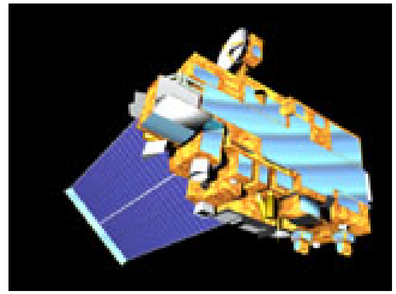
MODIS Product Overview IMAPP Workshop

Andenes, Norway

1 March 2006

Kathleen Strabala



Cooperative Institute for Meteorological Satellite Studies

University of Wisconsin-Madison USA

Key Areas of Uncertainty in Understanding Climate & Global Change

- Earth's radiation balance and the influence of clouds on radiation and the hydrologic cycle
- Oceanic productivity, circulation and air-sea exchange
- Transformation of greenhouse gases in the lower atmosphere, with emphasis on the carbon cycle
- Changes in land use, land cover and primary productivity, including deforestation
- Sea level variability and impacts of ice sheet volume
- Chemistry of the middle and upper stratosphere, including sources and sinks of stratospheric ozone
- Volcanic eruptions and their role in climate change

MODIS Science Team

- Land, Ocean, Atmosphere, Calibration Teams
  - http://modis.gsfc.nasa.gov/
- Data Distribution Sites
  - Land
    - http://edcdaac.usgs.gov/dataproducts.asp
    - Snow/Ice data sets - http://nsidc.org/daac/modis/index.html
  - Atmosphere
    - http://daac.gsfc.nasa.gov/MODIS/products.shtml
  - Ocean
    - Ocean Color - http://oceancolor.gsfc.nasa.gov/
    - SST - http://daac.gsfc.nasa.gov/MODIS/products.shtml
  - L1B (Calibrated, Geolocated)
    - http://daac.gsfc.nasa.gov/MODIS/products.shtml

MODIS Team Product Comparisons http://modis.gsfc.nasa.gov/

Group	Level 2	Level 3
Calibration	Satellite Projection	None
Atmospheres	Satellite Projection	Daily, Eight Day, Monthly 1 degree equal angle
Land	L2G - Gridded	Daily, Eight Day 500m Sinusoidal*
Ocean	Satellite Projection	Daily, Weekly, Monthly, Yearly 1 km, 4 km, 36 km, 1 degree

MODIS Standard Products (1)

Calibration

- ***MOD 01 - Level-1A Radiance Counts***
- ***MOD 02 - Level-1B Calibrated Geolocated Radiances***
- ***MOD 03 - Geolocation Data Set***

Atmosphere

- ***MOD 04 - Aerosol Product***
- ***MOD 05 - Total Precipitable Water (Water Vapor)***
- ***MOD 06 - Cloud Product*** **** (CTP & IRPHASE only)***
- ***MOD 07 - Atmospheric Profiles***
- MOD 08 - Gridded Atmospheric Product
- ***MOD 35 - Cloud Mask***

MODIS Standard Products (2)

Land

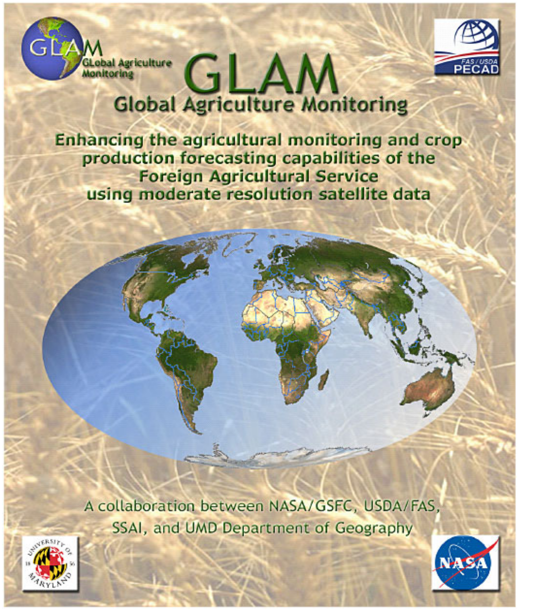
- MOD 09 - Surface Reflectance
- MOD 10 - Snow Cover
- MOD 11 - Land Surface Temperature & Emissivity
- MOD 12 - Land Cover/Land Cover Change
- MOD 13 - Gridded Vegetation Indices (Max NDVI & Integrated MVI)
- MOD 14 - Thermal Anomalies, Fires & Biomass Burning
- MOD 15 - Leaf Area Index & FPAR
- MOD 16 - Evapotranspiration
- MOD 17 - Net Photosynthesis and Primary Productivity
- MOD 29 - Sea Ice Cover
- MOD 43 - Bidirectional Reflectance Distribution Function (BRDF)
- MOD 44 - Vegetation Cover Conversion

MODIS Standard Products (3)

Ocean

- MOD 18 - Normalized Water-leaving Radiance
- MOD 19 - Pigment Concentration
- MOD 20 - Chlorophyll Fluorescence
- MOD 21 - Chlorophyll_a Pigment Concentration
- MOD 22 - Photosynthetically Available Radiation (PAR)
- MOD 23 - Suspended-Solids Concentration
- MOD 24 - Organic Matter Concentration
- MOD 25 - Coccolith Concentration
- MOD 26 - Ocean Water Attenuation Coefficient
- MOD 27 - Ocean Primary Productivity
- ***MOD 28 - Sea Surface Temperature***
- MOD 36 - Total Absorption Coefficient
- MOD 37 - Ocean Aerosol Properties
- MOD 39 - Clear Water Epsilon

GLobal Agricultural Monitoring (GLAM)



- **Upgrade from AVHRR 8km to MODIS**
  - **Establish Data Continuity**
- **NRT MODIS Rapid Response Data**
  - **Customized products**
- **MODIS Crop Mask / Type Mapping**
- **MODIS/AVHRR Time-series Data Base**
- **Improved GUI for Information Extraction**
- **Develop an Operational FAS Prototype based at GSFC**
- **Prepare for use of NPP VIIRS**

Project website: http://tripwire.geog.umd.edu/usda/index.asp

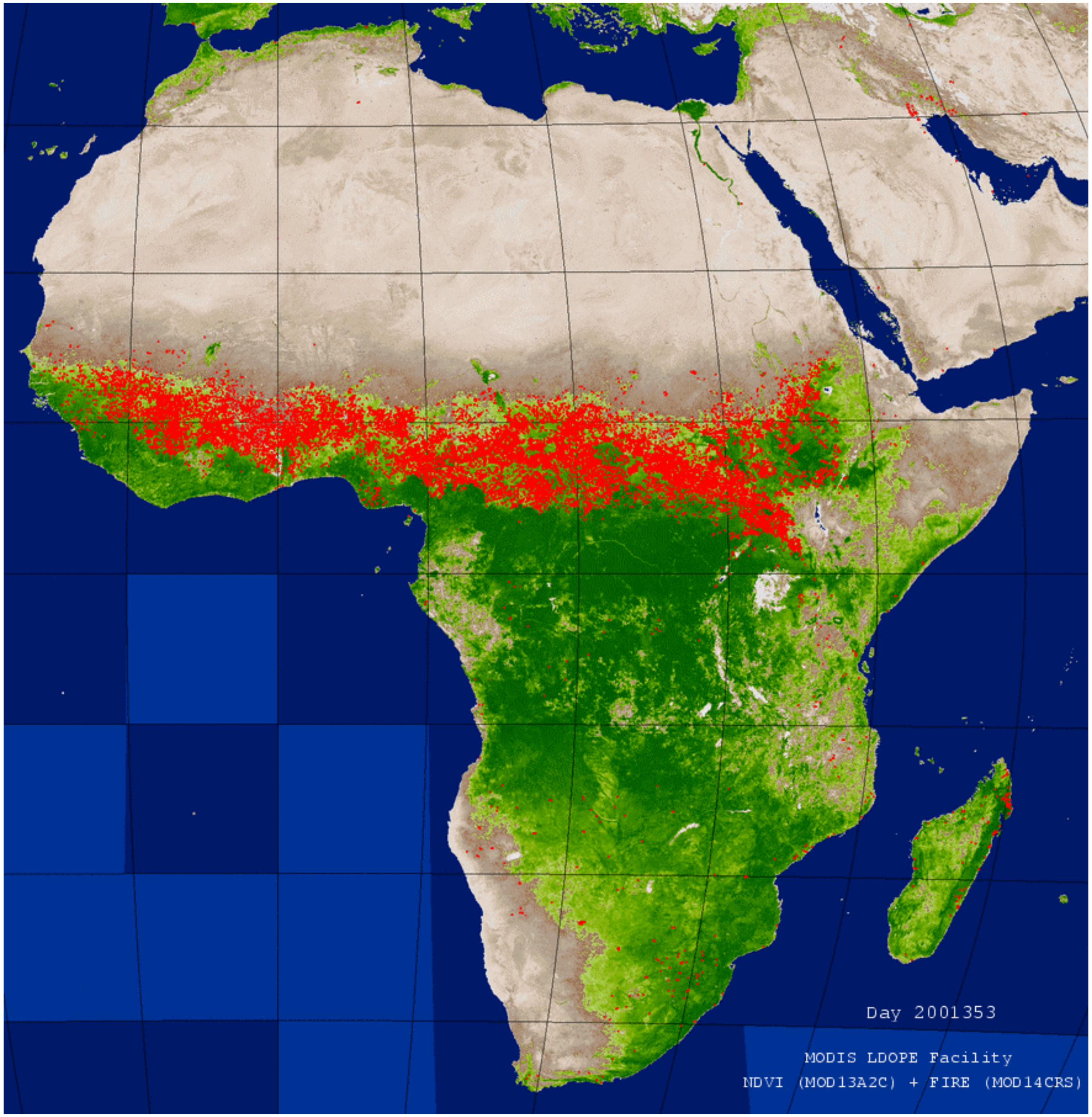
Large-scale monitoring of spatio-temporal fire dynamics

ACTIVE FIRES and VI

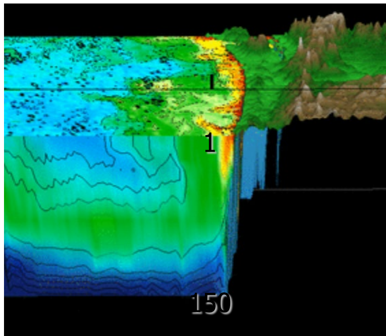
2001 animation

1km MODIS active fire detections (red)

superimposed on MODIS 16 day NDVI

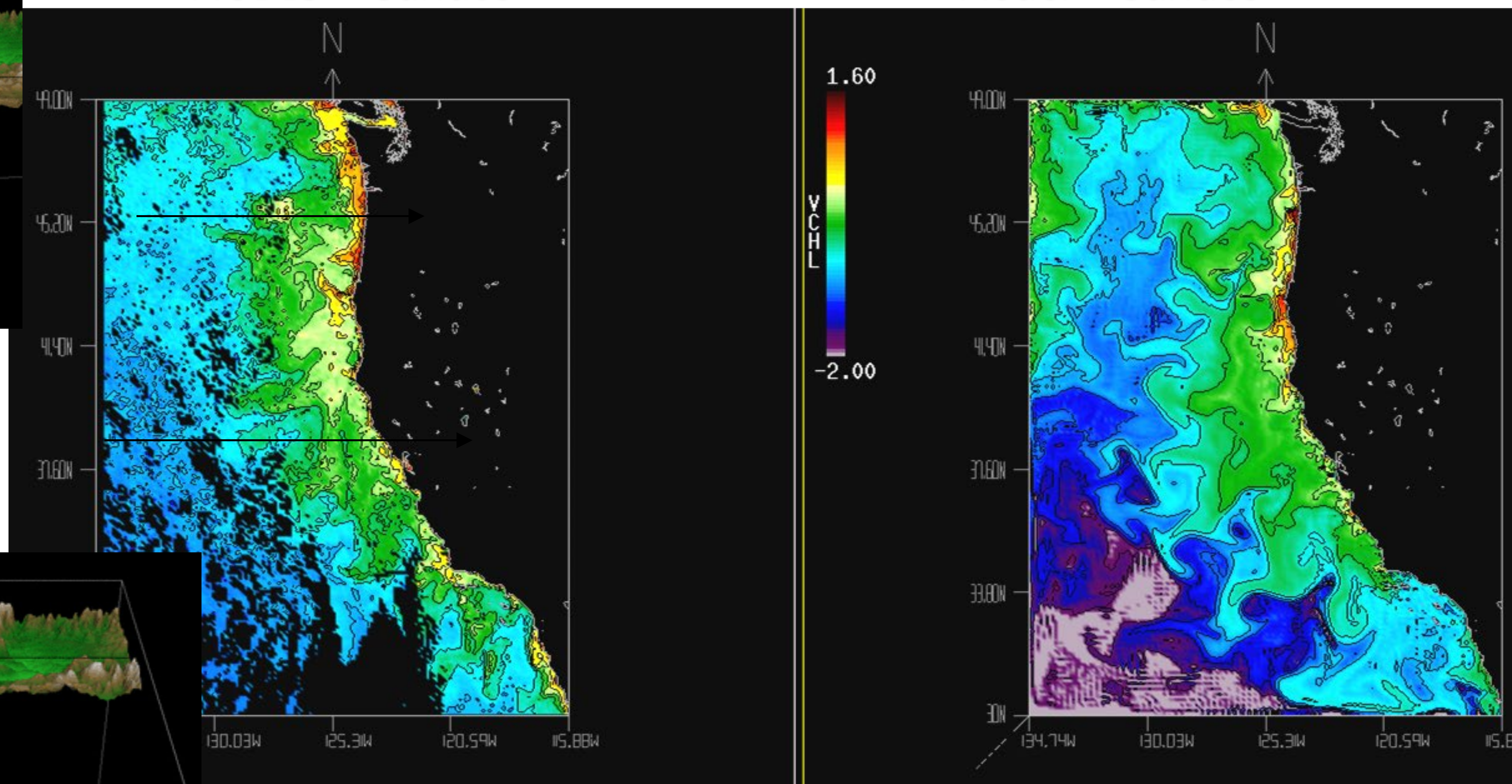


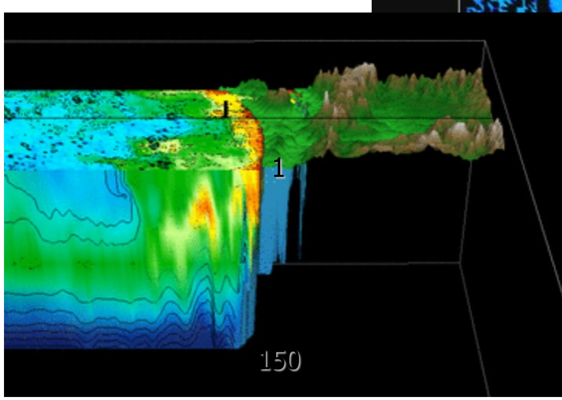
Looking below the Surface Satellite Ocean Color
Combining the Biological Model with MODIS Surface Chlorophyll

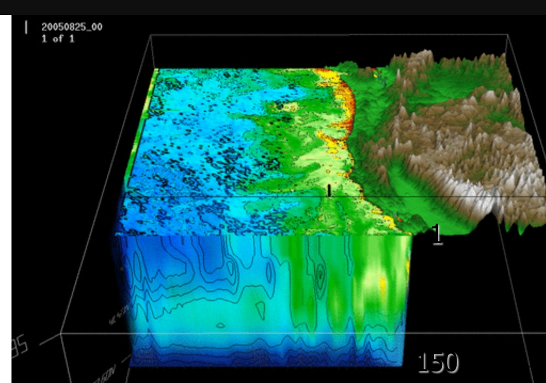


MODIS – Surface

Model – Surface





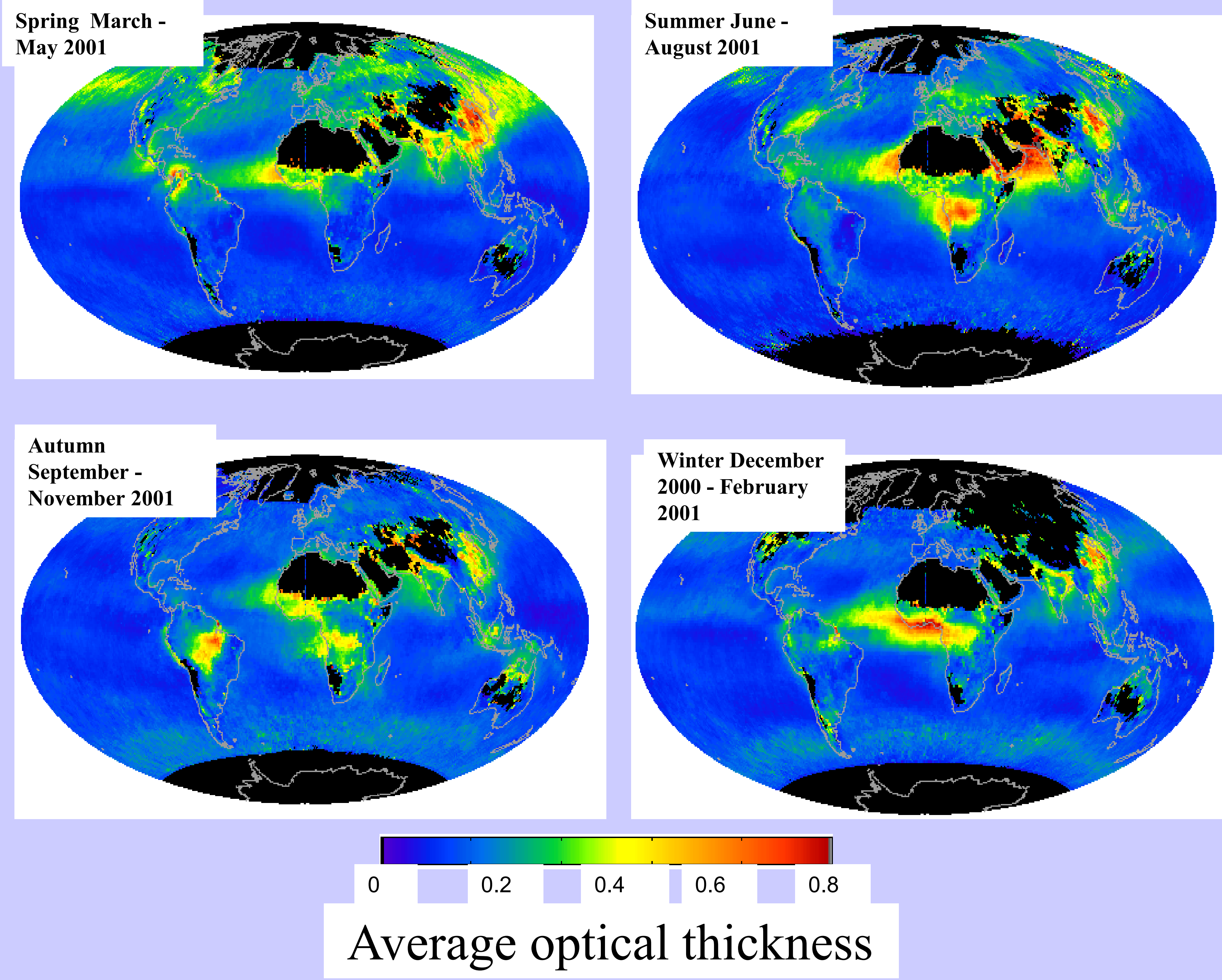


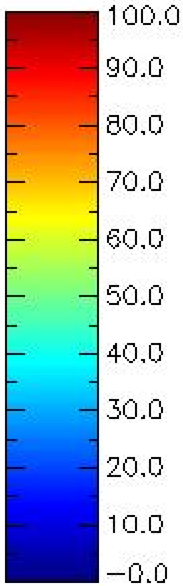
Subsurface Chlorophyll Light Field West Coast

