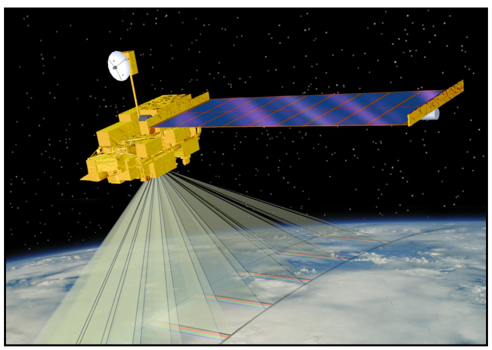
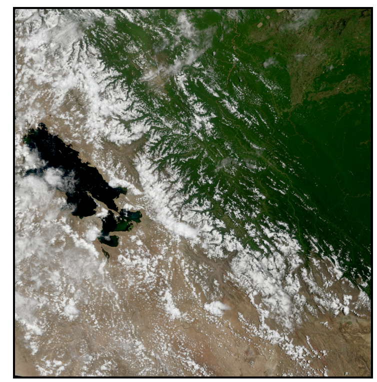
MODIS Products

2011 IMAPP Training Workshop: Satellite Direct Broadcast for Real-Time Environmental Applications



ECNU, China
3 June 2011
Part 1



Kathleen Strabala
Cooperative Institute for Meteorological Satellite Studies
Space Science and Engineering Center
University of Wisconsin-Madison

Information about MODIS Products

Main MODIS website - http://modis.gsfc.nasa.gov/

- MODIS Land Team Website
  http://modis-land.gsfc.nasa.gov/
- MODIS Atmosphere Website
  http://modis-atmos.gsfc.nasa.gov/
- MODIS Ocean Biology Group
  http://oceancolor.gsfc.nasa.gov/
- MODIS Calibration and Geolocation
  http://mcst.gsfc.nasa.gov/

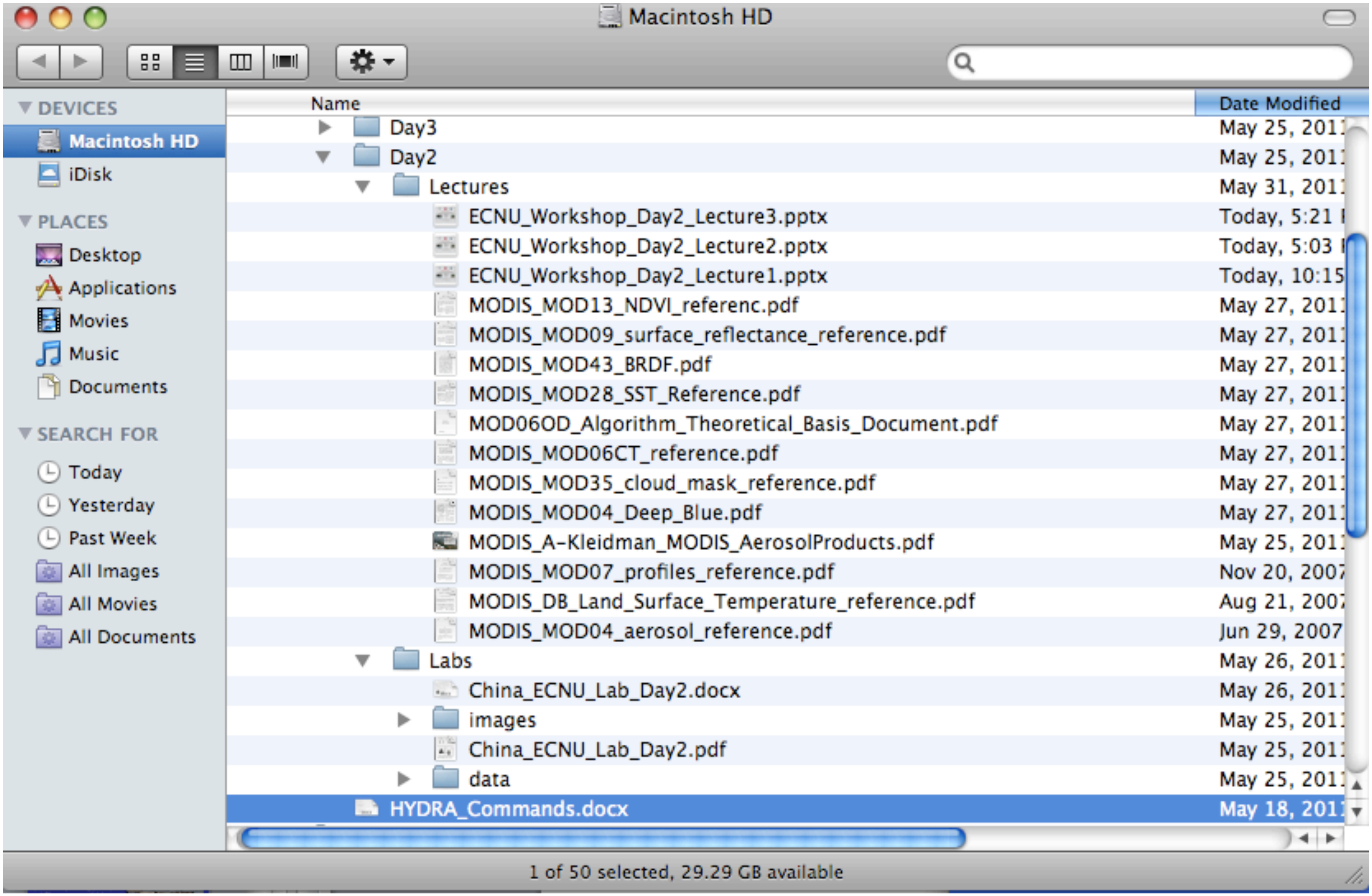
Algorithm Theoretical Basis Documents (ATBDs)

Detailed description of the techniques for each product:

http://modis.gsfc.nasa.gov/data/atbd/index.php

ATBD #	Name	Latest Version	Latest Date
ATBD-MOD-02	Algorithm for Remote Sensing of Tropospheric Aerosol from MODIS		11/01/2006
ATBD-MOD-03	Near-IR Water Vapor Algorithm		11/13/1998
ATBD-MOD-04	Cloud Top Properties and Cloud Phase	8.0	10/01/2008
ATBD-MOD-05	Cloud Retrieval Algorithms: Optical Thickness, Effective Particle Radius, and Thermodynamic Phase	5.0	12/23/1997
ATBD-MOD-06	Discriminating Clear Sky from Cloud	6.1	10/01/2010
ATBD-MOD-07	Atmospheric Profile Retrieval	6.0	10/25/2006
ATBD-MOD-30	MODIS Atmosphere L3 Gridded Product	1.1	12/2008

References Provided



MODIS Standard Products (1)

Atmosphere

- ***MOD 04 - Aerosol Product***
- MOD 05 - Total Precipitable Water (Water Vapor)
- ***MOD 06 - Cloud Product***
  - ***Cloud Top Properties (MOD06CT)***
  - ***Cloud Phase (part of MOD06CT)***
  - *Cloud Optical Depth (MOD06OD)*
- ***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 (NDVI & EVI)***
- ***MOD 14 - Thermal Anomalies (Fires)***
- 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

Lecture Outline

- MODIS Level 2 Atmosphere product theory and algorithms
  - MODIS Cloud Mask Product (MOD35)
  - MODIS Cloud Phase Product (part of MOD06)
  - MODIS Cloud Top Properties Product (part of MOD06)
  - MODIS Atmospheric Profiles Product (MOD07)
  - MODIS Aerosol Optical Depth Product (MOD04)
- MODIS Level 2 Land product theory and algorithms
  - MODIS Vegetation Indices (MOD13)
  - MODIS Surface Reflectance and BRDF Product (MOD09 and MOD43)
  - MODIS Fire Product (Thermal Anomalies) (MOD14)
- MODIS Level 2 Ocean product theory and algorithms (SeaDAS)
  - Ocean Color (MOD20)
  - Sea Surface Temperatures (MOD28)

MODIS Atmosphere Products

MODIS Cloud Mask (MOD35)

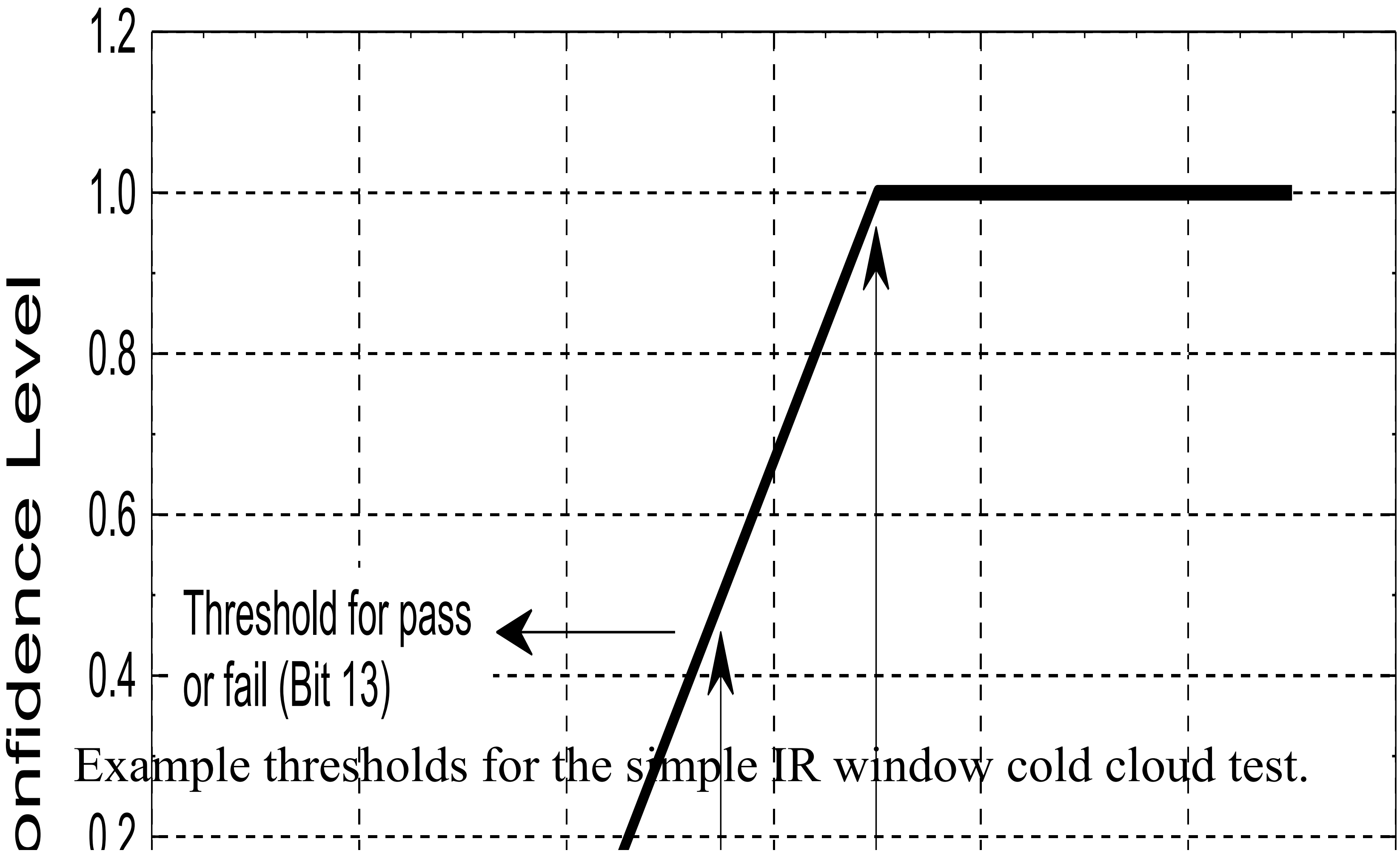
MODIS Cloud Mask

Ackerman, Frey, Strabala –SSEC

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

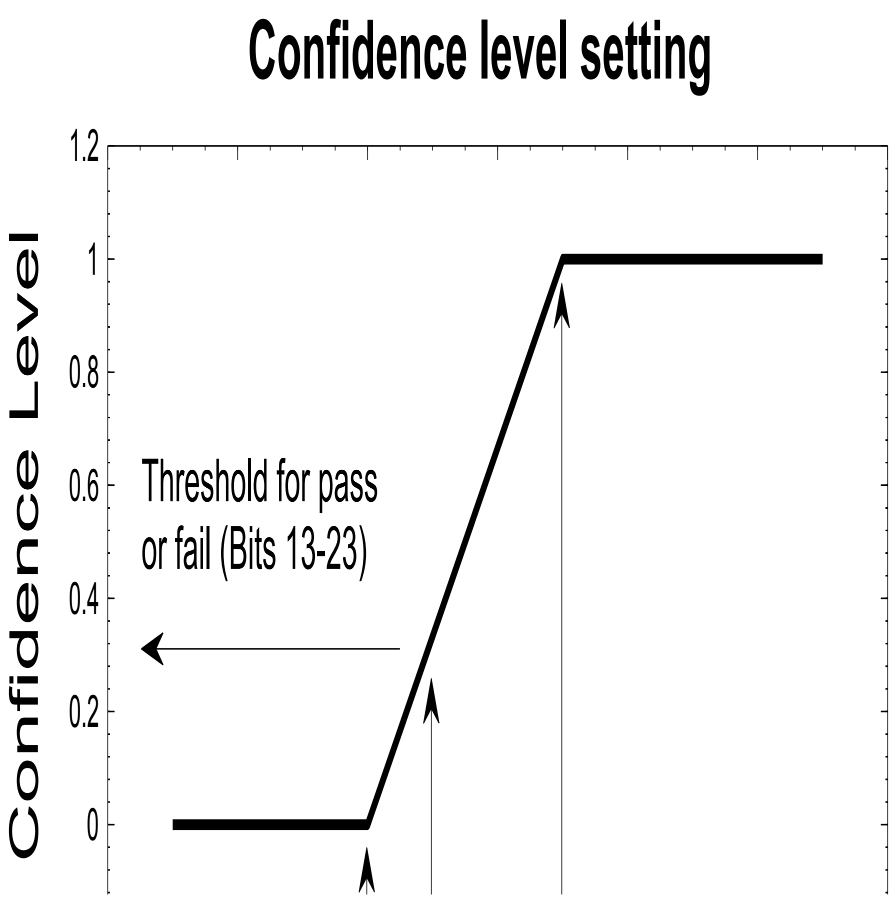
- **1 km** nadir spatial resolution **day & night**, (250 m day)
  - **19 spectral bands (0.55-13.93 µm, incl. 1.38 µm)**
    11 individual spectral tests (function of 5 processing paths) combined for initial pixel confidence of clear
  - spatial variability test over ocean
  - clear sky restoral tests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

Confidence Level of Clear



Example thresholds for the simple IR window cold cloud test.

