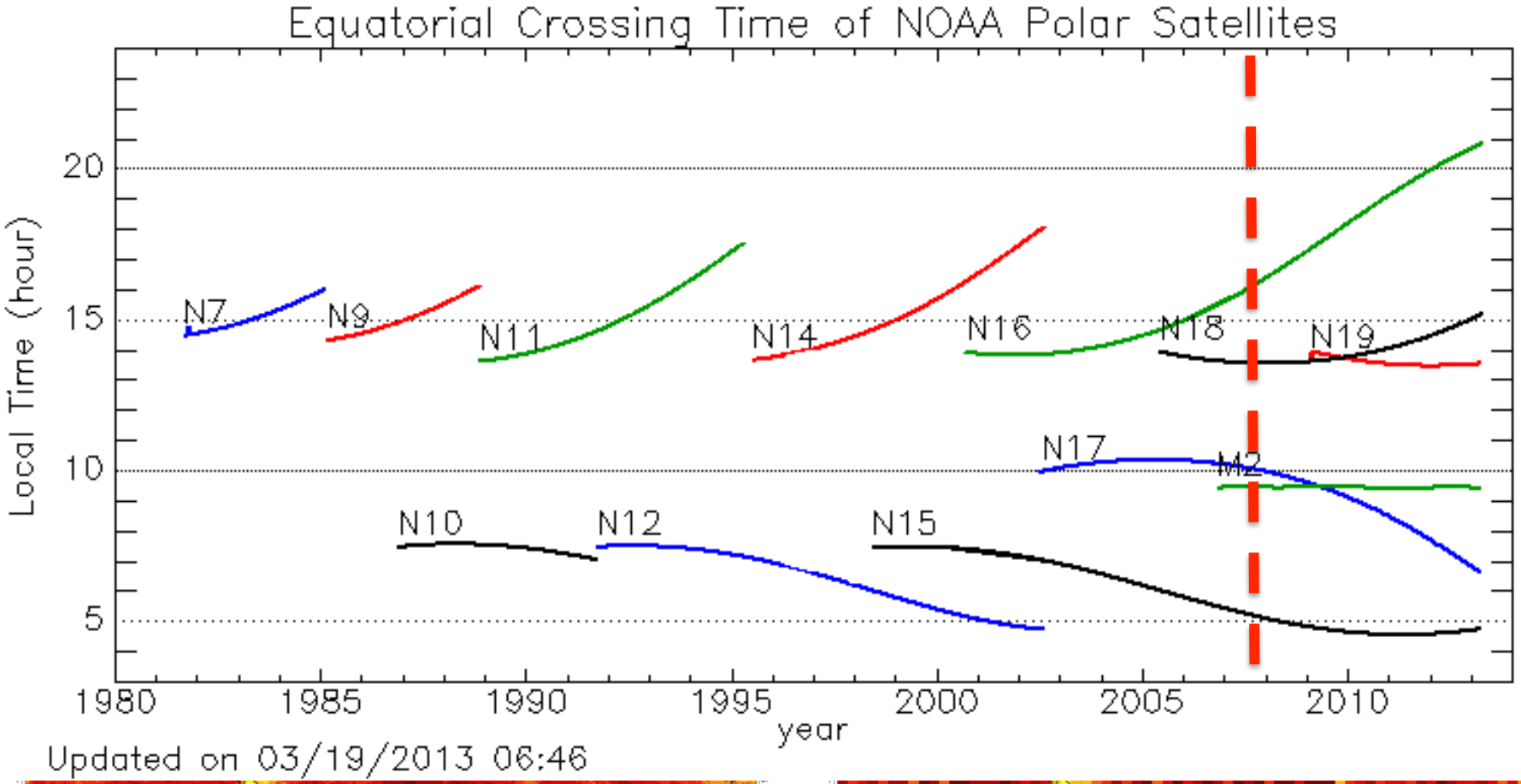
- **LaRC AVHRR quite close to CERES MODIS and CALIPSO**
- **5-10% uncertainty amongst algorithms common in non-polar regions**
- **Polar uncertainty much greater**

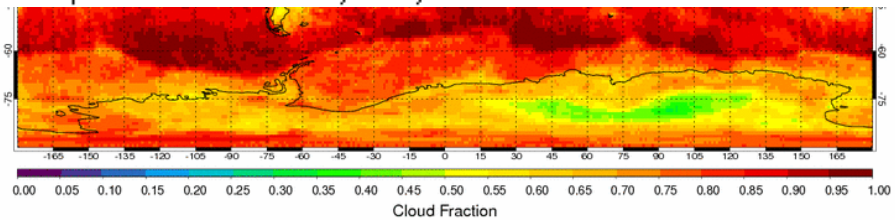
LaRC NOAA-18 Cloud Fraction October 2007: 2 AM/PM

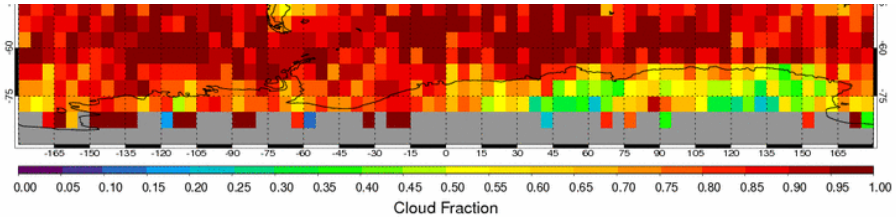


LaRC NOAA-16 Cloud Fraction October 2007: 4 AM/PM

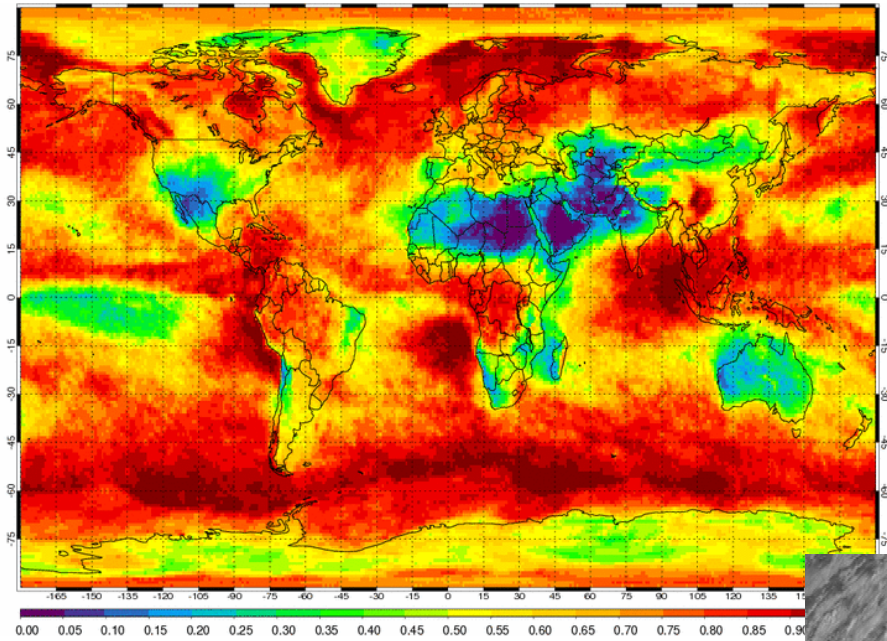




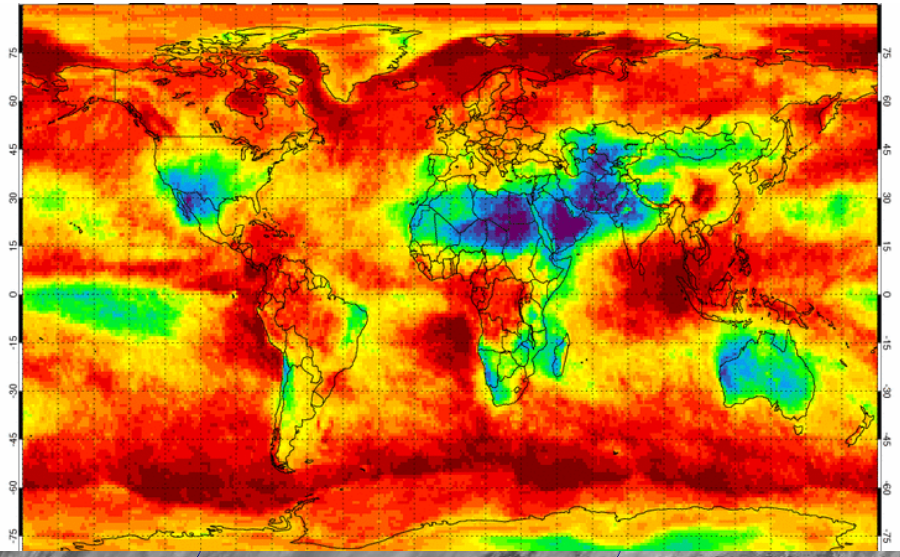




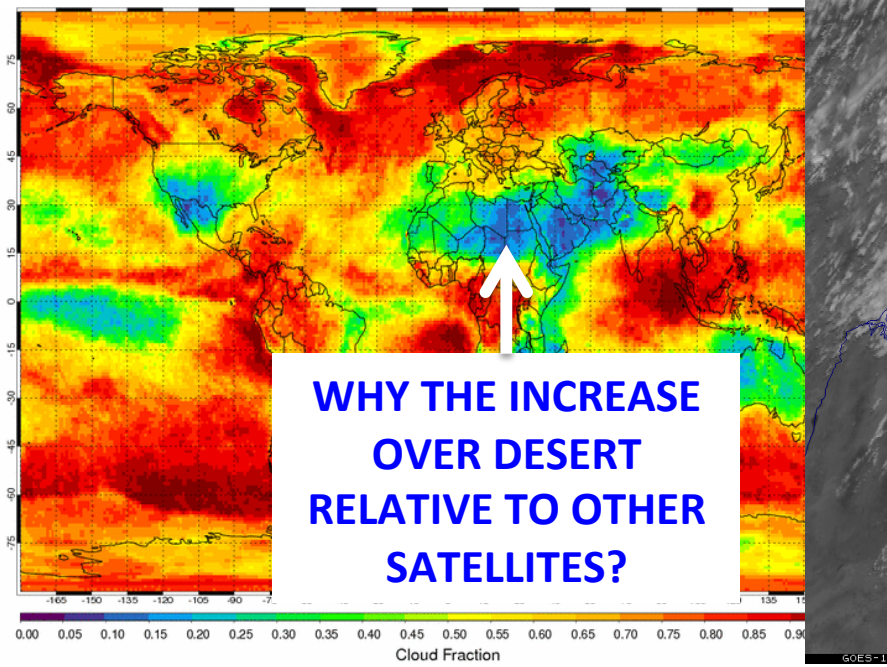
LaRC NOAA-18 Cloud Fraction October 2007: 2 AM/PM