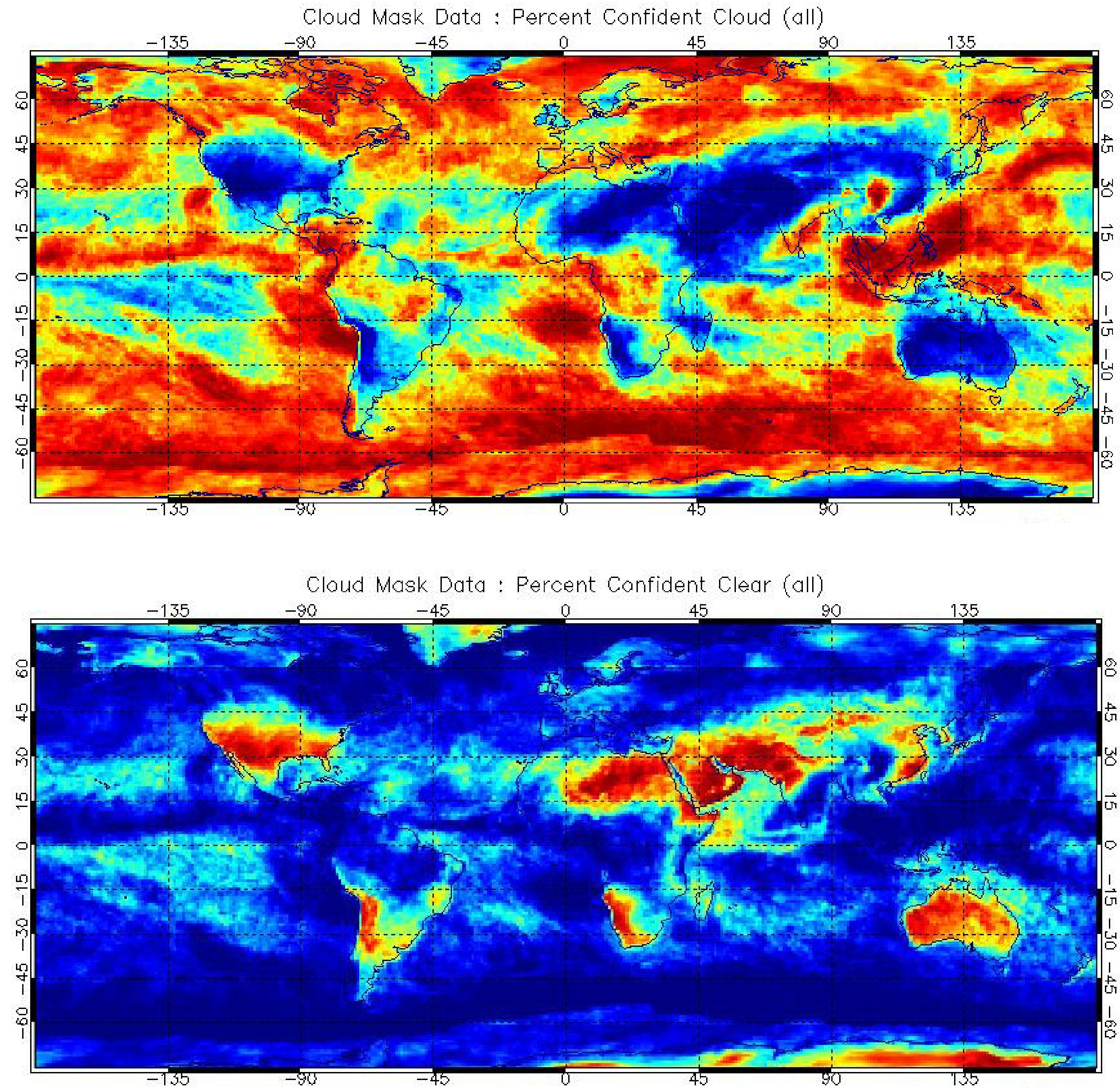
West Coast 3d-Chlorophyll

MontereyBay MODIS 3d-Chlorophyll

Courtesy of Penta and Kindle

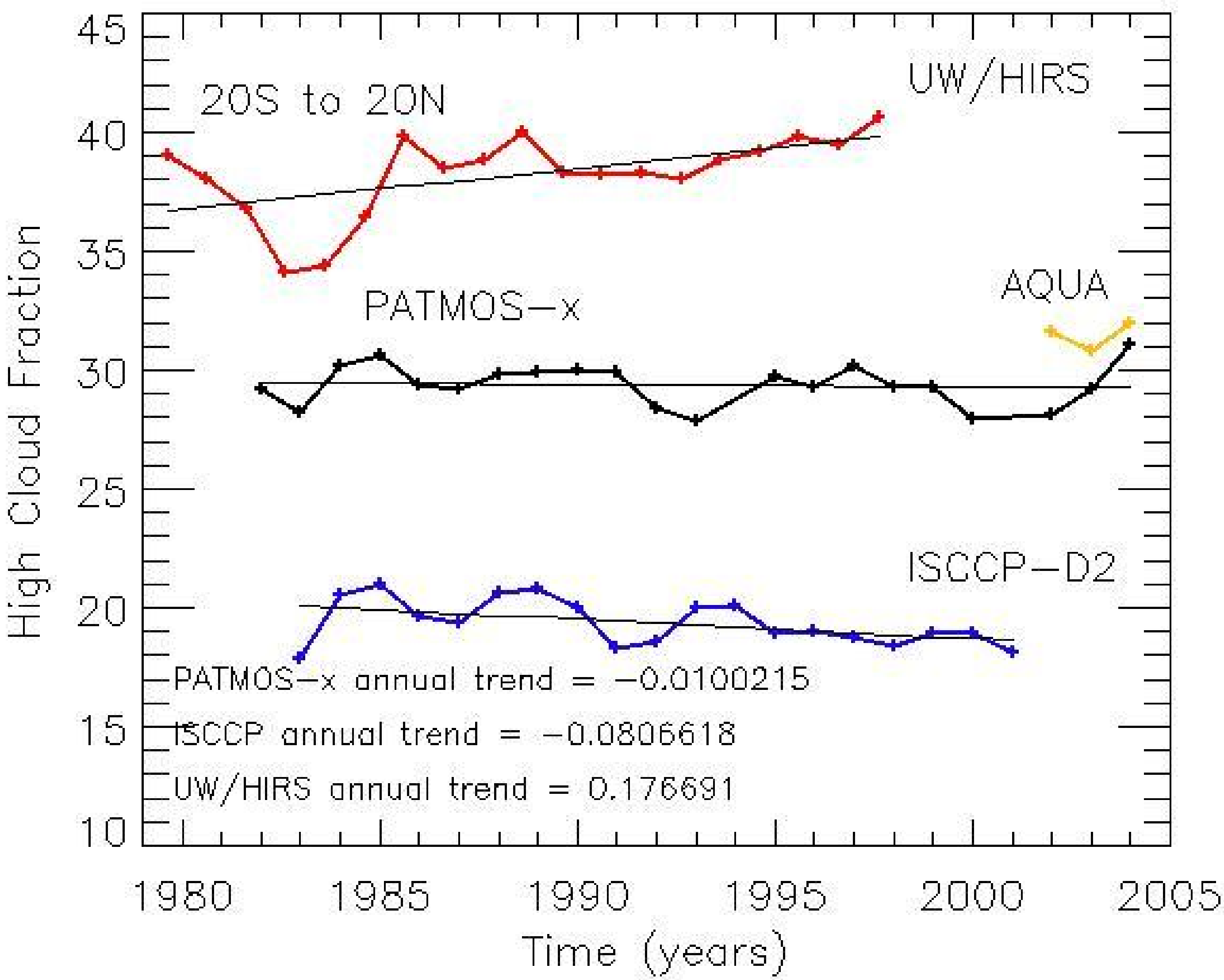

Spring March - May 2001
Summer June - August 2001
Autumn September - November 2001
Winter December 2000 - February 2001
0
0.2
0.4
0.6
0.8
Average optical thickness





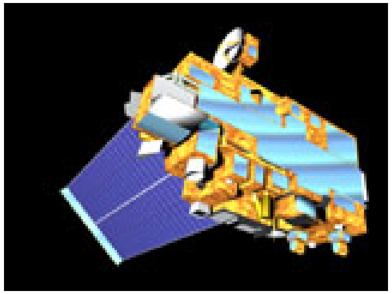
Terra October 2003

Extending Cloud Climatologies



Remote Sensing Training Workshop
IMAPP MODIS Level 2 Products

1 March 2006



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Direct Broadcast

- Surprise to find local small time scale applications from climate research satellite
- Funding for the International MODIS / AIRS Processing Package (IMAPP)
- Example of IMAPP applications
  - Polar wind and MODIS products in Antarctica
  - Cloud and water vapor MODIS products used by forecasters in Argentina
  - MODIS cloud products used as part of CLOUDMAP2 European Union numerical weather prediction study

IMAPP Level 2 Products

- Attempt was made to match DAAC products as closely as possible
- Requires no outside toolkits besides HDF libraries
- All required ancillary data is gathered and distributed from our ftp site (see http site below)
- Tested on 5 different PC/Unix platforms (including Linux, Sun, IRIX, AIX and HP)
- Code is efficient – All current IMAPP products running and producing products ~ 1.5-2 hours after data collection ends
- Products can be created using LIB DAAC files or IMAPP L1B files
- *Available from:*

http://cimss.ssec.wisc.edu/~gumley/IMAPP/

Current IMAPP Status

MODIS products – Level 1B and Geolocation

- cloud mask, cloud properties - height, temperature, emissivity, phase ***(Collect 5)***
- atmospheric profiles (T, q, tpw, total ozone, stability) ***(Collect 5)***
- aerosol optical depth
- sea surface temperatures
- near-infrared water vapor

MODIS utilities

- de-striping band 26 (correction for band 5 spectral leak)
- creating true color images tutorial

AIRS products - Level 1B (with JPL)

- AIRS/AMSU/HSB Level 1 (with JPL)
- AIRS Level 2 profiles in testing (both single pixel and 3x3)

AMSR-E products – RSS L1B software

- Rain rate, rain type (B05 algorithm)

IMAPP Output L2 Product Format

- Binary flat file with accompanying text header file
- Band interleaved
  - cloud mask is exception – byte sequential
- IDL code included in release to turn products into HDF near –DAAC format if desired by user

Available from:

http://cimss.ssec.wisc.edu/~gumley/IMAPP/

MODIS Cloud Products

- IMAPP products only:
  - Cloud Mask (48 bit product)
  - Cloud Top Properties (Pressure, Temperature, Emissivity, Fraction)
  - Cloud Phase (Infrared Technique)

MODIS Cloud Mask

Ackerman, Frey, Strabala – CIMSS

http://modis-atmos.gsfc.nasa.gov/MOD35_L2/index.html

- **1 km** nadir spatial resolution **day & night**, (250 m day)
  - **19 spectral bands (0.55-13.93 µm, incl. 1.38 µm)** 11 individual spectral tests (function of 5 processing paths) combined for initial pixel confidence of clear
  - temporal consistency test over ocean, desert (nighttime); spatial variability test over ocean
- **48 bits per pixel** including individual test results and processing path
- **bits 1,2** give combined test results as: *confident clear*, *probably clear*, *probably cloudy*, *obstructed/cloudy* (clear sky conservative)

MODIS Cloud Mask

- Created in 1990's with these constraints:
  - Has to be useful to all three MODIS teams
    - Land, Ocean and Atmosphere
  - CPU constraints – Must be efficient
    - Eliminated the use of neuro-networks, etc.
  - File size constraints – Must be a usable size
    - Information stored at bit level
  - Comprehension – Mask must be easily understood by users

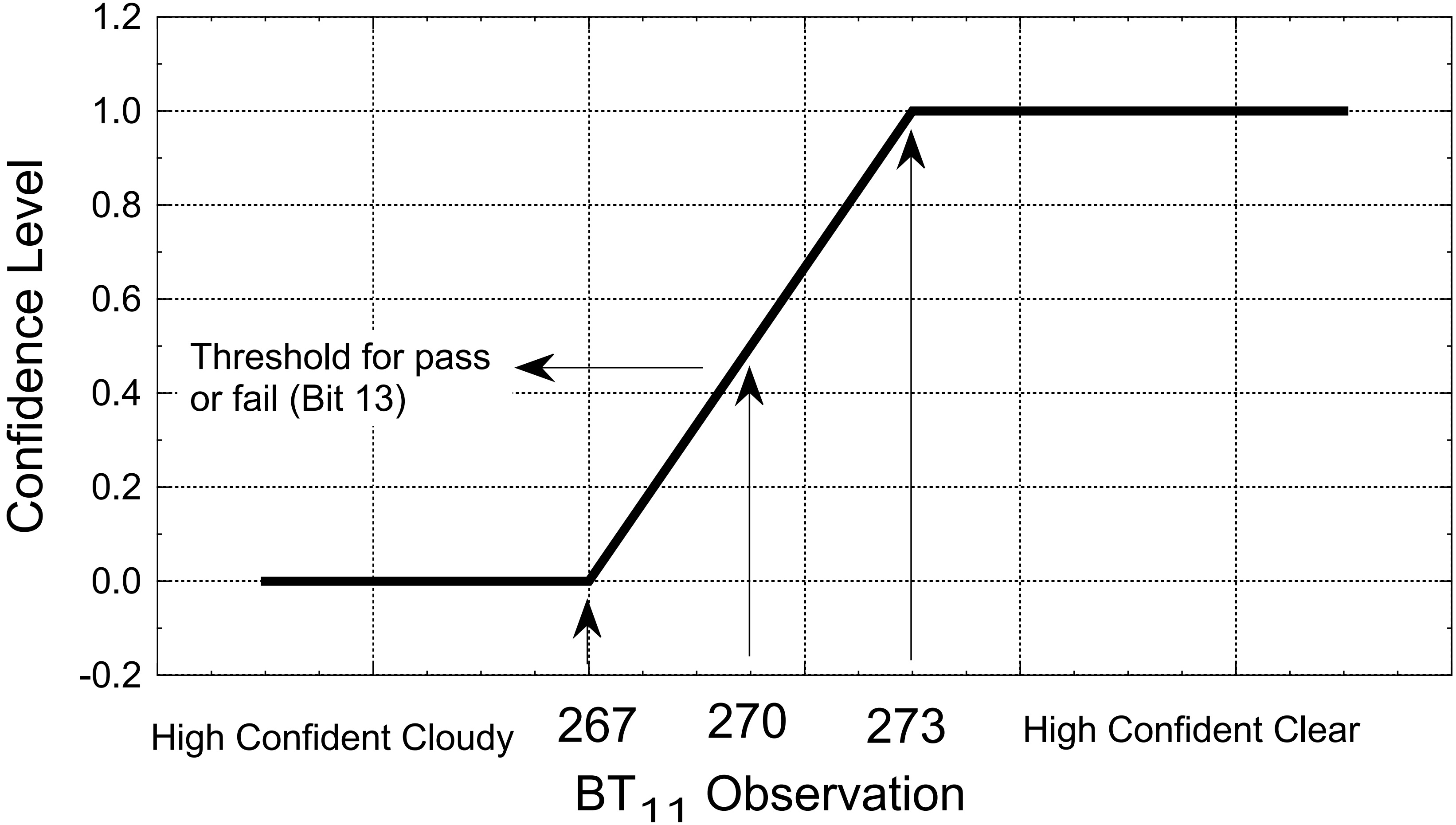
Algorithm Development

- Built upon work done by others:
  - ISCCP – Rossow and Garder 1993
  - CLAVR – Stowe et al. 1991
  - APOLLO – Saunders and Kriebel 1988
- New spectral channels – new tests
  - 1.38 micron high cloud reflectance test
- Many spectral channels
  - more tests go into final product
  - first platform with 8-11 (can use tri-spectral tests)

Algorithm Development

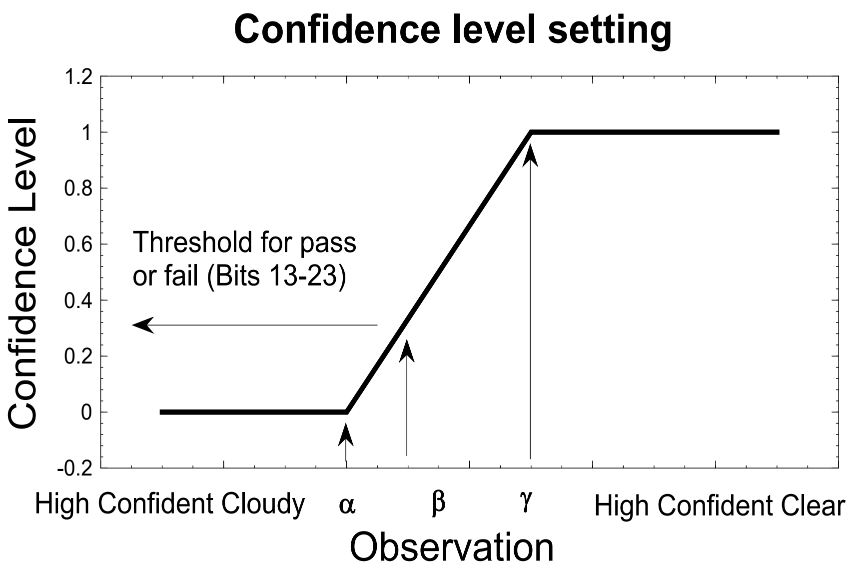
- Solution
  - Cloud mask based on combination of individual spectral tests.
  - Given constraints and building on previous work, best possible chance of an end product that would be useful to as many people as possible.

Confidence Level of Clear



Example thresholds for the simple IR window cold cloud test.

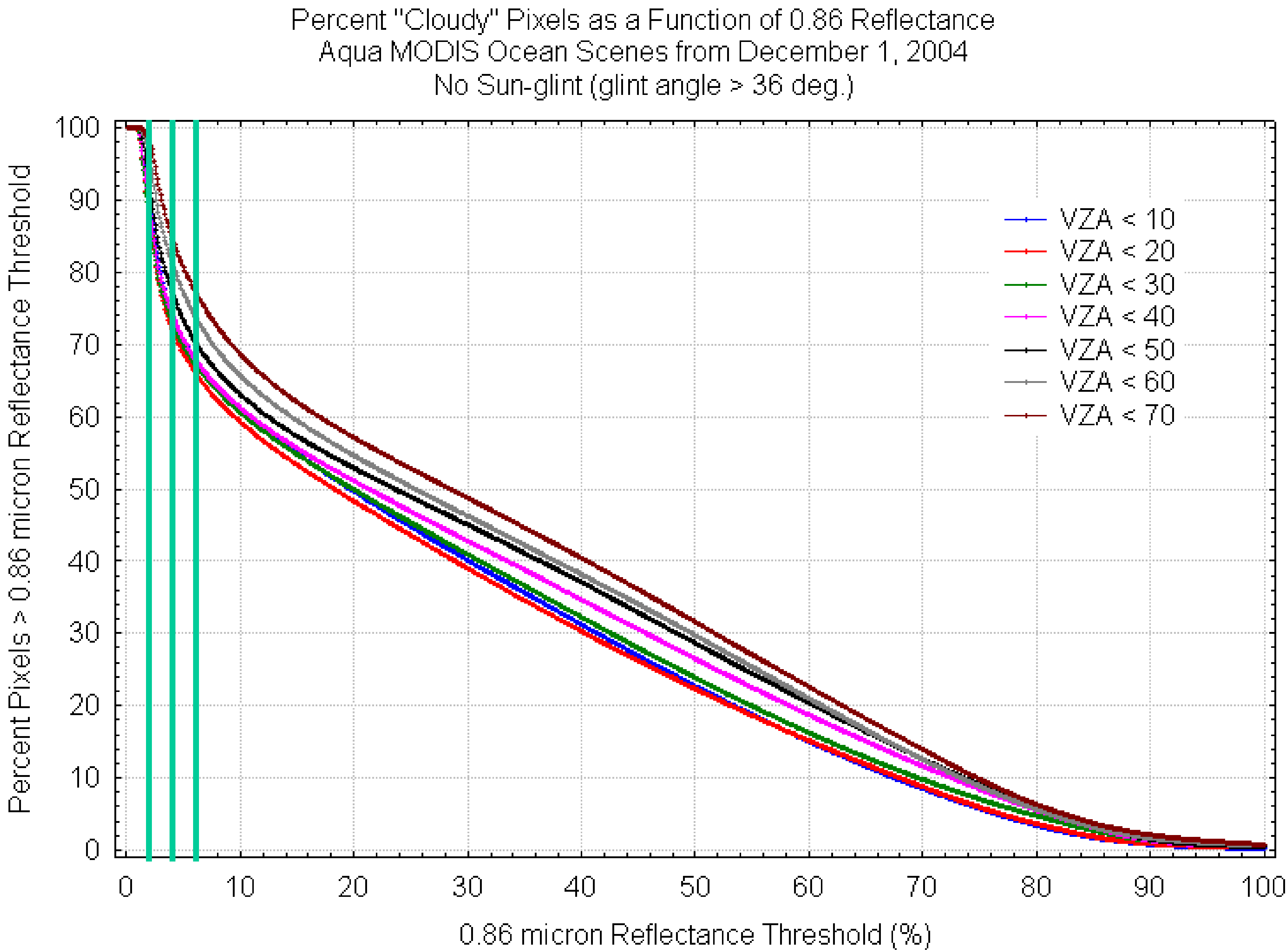
Quality Flags



- Each test returns a confidence (F) ranging from 0 to 1.
- Similar tests are grouped and minimum confidence selected [min (F_i)]
- Quality Flag is

$$Q = \sqrt[N]{\prod_{i=1}^{N} \min(F_i)}$$

- Four values; 0, >.66, >.95 and >.99



Percent "Cloudy" Pixels as a Function of 0.86 Reflectance
Aqua MODIS Ocean Scenes from December 1, 2004
No Sun-glint (glint angle > 36 deg.)
Percent Pixels > 0.86 micron Reflectance Threshold
0.86 micron Reflectance Threshold (%)
VZA < 10
VZA < 20
VZA < 30
VZA < 40
VZA < 50
VZA < 60
VZA < 70
0
10
20
30
40
50
60
70
80
90
100

Thresholds Domains

- Day/Night – Solar Zenith > 85 = night
- Land/Water – Based upon 1km USGS map
- Desert – Based upon USGS 1 km Olson Ecosystem map
- Polar Day/Night – Latitude greater than 60
- Coast – 2 pixels surrounding water bodies
- High Elevation - > 2000 m
- Sunglint – Intense point of solar reflection

"Mirror" reflection of sunlight off calm water.

Sun Glint

Simple example where your eye is the sensor

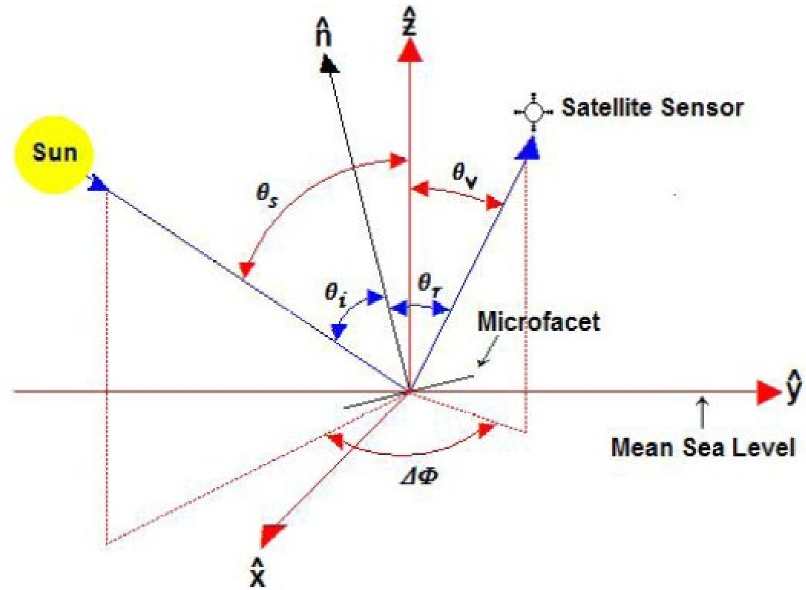
Sun Glint Ellipse Defined by: $\theta_r < 36$

$\cos\theta_r = \sin\theta_v \cos\theta_s \cos\Delta\Phi + \sin\theta_v \cos\theta_s$

Where θ_v = Viewing Zenith Angle

θ_s = Solar Zenith Angle

$\Delta\Phi$ = Relative Angle – difference between the Solar and Viewing azimuth angles.