Quality Flags

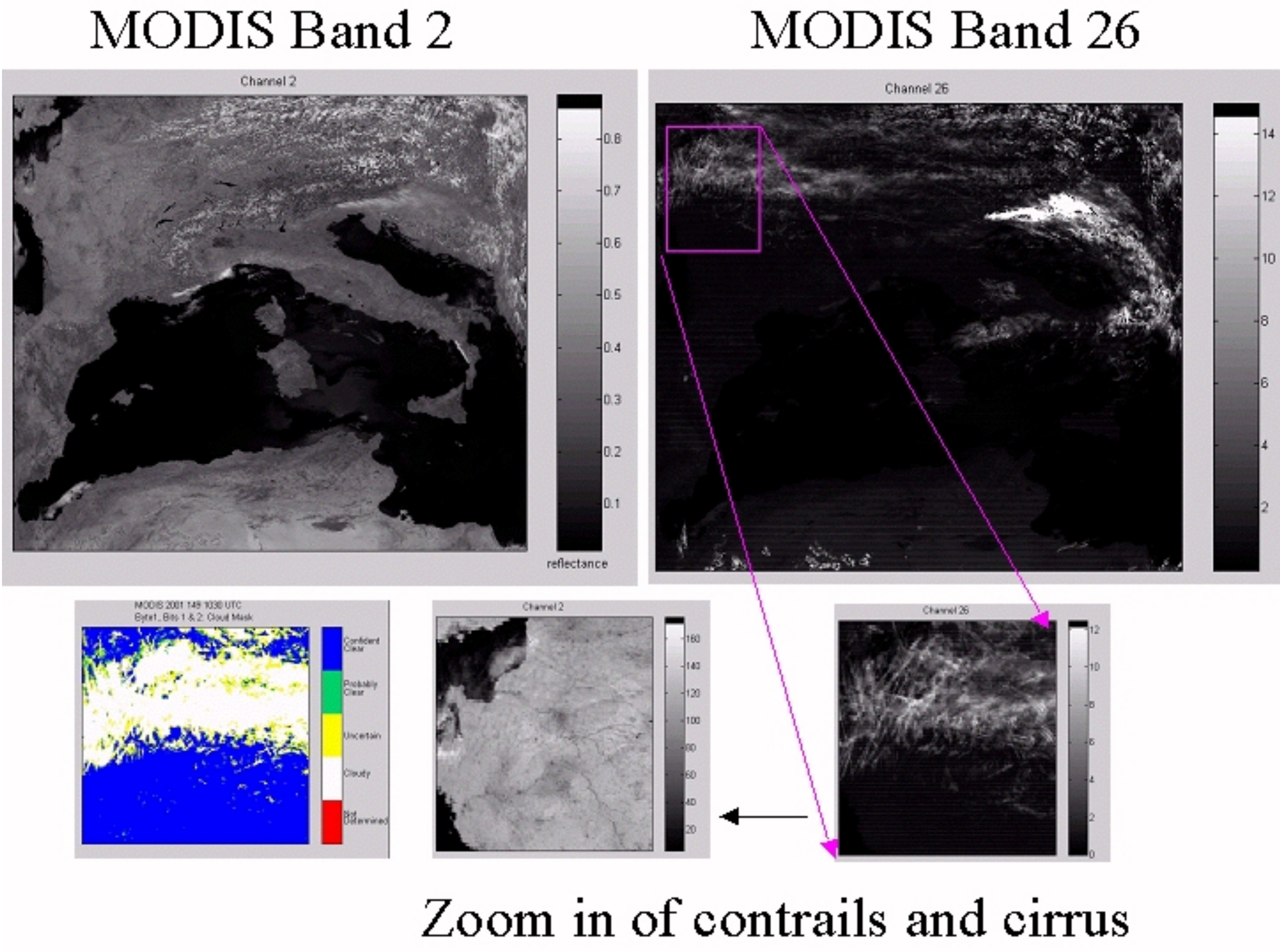


- Each test returns a confidence (F) ranging from 0 to 1.
- Similar tests are grouped and minimum confidence selected [min (F_i)]
- Quality Flag is

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

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

Some tests see cloud, some don’t



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

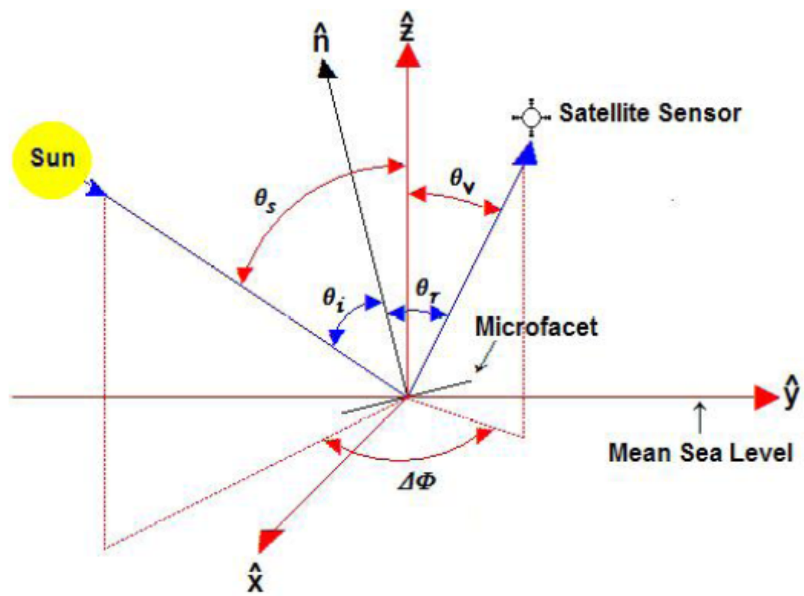
Sun Glint Ellipse Defined by: $\theta_r < 36$

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

Where θ_v = Viewing Zenith Angle

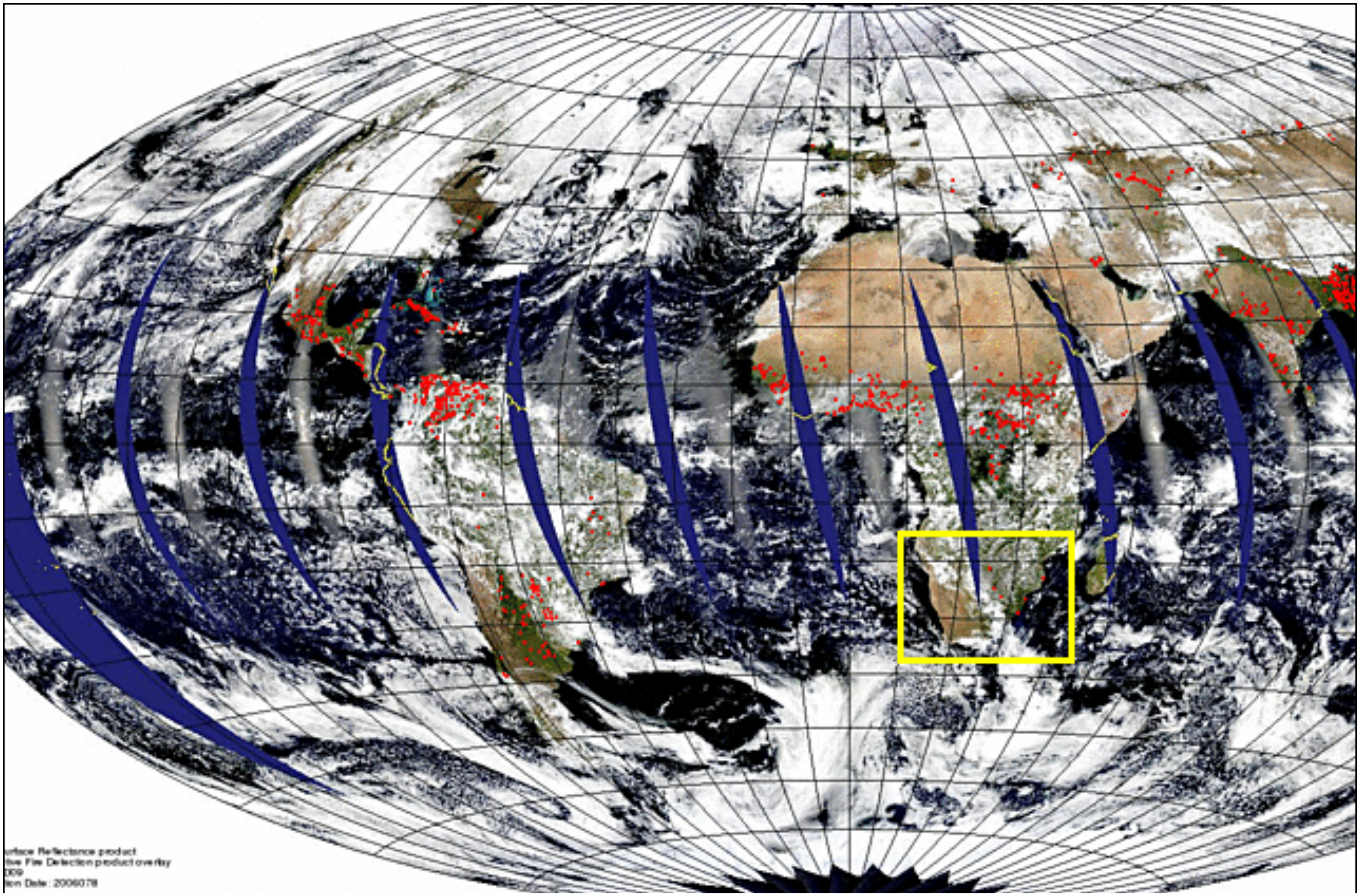
θ_s = Solar Zenith Angle

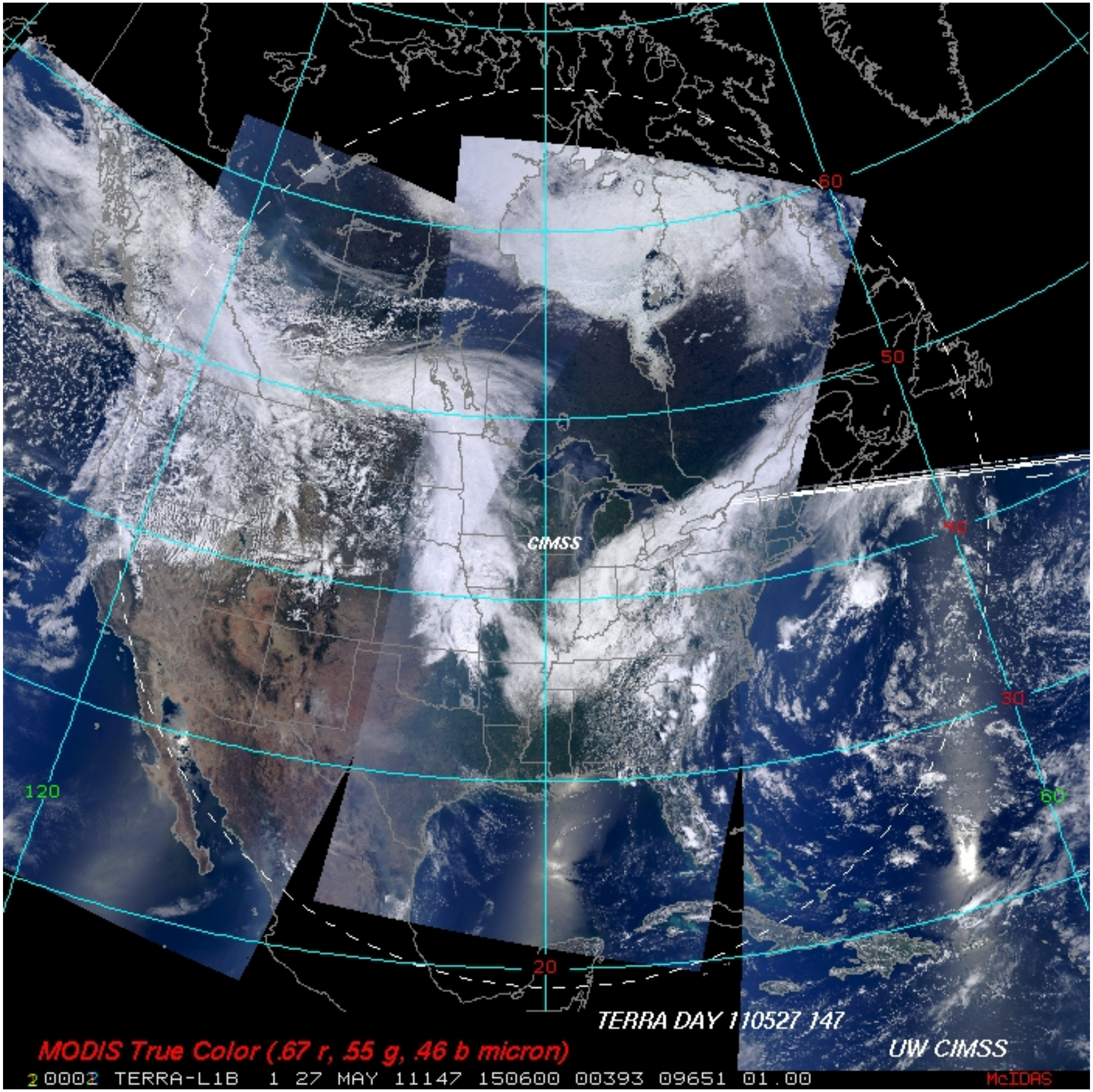
$\Delta\Phi$ = Relative Angle – difference between the Solar and Viewing azimuth angles.