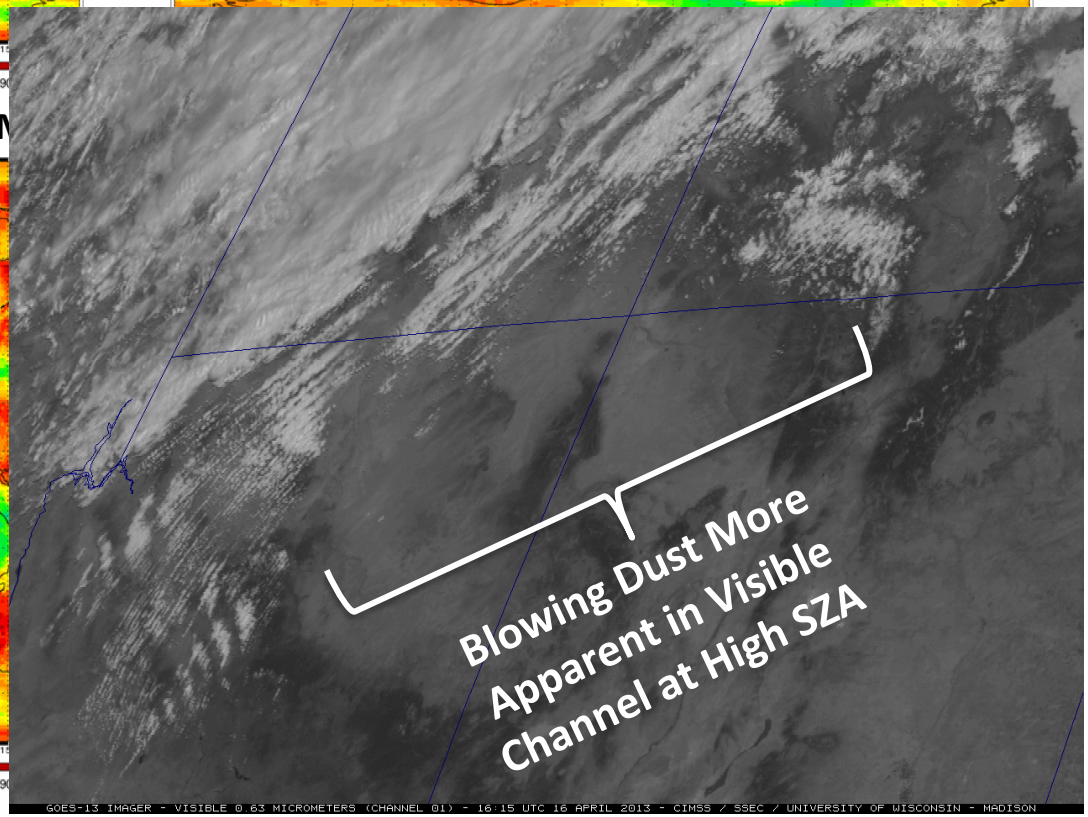
LaRC NOAA-16 Cloud Fraction October 2007: 4 AM/PM



LaRC NOAA-15 Cloud Fraction October 2007: 5 AM



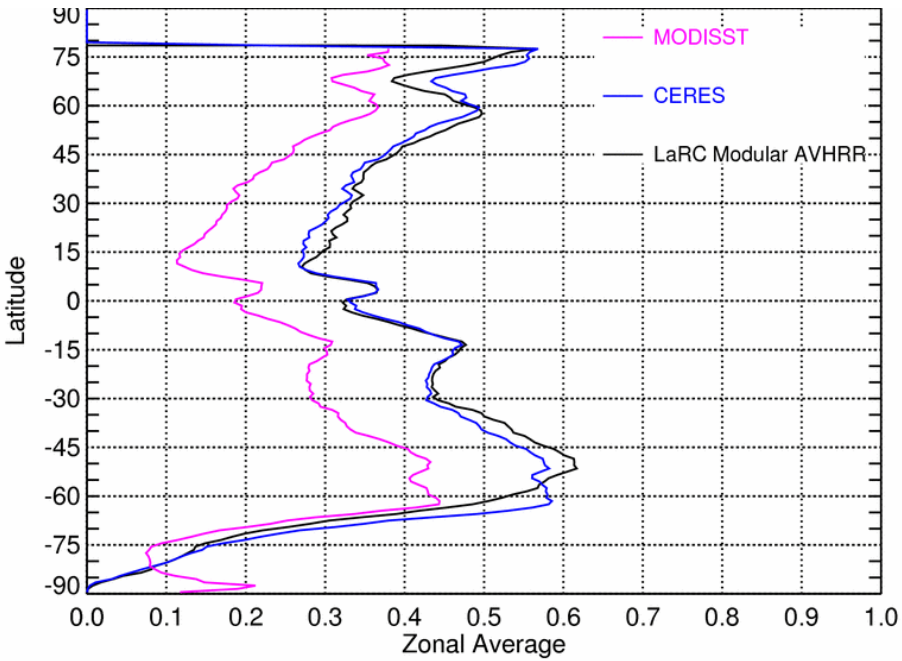
WHY THE INCREASE OVER DESERT RELATIVE TO OTHER SATELLITES?



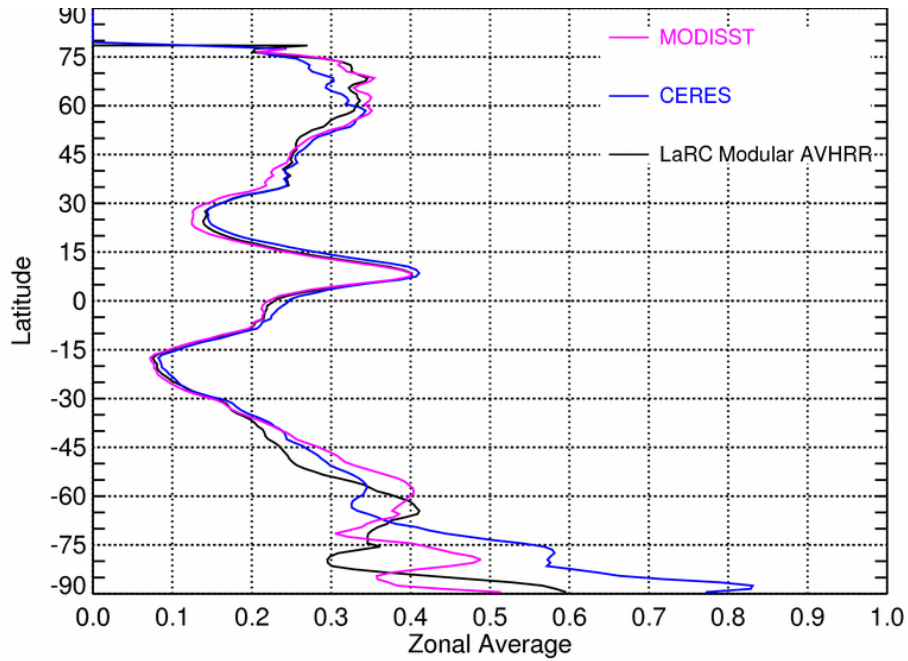
Daytime Cloud Fraction By Cloud Phase

- **Good agreement between LaRC AVHRR and CERES in non-polar regions**
- **GSFC MODIS Science Team product agrees well for ice clouds but does not assign enough water phase**

Water Cloud Fraction: October 2008



Ice Cloud Fraction: October 2008



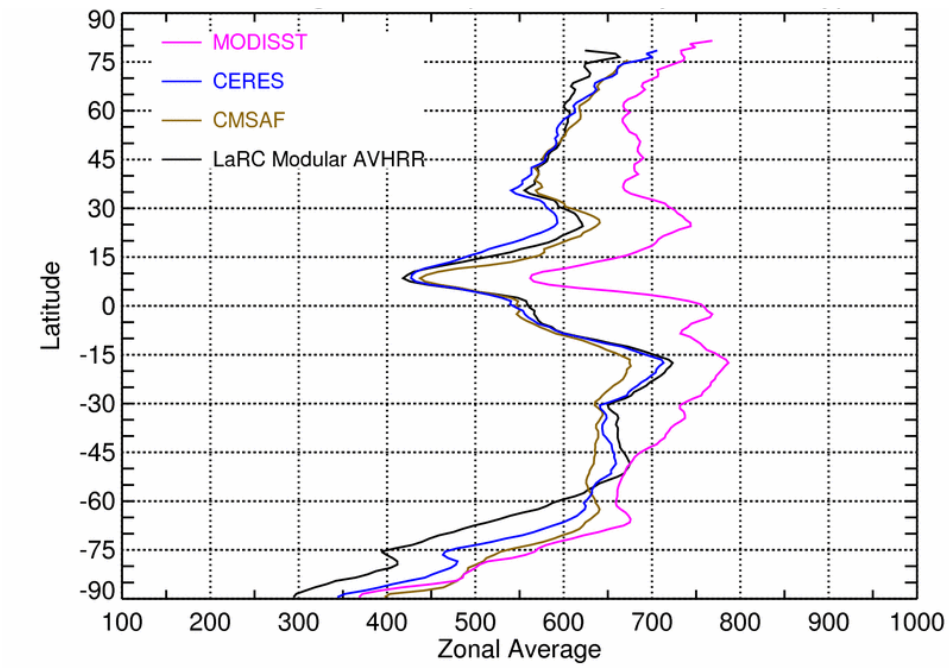
Cloud Top Pressure

- **AVHRR-CERES agreement quite good, except night-time tropical where AVHRR underestimates**