Detecting Clouds (IR) **Thresholds vary based upon scene type**

IR Brightness Temperature Threshold Tests

IR tests sensitive to sfc emissivity and atm PW, dust, and aerosols

BT11 < SST- 6 K (Reynolds blended SST global 1 degree - oisst.20060215
Land - GDAS sfc temp global 1 degree -gdas1.PGrbF00.060220.18z)

BT6.7 < Threshold mid-level cloud

BT13.9 < Threshold cold high cloud (large viewing zenith angles cause problems)

IR Brightness Temperature Difference Tests

BT8 - BT11 > Threshold (High thin cloud)

BT11-BT12 > Threshold (High thin cloud)

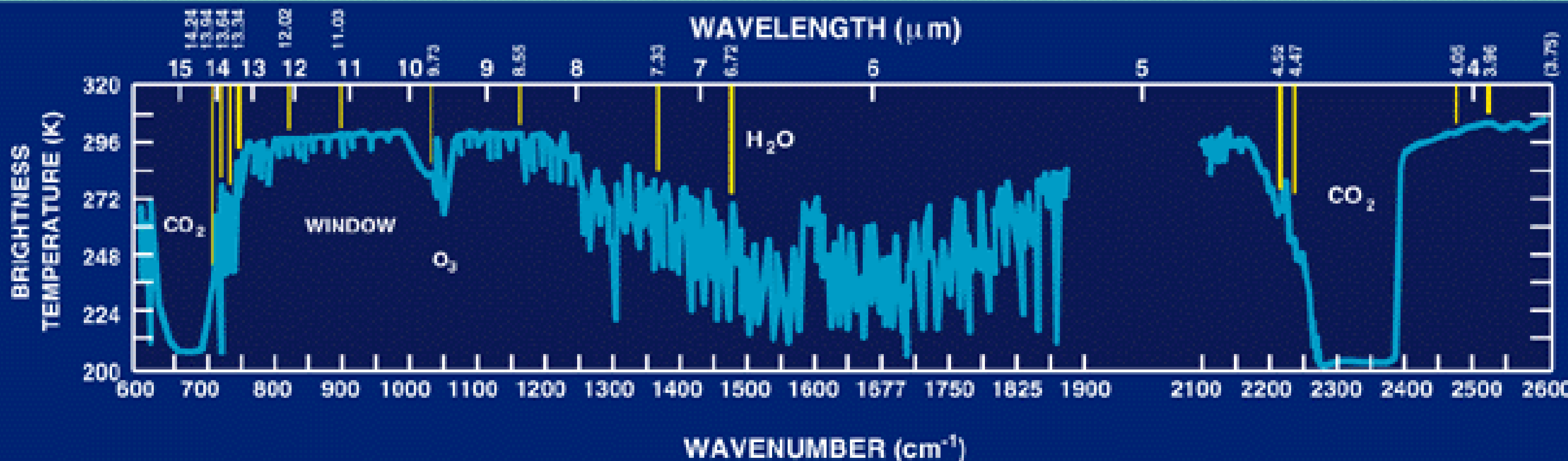
BT3.9 - BT11 > 12 indicates daytime low cloud cover

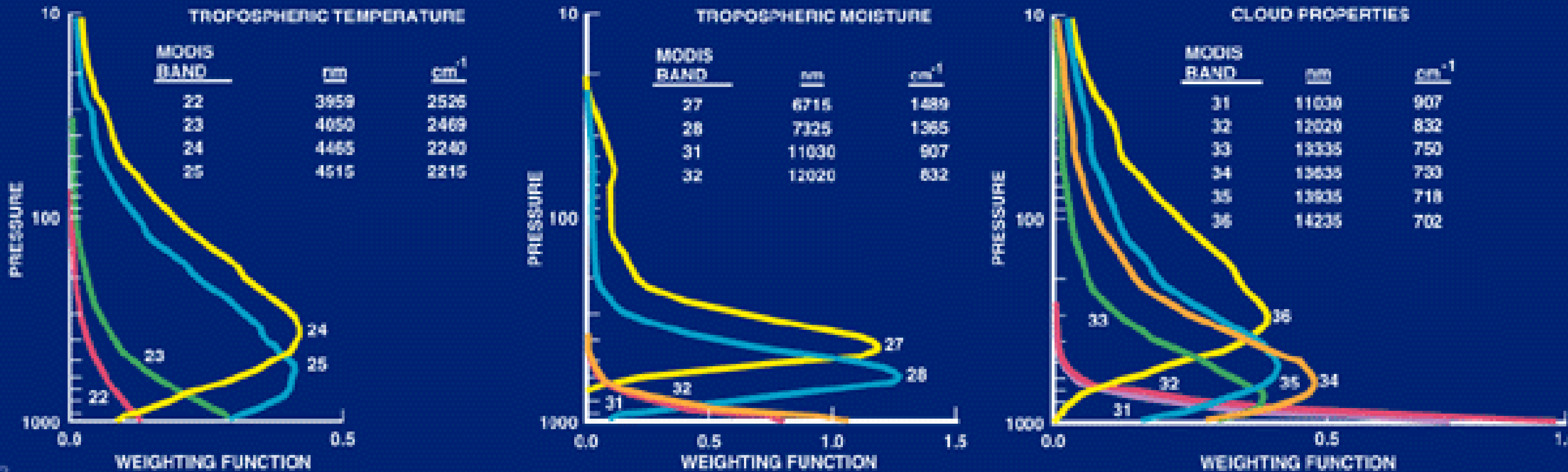
BT11 - BT6.7 large neg diff for clr sky over Antarctic Plateau winter

BT11 – BT7.3 Temperatures close in poles or snow/ice mean cloud

BT8.6 – BT7.3 < 16 indicates cloud over ocean

ATMOSPHERE - THERMAL RADIATION





E351.002 5/93

Detecting Clouds (vis)

Reflectance Threshold Test

r.87 > 5.5% over ocean indicates cloud
r.66 > 18% over vegetated land indicates cloud

Near IR Thin Cirrus Test

r1.38 > threshold indicates presence of thin cirrus cloud
ambiguity of high thin versus low thick cloud (resolved with BT13.9)
problems in high terrain

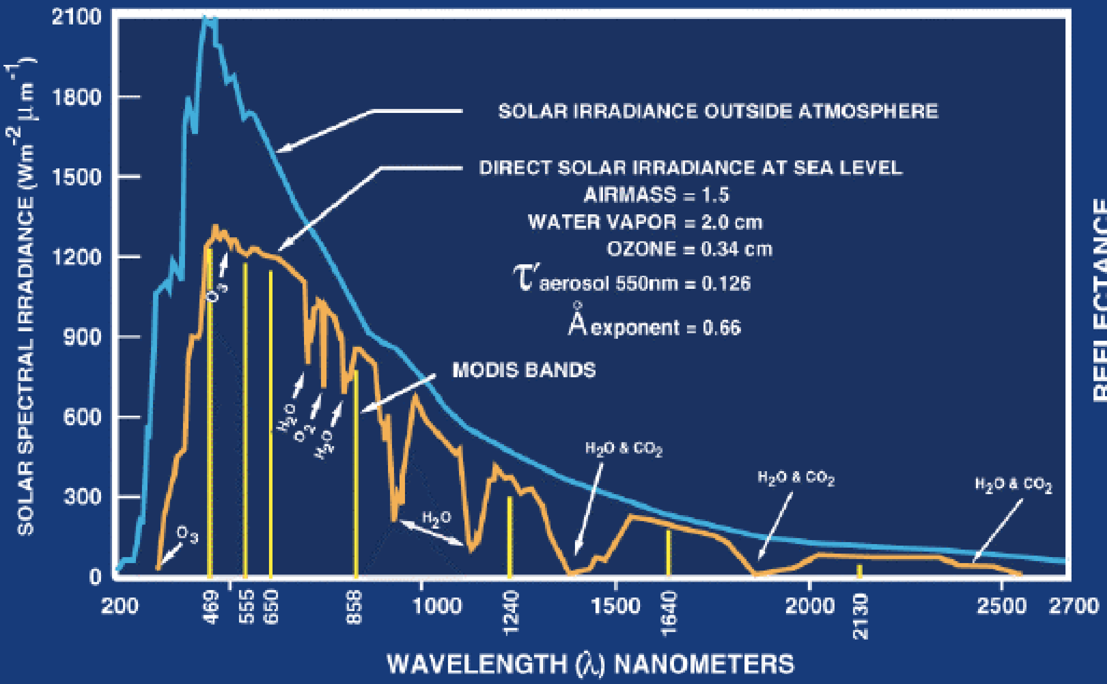
Reflectance Ratio Test

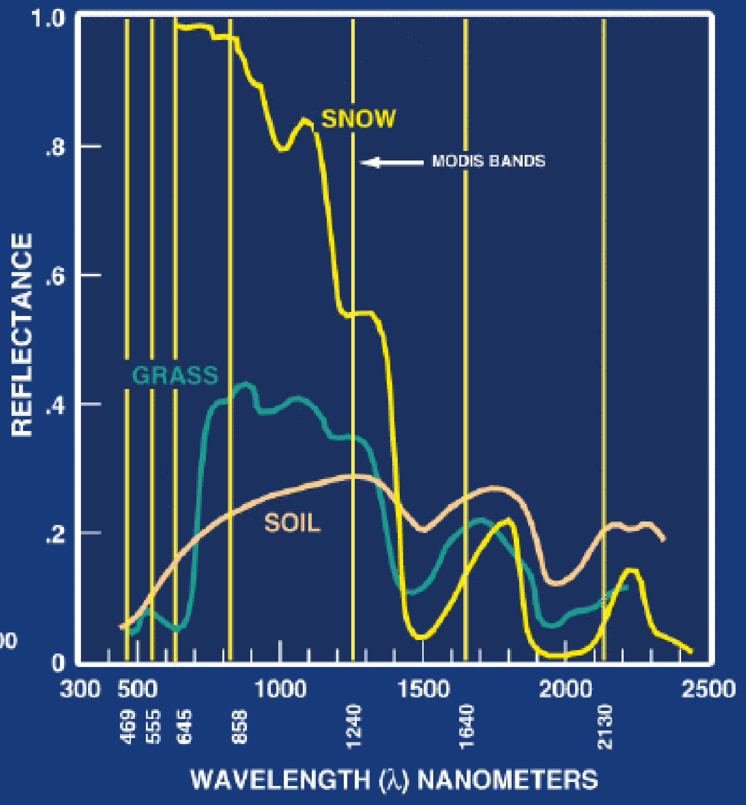
r.87/r.66 between 0.9 and 1.1 for cloudy regions
must be ecosystem specific – snow causes false signal

Snow Test

NDSI = [r.55-r1.6]/ [r.55+r1.6] > 0.4 and r.87 > 0.1 then snow

LAND-SOLAR RADIATION





Other Tests

- BT11 Spatial variability test (3x3 pixels)
  - Cloud if > .50 K
- Clear Sky Restoral Tests (sanity checks)
  - Clear if land night BT11 > 292 K
  - Desert clear if r1.2 /r.55 > 2.0
  - Desert clear if BT11 > 300 K

Use of Threshold File

Code section from Fortran Land_Day.f subroutine

```
c ********  START OF GROUP 3 TESTS
     ***************
c ... visible (channel 1) reflectance threshold test.
      if (visusd) then
        if (nint(masv66) .ne. nint(bad_data)) then
          nmtests = nmtests + 1
          call set_qa_bit(qa_bits,20)
          if (masv66.le.dlref1(2)) then
            call set_bit(testbits,20)
            nptests = nptests + 1
          end if
          call
        conf_test(masv66,dlref1(1),dlref1(3),dlref1(4),
     +               dlref1(2),1,c5)
          cmin3 = min(cmin3,c5)
          ngtests(3) = ngtests(3) + 1
        end if
      end if
```

Daytime Land Thresholds from **thresholds.dat.Aqua** file

```
! Daytime land

dl11_12hi     : 3.0
dl11_4lo      : -14.0, -12.0, -10.0, 1.0
dlco2         : 222.0, 224.0, 226.0, 1.0
dlh20         : 215.0, 220.0, 225.0, 1.0
dlref1        : 0.22,  0.18,  0.14,  1.0
dlref3        : 0.04,  0.035, 0.03,  1.0
dlvrat        : 1.85,  1.90,  1.95,  1.0
dltci         : 0.035, 0.0125
```

Users can fine tune thresholds for a region of interest

- Thresholds file included in delivery
  - thresholds.dat.Aqua
  - thresholds.dat.Terra
  - Contain Cloud mask 0, 1 and inflection point thresholds values for each test
  - File can be updated and the scene rerun

Example for daytime land reflectance in band 1:

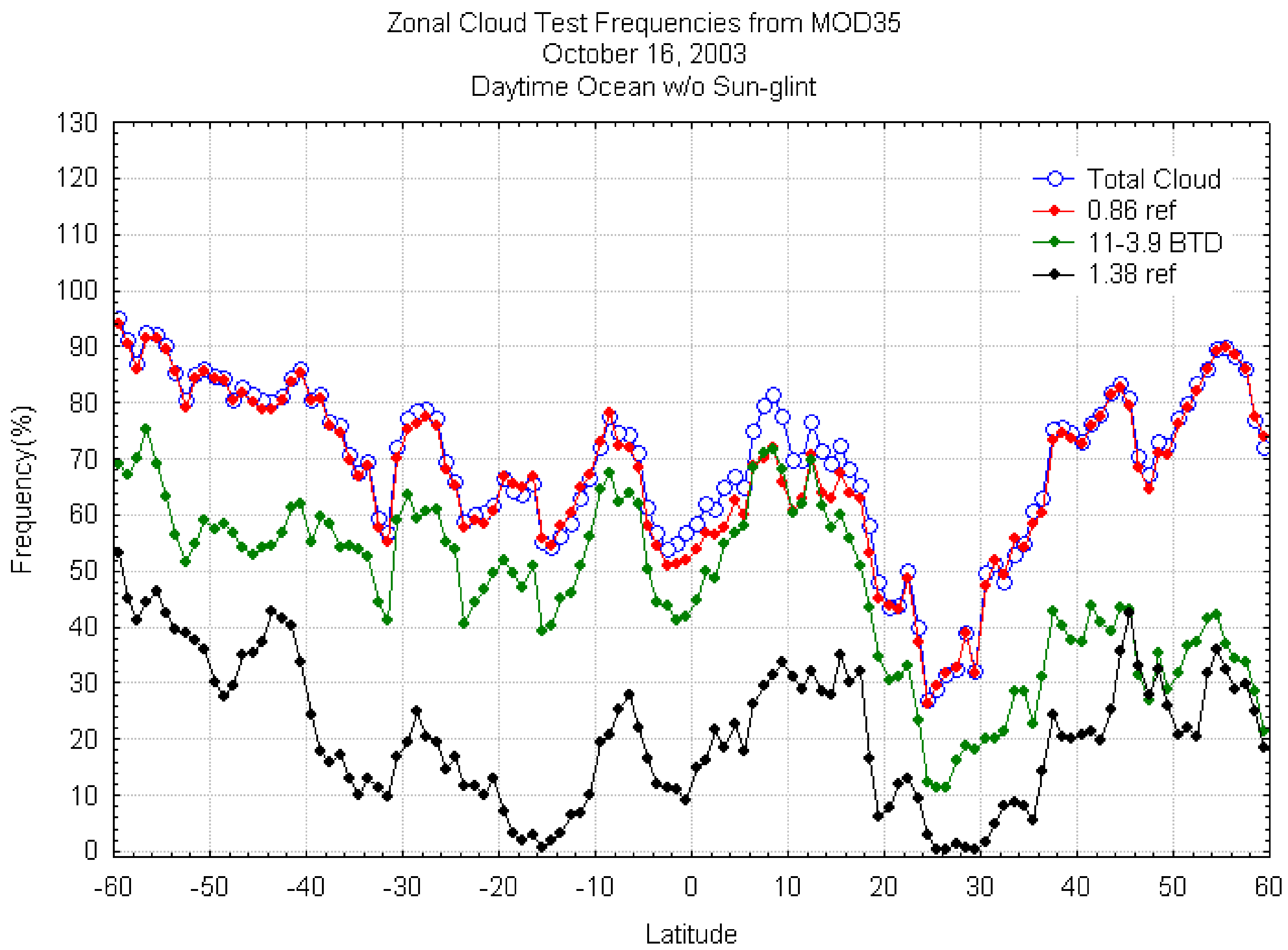
dlref1 : 0.22, 0.18, 0.14, 1.0

if too much cloud found, change to

dlref1 : 0.24, 0.20, 0.16, 1.0

Non-static Inputs

- MODIS L1B (MOD021KM, MOD02QKM) and geolocation file (MOD03)
- Daily Near Real-Time SSM/I EASE-Grid Daily Global Ice Concentration and Snow Extent (NISE) (Nighttime)
  ex: NISE_SSMIF13_20020430.HDFEOS
- Daily SSMI sea ice concentration from the National Centers for Environmental Predition (NCEP) (Nighttime) ex: eng.020430
- 6 hourly Global Data Assimilation System T126 resolution analysis from NCEP (Land Surface Temperature)
  ex: gdas1.PGrbF00.020430.00z
- Weekly Optimum Interpolation (OI) Sea Surface Temperature (SST) Analysis ex: oisst.20050608
- Latest 7 days ancillary data and documentation available from: ftp://aqua.ssec.wisc.edu/pub/terra/ancillary



Zonal Cloud Test Frequencies from MOD35
October 16, 2003
Daytime Ocean w/o Sun-glint
Total Cloud
0.86 ref
11-3.9 BTD
1.38 ref
Frequency(%)
Latitude
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60

Output Product Description

Product Resolution: 1 km and 250 m

bit field	Description Key	Result
0	Cloud Mask Flag	0 = not determined
		1 = determined
1-2	FOV Confidence Flag	00 = cloudy
		01 = uncertain
		10 = probably clear
		11 = confident clear
Processing Path Flags		
3	Day / Night Flag	0 = Night / 1 = Day
4	Sun glint Flag	0 = Yes / 1 = No
5	Snow / Ice Background Flag	0 = Yes/ 1 = No
6-7	Land / Water Flag	00 = Water
		01 = Coastal
		10 = Desert
		11 = Land

ADDITIONAL INFORMATION

bit field	Description Key	Result
8	Heavy Aerosol Flag	0 = Yes / 1 = No
9	Thin Cirrus Detected (solar)	0 = Yes / 1 = No
bit field	**Description Key**	**Result**
10	Shadow Found	0 = Yes / 1 = No
11	Thin Cirrus Detected (IR)	0 = Yes / 1 = No
12	Spare	

1-km Spectral Test Cloud Flags

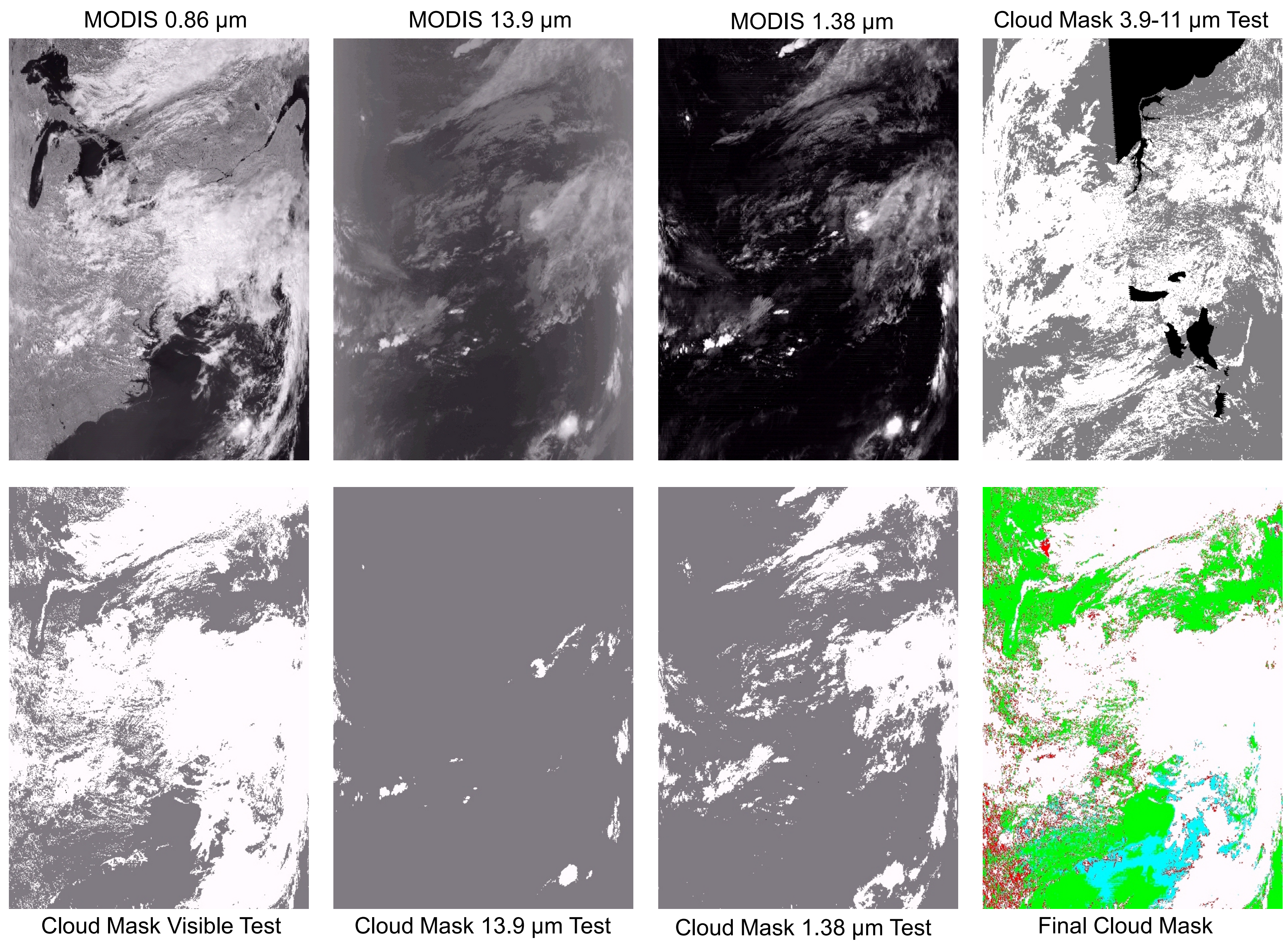
bit field	Description Key	Result
13	Cloud Flag - 11 µm IR Threshold	0 = Yes / 1 = No
14	High Cloud Flag - CO_2 Threshold Test	0 = Yes / 1 = No
15	High Cloud Flag - 6.7 µm Test	0 = Yes / 1 = No
16	High Cloud Flag - 1.38 µm Test	0 = Yes / 1 = No
17	High Cloud Flag - 3.7-12 µm Test	0 = Yes / 1 = No
18	Cloud Flag - IR Temperature Difference	0 = Yes / 1 = No
19	Cloud Flag - 3.9-11 µm Test	0 = Yes / 1 = No
20	Cloud Flag - Visible Reflectance Test	0 = Yes / 1 = No
21	Cloud Flag - Visible Ratio Test	0 = Yes / 1 = No
22	Clear-sky Restoral Test	0 = Yes / 1 = No
23	Cloud Flag - 7.3-11 µm Test	0 = Yes / 1 = No