Aqua MODIS Sun Glint Example

19 March 2006





60
50
40
30
20
120
60
CIMSS
TERRA DAY 110527 147
MODIS True Color (.67 r, .55 g, .46 b micron)
UW CIMSS
2 0002 TERRA-L1B 1 27 MAY 11147 150600 00393 09651 01.00
McIDAS

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

IR Brightness Temperature Threshold Tests

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)

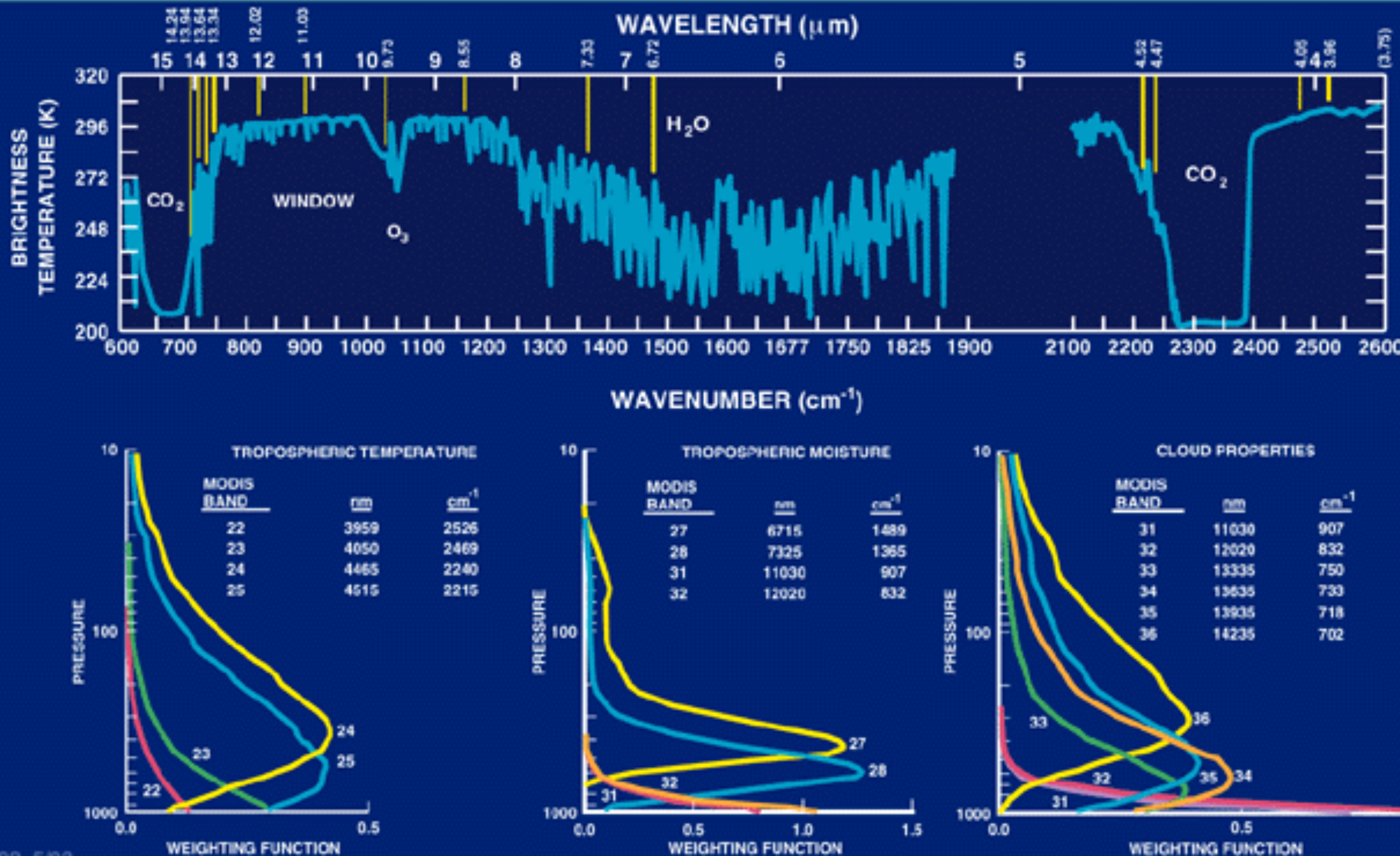
BT11-BT12 > Threshold (High thin cloud)

BT3.9 - BT11 > 12 K 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

ATMOSPHERE - THERMAL RADIATION



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

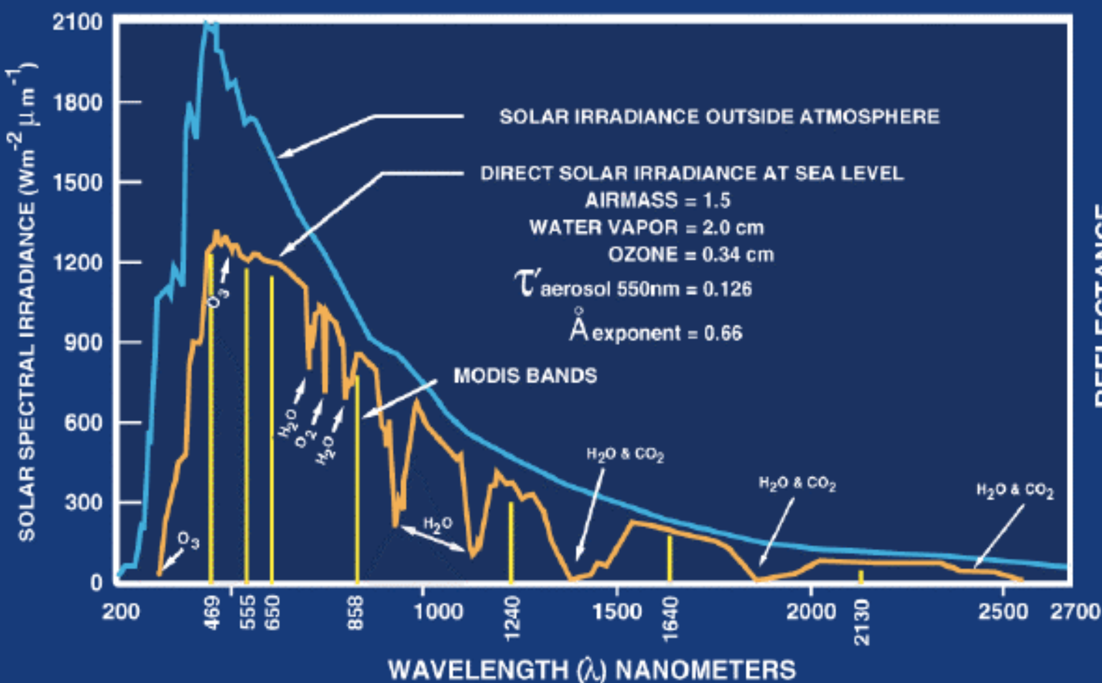
Reflectance Ratio Test

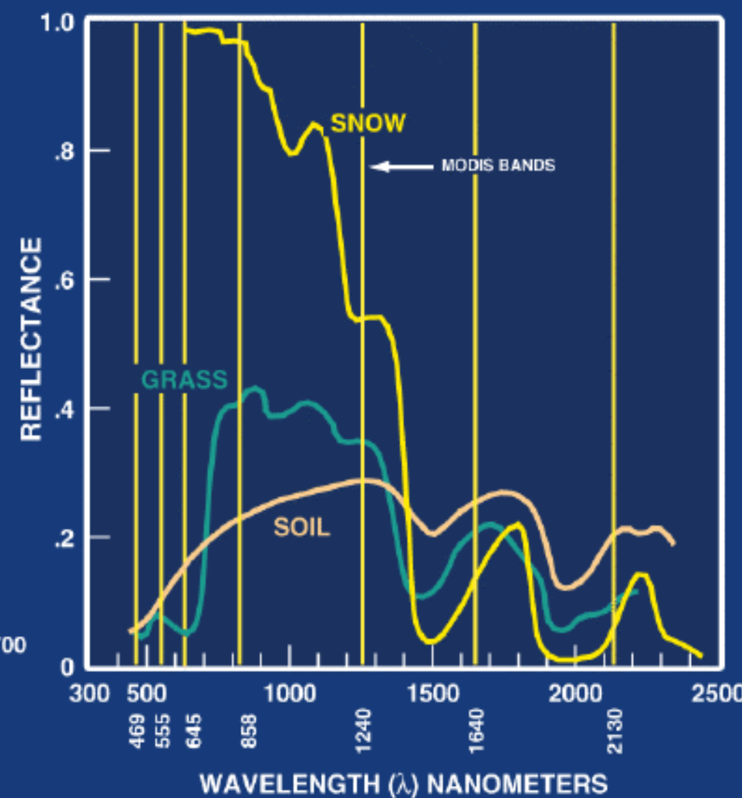
r.87/r.66 between 0.9 and 1.1 for cloudy regions
must be ecosystem specific – snow causes false signal

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 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

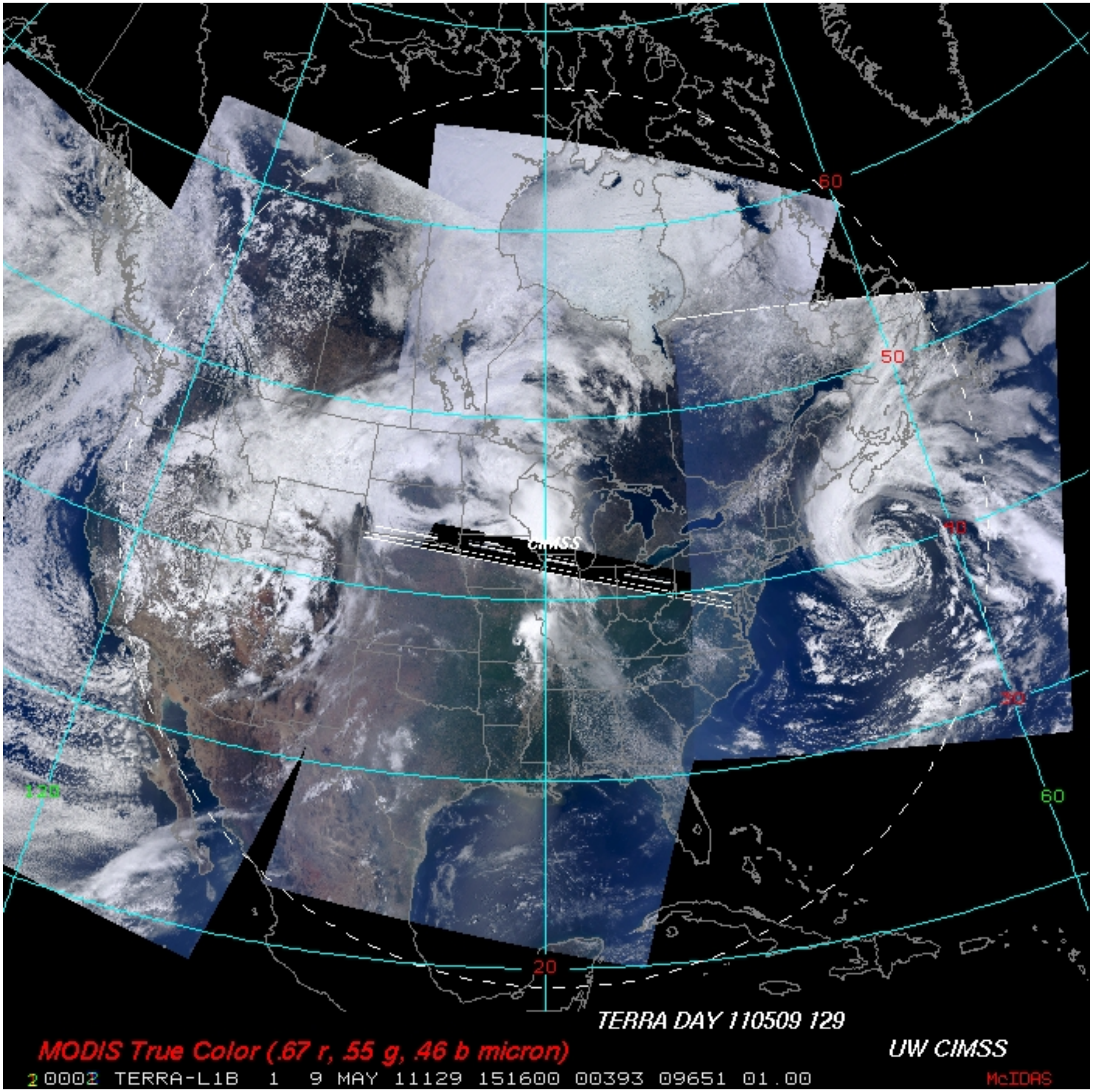
Output Product Description

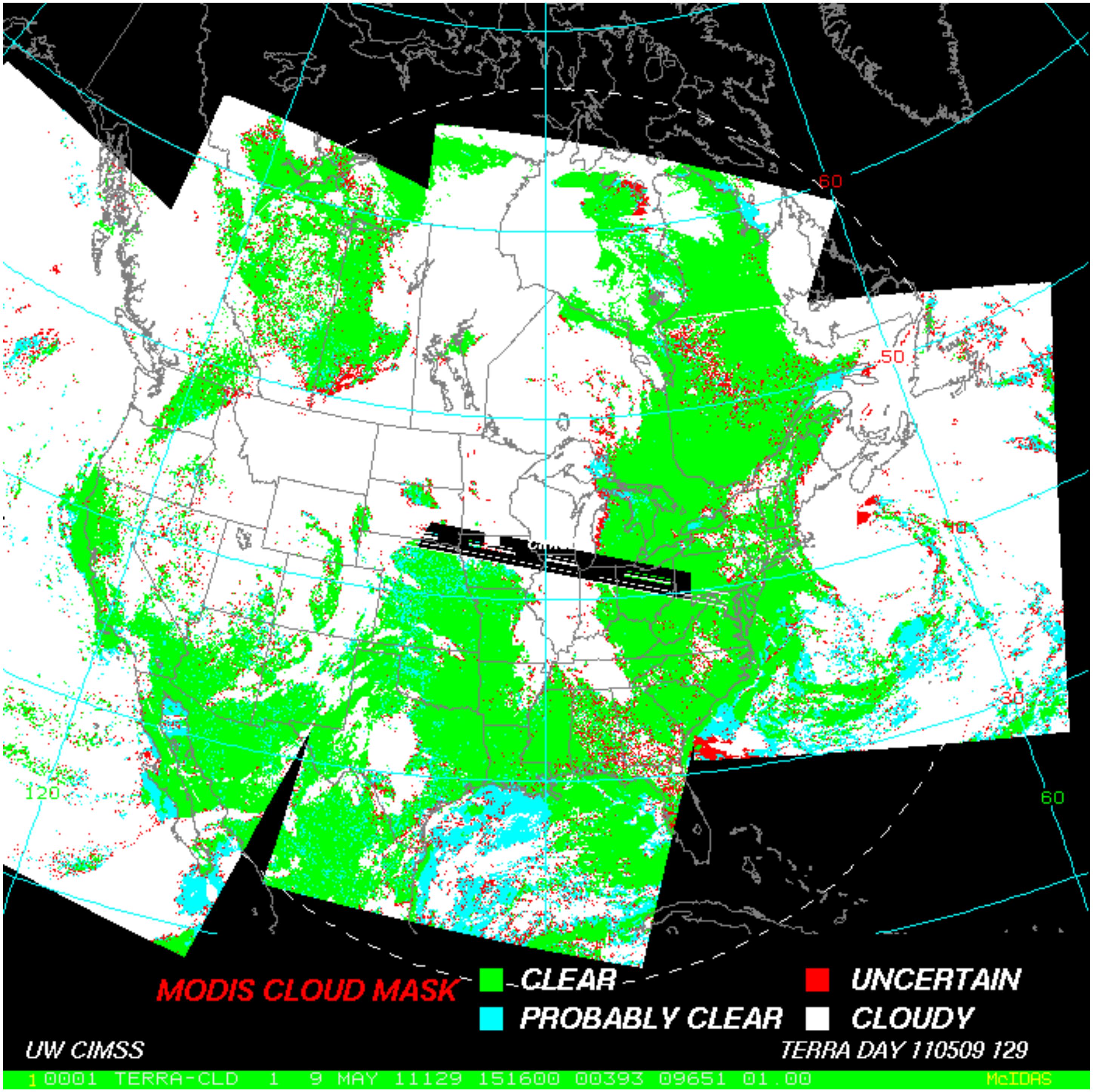
Product Resolution: 1 km and 250 m

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


60
50
40
30
20
120
60
CIMSS
TERRA DAY 110509 129
MODIS True Color (.67 r, .55 g, .46 b micron)
UW CIMSS
2 0002 TERRA-L1B 1 9 MAY 11129 151600 00393 09651 01.00
McIDAS