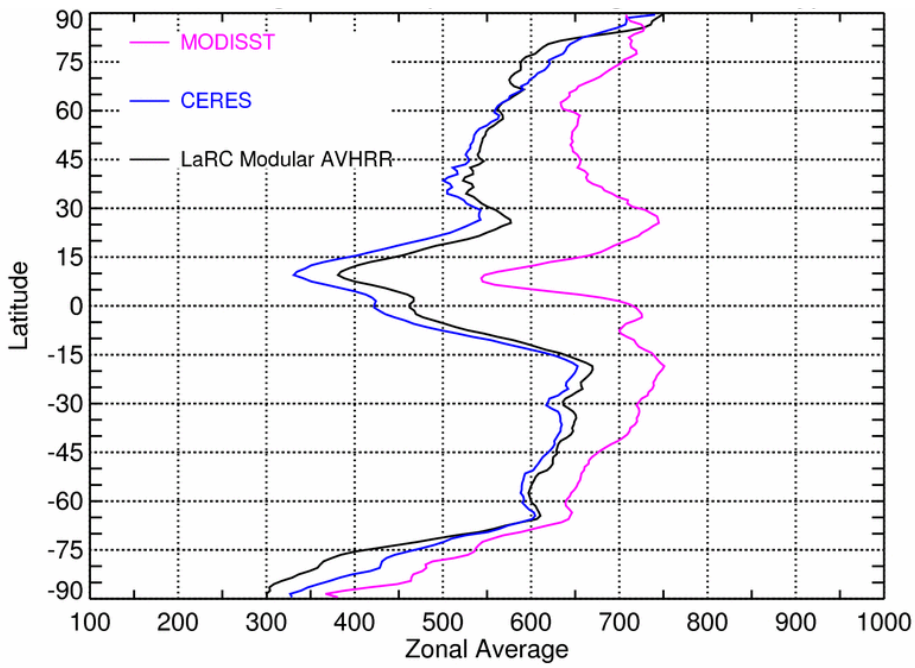
- **Maximum AVHRR-CERES zonal mean difference during day**
  - non-polar = 20 hPa polar: 60 hPa

- **Maximum AVHRR-CERES zonal mean difference during night**
  - non-polar and polar: 60 hPa

Day Cloud Top Pressure: October 2008

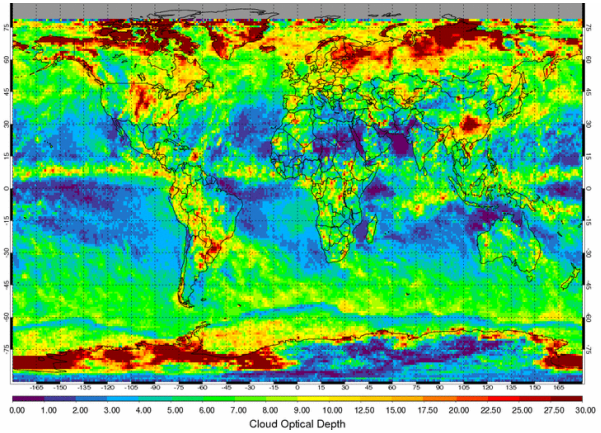


Night Cloud Top Pressure: October 2008

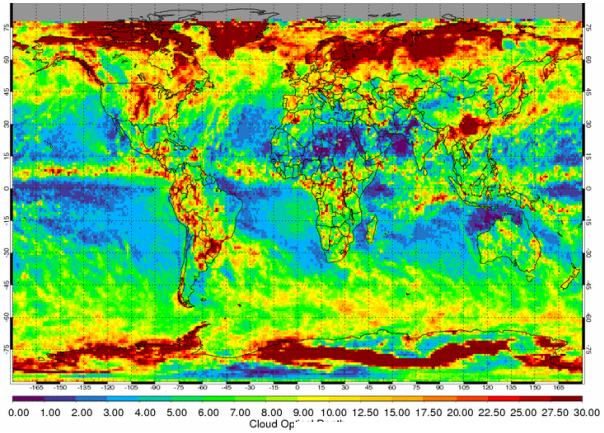


Monthly Average Cloud Optical Depth
October 2008, Daytime

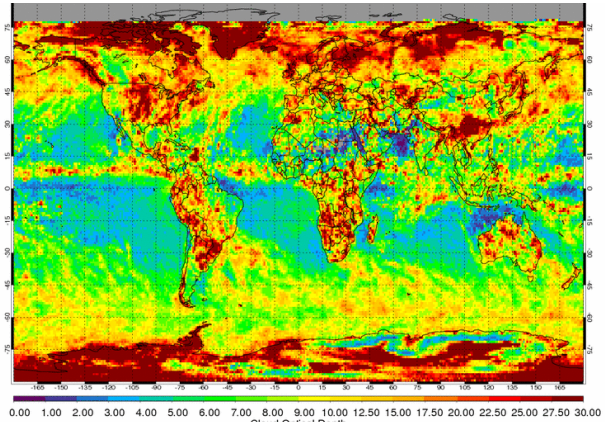
LaRC NOAA-18



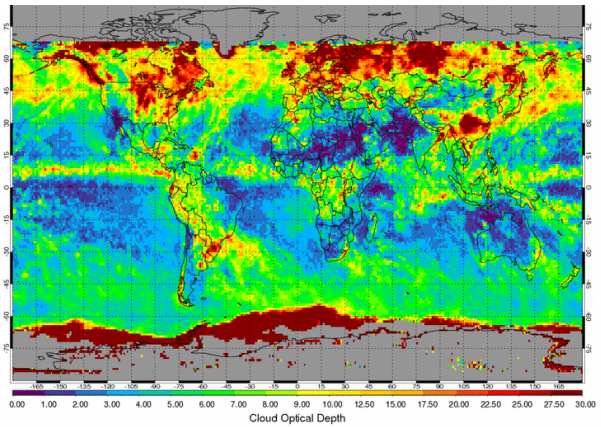
CERES Edition 4



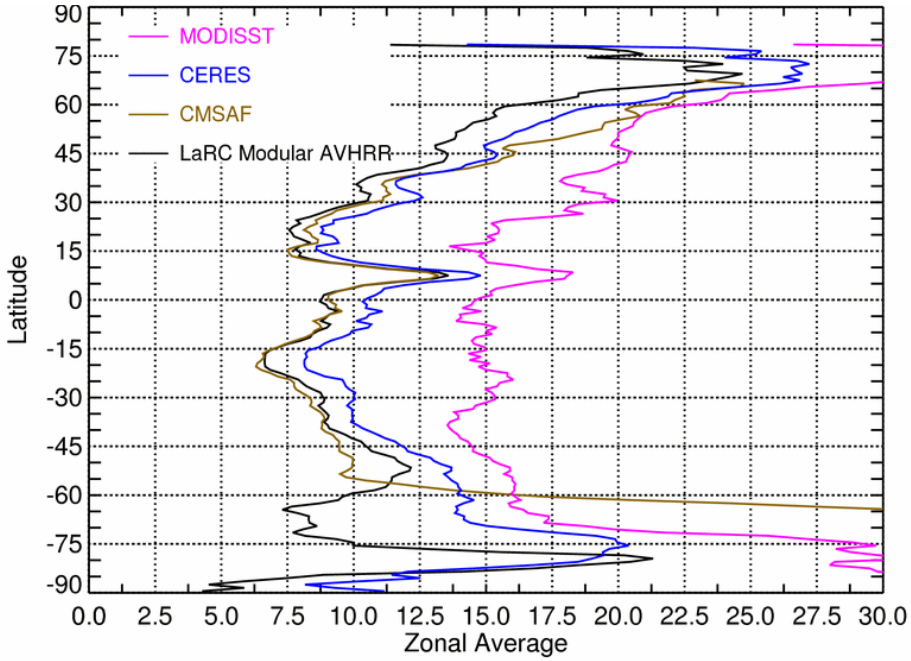
MODIS Science Team (Col. 5)