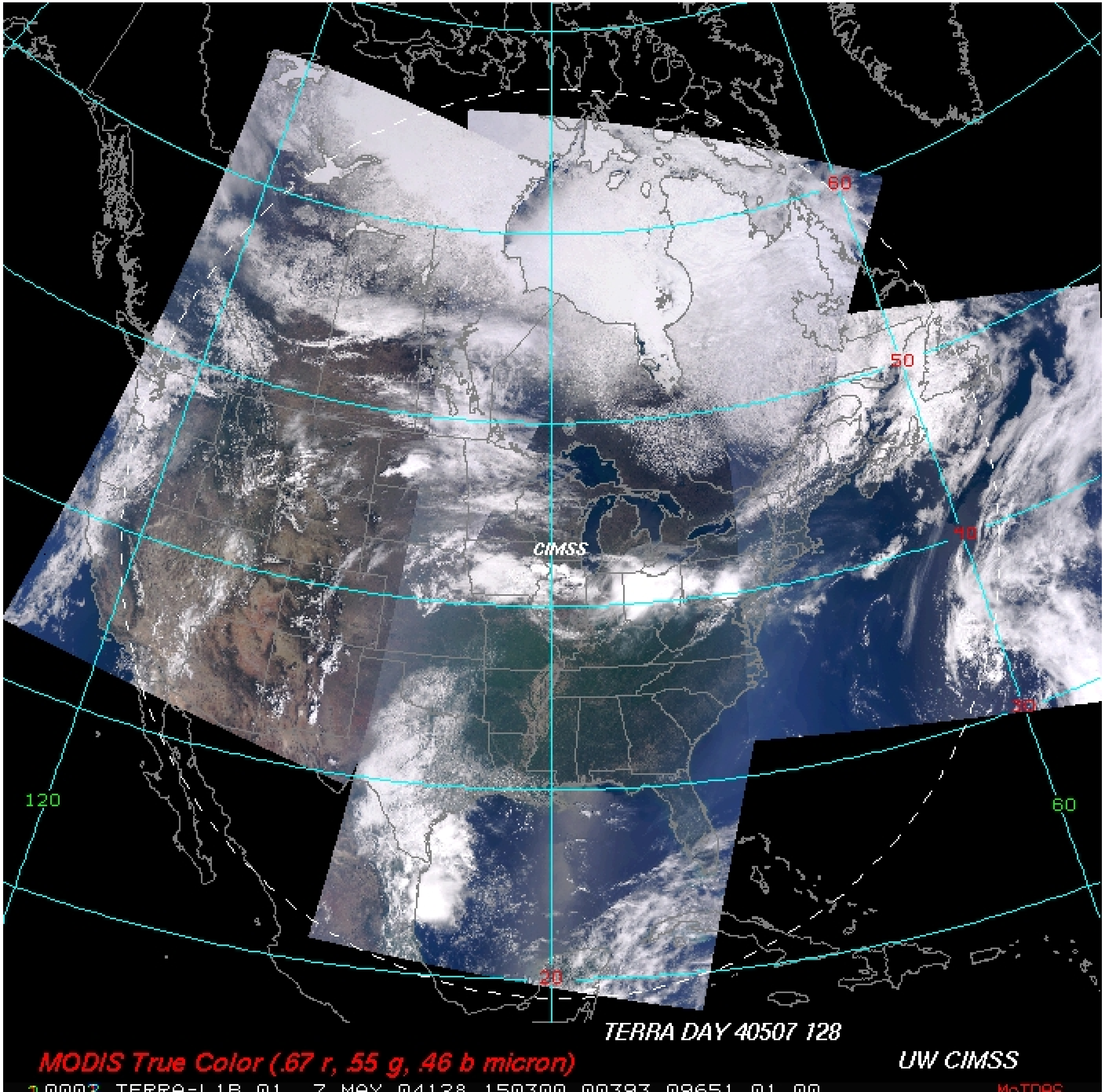
Additional Tests

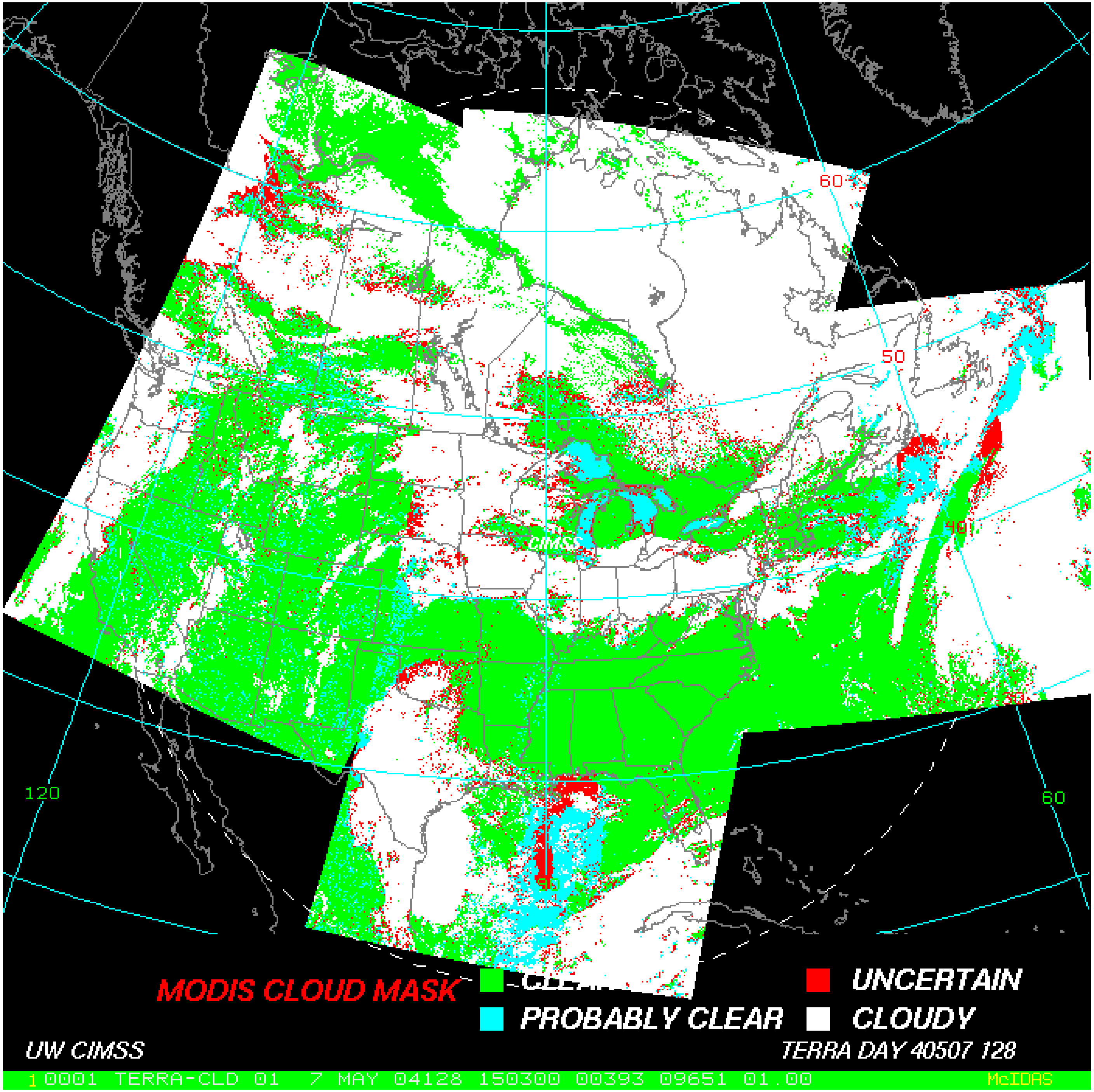
bit field	Description Key	Result
24	Cloud Flag - Temporal Consistency	0 = Yes / 1 = No
25	Cloud Flag - Spatial Consistency	0 = Yes / 1 = No
26	Clear-sky Restoral Tests	0 = Yes / 1 = No
27	Cloud Test – Surface Temp. Comparison	0 = Yes / 1 = No
28	Suspended Dust Flag	0 = Yes / 1 = No
29	Cloud Flag – 8.6-7.3 μm Test	0 = Yes / 1 = No
30	Cloud Flag – 11 μm Spatial Variability	0 = Yes / 1 = No
31	Spare	

250-m Cloud Flag - Visible Tests

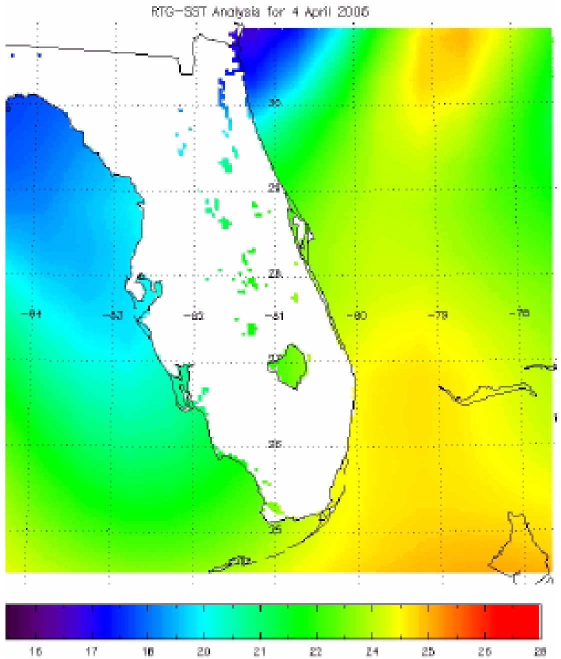
32-47	250 m visible reflectance test	0 = Yes / 1 = No

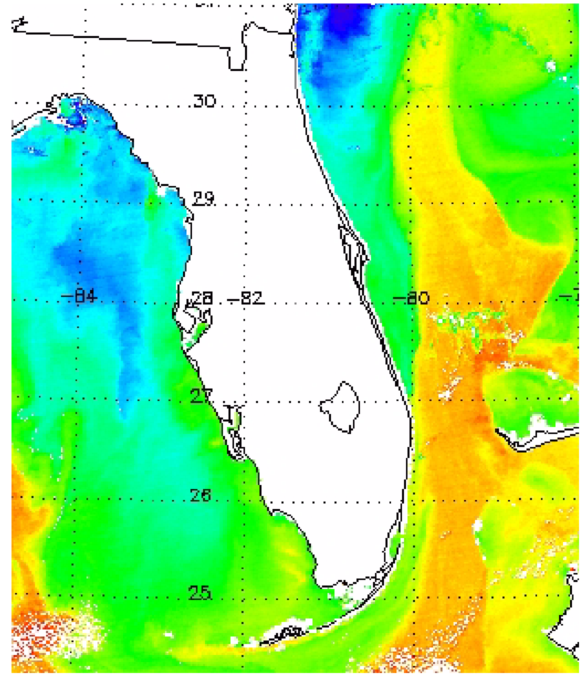

MODIS 0.86 µm
MODIS 13.9 µm
MODIS 1.38 µm
Cloud Mask 3.9-11 µm Test
Cloud Mask Visible Test
Cloud Mask 13.9 µm Test
Cloud Mask 1.38 µm Test
Final Cloud Mask


60
50
40
30
20
120
60
CIMSS
TERRA DAY 40507 128
MODIS True Color (.67 r, .55 g, .46 b micron)
UW CIMSS
2 0002 TERRA-L1B 01 7 MAY 04128 150300 00393 09651 01.00
McIDAS


60
50
40
120
60
MODIS CLOUD MASK
PROBABLY CLEAR
UNCERTAIN
CLOUDY
UW CIMSS
TERRA DAY 40507 128
1 0001 TERRA-CLD 01 7 MAY 04128 150300 00393 09651 01.00
McIDAS

Global .5 degree SST

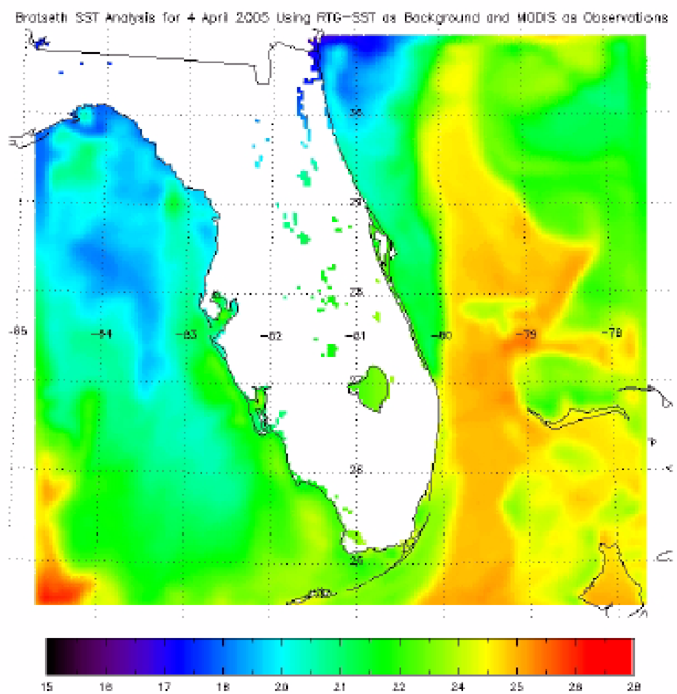




MODIS 1842 UTC SST

Sea Surface Temperatures

4 April 2005

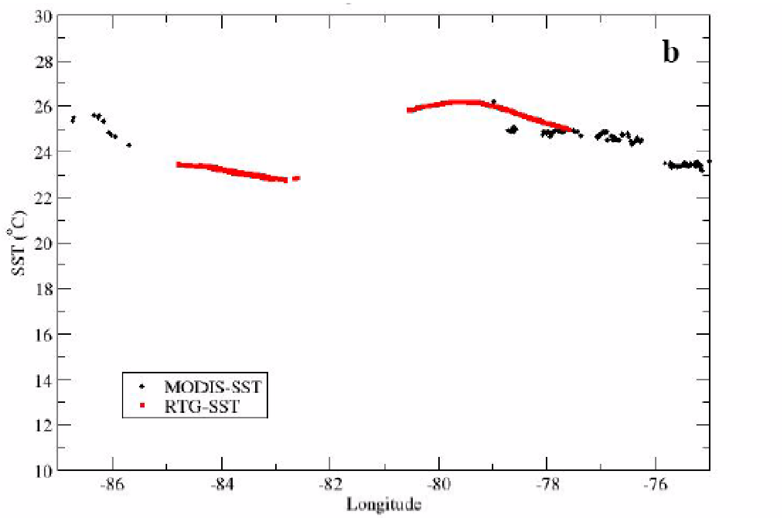


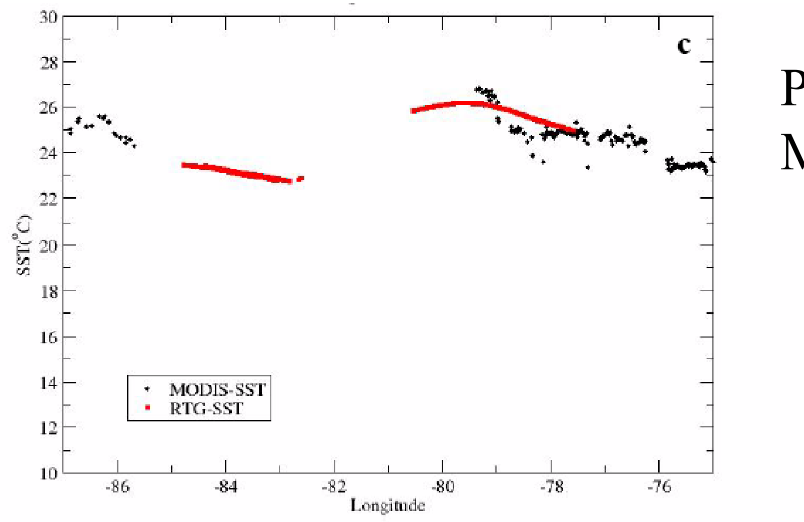
Bratseth analysis combining the RTG-SST and MODIS data.

SST Comparison – MODIS and Global Gridded

10 December 2005 - 28 N Latitude

Confident Clear Cloud
Mask Threshold





Probably Clear Cloud
Mask Threshold

IMAPP MODIS Product Page, Moscow, Russia

Use IMAPP MODIS cloud mask as a means of choosing scenes for users

EOStation.ScanEx.ru

- EOStation
- Schedules
- >MODIS data
  - Product calendar
  - MRDS
  - Search&Browse
  - Sample files
- Custom service
- Under the hood
- Software
- Image gallery
- Contact us

Login to your private area:

Password:

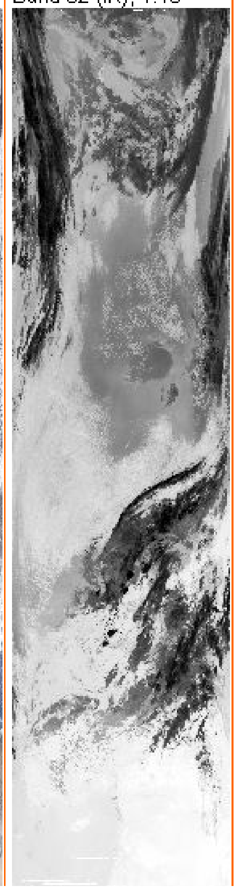
Login

MODIS Data >> Single Pass Browse [AM0409050814]

Pass ID:	AM0409050814
Satellite:	Terra
Start time:	2004-09-05 08:14 UTC

RGB: 1-4-3, 1:10

Band 32 (IR), 1:10



Product files currently available for this pass that may be downloaded or requested on CDs.
Use links on file names to download the files. If file names are not marked as a link then the file is missing or you have no permission to access corresponding data type.

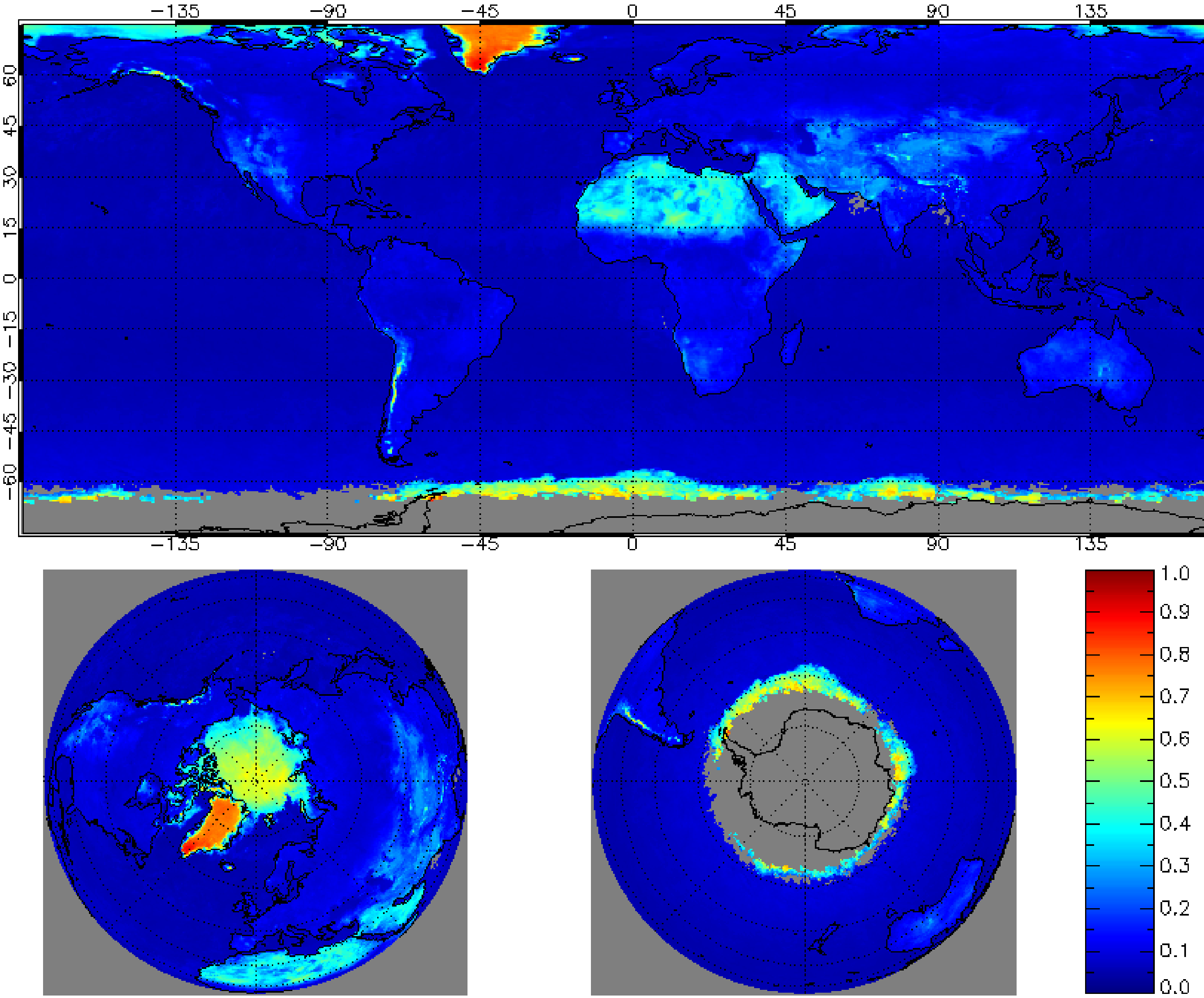
File	Size	Notes
TCB1.AM0409050814.ecw	1823 kB	True color (1-4-3) image, ECW compressed, 1km
-	-	MODIS Level-0(raw) data
-	-	MOD01, unpacked image data
-	-	MOD03, geolocation data
-	-	MOD021KM, geolocated calibrated radiances (1km)
-	-	MOD02HKM, geolocated calibrated radiances (500m)
-	-	MOD021KM, geolocated calibrated radiances (250m)
-	-	MOD021OBC, onboard calibrator data
MOD35.AM0409050814.cl.gif	623 kB	1km MODIS cloud mask. GIF image, levels of free sky confidence
MOD14_AM0409050814.zip	26 MB	MOD14, MODIS fire mask (ZIP compressed)
MOD14shp_AM0409050814.zip	13 kB	MODIS fire points vector map (ESRI SHP, ZIP compressed)

http://eostation.scanex.ru/data/cellquery.html

Known Problems

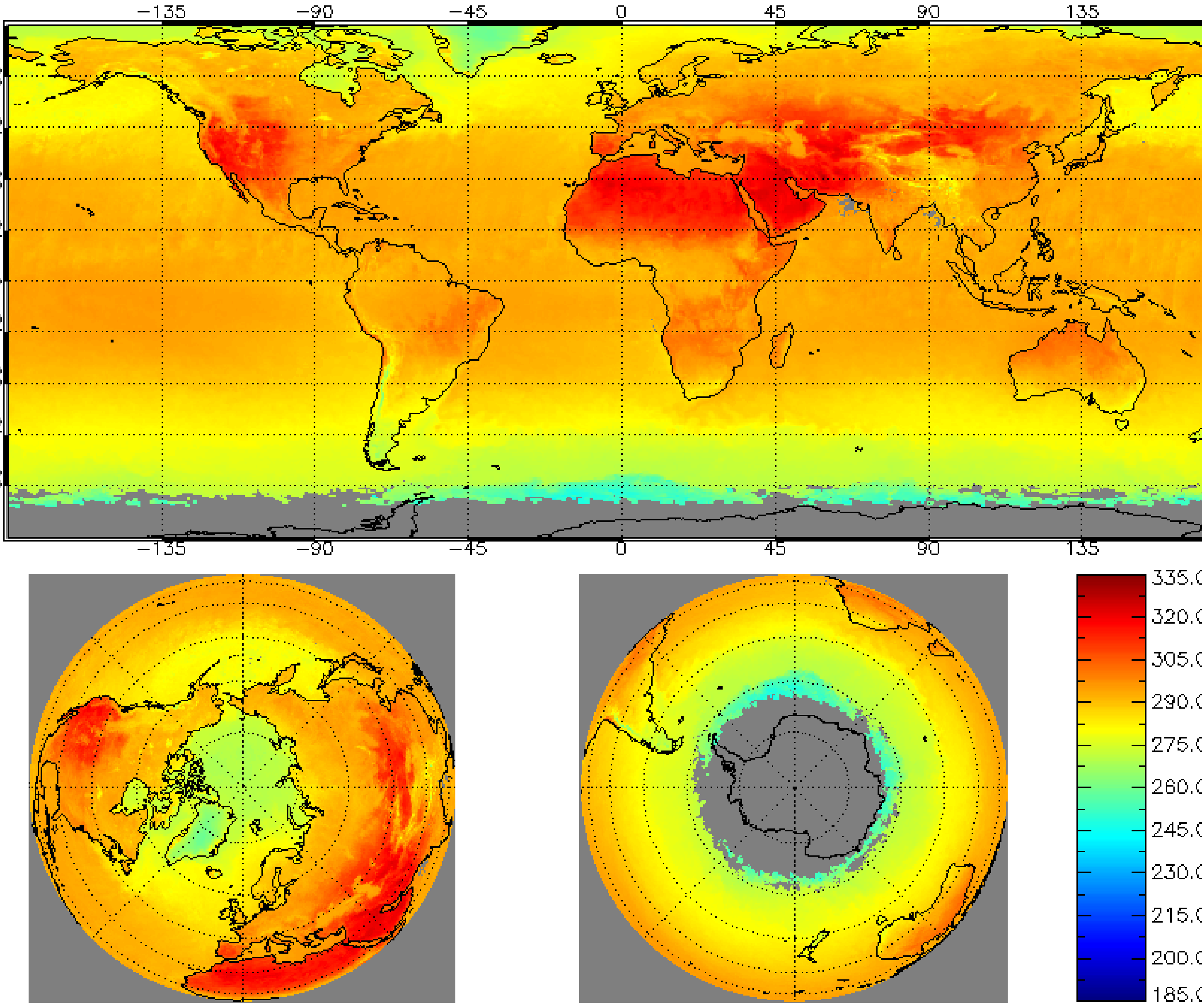
- MODIS algorithm is clear sky conservative
  - If is doubt, it is cloudy
- Nighttime algorithm is different –
  - 16 versus 36 channels available
- Transition regions
  - terminator, edges of desert regions, edges of snow regions, etc.
- Very specific regions
  - Certain surfaces, certain times of year, certain sun angles (bare soils over the midwest during the spring)