60
50
40
30
120
60
MODIS CLOUD MASK
CLEAR
PROBABLY CLEAR
UNCERTAIN
CLOUDY
UW CIMSS
TERRA DAY 110509 129
1 0001 TERRA-CLD 1 9 MAY 11129 151600 00393 09651 01.00
McIDAS

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

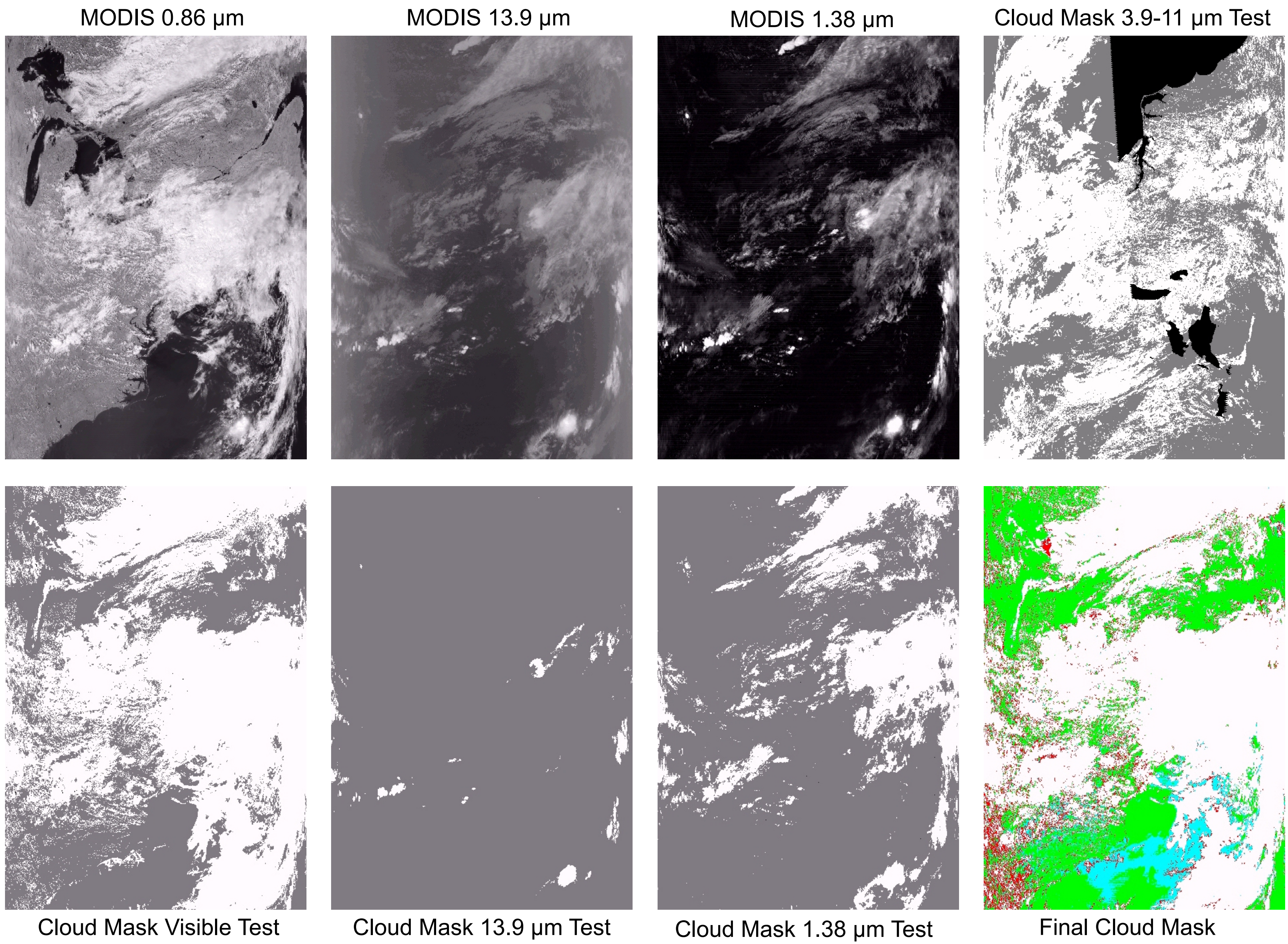
bit field	Description Key	Result
13	Cloud Flag - 11 μm IR Threshold	0 = Yes / 1 = No
14	High Cloud Flag - CO_2 Threshold Test	0 = Yes / 1 = No
15	High Cloud Flag - 6.7 μm Test	0 = Yes / 1 = No
16	High Cloud Flag - 1.38 μm Test	0 = Yes / 1 = No
17	High Cloud Flag - 3.7-12 μm Test	0 = Yes / 1 = No
18	Cloud 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

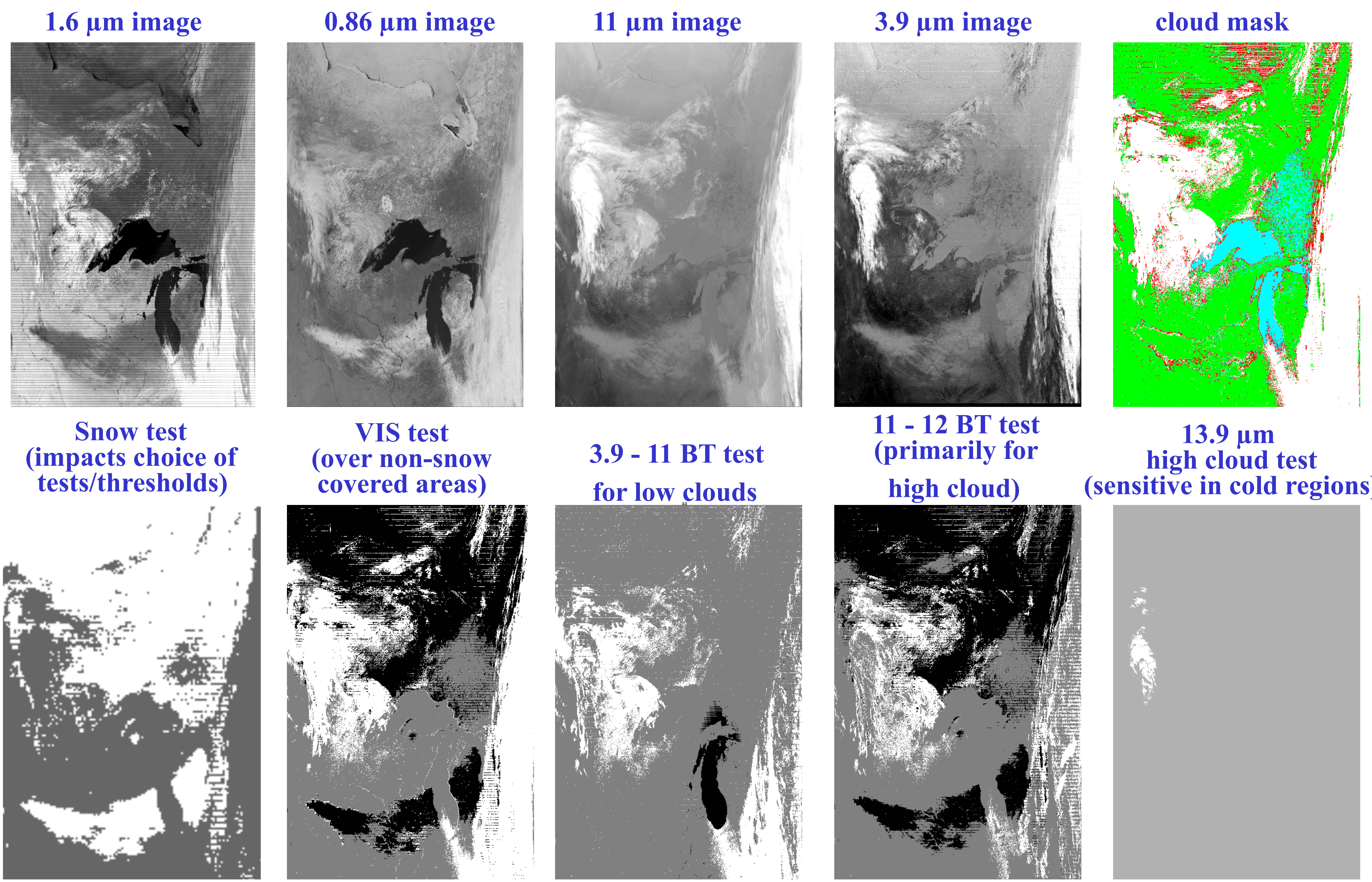
Additional Tests

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

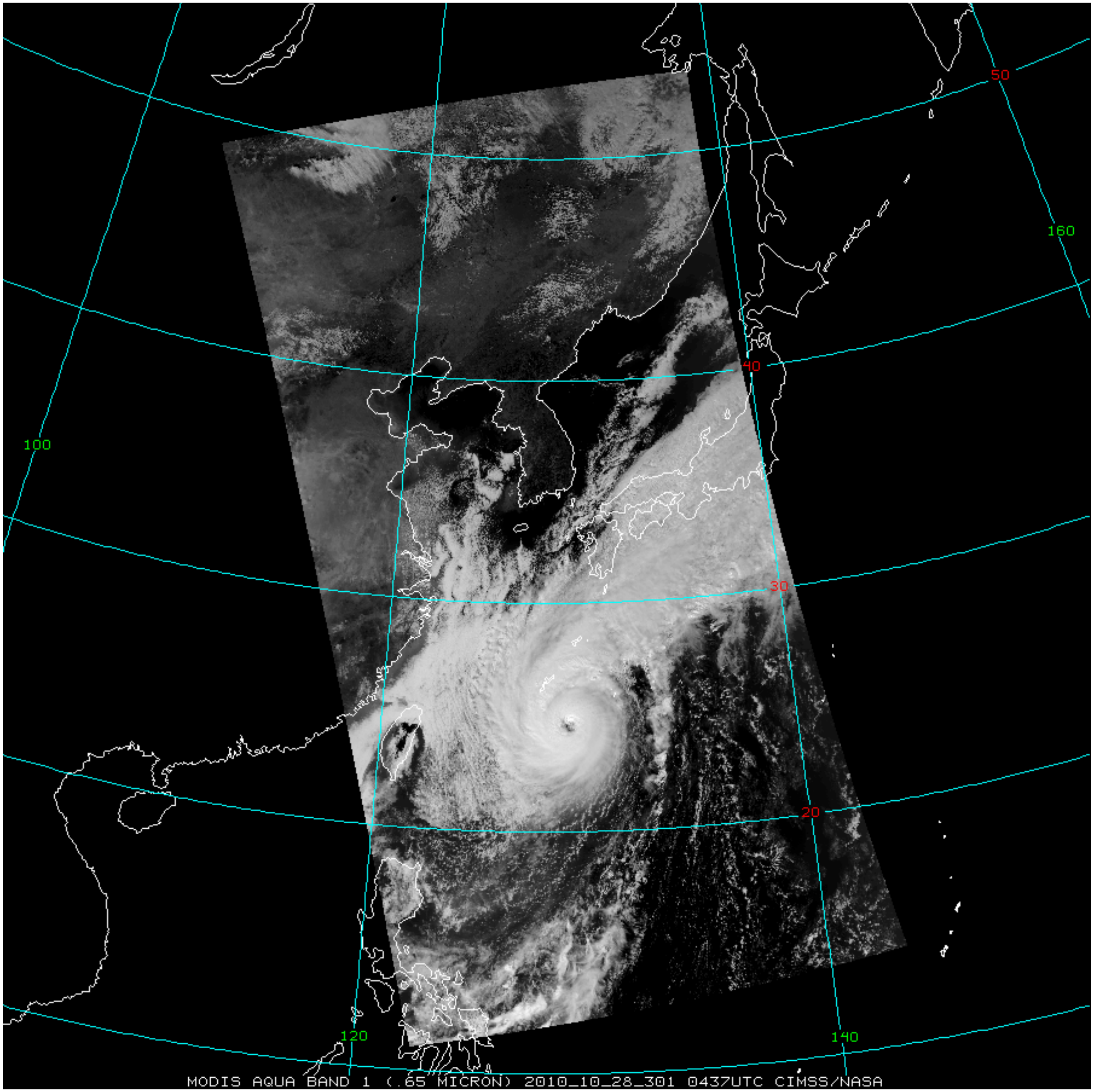
32-47	250 m visible reflectance test	0 = Yes / 1 = No