CMSAF

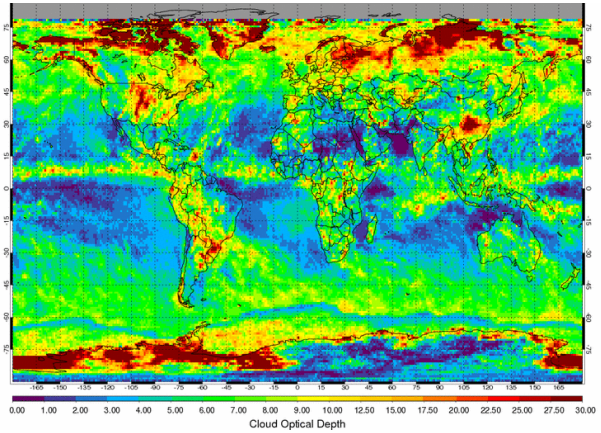


October 2008 Zonal Average Optical Depth

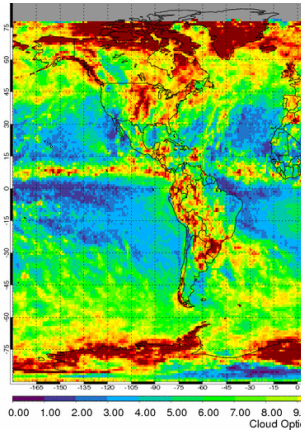


Monthly Average C
October 20(

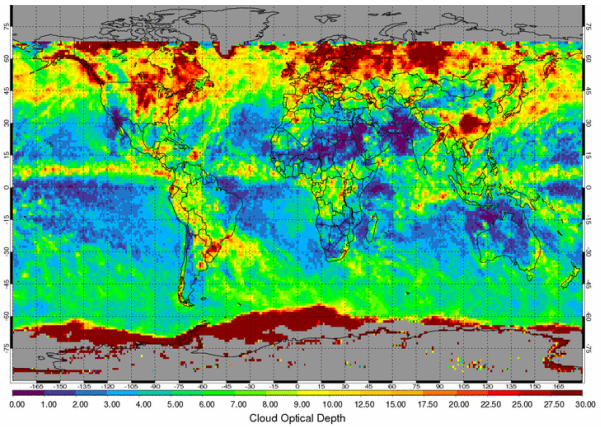
LaRC NOAA-18



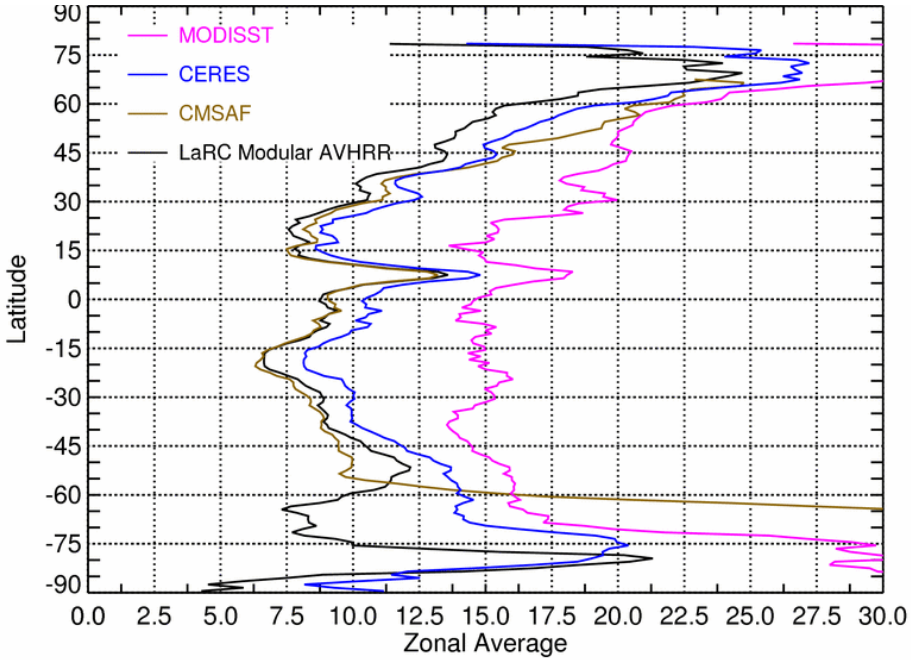
CERES E



CMSAF



October 2008 Zonal Average Optical Depth



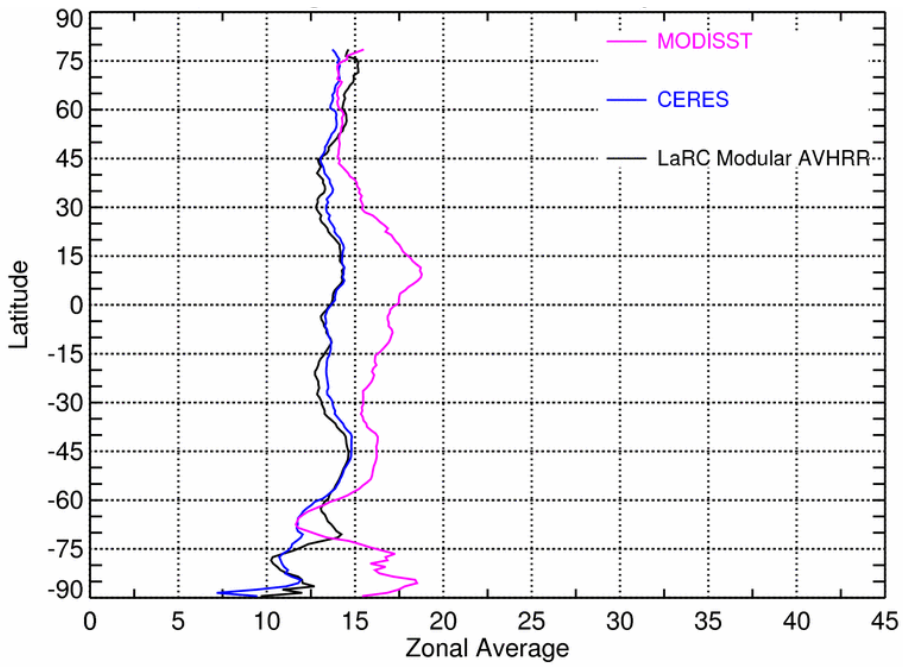
- **Optical depth difference between AVHRR and CERES caused by a low bias for water clouds**
  - Bias correction currently being developed

- **An IR-only approach being applied to many cloud pixels over snow/ice**
  - This attempts to address the fact that it is very difficult to separate the cloud reflectance from the snow/ice surface reflectance in the 0.63 µm channel which typically causes a high bias in retrieved optical depth

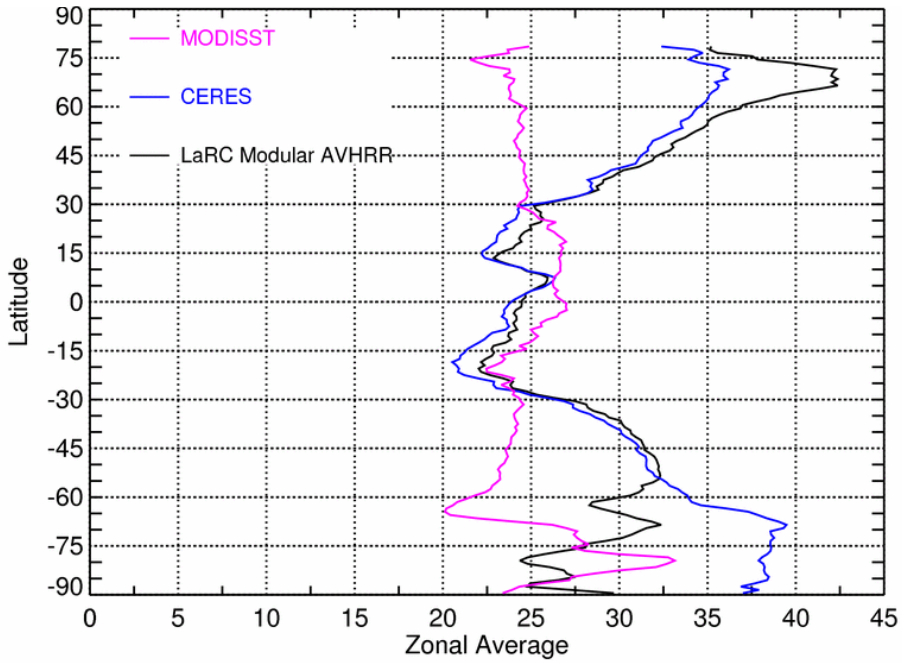
Cloud Particle Effective Radius

- **Good CERES-AVHRR agreement for water cloud, AVHRR 1 µm too high for ice clouds over non-polar scenes**

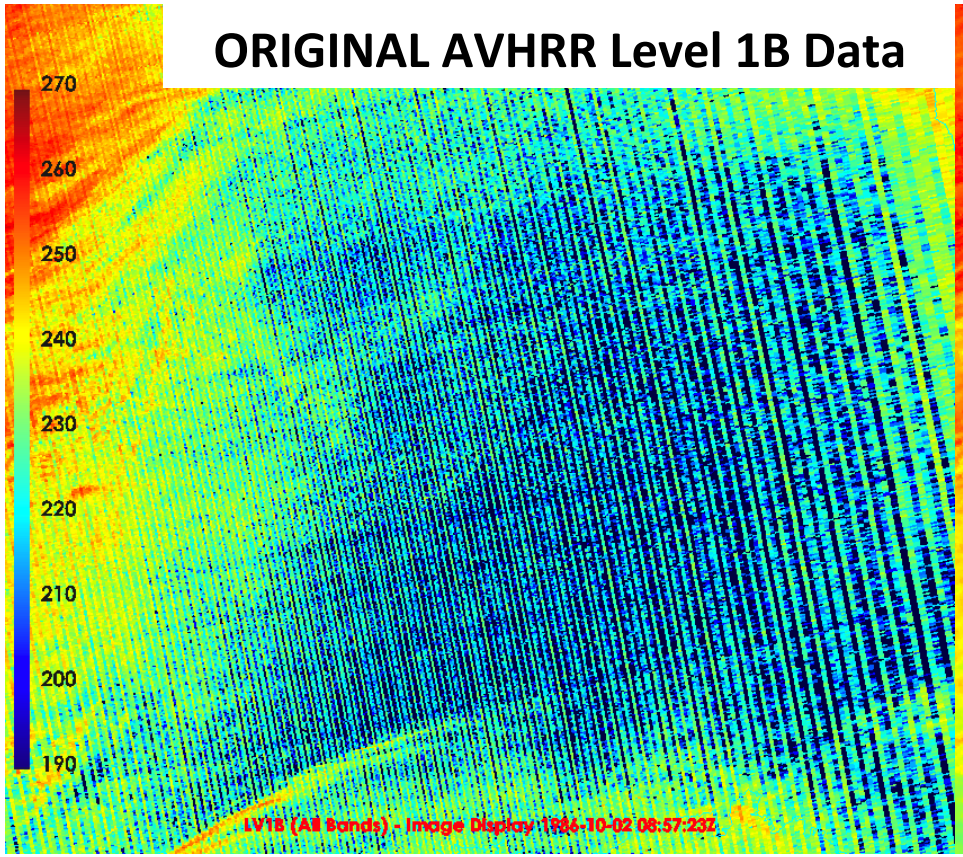
Water Effective Radius: Day, October 2008