MODIS Clear Sky Product



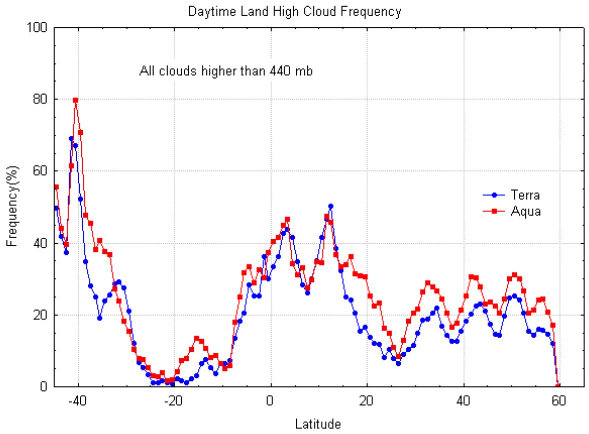
Daytime
Band 1
(.65 µm)
Reflectance
July 2002

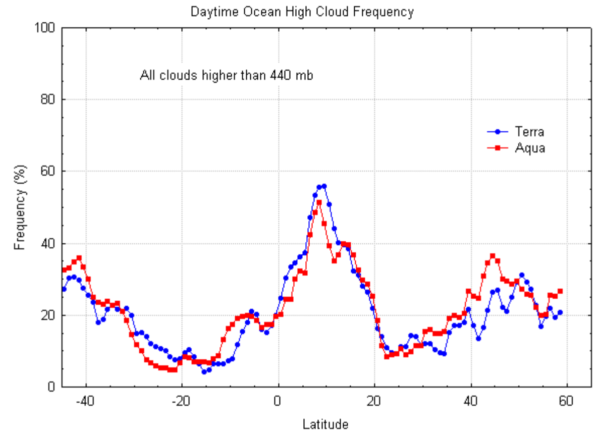
MODIS Clear Sky Product

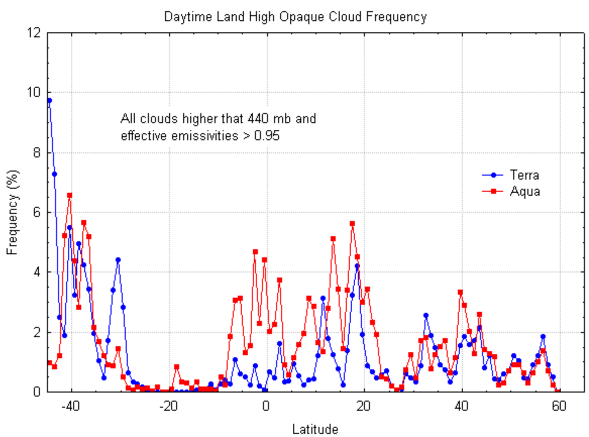


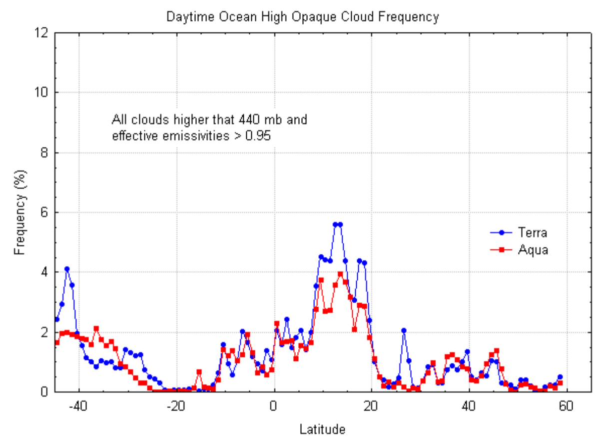
Daytime Band 31 (11 µm)
Brightness Temperature
July 2002

3-Hourly Cloud Changes Measured by Terra and Aqua





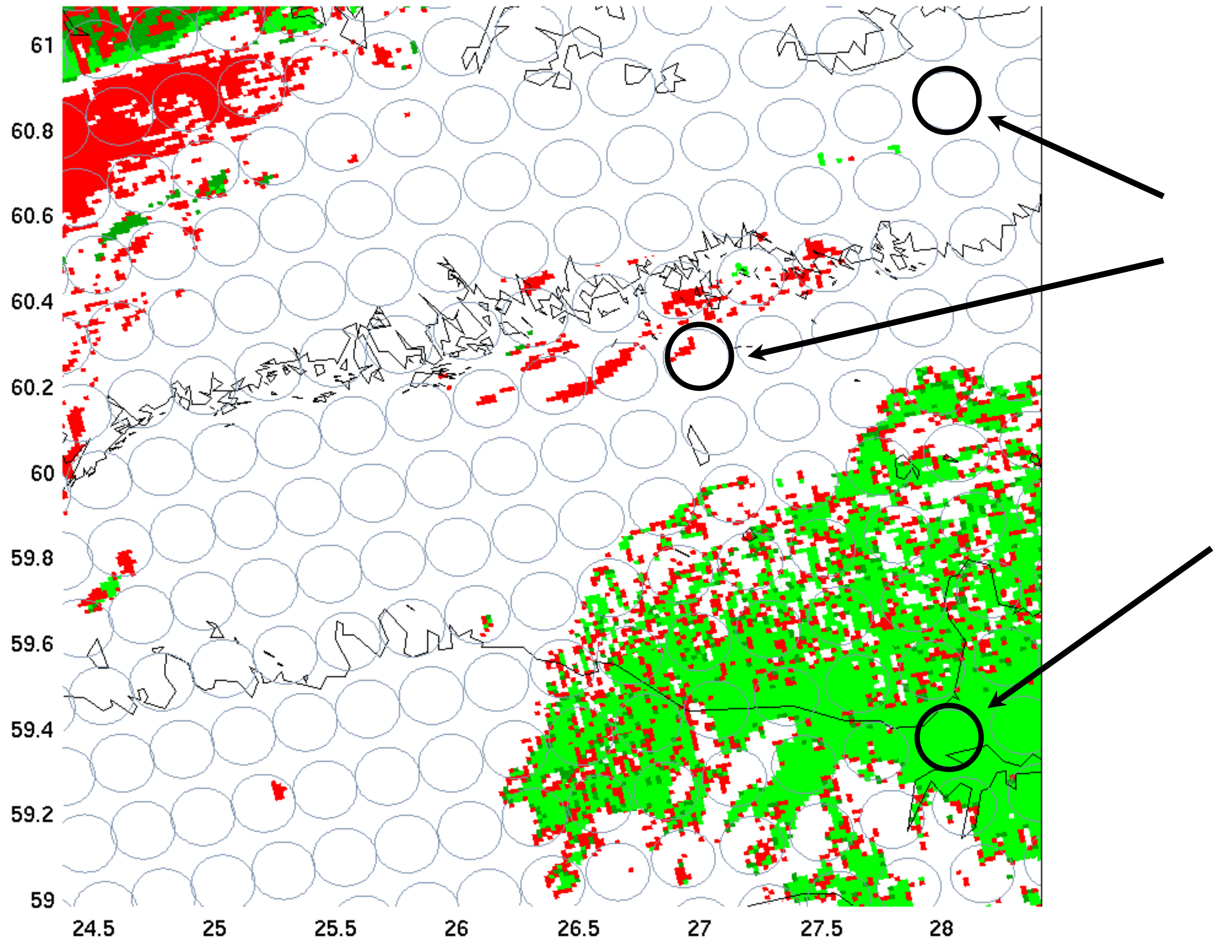




Shown at left are zonal values of daytime land Terra and Aqua total high cloud frequency (top), and high, opaque cloud frequency (bottom) from August 24, 2002. The latter are mostly cold convective towers. With a local observing time of about 1:30 pm, roughly three hours later than Terra, we expect the Aqua measurements to indicate more convective activity and hence more thick, high clouds and more high clouds in general. This is clearly seen in the tropics and northern hemisphere where solar heating is greatest. For reference, the same data is plotted for ocean surfaces (right) where we would not expect to see changes in high clouds due to solar heating. Differences between Terra and Aqua are small as we expect, especially for high, opaque clouds

AIRS Clear Flag from MODIS cloud mask

Not Determined	Cloudy	Uncertain	Probably Clear	Confident Clear



Cloud Top Properties

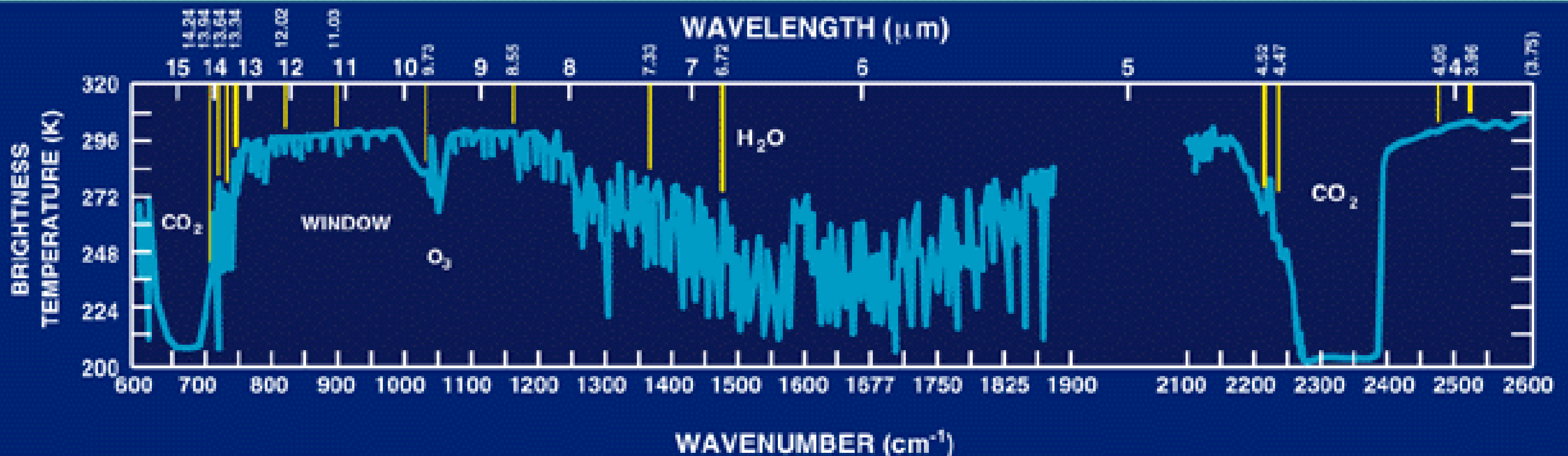
Menzel, Wylie - CIMSS

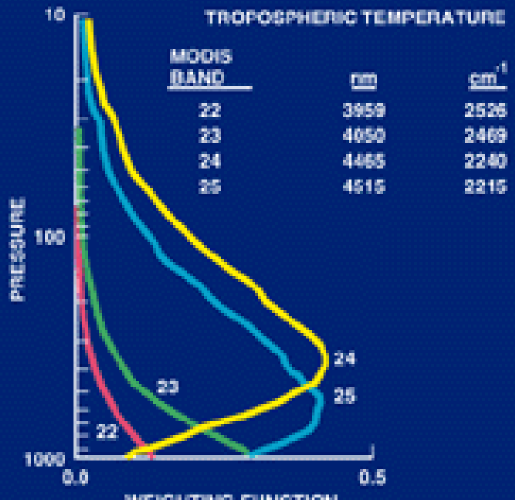
- Cloud Top Pressure, Temperature, Emissivity derived using CO_2 "slicing"
- MODIS product utilizes 4 spectral channels in the 13 – 14 μm region.
- 5x5 1 km pixel retrievals where at least 5 of the 1 km pixels are cloudy as determined by the cloud mask
- Cloud properties retrieved both day and night

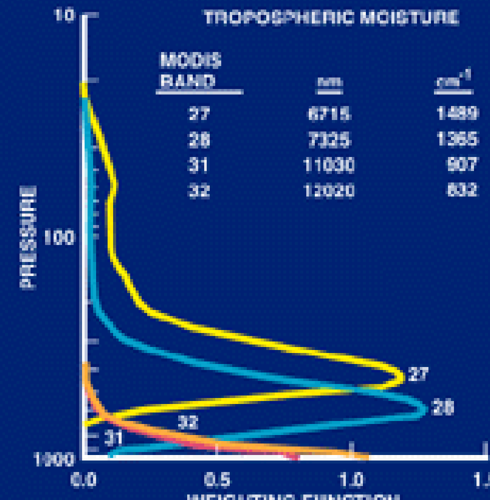
Inputs

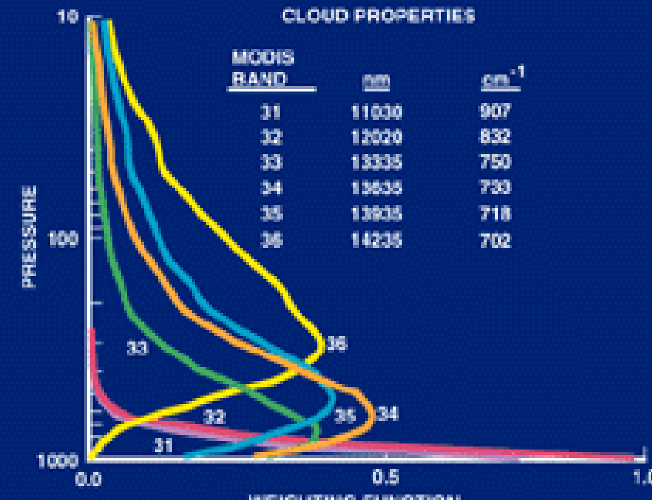
- MODIS L1B (MOD021KM, MOD02QKM) and geolocation file (MOD03)
- MODIS Cloud Mask (MOD35)
- 6 hourly Global Data Assimilation System T126 resolution analysis from NCEP (Vertical Profiles of Temperature and Moisture)
  ex: gdas1.PGrbF00.020430.00z
- Weekly Optimum Interpolation (OI) Sea Surface Temperature (SST) Analysis
  ex: oisst.20050608
- Latest 7 days ancillary data and documentation available from:
  ftp://aqua.ssec.wisc.edu/pub/terra/ancillary

ATMOSPHERE - THERMAL RADIATION



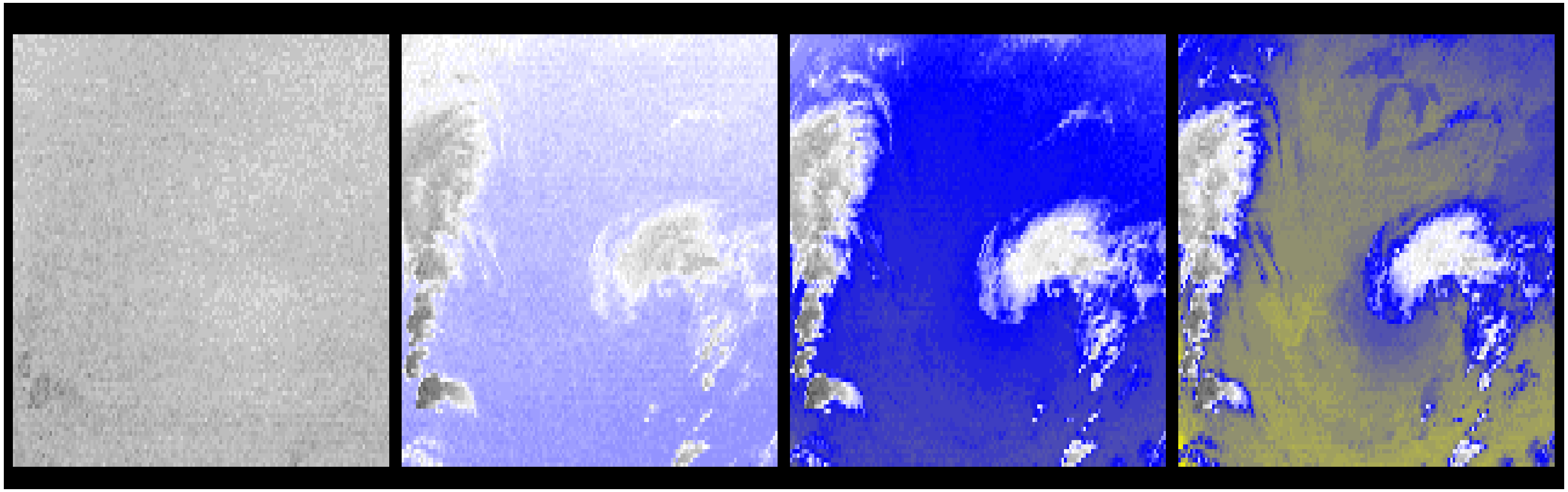






E351.002 5/93

CO2 channels see to different levels in the atmosphere



14.2 um 13.9 um 13.6 um 13.3 um

Radiative Transfer Equation

The radiance leaving the earth-atmosphere system sensed by a satellite borne radiometer is the sum of radiation emissions from the earth-surface and each atmospheric level that are transmitted to the top of the atmosphere. Considering the earth's surface to be a blackbody emitter (emissivity equal to unity), the upwelling radiance intensity, I_λ, for a cloudless atmosphere is given by the expression

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_{sfc}) \tau_\lambda(sfc - top) + \sum_{layers} \varepsilon_\lambda^{layer} B_\lambda(T_{layer}) \tau_\lambda(layer - top)$$

where the first term is the surface contribution and the second term is the atmospheric contribution to the radiance to space.

In standard notation,

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T(p_s)) \tau_\lambda(p_s) + \sum_p \varepsilon_\lambda(\Delta p) B_\lambda(T(p)) \tau_\lambda(p)$$

The emissivity of an infinitesimal layer of the atmosphere at pressure p is equal to the absorptance (one minus the transmittance of the layer). Consequently,

$$\varepsilon_\lambda(\Delta p) \tau_\lambda(p) = [1 - \tau_\lambda(\Delta p)] \tau_\lambda(p)$$

Since transmittance is an exponential function of depth of absorbing constituent,

$$\tau_\lambda(\Delta p) \tau_\lambda(p) = \exp [- \int_p^{p+\Delta p} k_\lambda q g^{-1} dp] * \exp [- \int_o^p k_\lambda q g^{-1} dp] = \tau_\lambda(p + \Delta p)$$

Therefore

$$\varepsilon_\lambda(\Delta p) \tau_\lambda(p) = \tau_\lambda(p) - \tau_\lambda(p + \Delta p) = - \Delta\tau_\lambda(p) .$$

So we can write

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T(p_s)) \tau_\lambda(p_s) - \sum_p B_\lambda(T(p)) \Delta\tau_\lambda(p) .$$

which when written in integral form reads

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T(p_s)) \tau_\lambda(p_s) - \int_o^{p_s} B_\lambda(T(p)) [d\tau_\lambda(p) / dp] dp .$$

When reflection from the earth surface is also considered, the Radiative Transfer Equation for infrared radiation can be written

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_s) \tau_\lambda(p_s) + \int_{p_s}^{o} B_\lambda(T(p)) F_\lambda(p) [d\tau_\lambda(p)/ dp] dp$$

where

$$F_\lambda(p) = \{ 1 + (1 - \varepsilon_\lambda) [\tau_\lambda(p_s) / \tau_\lambda(p)]^2 \}$$

The first term is the spectral radiance emitted by the surface and attenuated by the atmosphere, often called the boundary term and the second term is the spectral radiance emitted to space by the atmosphere directly or by reflection from the earth surface.

The atmospheric contribution is the weighted sum of the Planck radiance contribution from each layer, where the weighting function is [$d\tau_\lambda(p) / dp$]. This weighting function is an indication of where in the atmosphere the majority of the radiation for a given spectral band comes from.

RTE in Cloudy Conditions

$$I_\lambda = \eta I_\lambda^{cd} + (1 - \eta) I_\lambda^{clr}$$ where cd = cloud, clr = clear, η = cloud fraction

$$I_\lambda^{clr} = B_\lambda(T_s)\, \tau_\lambda(p_s) + \int_{p_s}^{o} B_\lambda(T(p))\, d\tau_\lambda .$$

$$I_\lambda^{cd} = (1-\varepsilon_\lambda)\, B_\lambda(T_s)\, \tau_\lambda(p_s) + (1-\varepsilon_\lambda) \int_{p_s}^{p_c} B_\lambda(T(p))\, d\tau_\lambda$$

$$+ \varepsilon_\lambda B_\lambda(T(p_c))\, \tau_\lambda(p_c) + \int_{p_c}^{o} B_\lambda(T(p))\, d\tau_\lambda$$

ε_λ is emittance of cloud. First two terms are from below cloud, third term is cloud contribution, and fourth term is from above cloud. After rearranging

$$I_\lambda - I_\lambda^{clr} = \eta \varepsilon_\lambda \int_{p_s}^{p_c} \tau(p) \frac{dB_\lambda}{dp} dp .$$

Cloud Properties from CO2 Slicing

RTE for cloudy conditions indicates dependence of cloud forcing (observed minus clear sky radiance) on cloud amount ($\eta\varepsilon_\lambda$) and cloud top pressure (p_c)

$$(I_\lambda - I_\lambda^{clr}) = \eta\varepsilon_\lambda \int_{p_s}^{p_c} \tau_\lambda \, dB_\lambda \, .$$

Higher colder cloud or greater cloud amount produces greater cloud forcing; dense low cloud can be confused for high thin cloud. Two unknowns require two equations.