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

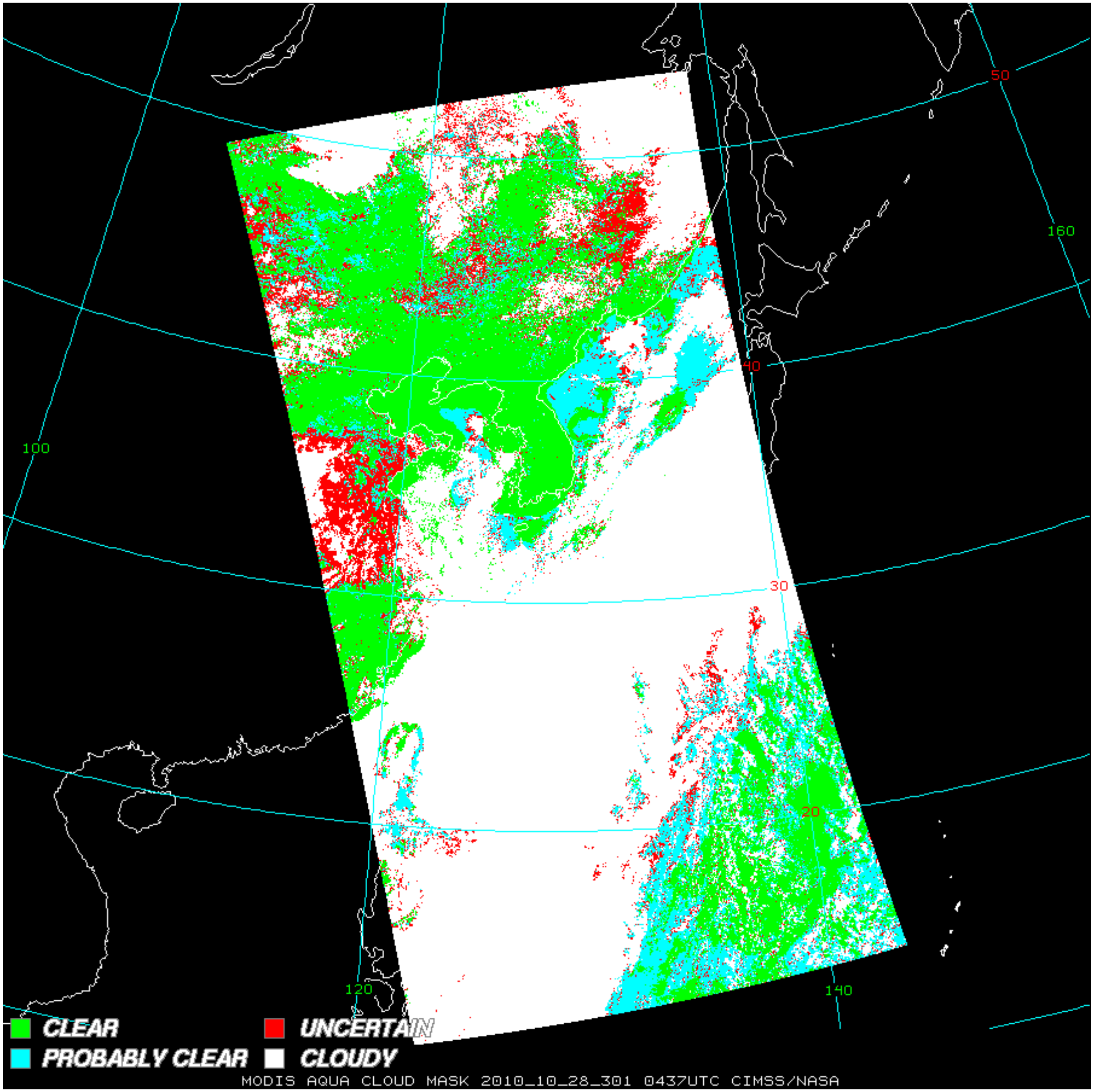


MODIS cloud mask example

(**confident clear** is green, **probably clear** is blue, **uncertain** is red, **cloud** is white)



50
160
40
100
30
20
120
140
MODIS AQUA BAND 1 (.65 MICRON) 2010_10_28_301 0437UTC CIMSS/NASA


50
160
40
100
30
20
120
140
CLEAR
UNCERTAIN
PROBABLY CLEAR
CLOUDY
MODIS AQUA CLOUD MASK 2010_10_28_301 0437UTC CIMSS/NASA

Known Problems

- MODIS algorithm is clear sky conservative
  - If there is a 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)

References

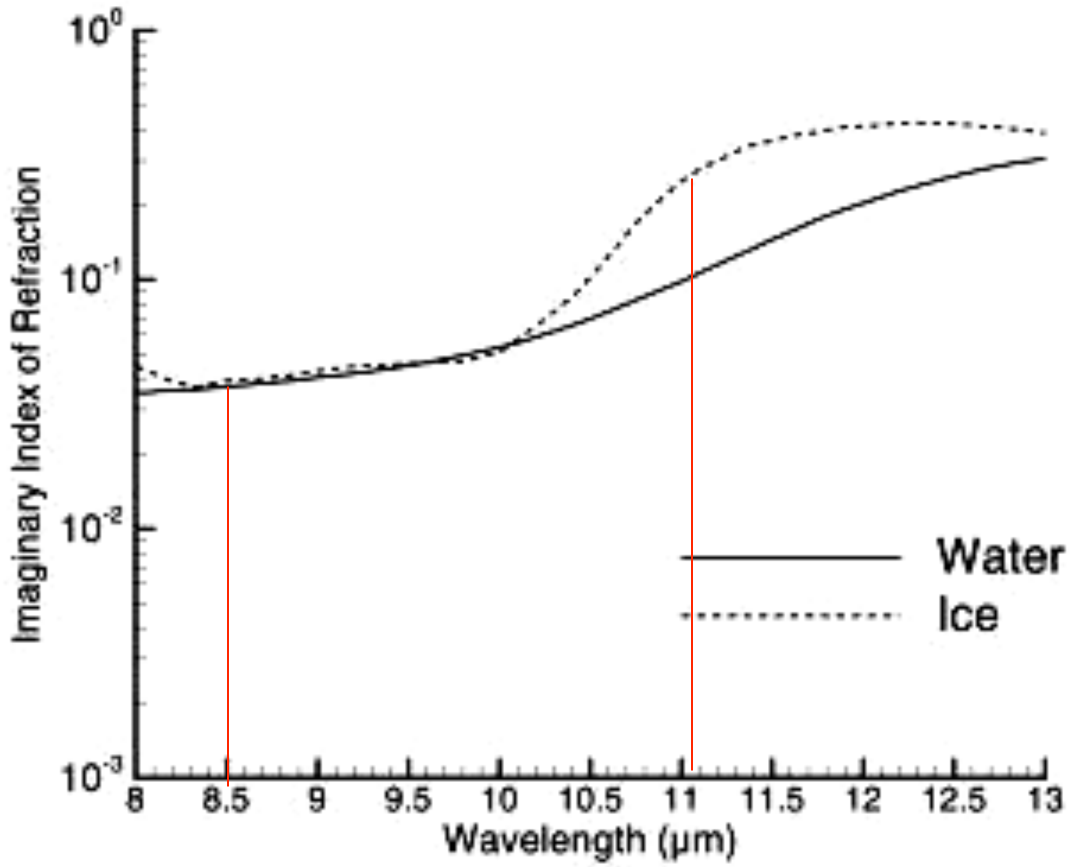
- Ackerman, S. A., K. I. Strabala, W. P. Menzel, R. A. Frey, C. C. Moeller, and L. E. Gumley, 1998: Discriminating clear sky from clouds with MODIS. J. Geophys. Res., 103, 32 141– 32 157.
- Frey, R., S. A. Ackerman, Y. Liu, K. I. Strabala, H. Zhang, J. Key, and X. Wang (2008), Cloud detection with MODIS: Part I. Improvements in the MODIS Cloud Mask for Collection 5, J. Atmos. Oceanic Technol., 25, 1057 – 1072.
- Ackerman, S. A., R. E. Holz, R. Frey, E. W. Eloranta, B. Maddux, and M. J. McGill (2008), Cloud detection with MODIS: Part II. Validation, J. Atmos. Oceanic Technol., 25, 1073 – 1086.

MODIS Cloud Phase (part of MOD06CT)

Cloud Phase

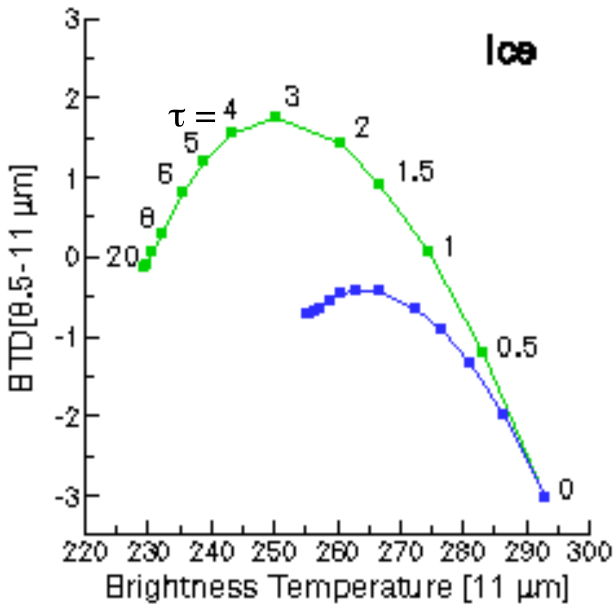
Dr. Bryan Baum SSEC

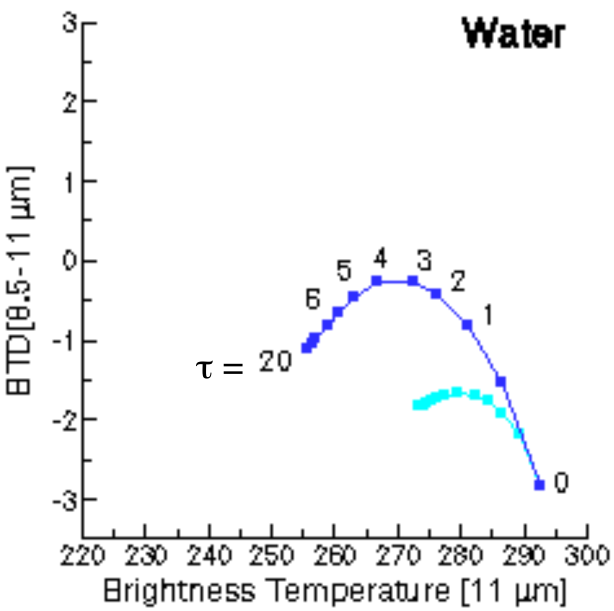
- Based upon the differential absorption of ice and water between 8 and 11 microns
- Simple brightness temperature difference (8-11 BTDIF) thresholding technique
- Included as part of the MOD06 product



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

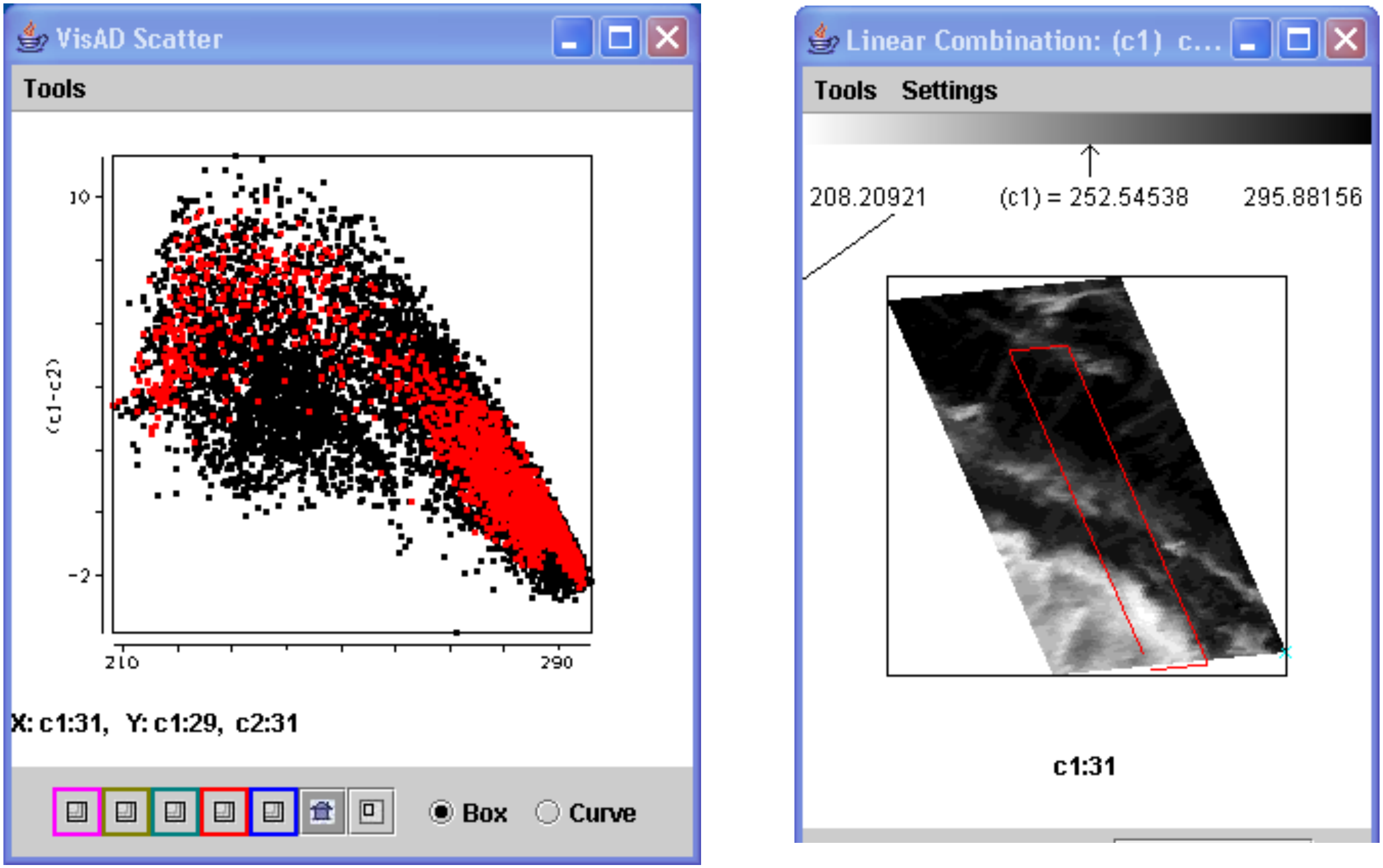
- BTD[8.5-11] values are similar (*i.e.*, negative) for both water and ice clouds
- T_{cld} = 253 K

Low-level, warm clouds

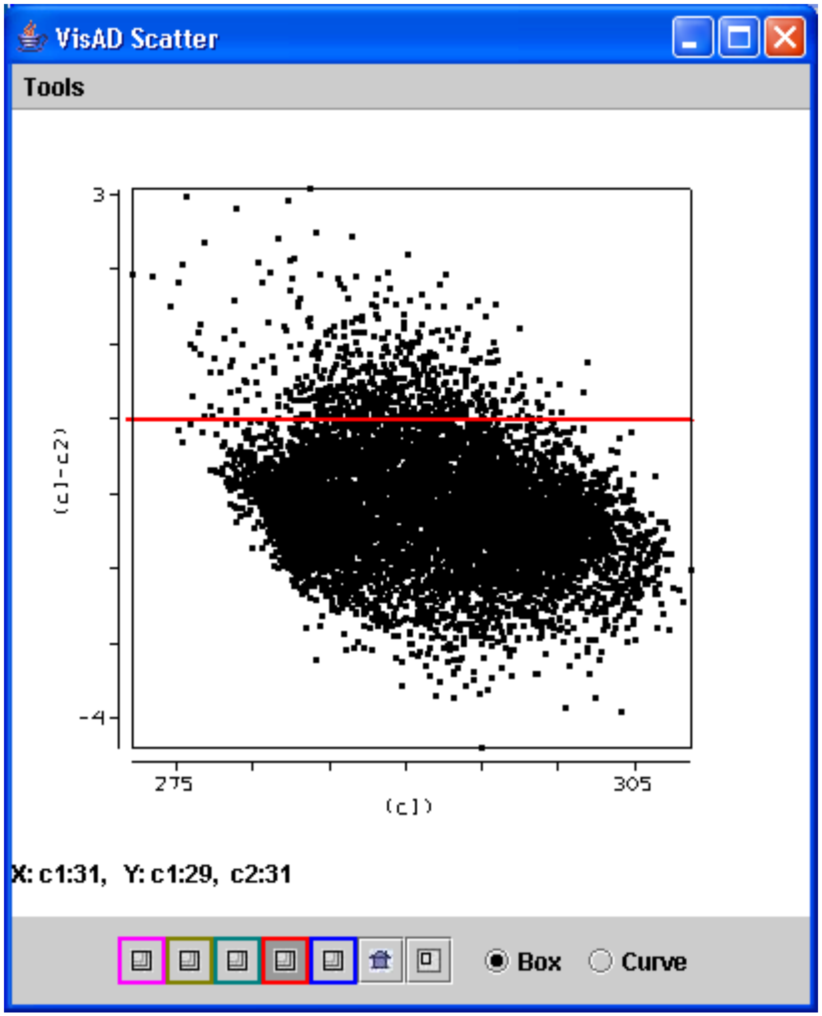
- BTD[8.5-11] values always negative
- T_{cld} = 273 K