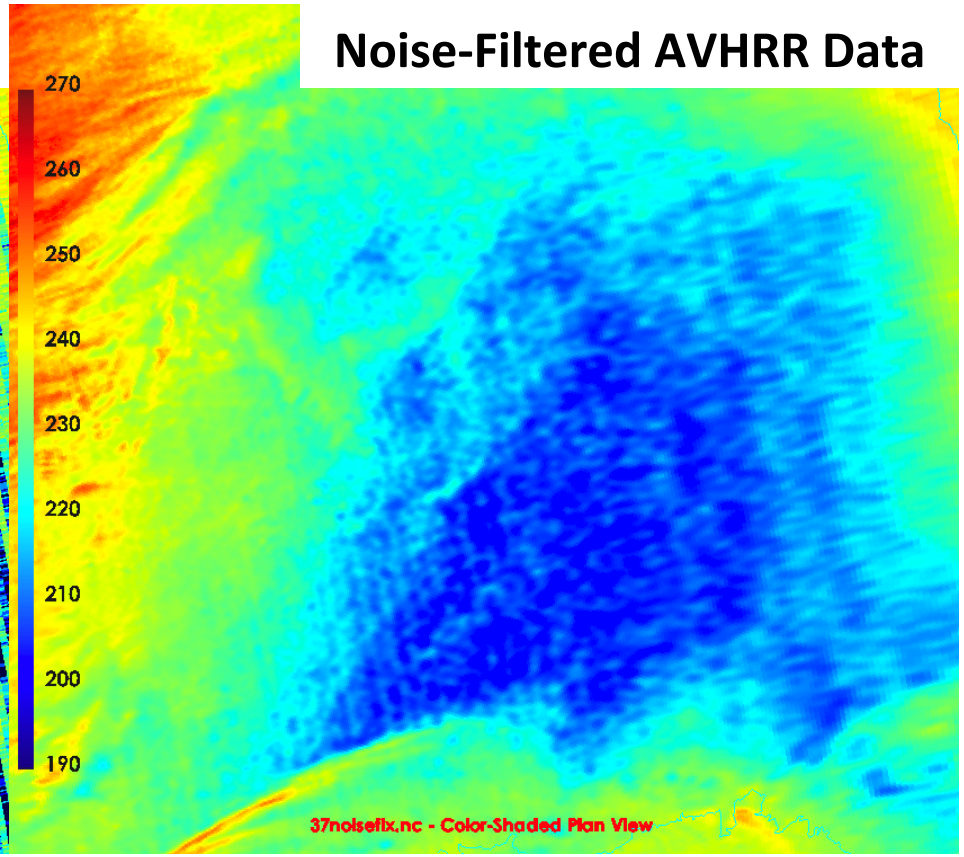


Ice Effective Radius: Day, October 2008



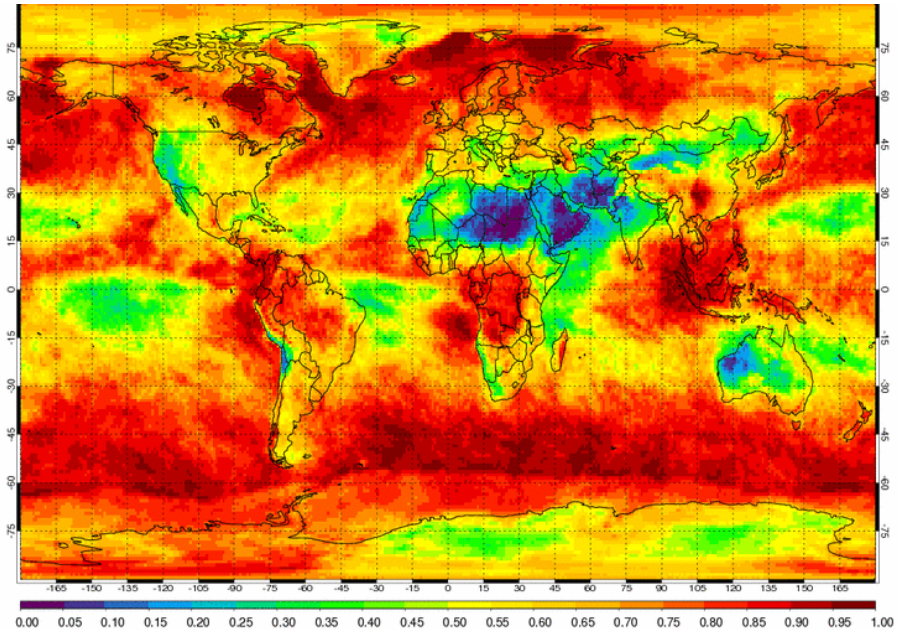
NOAA-6 to -14 3.74 µm Channel Noise



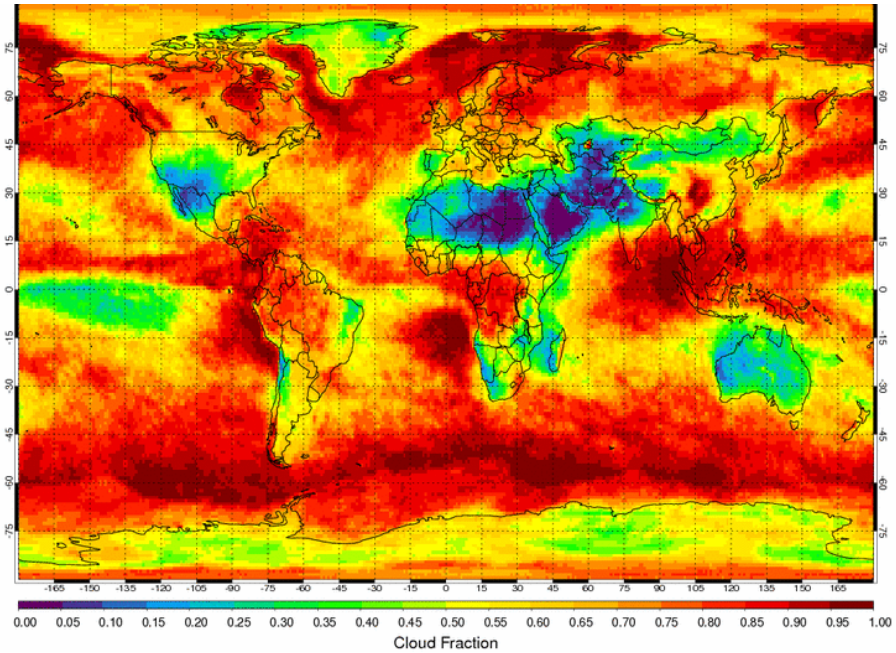


- **AVHRR 3.74 micron channel data prior to NOAA-15 suffers from significant "striping" oriented along track and noise at cold temperatures**
- **These issues have significant impact on cloud mask and retrievals if not addressed**
- **Noise filter uses Fast Fourier Transform to minimize striping and spatial smoothing that increases in intensity with colder 11 µm BT. Some noise still remains though…**