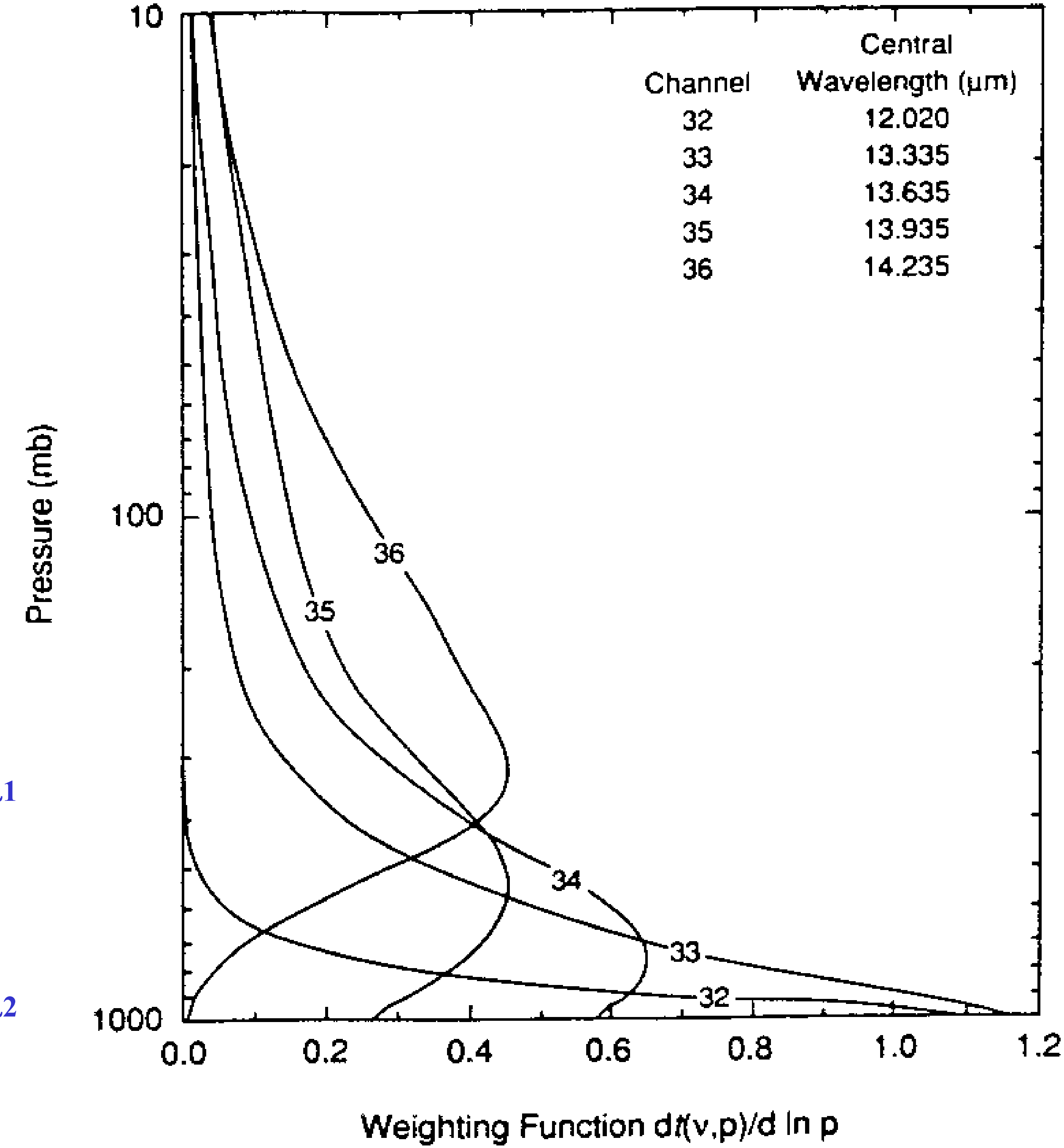
p_c can be inferred from radiance measurements in two spectral bands where cloud emissivity is the same. $\eta\varepsilon_\lambda$ is derived from the infrared window, once p_c is known.

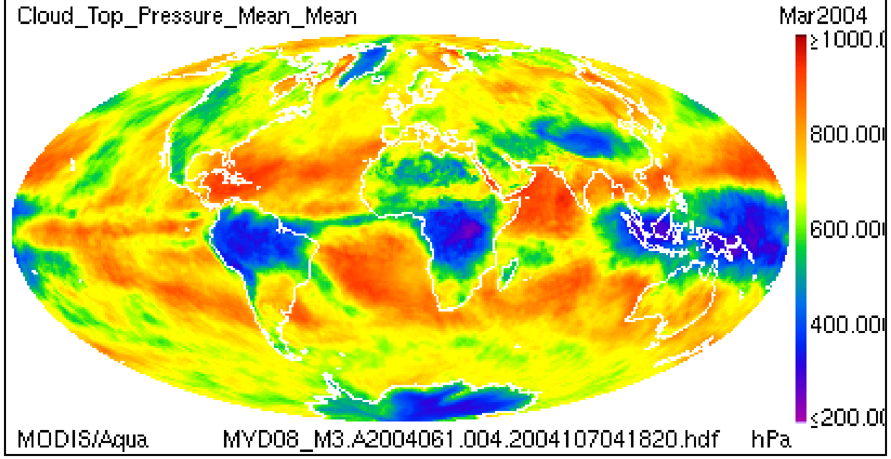
Different ratios reveal cloud properties at different levels

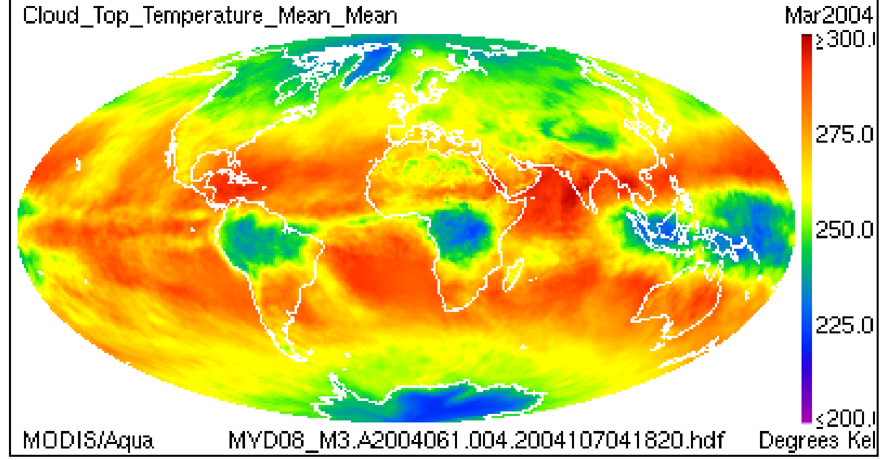
hi - 14.2/13.9
mid - 13.9/13.6
low - 13.6/13.3

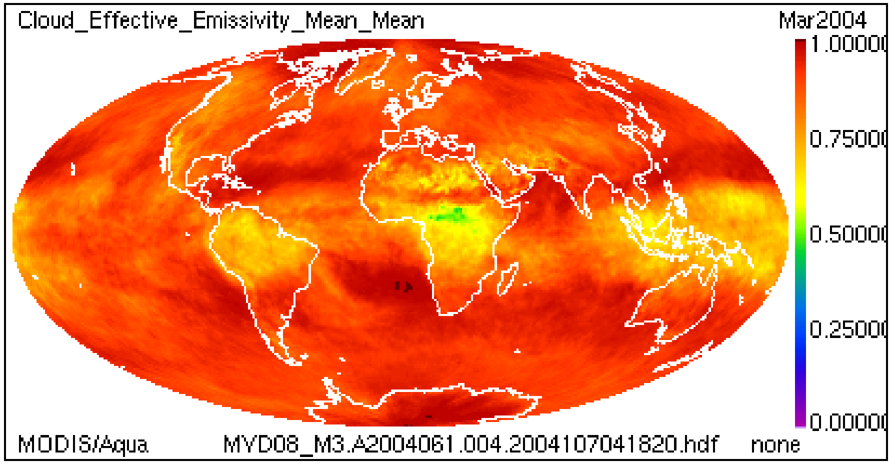
Meas **Calc**

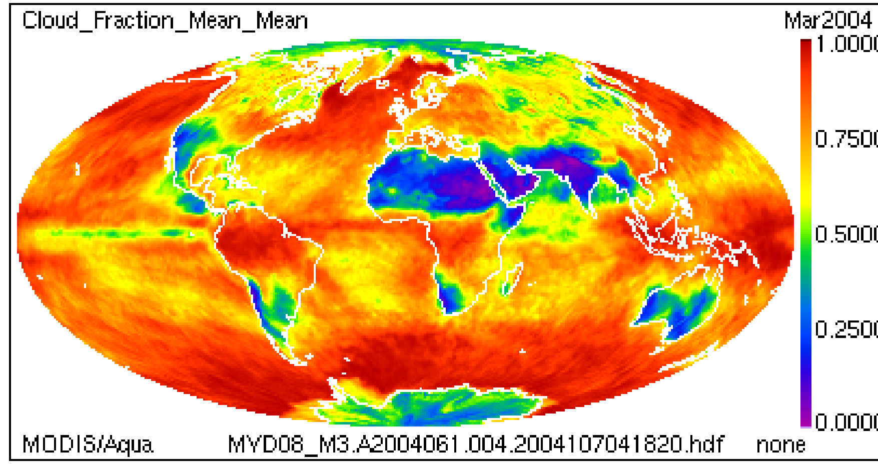
$$\frac{(I_{\lambda 1}-I_{\lambda 1}^{clr})}{(I_{\lambda 2}-I_{\lambda 2}^{clr})} = \frac{\eta \varepsilon_{\lambda 1} \int_{p_s}^{p_c} \tau_{\lambda 1}\, dB_{\lambda 1}}{\eta \varepsilon_{\lambda 2} \int_{p_s}^{p_c} \tau_{\lambda 2}\, dB_{\lambda 2}}$$

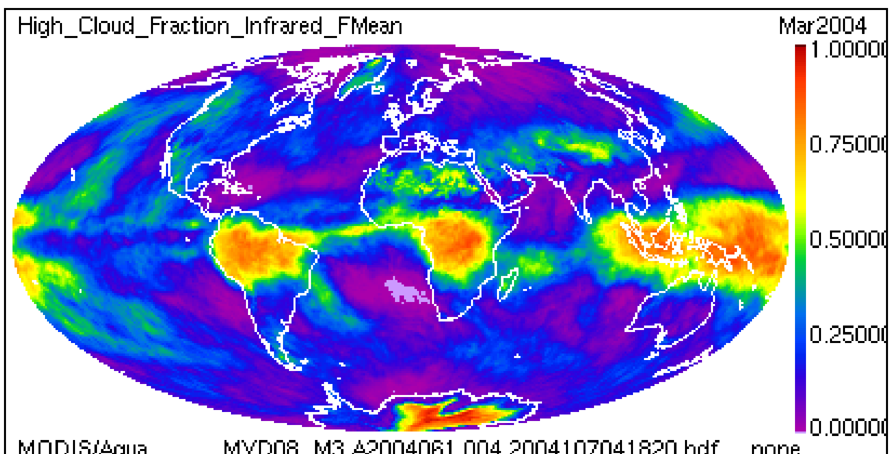




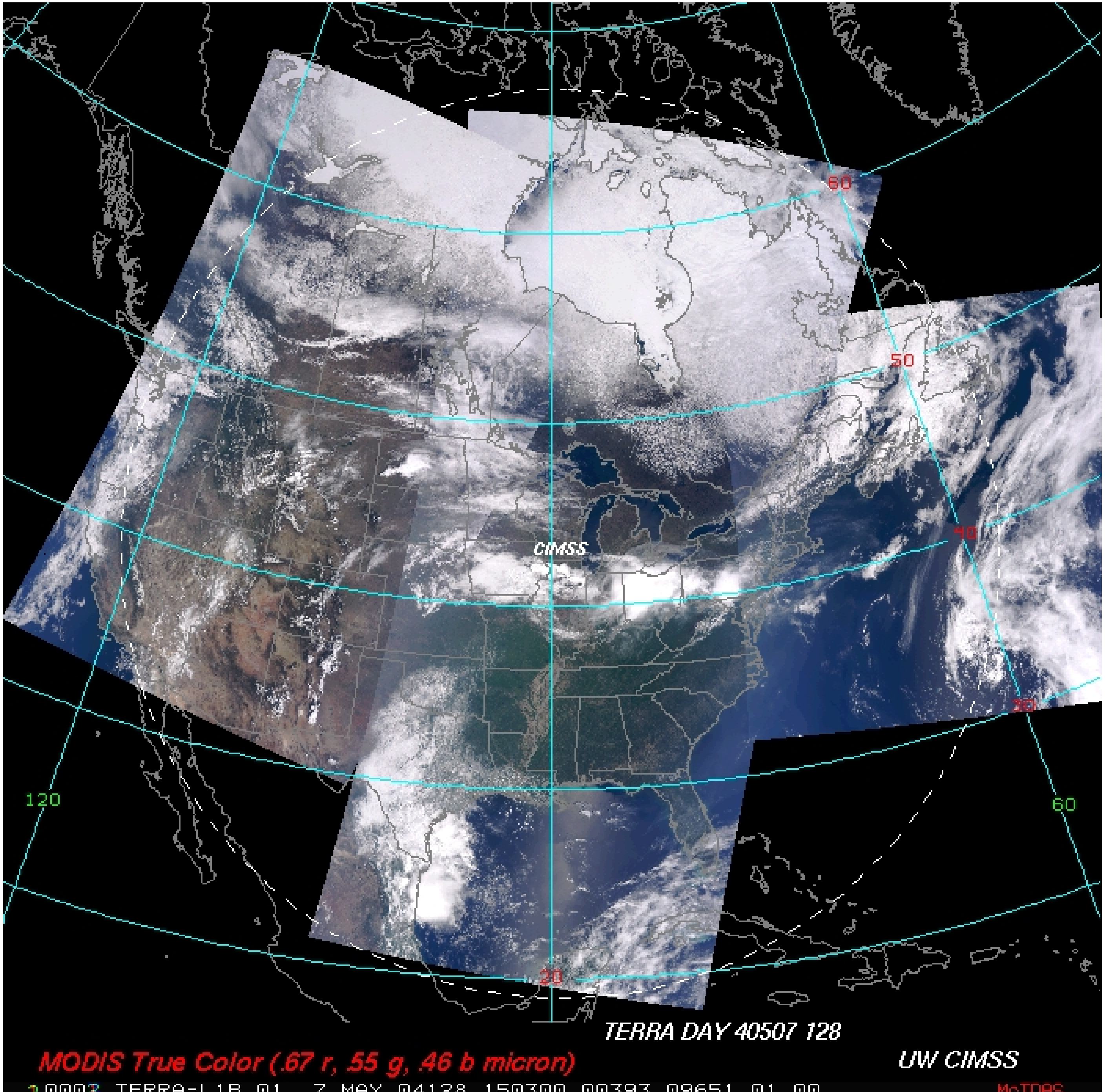




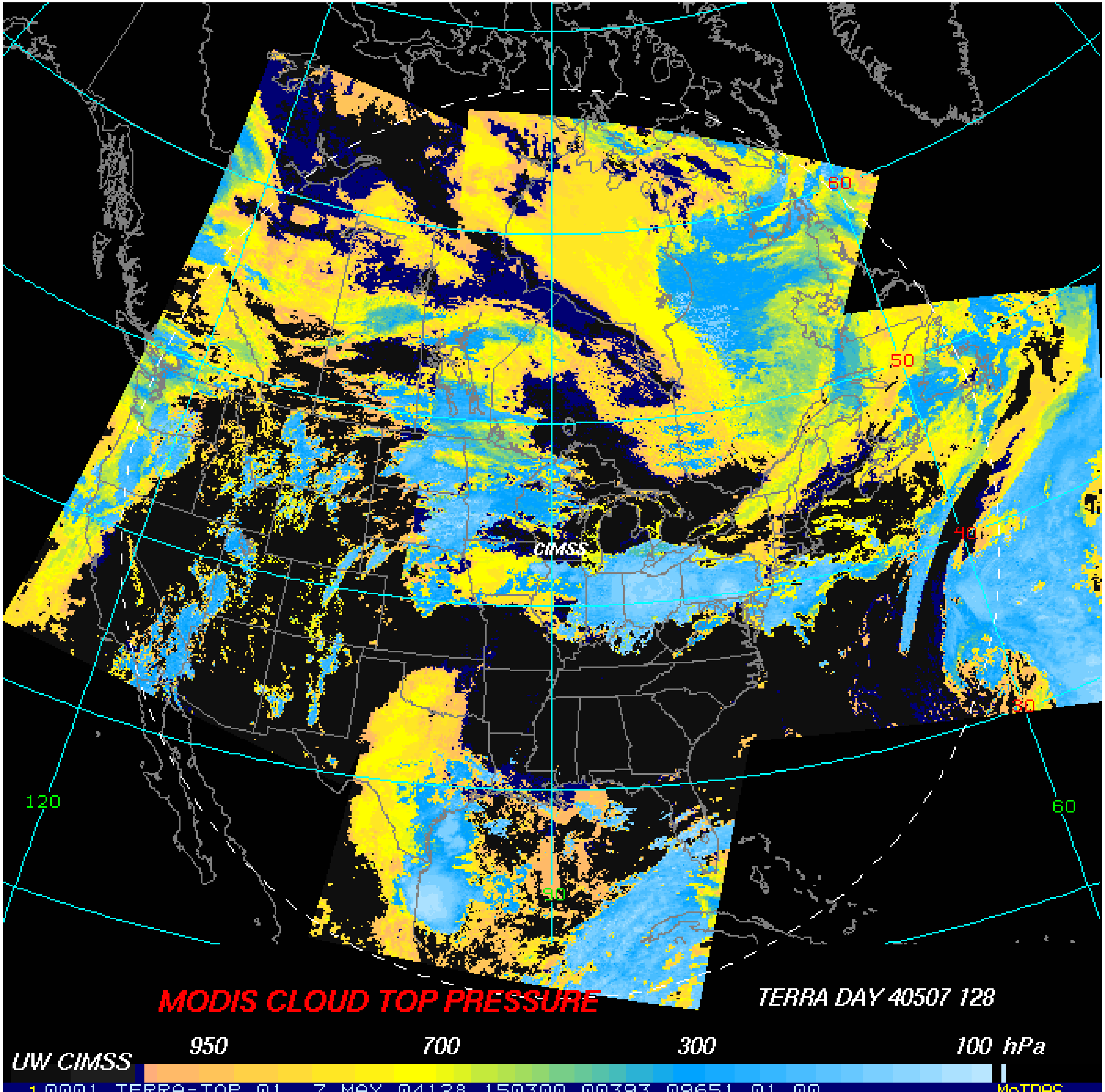




MODIS Cloud Top Properties Level 3 Products March 2004



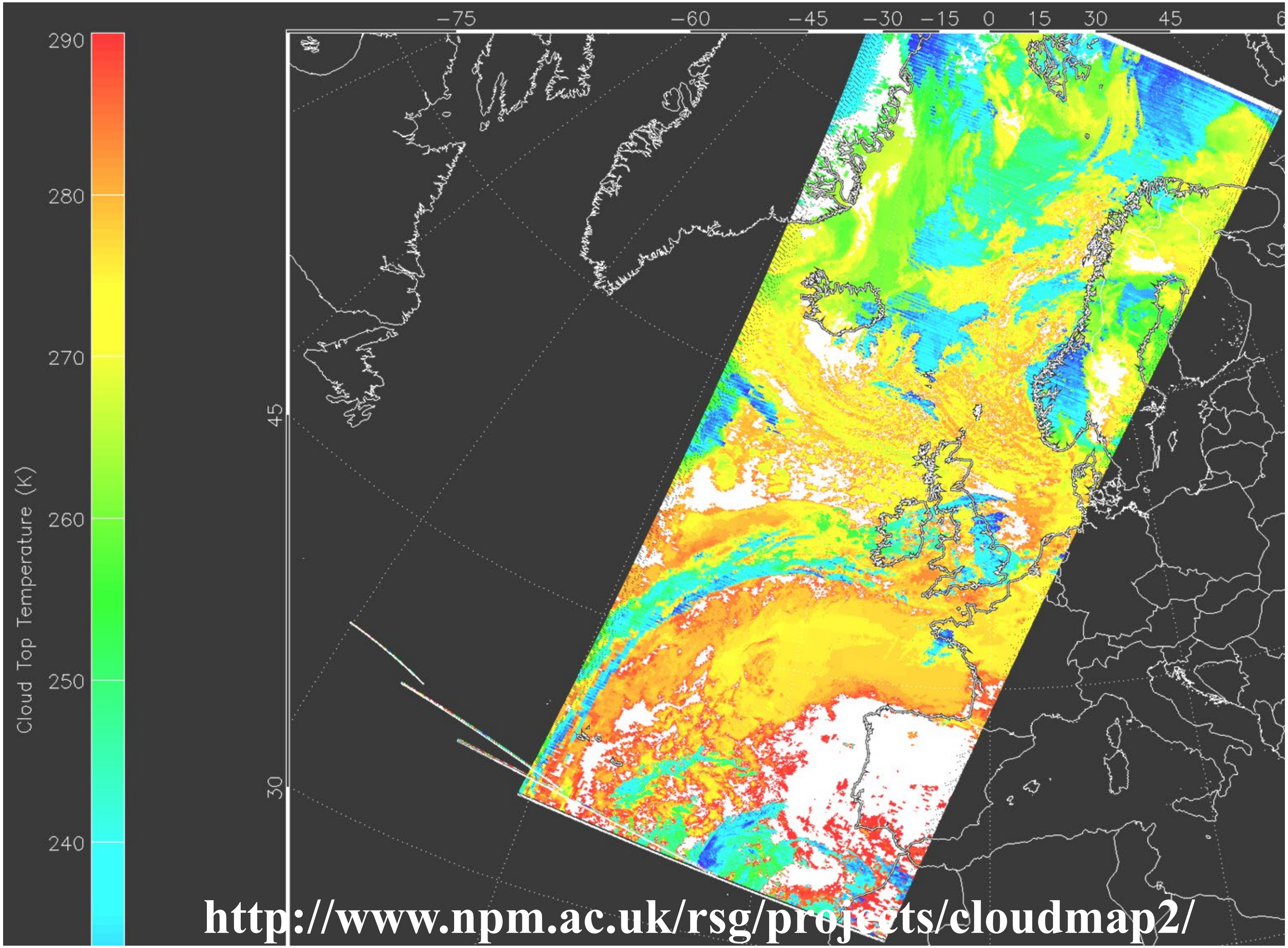
60
50
40
30
20
120
60
CIMSS
TERRA DAY 40507 128
MODIS True Color (.67 r, .55 g, .46 b micron)
UW CIMSS
20002 TERRA-L1B 01 7 MAY 04128 150300 00393 09651 01.00
McIDAS



MODIS CLOUD TOP PRESSURE
TERRA DAY 40507 128
CIMSS
UW CIMSS
950
700
300
100 hPa
1 0001 TERRA-TOP 01 7 MAY 04128 150300 00393 09651 01.00
McIDAS
60
50
40
30
120
90
60