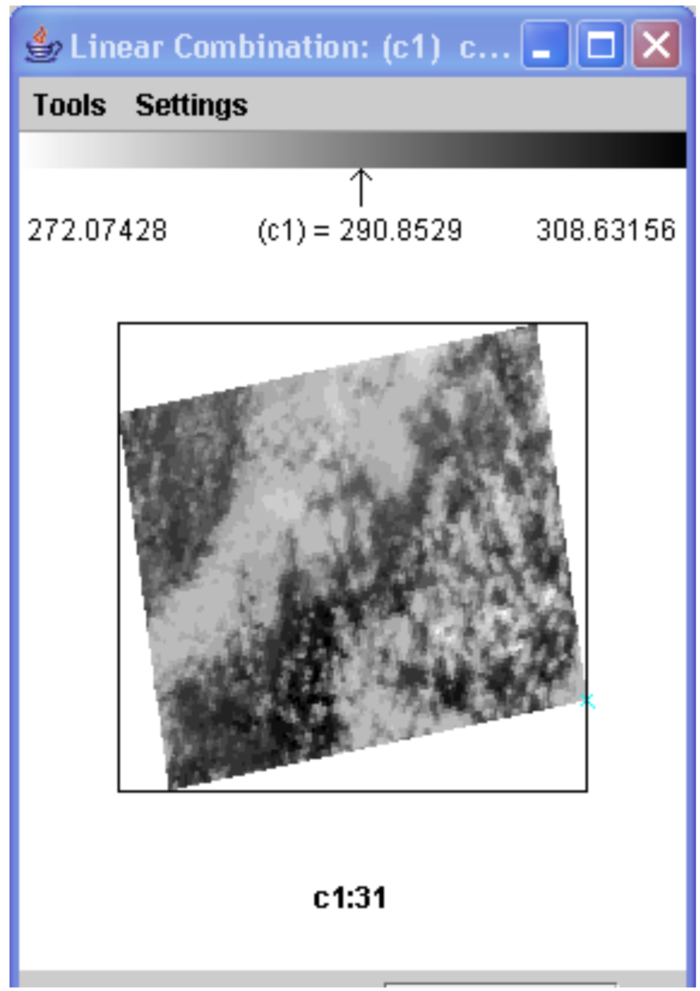
Ice: Cirrus model derived from FIRE-I in-situ data (Nasiri et al, 2002)
Water: r_e=10 μm
Angles: $\theta_o = 45^o$, $\theta = 20^o$, and $\phi = 40^o$
Profile: midlatitude summer

Ice Cloud Example



Water Cloud Example





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

MOD06 Cloud Phase 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
- **Cloud_Phase_Infrared**
- Cloud Optical Depth (daytime – 1 km product)
- Cloud Effective Radius (daytime – 1km)

Output Product Description

4 categories

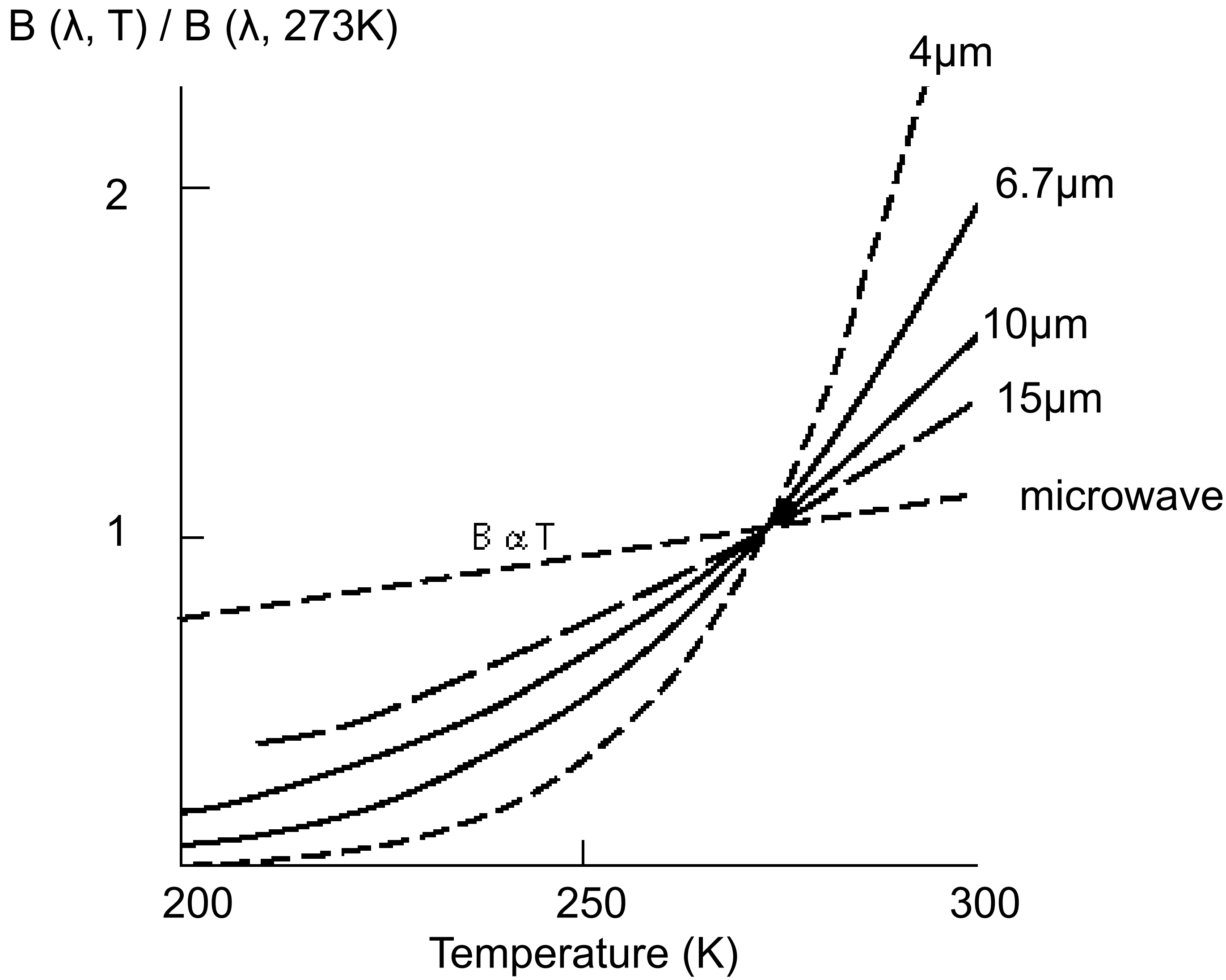
1 – Water Cloud

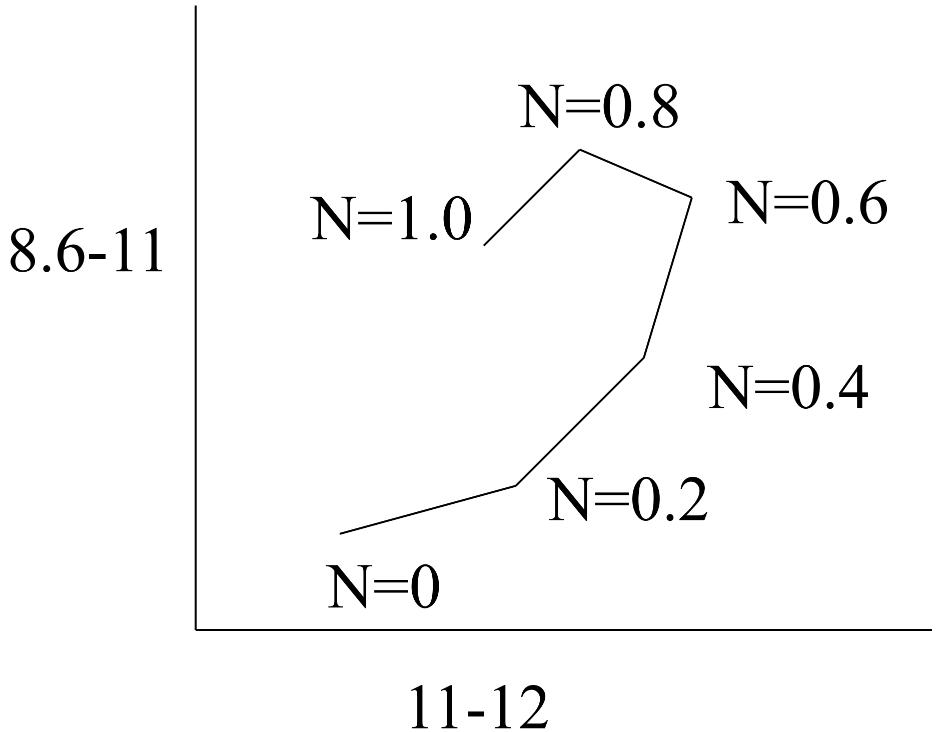
2 – Ice Cloud

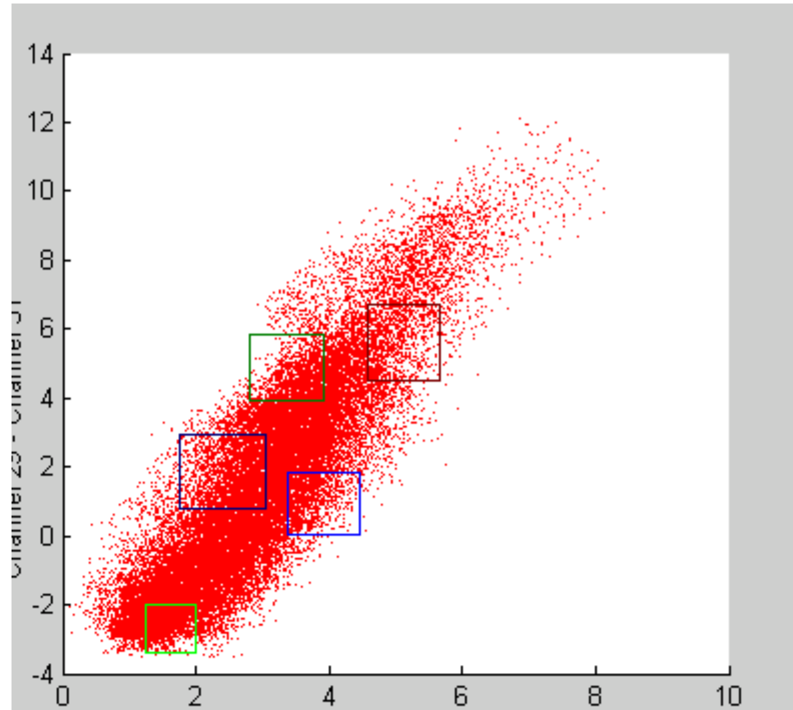
3 – Mixed Phase Cloud

6 – Undecided

Temperature Sensitivity of B(λ,T) for typical earth scene temperatures







Broken clouds appear different in 8.6, 11 and 12 um images;
assume Tclr=300 and Tcld=230

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

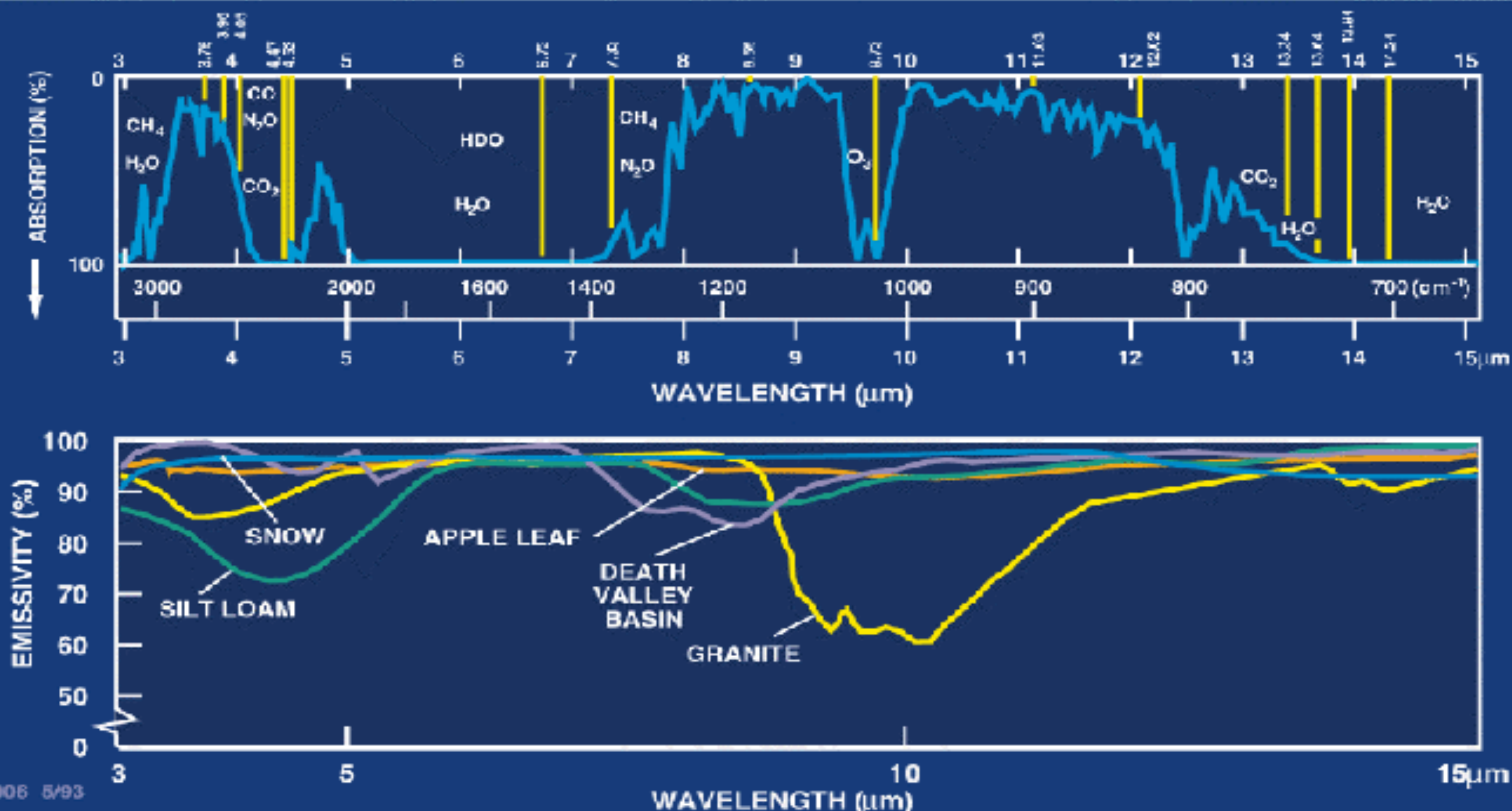
$$T(8.6)-T(11)=[(1-N)*B8.6(Tclr)+N*B8.6(Tcld)]^{-1} - [(1-N)*B11(Tclr)+N*B11(Tcld)]^{-1}$$