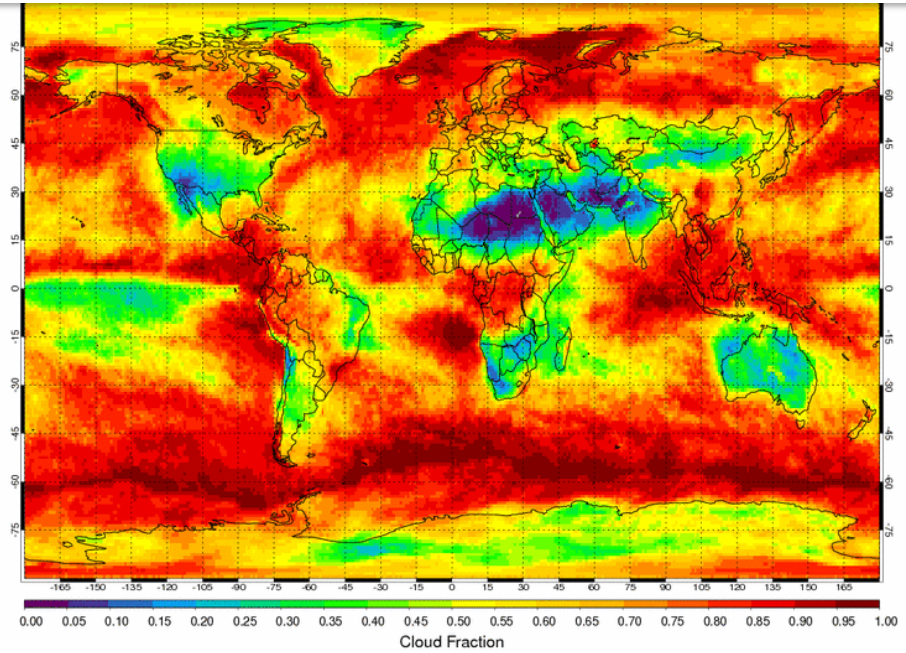
NOAA-09 October 1986



NOAA-18 October 2007



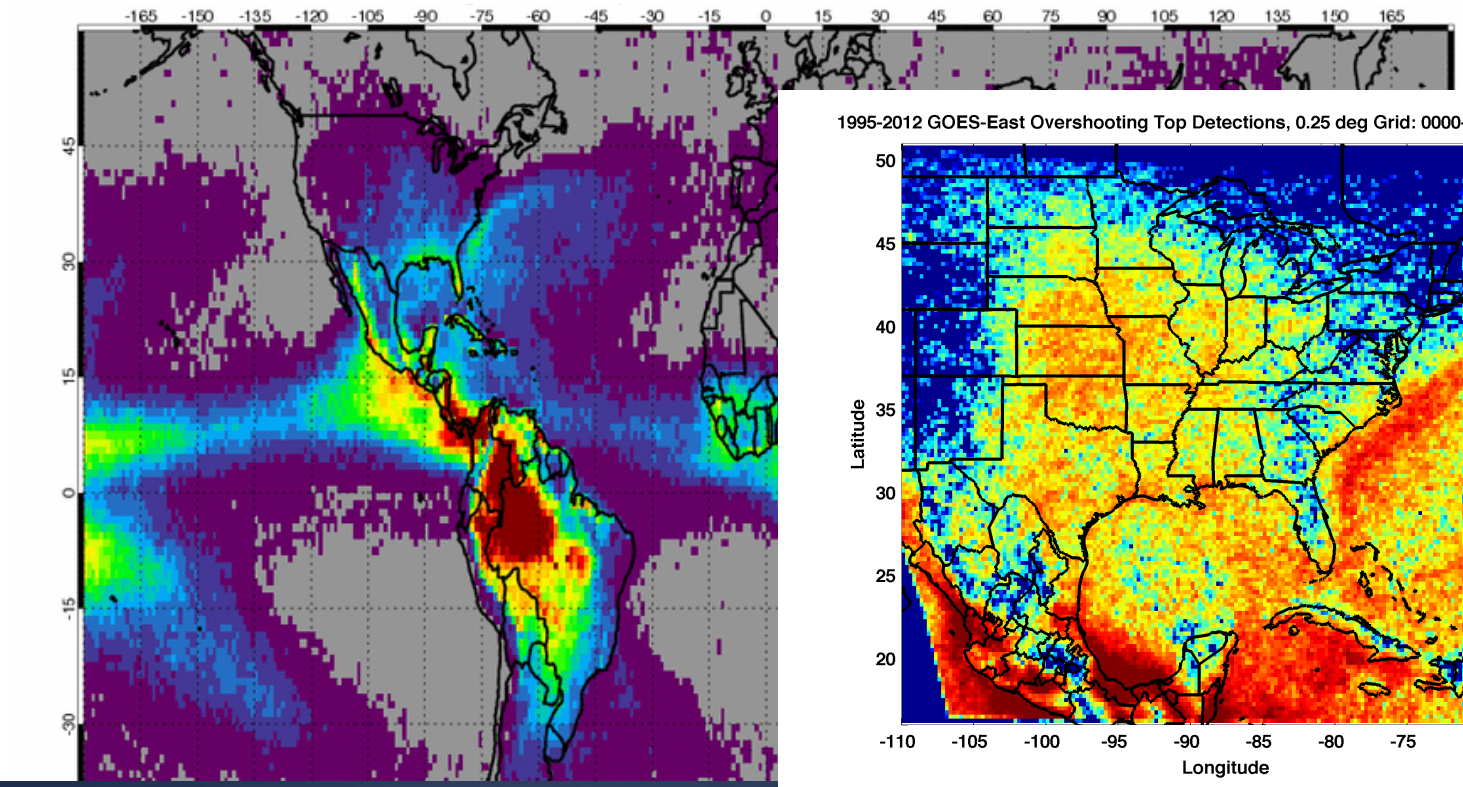
NOAA-18 October 2008

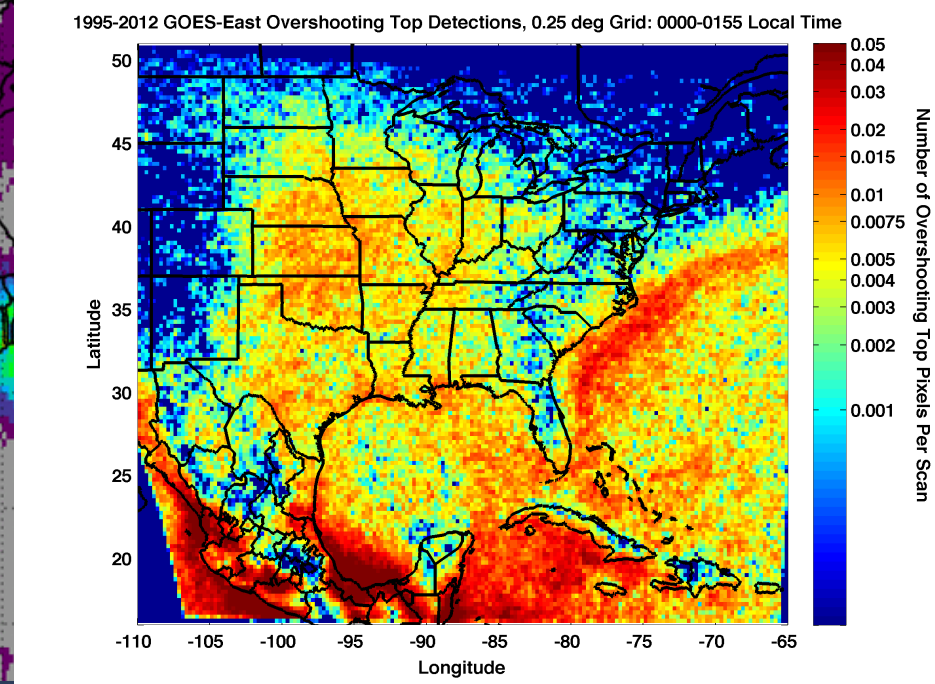


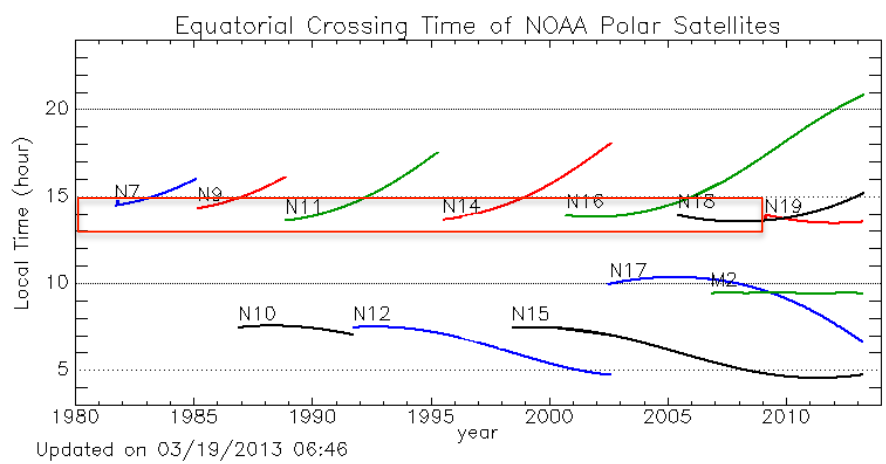
NOAA-9 vs NOAA-18 Cloud Fraction

- **Differences in "weather" across years precludes a 1:1 match**
- **Biggest differences over cold polar regions where AVHRR sensor noise induces some false cloud detection**

NOAA AVHRR Global Gridded Overshooting Top Detections 0100-0300 AM/PM Local Time, 17 Years of Orbits

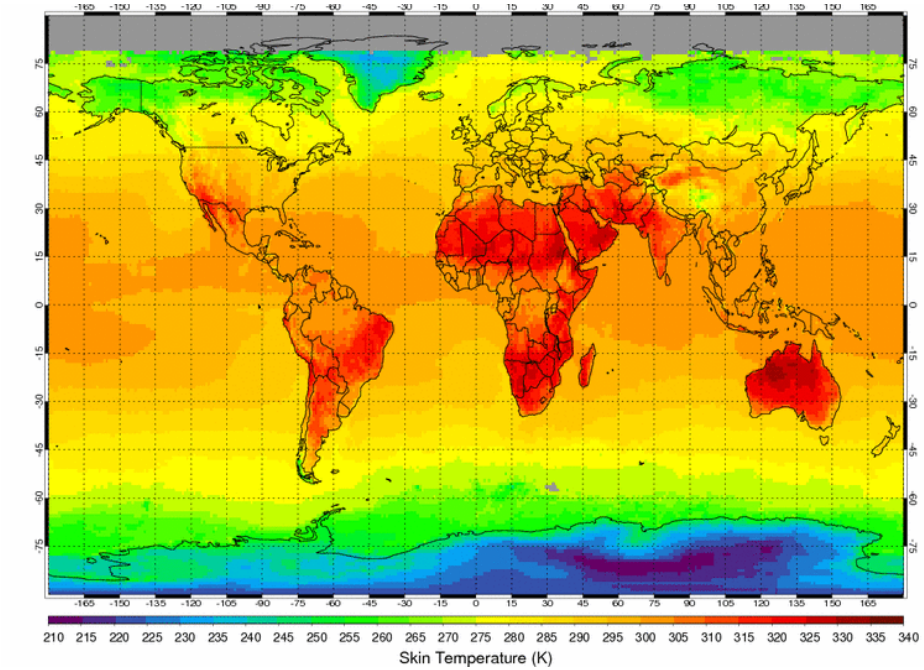




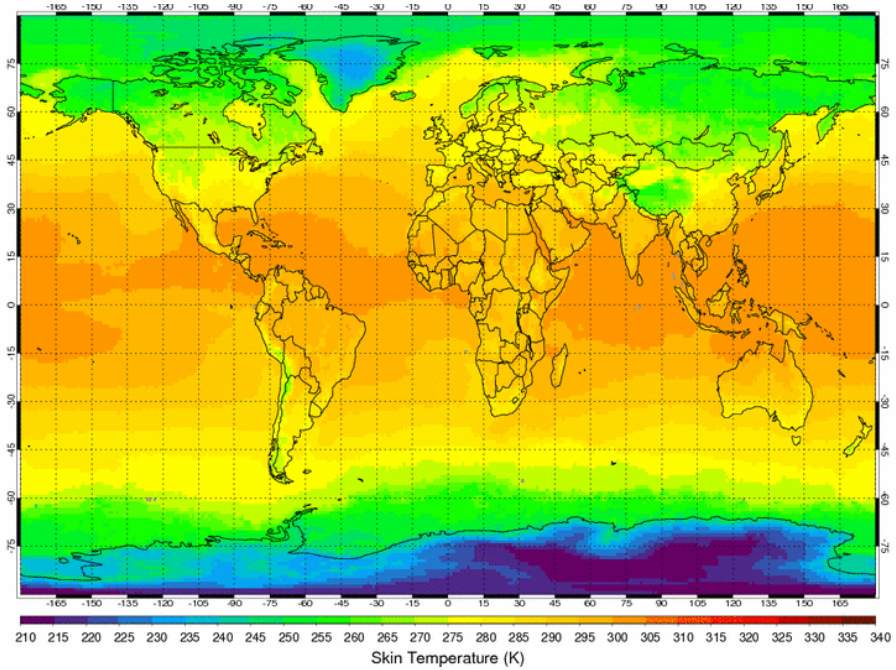


October 2008 AVHRR Skin Temperature

Day



Night



- **AVHRR cloud mask used to identify clear sky pixels for Tskin retrieval**

- **Correlated k-distribution radiative transfer approach (Kratz et al.) used to compute atmospheric transmissivity. This is then used to derive a surface IR temperature from the observed 10.8-µm clear-sky TOA IR temperature**
  - Application of surface emissivity model yields land/ocean surface skin temperature