Cloud Top Temperature Plymouth Marine Lab, UK

10 October 2003   11:57 UTC



http://www.npm.ac.uk/rsg/projects/cloudmap2/

Output Product Description

MOD06 Key Output Parameters

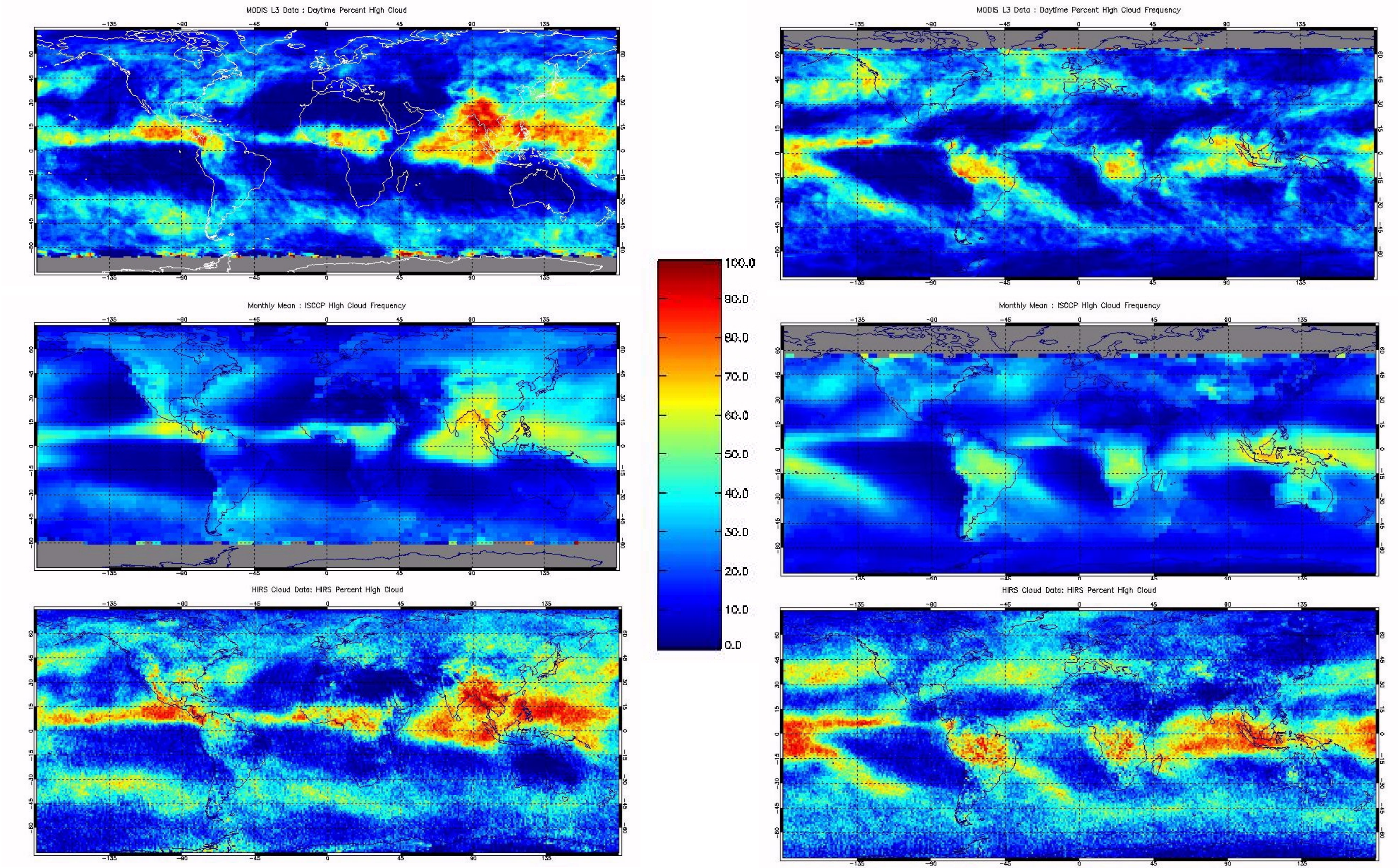
5x5 pixel (1km) resolution

- Surface_Temperature (GDAS input)
- Surface_Pressure (GDAS input)
- Cloud_Top_Pressure
- Cloud_Top_Temperature
- Tropopause_Height
- Cloud_Fraction
- Cloud_Effective_Emissivity
- Cloud_Top_Pressure_Infrared
- Brightness_Temperature_Difference_B29-B31
- Brightness_Temperature_Difference_B31-B32

Known Problems

- Low cloud
  - Vantage point of satellite means more sensitive to high cloud than low cloud. New algorithm address this
- Solution converges on highest pressure level
  - Addressed with latest algorithm

Validation - Comparison of HIRS/ISCCP/MODIS High Cloud Frequency



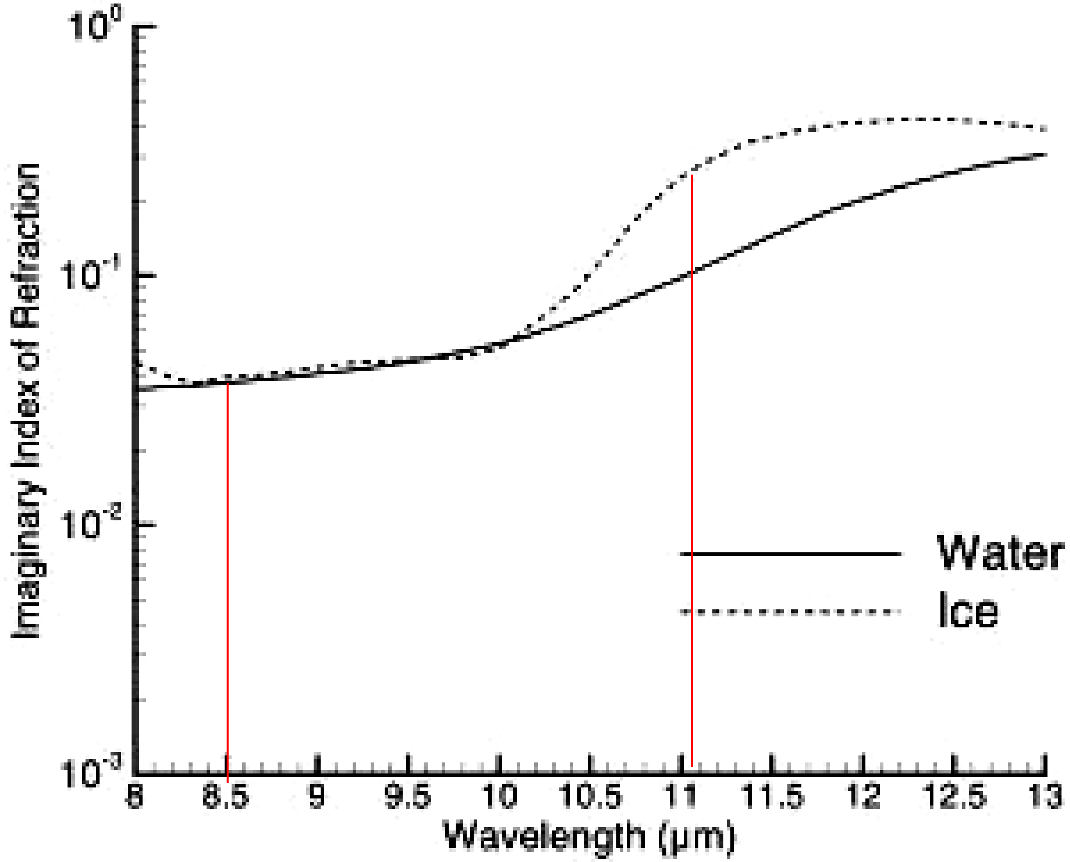
July 2002

December 2002

Cloud Phase

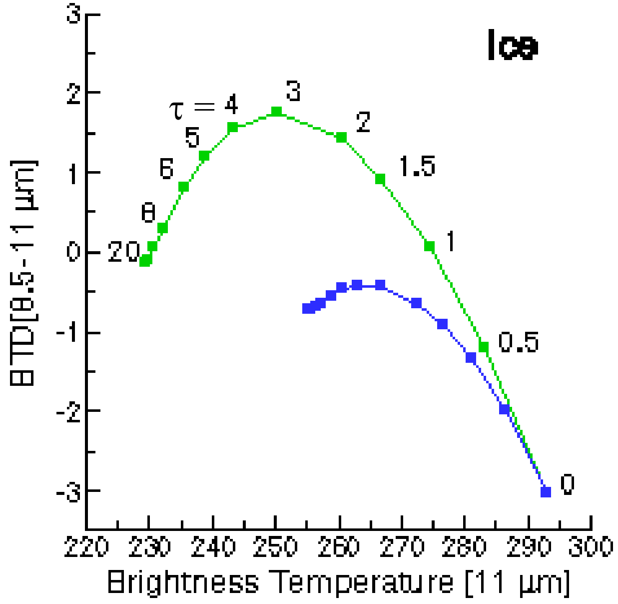
Dr. Bryan Baum CIMSS

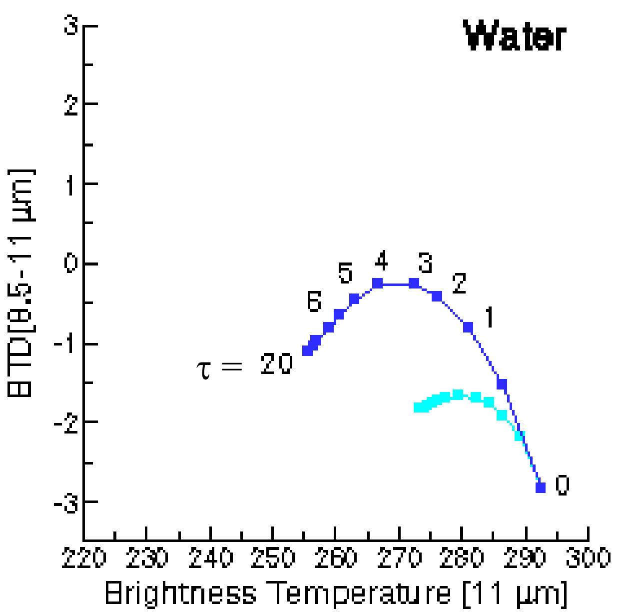
- Based upon the differential absorption of ice and water between 8 and 11 microns
- Simple brightness temperature difference (8-11 BTDIF) technique
- Included as part of the IMAPP MOD06 product



Imaginary Index of Refraction of Ice and Water
8 – 13 microns

Simulations of Ice and Water Phase Clouds
8.5 - 11 μm BT Differences





High Ice clouds

• BTD[8.5-11] > 0 over a large range of optical thicknesses τ

•T_{cld} = 228 K

Midlevel clouds

• BTD[8.5-11] values are similar (*i.e.*, negative) for both water and ice clouds

•T_{cld} = 253 K

Low-level, warm clouds

• BTD[8.5-11] values always negative

•T_{cld} = 273 K

*Ice: Cirrus model derived from FIRE-I in-situ data (*Nasiri et al, 2002)

Water: r_e=10 μm

Angles: θ_o = 45°, θ = 20°, and $\phi = 40°$

Profile: midlatitude summer

IRPHASE Thresholds

- Ice Cloud
  - BT11 < 238 K or BTD8-11> 0.5 K
- Mixed Phase
  - BT11 between 238 and 268 K

    and

  - BTD8-11 between –0.25 and –1.0 K
- Water Cloud
  - BT11 > 238 K and BTD8-11 < -1.5 K

    or

  - BT11>285 and BTD8-11 < -0.5 K

Output Product Description

4 categories

1 – Water Cloud

2 – Ice Cloud

3 – Mixed Phase Cloud

6 – Undecided

MOD06 Key Output Parameters

5x5 pixel (1km) resolution

- Surface_Temperature (GDAS input)
- Surface_Pressure (GDAS input)
- Cloud_Top_Pressure
- Cloud_Top_Temperature
- Tropopause_Height
- Cloud_Fraction
- Cloud_Effective_Emissivity
- Cloud_Top_Pressure_Infrared
- **Brightness_Temperature_Difference_B29-B31**
- **Brightness_Temperature_Difference_B31-B32**

Temperature sensitivity, or the percentage change in radiance corresponding to a percentage change in temperature, α, is defined as

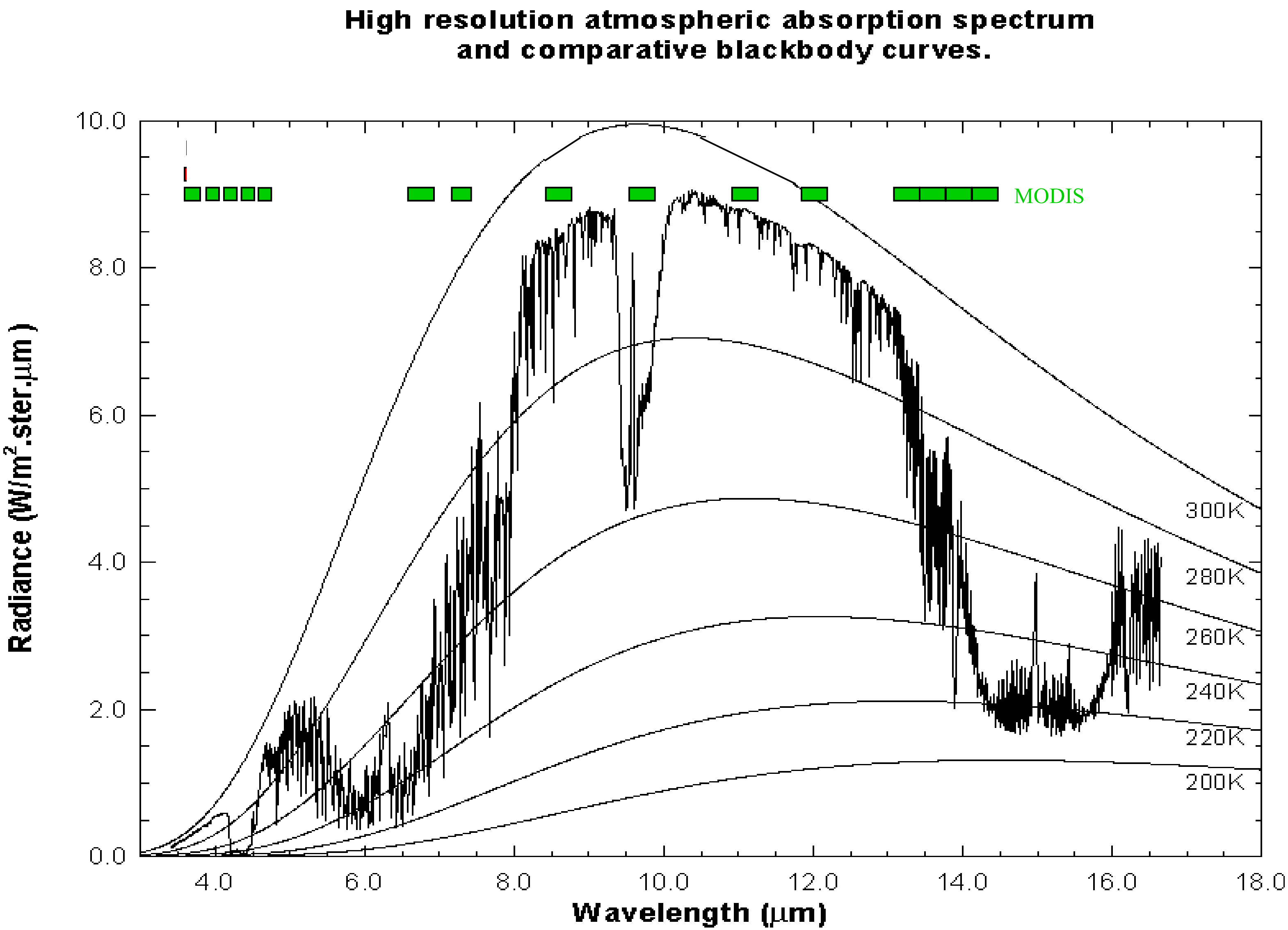
$$dB/B = \alpha\, dT/T.$$

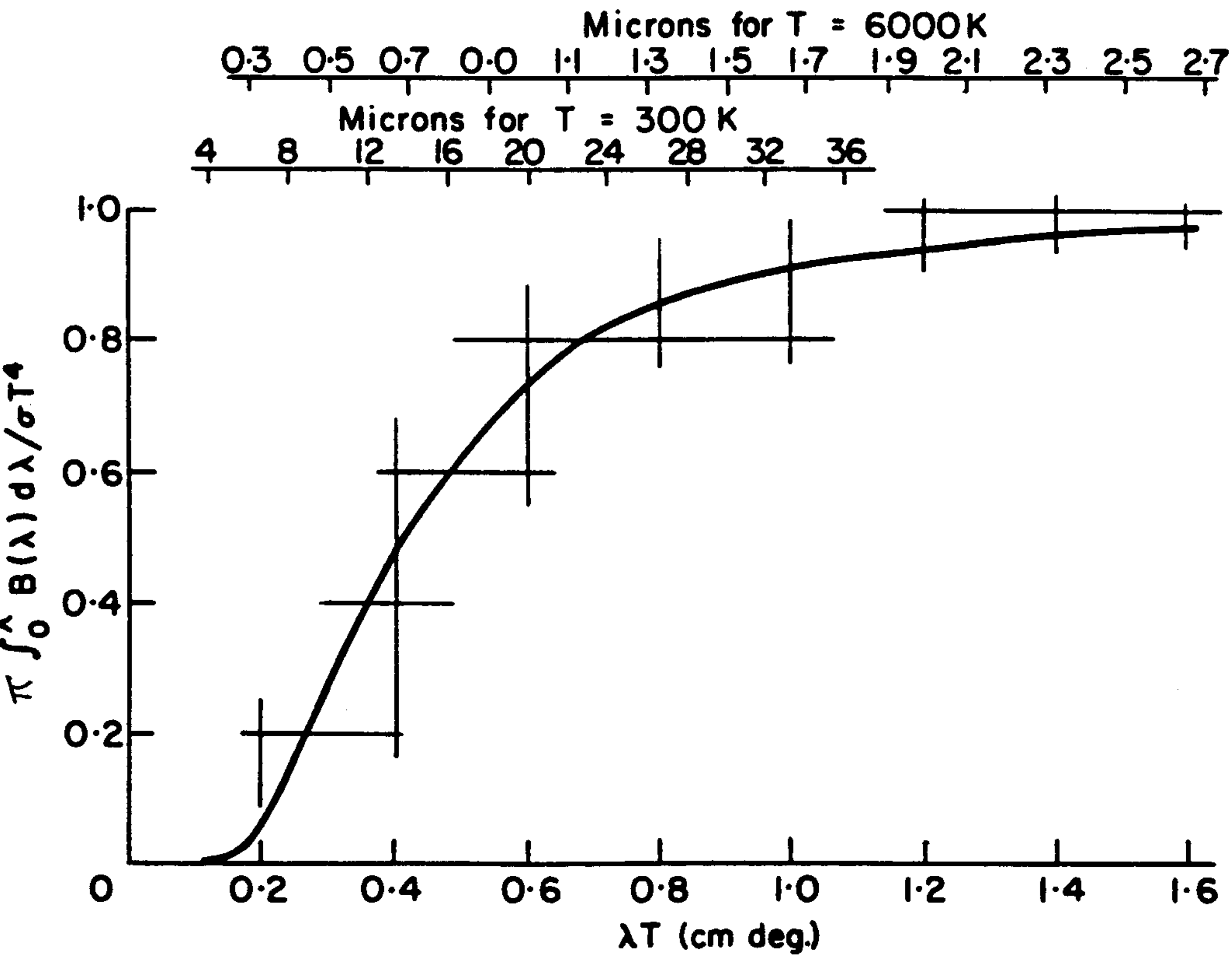
The temperature sensivity indicates the power to which the Planck radiance depends on temperature, since B proportional to T^{α} satisfies the equation. For infrared wavelengths,

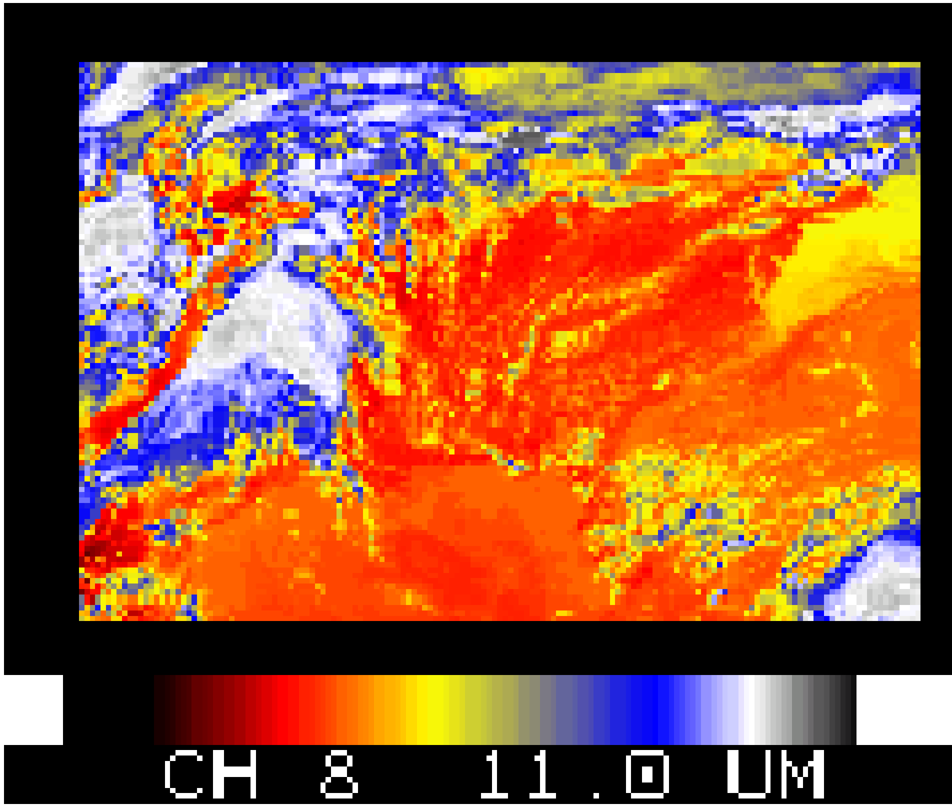
$$\alpha = c_2\nu/T = c_2/\lambda T.$$

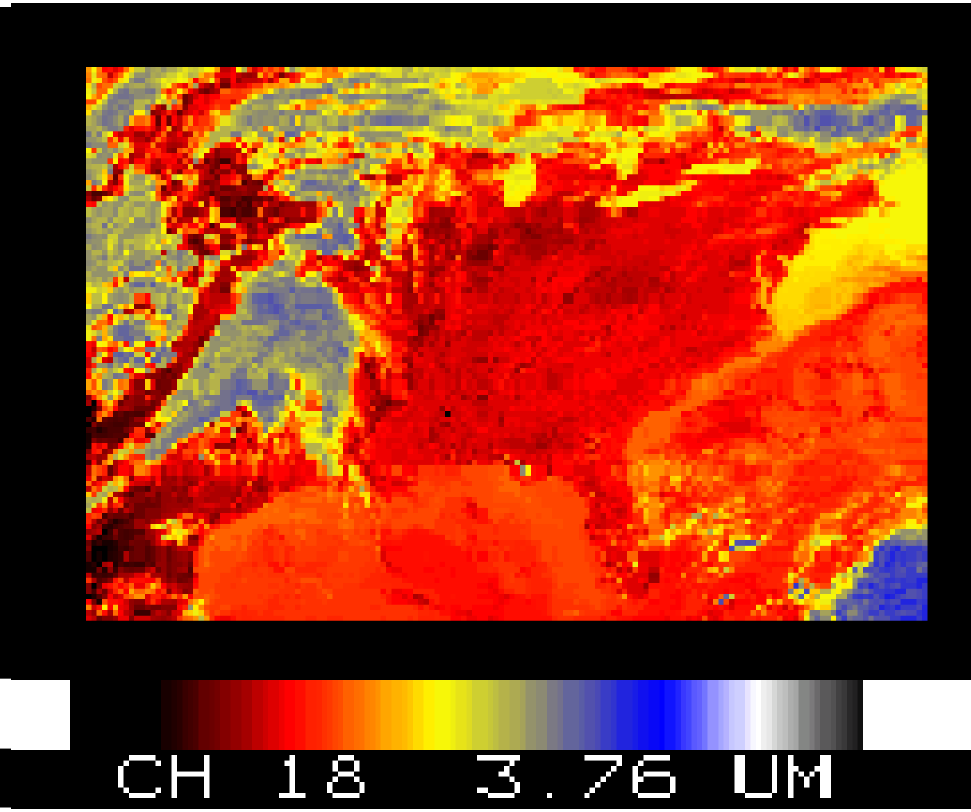
Wavenumber	Typical Scene Temperature	Temperature Sensitivity
700 (14 µm)	220	4.58
900 (11 µm)	300	4.32
1200 (8.3 µm)	300	5.76
1600 (6.5 µm)	240	9.59
2300 (4.4 µm)	220	15.04
2500 (4.0 µm)	300	11.99