Warm part of pixel has more influence at shorter wavelengths

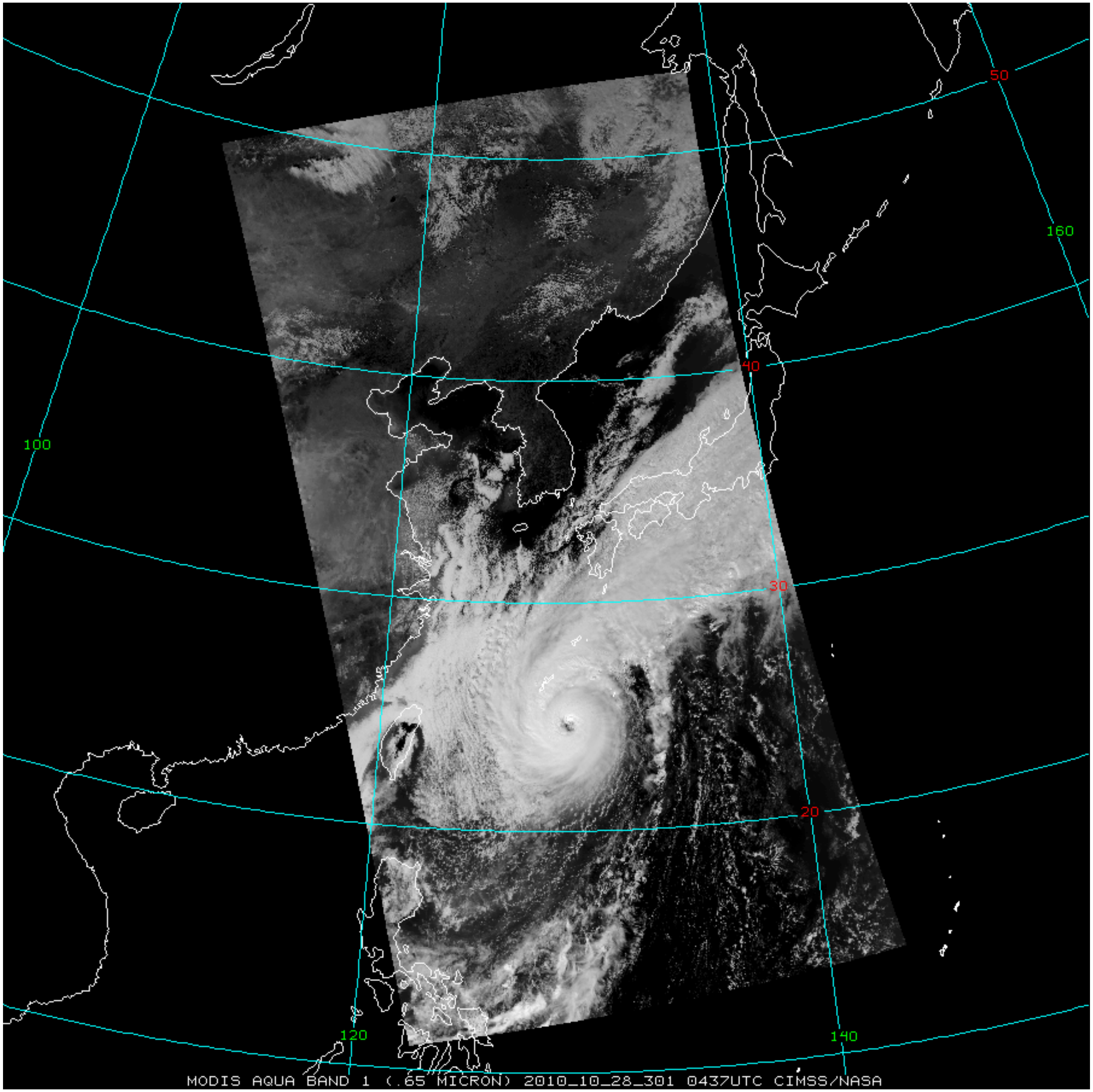
Known Problems

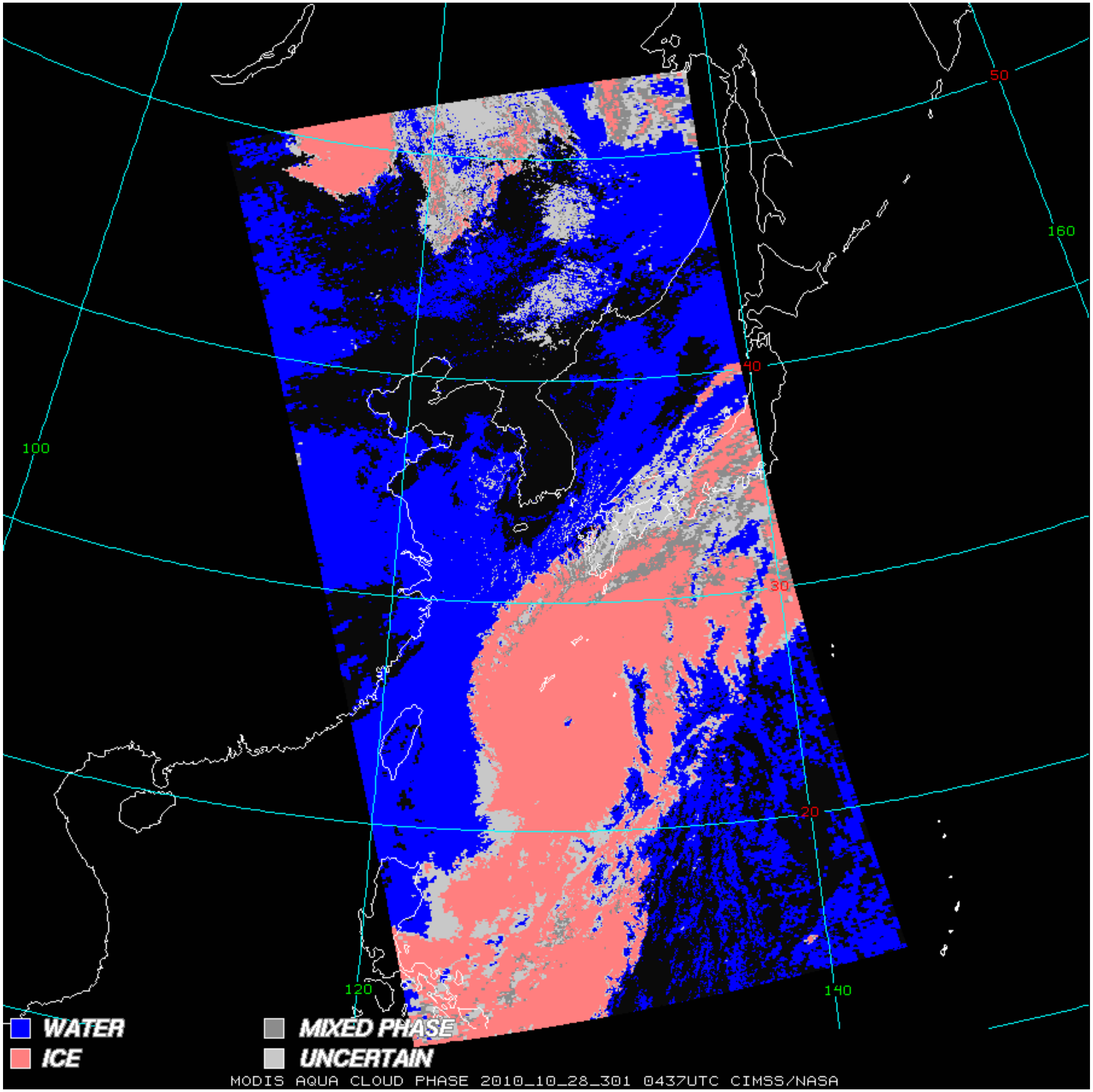
- Mid-level cloud (BT ~ 250 K)
  - Ambiguous solution
- Surface Emissivity Effects
  - Not always the same over the IR window (granite)
- Mixed phase cloud category
  - should be considered as undecided

LAND - THERMAL RADIATION



C351.006 5/93


50
160
40
100
30
20
120
140
MODIS AQUA BAND 1 (.65 MICRON) 2010_10_28_301 0437UTC CIMSS/NASA



50
40
30
20
160
100
120
140
WATER
ICE
MIXED PHASE
UNCERTAIN
MODIS AQUA CLOUD PHASE 2010_10_28_301 0437UTC CIMSS/NASA

Applications

1. Meteorological
   - Aviation - icing
   - Thunderstorm maturity - glaciation
   - Freezing rain
   - Numerical Weather Prediction Models

2. Climatological
   - Global Cloud Modeling - Ice and water clouds absorb and reflect differently at different wavelengths

References

- Strabala, K. I., S. A. Ackerman, and W. P. Menzel, 1994: Cloud properties inferred from 8-12 μm data. *J. Appl. Meteor.*, ***33, 212-229.***

MODIS Cloud Top Properties (MOD06CT)

Cloud Top Properties

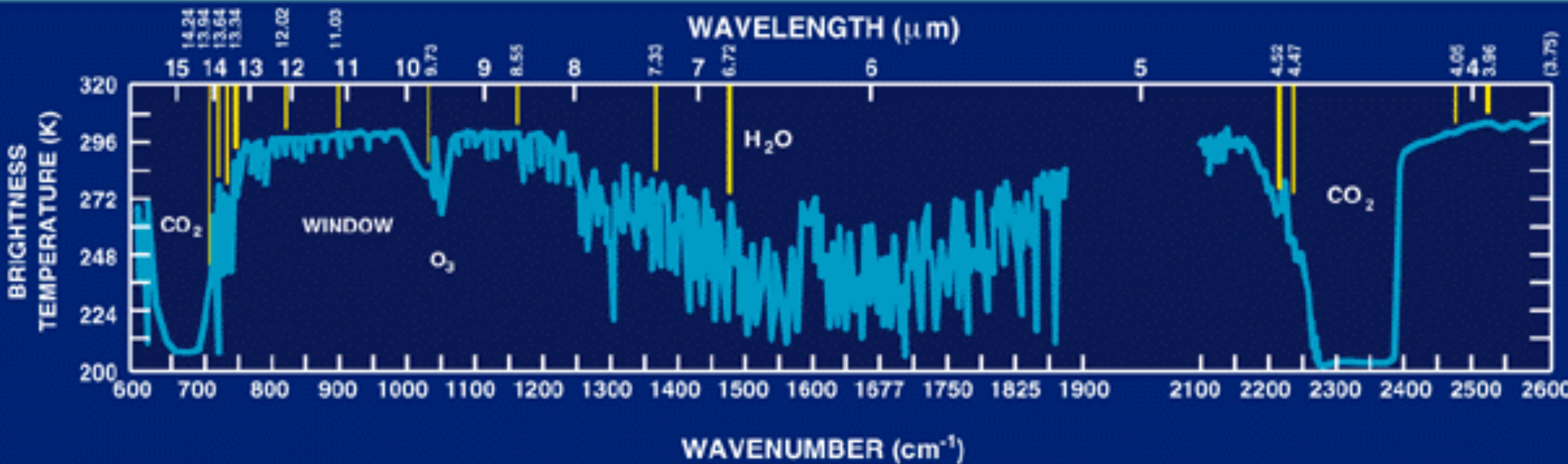
Menzel, Frey - SSEC

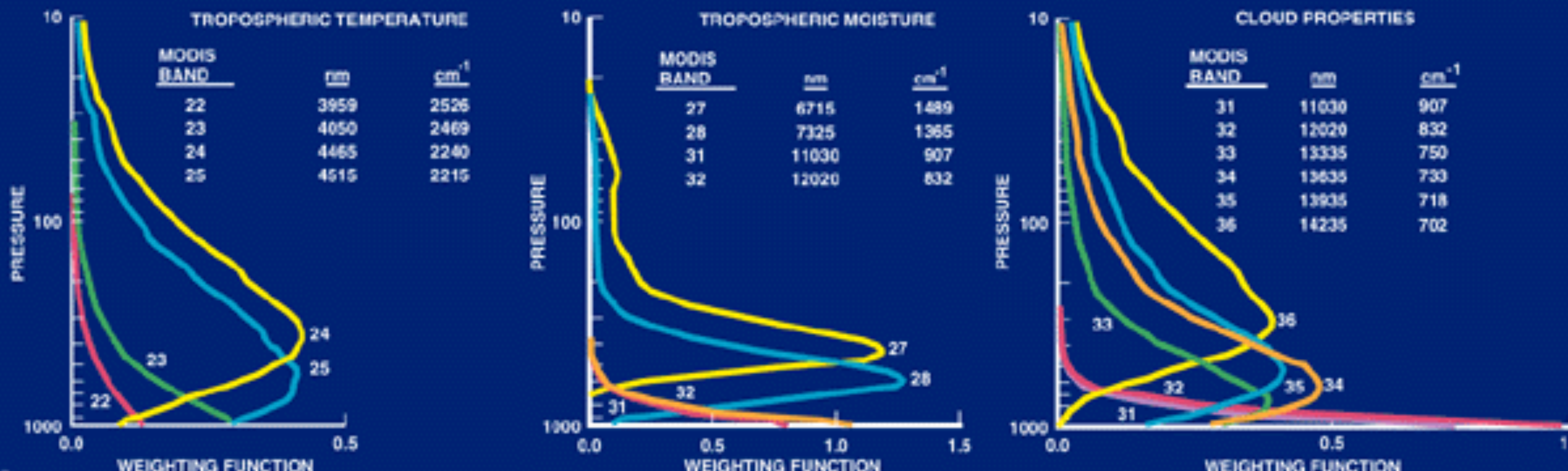
- Cloud Top Pressure, Temperature, Emissivity derived using CO_2 “slicing”
- MODIS product utilizes 4 spectral channels in the 13 – 14 μm region.
- 5x5 1 km pixel retrievals where at least 5 of the 1 km pixels are cloudy as determined by the cloud mask
- Cloud properties retrieved both day and night