- **Quality flags indicate confidence for each Tskin pixel retrieval**

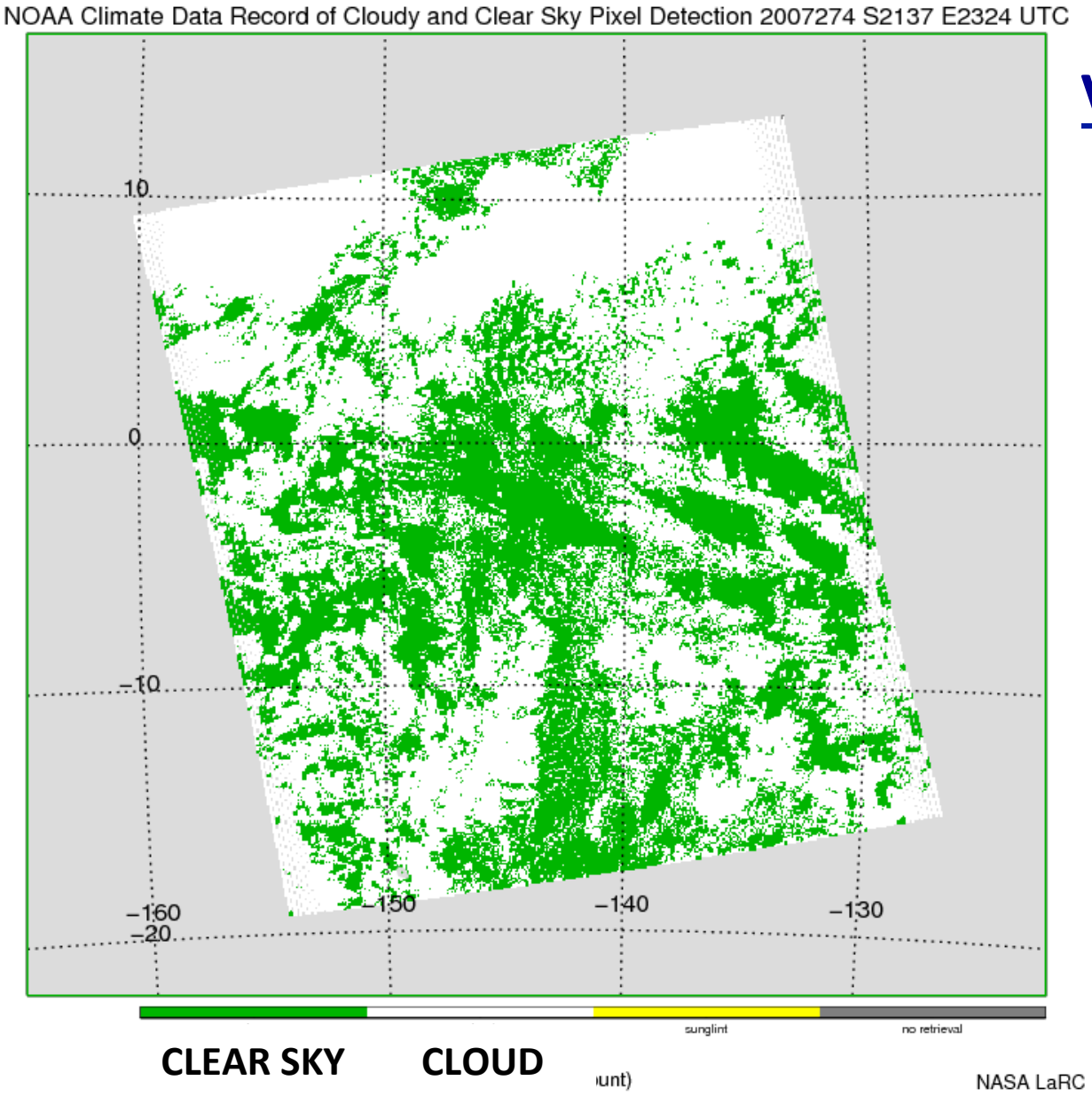
NASA LaRC AVHRR CDR: Quality Assurance

Three approaches for quality assurance and product validation

1) **Detailed interactive inspection of pixel-level output using McIDAS-X and –V and IDL-based graphics with interactive Flash toggle/zoom/fade features**

2) **Comparison with other gridded monthly-averaged cloud property climatololgies such as CERES MODIS, GSFC MODIS, ISCCP, EUMETSAT CMSAF, and CALIPSO to ensure that AVHRR results are reasonable**

3) **Pixel-level product comparison with space/ground-based instrumentation or other comparable and proven products**
   a) Cloud Mask -> CALIPSO Vertical Feature Mask
   b) Cloud Phase -> CALIPSO Vertical Feature Mask
   c) Cloud Top Height -> CALIPSO Cloud Layers
   d) Cloud Base Height -> CloudSat GEOPROF-LIDAR
   e) Cloud Optical Depth -> CALIPSO Cloud Layers, only thin clouds
   f) Liquid Water Path -> AMSR-E
   g) Sea Surface Temperature -> NOAA Optimal Interpolation SST product
   h) Land Surface Skin Temperature -> DOE ASR IR Thermometer over Oklahoma, NOAA SURFRAD sites, and MODIS Land Surface Temperature



Quality Assurance Via Subjective Image Analysis

- **Comparison of cloud mask and cloud phase products with 3-channel false-color RGB composites is very useful for identifying detection/ retrieval errors**

- **McIDAS' ability to:**

1) Interactively create RGB composites
2) Overlay assorted products
3) Probe individual pixel values

allows us to efficiently define areas needing improvement or determine sources of error

- **A Flash-based web applet also offers some interactive analysis capability for IDL-based graphics**

NASA LaRC AVHRR Cloud Mask
Pixel-Level Validation vs. CALIPSO Vertical Feature Mask

- Validation uses a combination of 333 m and 5 km CALIPSO data

- AVHRR Cloud Mask Fraction Correct > 85% except for night polar ice/snow surface
  - Bias is toward missed clouds (not shown)-> caused by AVHRR spatial resolution?

- AVHRR accuracy typically within 1-3% of CERES MODIS

CALIPSO-BASED CLOUD DETECTION VALIDATION: OCTOBER 2008		
Land Surface Type, Geographic Region, and Time of Day	NOAA-18 AVHRR Fraction of Correct Clear and Cloudy Pixels NUM PTS: ~970,000	CERES MODIS Edition 4 Fraction Correct (12 Days Across Seasonal Months)
DAYTIME (0 < SZA < 82)		
Land, 60 S – 60 N, No Snow/Ice Cover	0.856	0.886
Land, Polar, No Snow/Ice Cover	0.930	0.907
Ocean, 60 S – 60 N, No Snow/Ice Cover	0.877	0.894
Ocean, Polar, No Snow/Ice Cover	0.954	0.942
Land & Ocean, Global, Snow/Ice Covered	0.854	0.868
NIGHT (SZA > 82)		
Land, 60 S – 60 N, No Snow/Ice Cover	0.865	0.873
Land, Polar, No Snow/Ice Cover	0.927	0.870
Ocean, 60 S – 60 N, No Snow/Ice Cover	0.888	0.905
Ocean, Polar, No Snow/Ice Cover	0.957	0.937
Land & Ocean, Global, Snow/Ice Covered	0.729	0.787

NASA LaRC AVHRR Cloud Phase
Pixel Level Validation vs. CALIPSO Vertical Feature MAsk

- **AVHRR Cloud Phase fraction correct ~92% on average (vs ~94% from CERES MODIS) in non-polar and snow/ice free regions**

- **Comparisons limited to single layer or multi-layer single phase CALIPSO observations**