MODIS IR Spectral Bands




Microns for T = 6000 K
0·3 0·5 0·7 0·0 1·1 1·3 1·5 1·7 1·9 2·1 2·3 2·5 2·7
Microns for T = 300 K
4 8 12 16 20 24 28 32 36
1·0
0·8
0·6
0·4
0·2
0
0·2 0·4 0·6 0·8 1·0 1·2 1·4 1·6
λT (cm deg.)
π ∫₀^λ B(λ) dλ/σT⁴

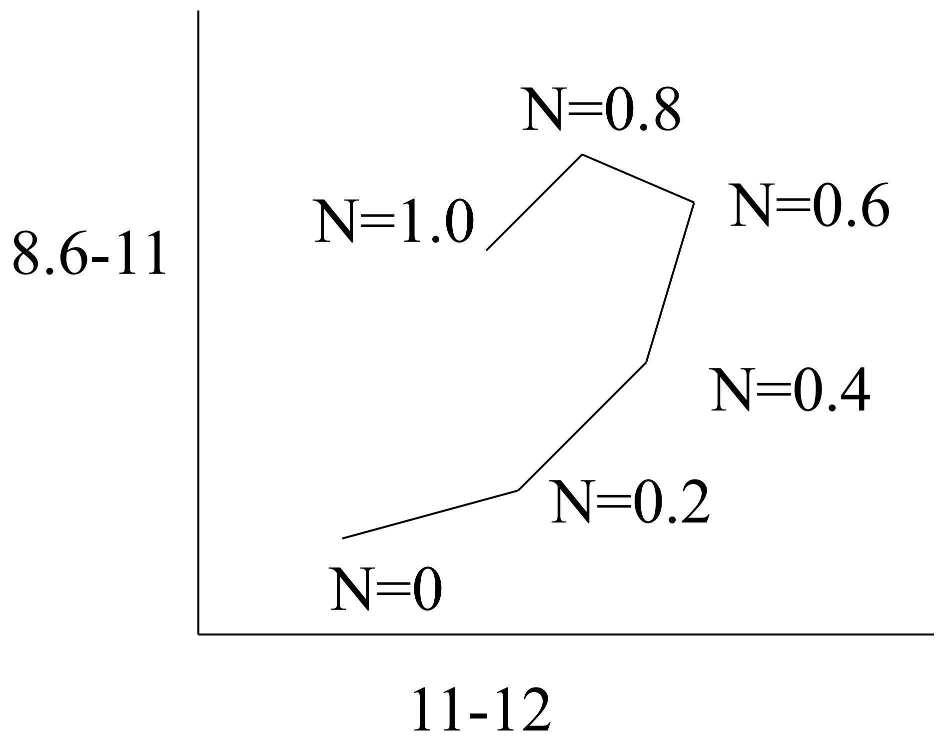


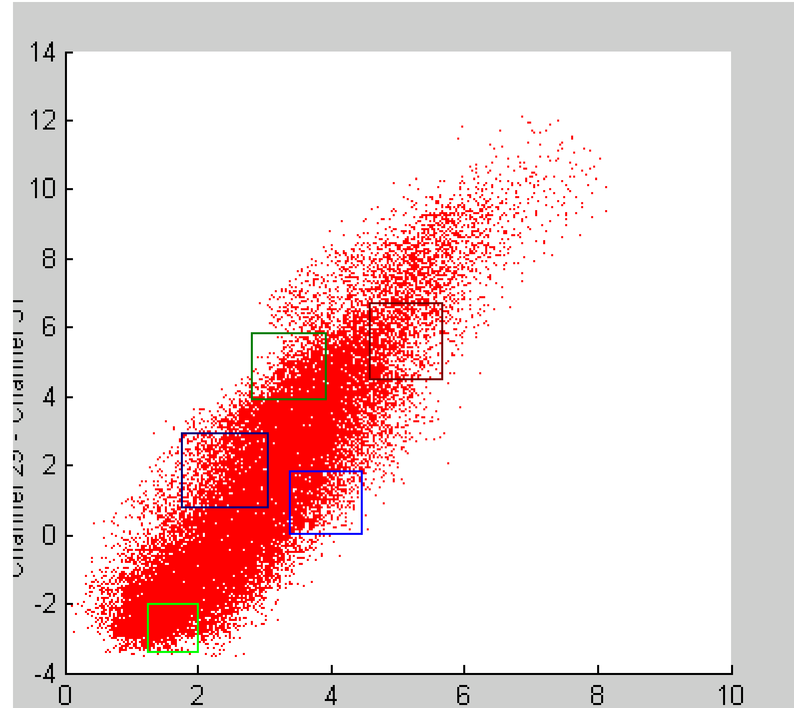


Cloud edges and broken clouds appear different in 11 and 4 um images.

T(11)**4=(1-N)*Tclr**4+N*Tcld**4~(1-N)*300**4+N*200**4
T(4)**12=(1-N)*Tclr**12+N*Tcld**12~(1-N)*300**12+N*200**12

Cold part of pixel has more influence for B(11) than B(4)
Warm part of pixel has more influence for B(4) than B(11)





Broken clouds appear different in 8.6, 11 and 12 um images;

assume Tclr=300 and Tcld=230

$$T(11)-T(12)=[(1-N)*B11(Tclr)+N*B11(Tcld)]^{-1} - [(1-N)*B12(Tclr)+N*B12(Tcld)]^{-1}$$

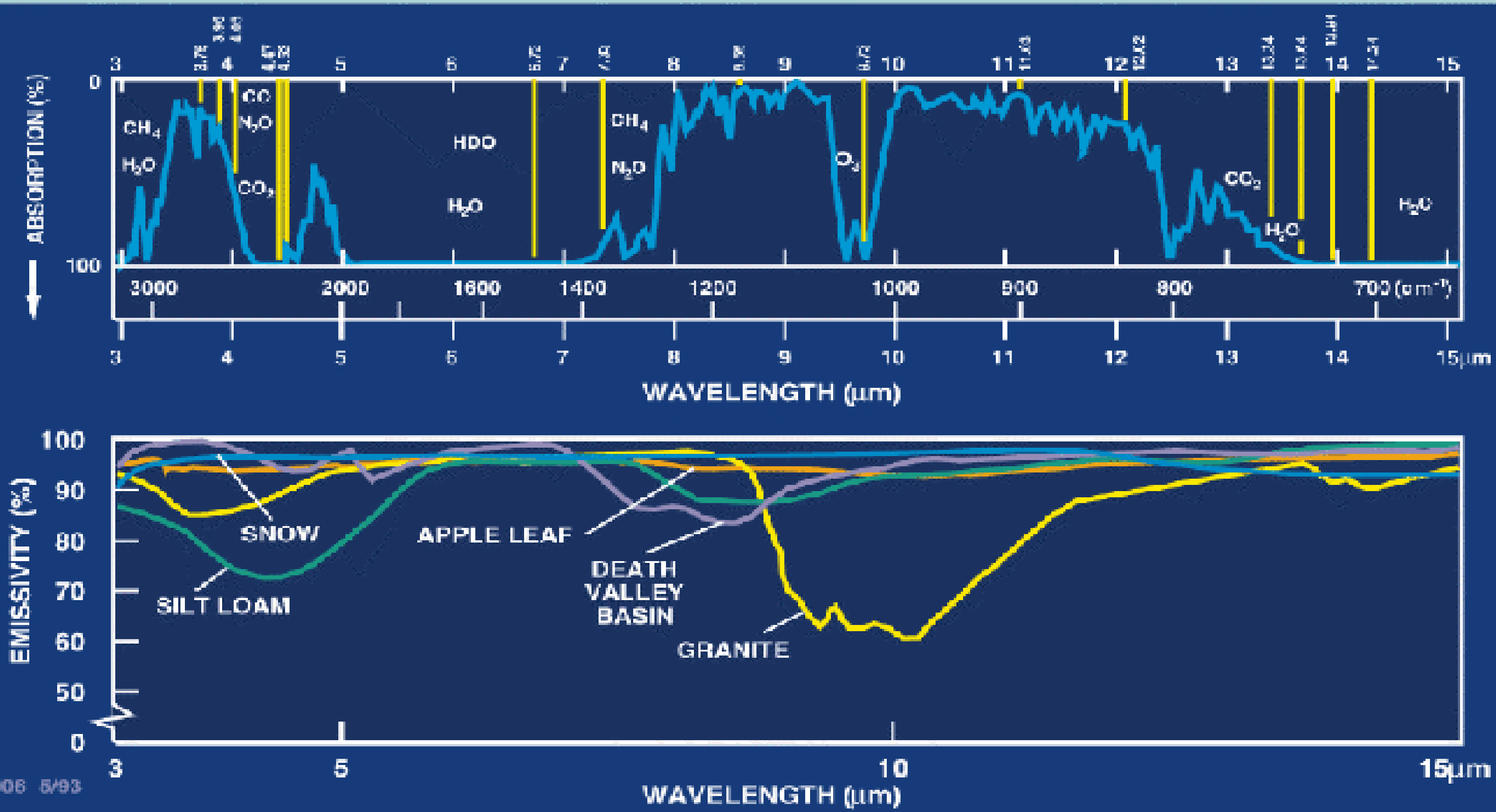
$$T(8.6)-T(11)=[(1-N)*B8.6(Tclr)+N*B8.6(Tcld)]^{-1} - [(1-N)*B11(Tclr)+N*B11(Tcld)]^{-1}$$

Cold part of pixel has more influence at longer wavelengths

Known Problems

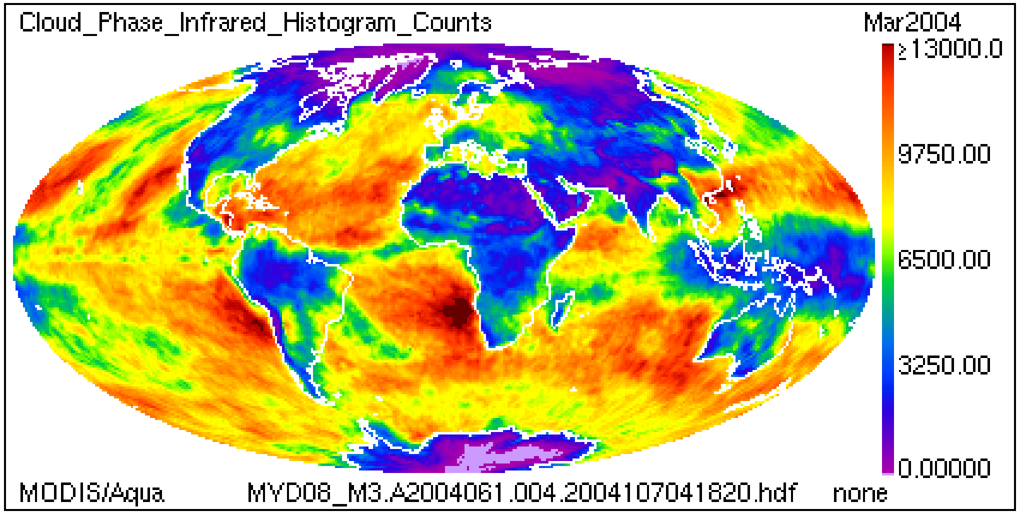
- Mid-level cloud (BT ~ 250 K)
  - Ambiguous solution
- Surface Emissivity Effects
  - Not always the same over the IR window (granite)
- Mixed phase cloud category
  - should be considered as undecided

LAND - THERMAL RADIATION

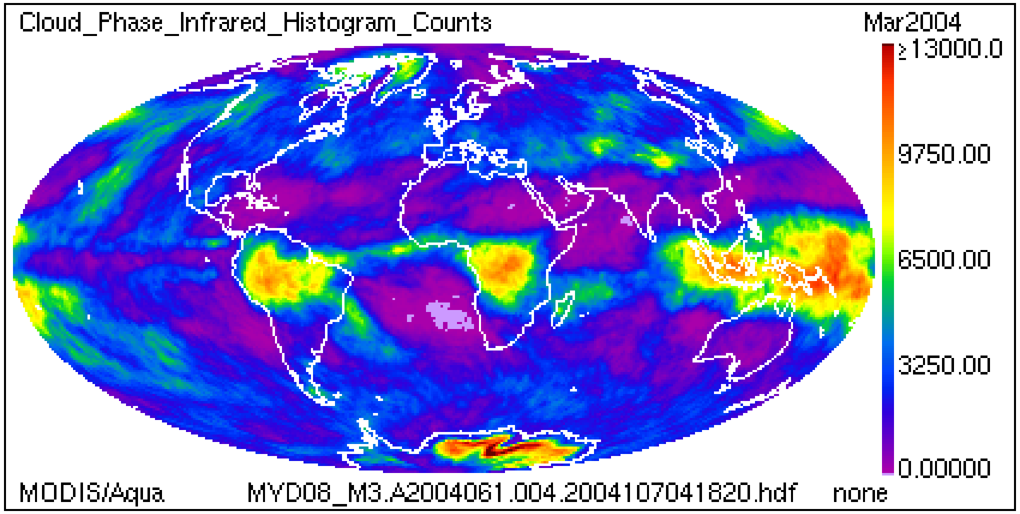


C351.006 5/93

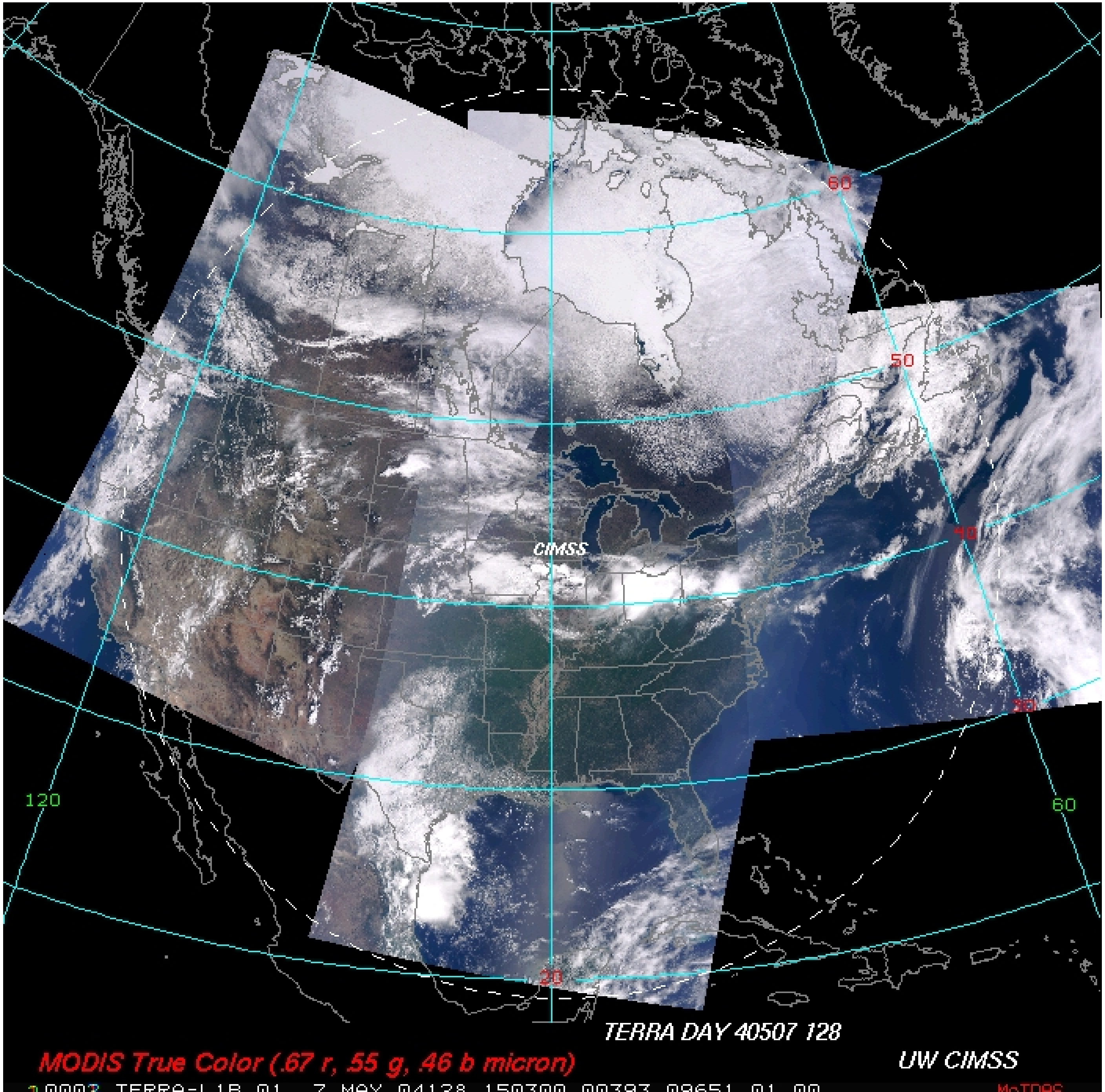
Cloud Phase Level 3 Product   March 2004



Water



Ice



60
50
40
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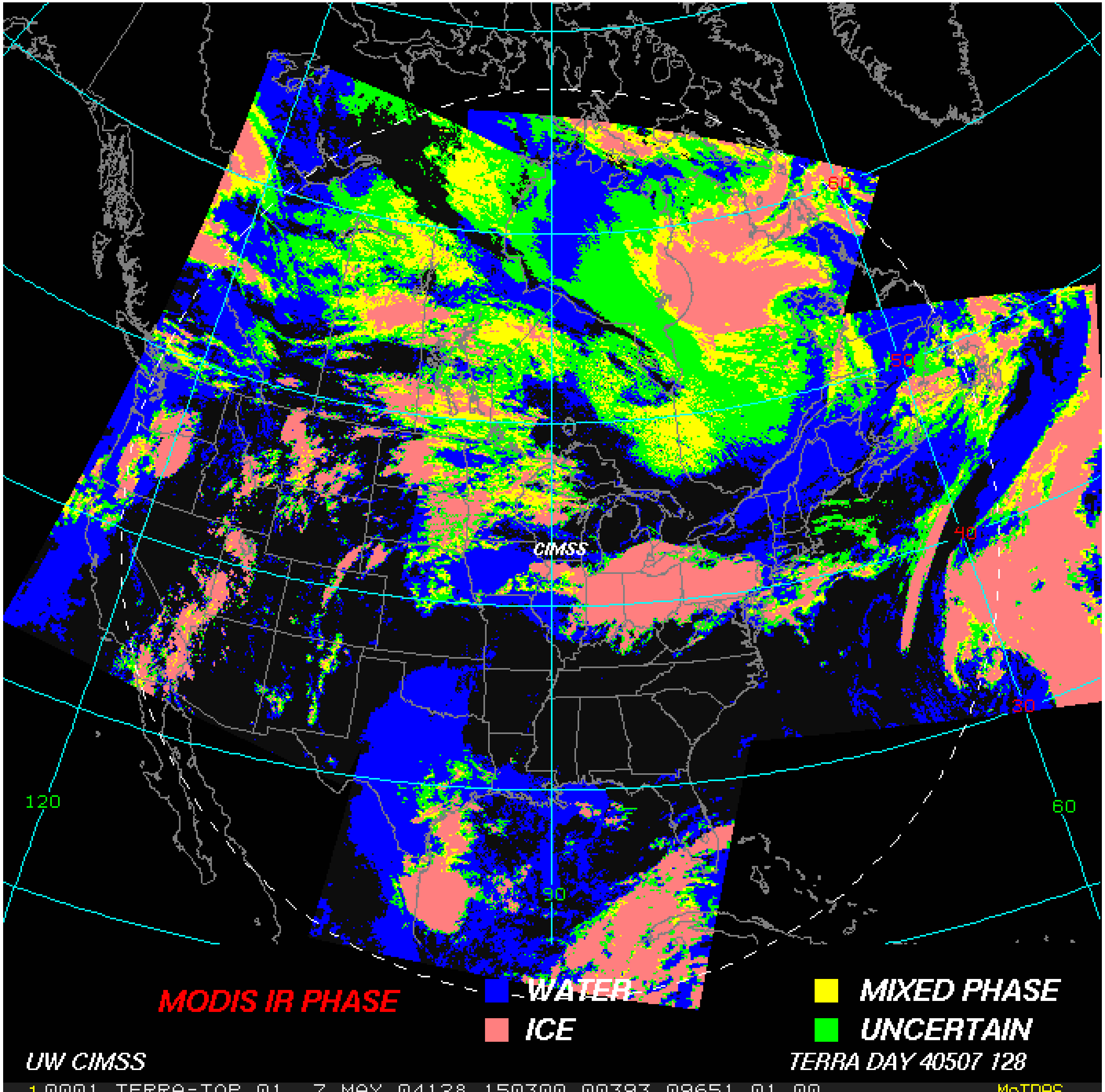
20
120
60
CIMSS
TERRA DAY 40507 128
MODIS True Color (.67 r, .55 g, .46 b micron)
UW CIMSS
20002 TERRA-L1B 01 7 MAY 04128 150300 00393 09651 01.00
McIDAS


MODIS IR PHASE
WATER
ICE
MIXED PHASE
UNCERTAIN
CIMSS
60
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UW CIMSS
TERRA DAY 40507 128
1 0001 TERRA-TOP 01 7 MAY 04128 150300 00393 09651 01.00
McIDAS