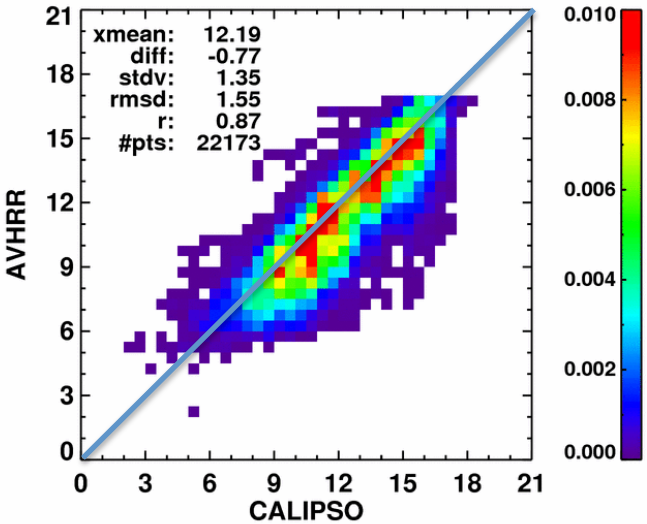
CALIPSO-BASED CLOUD PHASE VALIDATION: OCTOBER 2008		
Land Surface Type, Geographic Region, and Time of Day	NOAA-18 AVHRR Fraction of Correct Phase Identification NUM PTS: ~290,000	CERES MODIS Edition 4 Fraction of Correct Phase Identification (12 Days Across Seasonal Months)
DAYTIME (0 < SZA < 82)		
Land, 60 S – 60 N, No Snow/Ice Cover	0.926	0.936
Land, Polar, No Snow/Ice Cover	0.868	0.943
Ocean, 60 S – 60 N, No Snow/Ice Cover	0.960	0.978
Ocean, Polar, No Snow/Ice Cover	0.912	0.959
Land & Ocean, Global, Snow/Ice Covered	0.797	0.926
NIGHT (SZA > 82)		
Land, 60 S – 60 N, No Snow/Ice Cover	0.905	0.914
Land, Polar, No Snow/Ice Cover	0.922	0.915
Ocean, 60 S – 60 N, No Snow/Ice Cover	0.927	0.947
Ocean, Polar, No Snow/Ice Cover	0.816	0.912
Land & Ocean, Global, Snow/Ice Covered	0.869	0.876

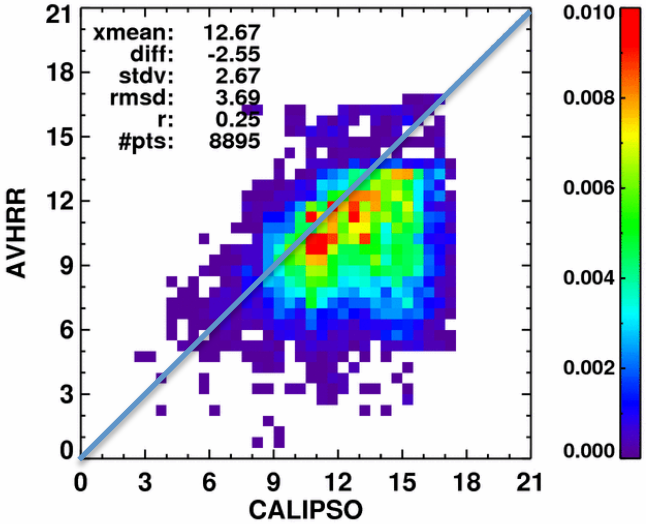
NASA LaRC AVHRR Cloud Top Height
Pixel-Level Validation vs. CALIPSO Cloud Layers Product

Optically Thick (τ > 8) Cloud

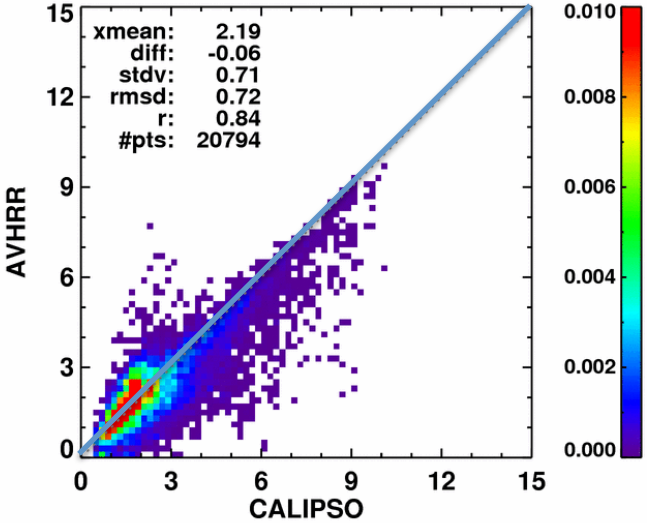
Optically Thin Cloud

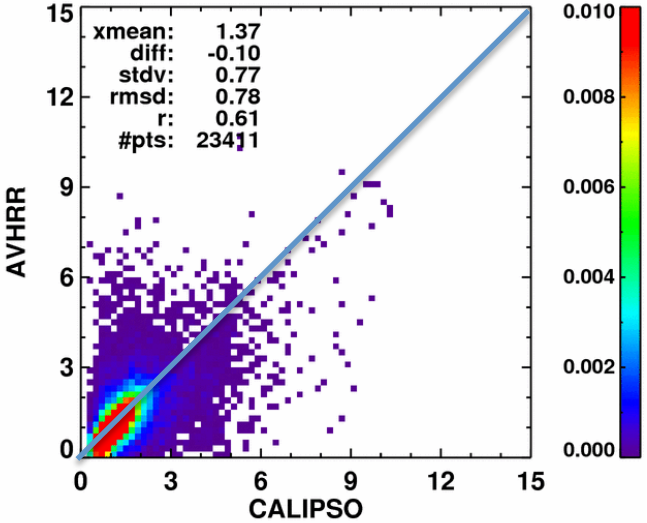
NON-POLAR ICE CLOUDS





NON-POLAR WATER CLOUDS

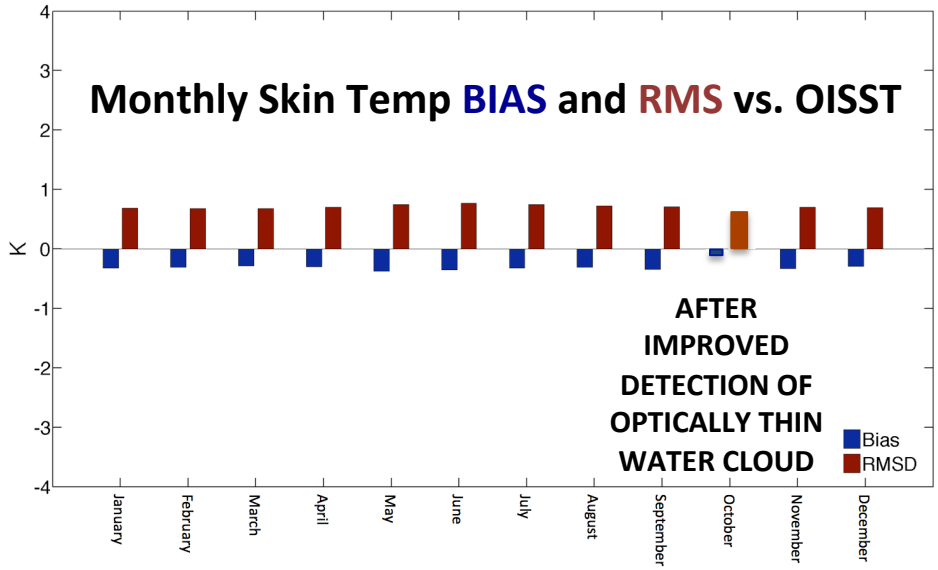


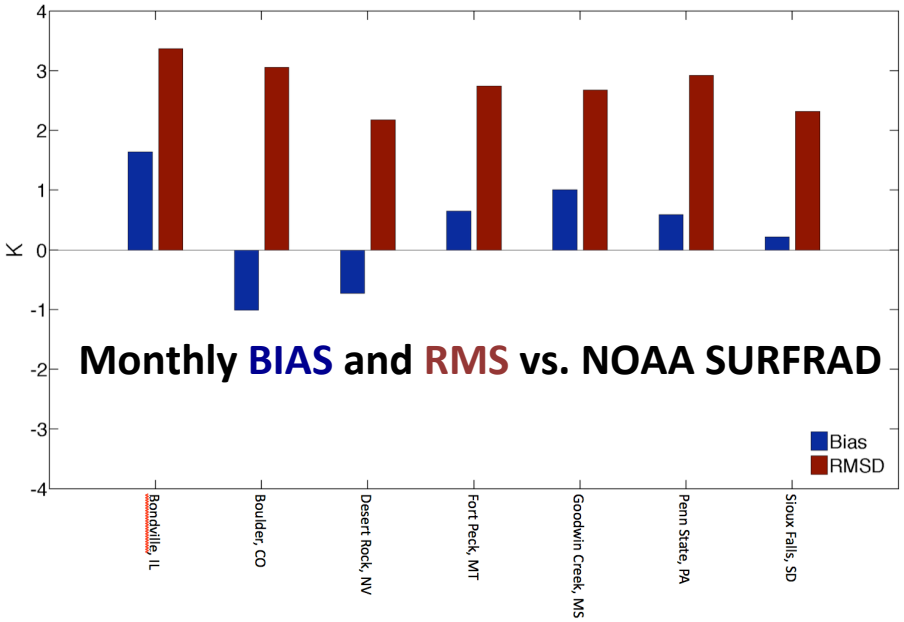


Sea/Land Surface Skin Temperature Comparisons

- **NOAA OISST: 0.25° daily product including AVHRR, AMSR (when available), and in-situ SST observations**
  - 2008 LaRC AVHRR pixel skin temperatures averaged to 0.25° across day/night. Skin temperature along cloud edges are excluded from validation

- **AVHRR pixel skin temperature during 2008 also compared with 8 NOAA SURFRAD sites**
  - SURFRAD upwelling radiation converted to skin temperature
  - ***Land heterogeneity within an AVHRR pixel contributes to relatively high RMS/bias***





NASA LaRC AVHRR CDR: Project Timeline

- **CDR Processing to begin within the following weeks**
  - 1 satellite year = 2.5 days of processing = 750 Gb of NetCDF output
  - Store as much data as possible locally but transfer full CDR to NOAA NCDC for archival and distribution
  - NOAA-18 first priority, then NOAA-9 (S. Kato ERBE CDR), followed by other modern-era satellites featuring nominal AVHRR channels
- **Level 3 daily/monthly/zonal mean products to be routinely generated throughout processing**
- **NOAA NCDC to provide access to the data via CLASS archive**
- **ATBD and validation documentation to be submitted by August**
- **We look forward to sharing this dataset with you and many future collaborations**