Inputs

- MODIS L1B (MOD021KM) 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

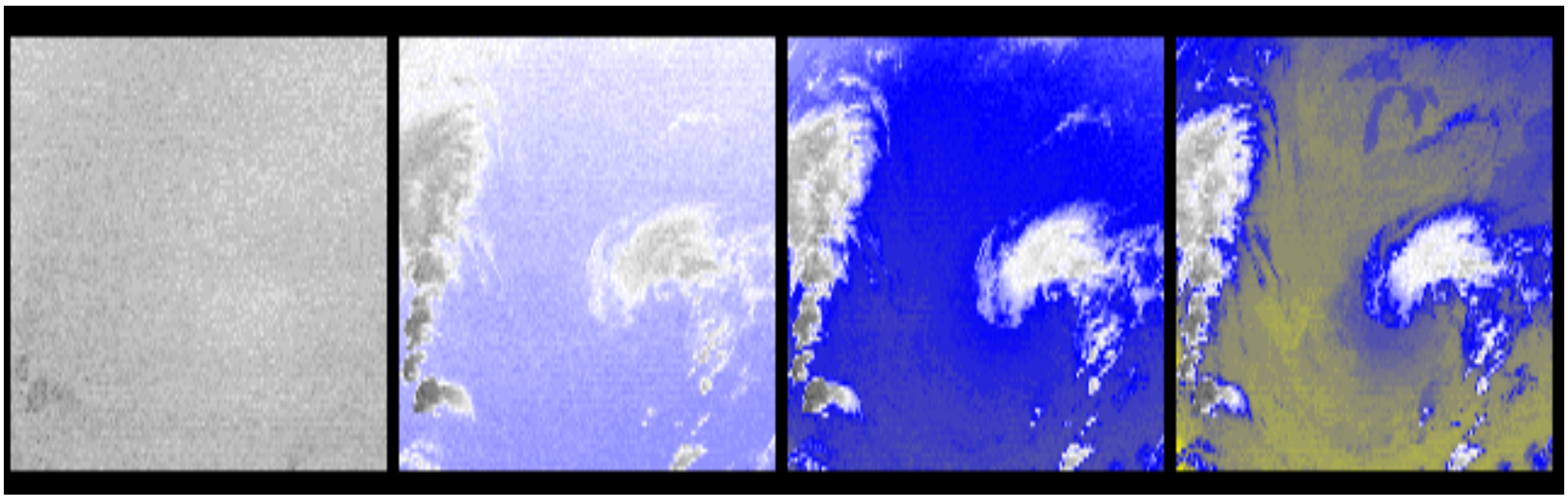
ATMOSPHERE - THERMAL RADIATION





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

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

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

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

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

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.

Radiative Transfer Equation

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

RTE in Cloudy Conditions

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

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

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

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

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

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

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)

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

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.

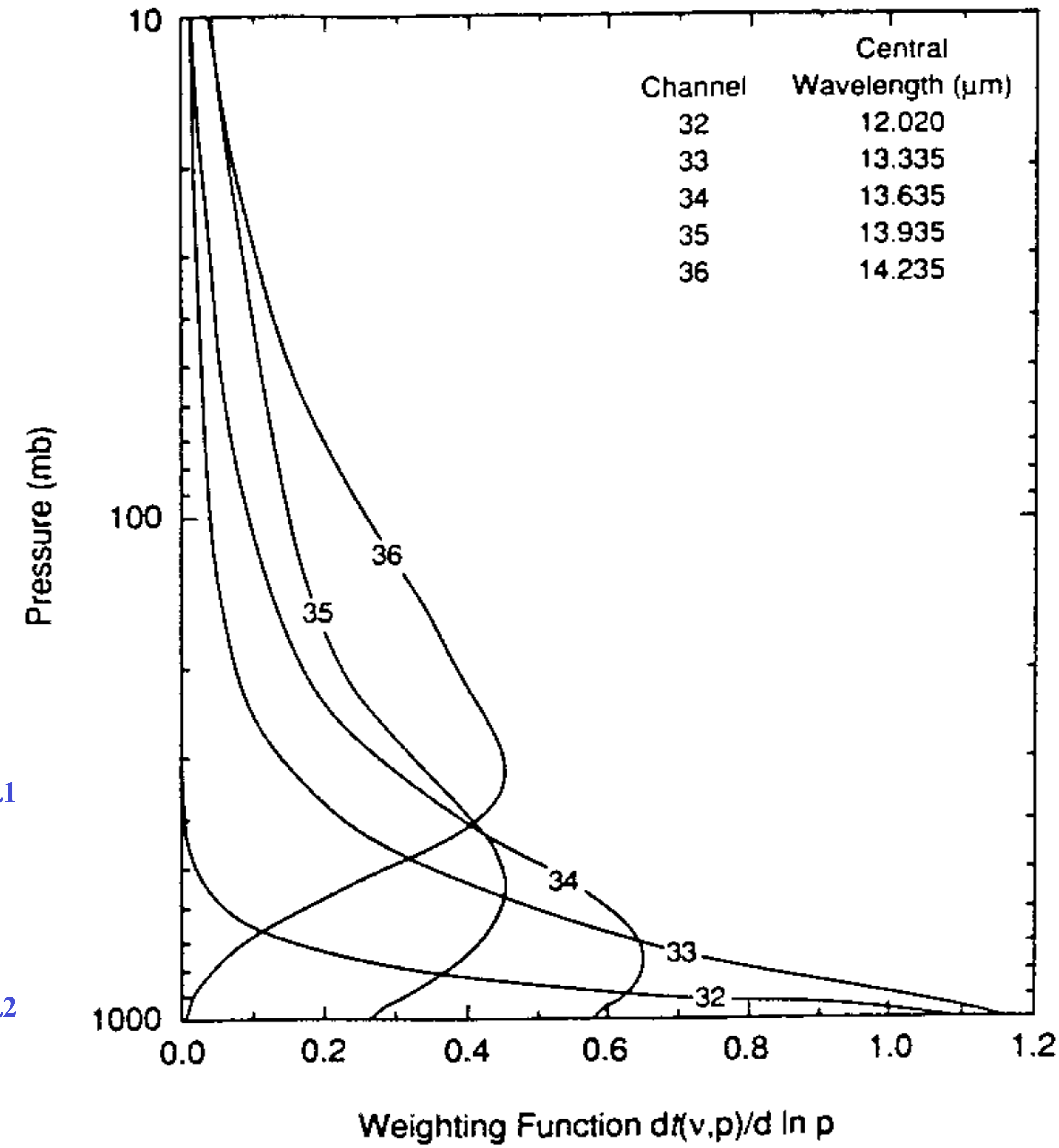
p_c can be inferred from radiance measurements in two spectral bands where cloud emissivity is the same. $\eta\varepsilon_\lambda$ is derived from the infrared window, once p_c is known.

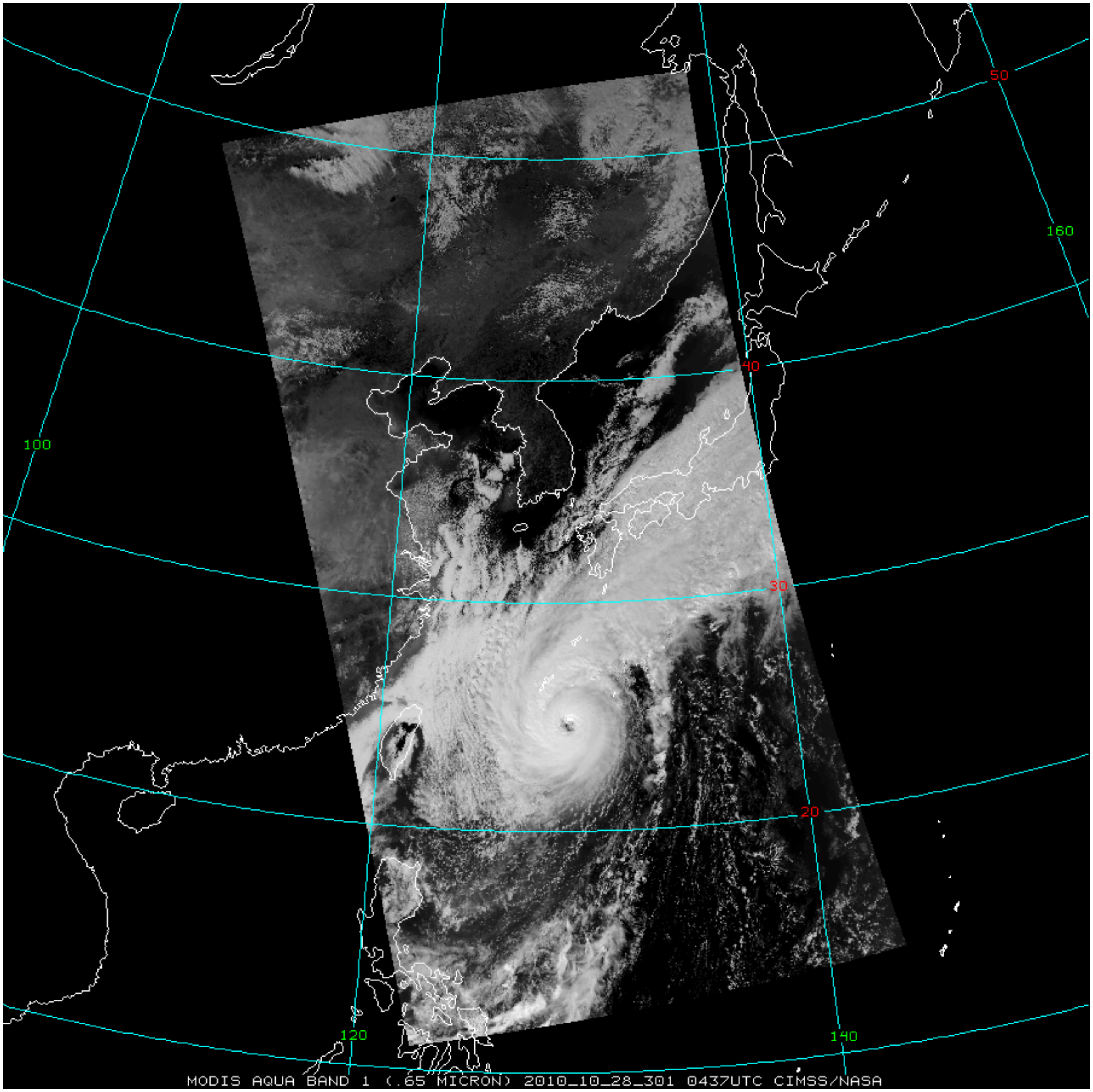
Different ratios reveal cloud properties at different levels

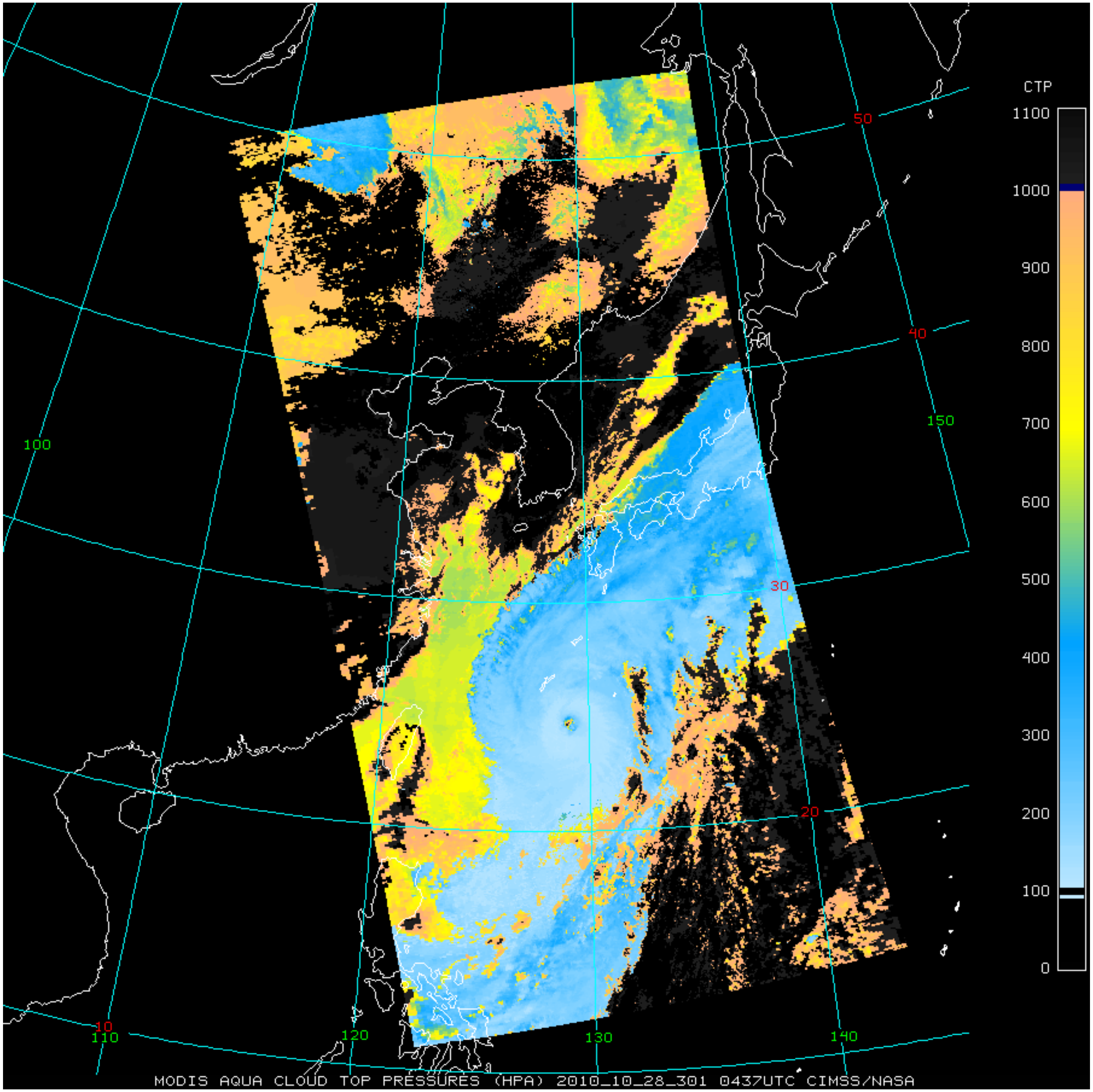
hi - 14.2/13.9
mid - 13.9/13.6
low - 13.6/13.3

Meas   **Calc**

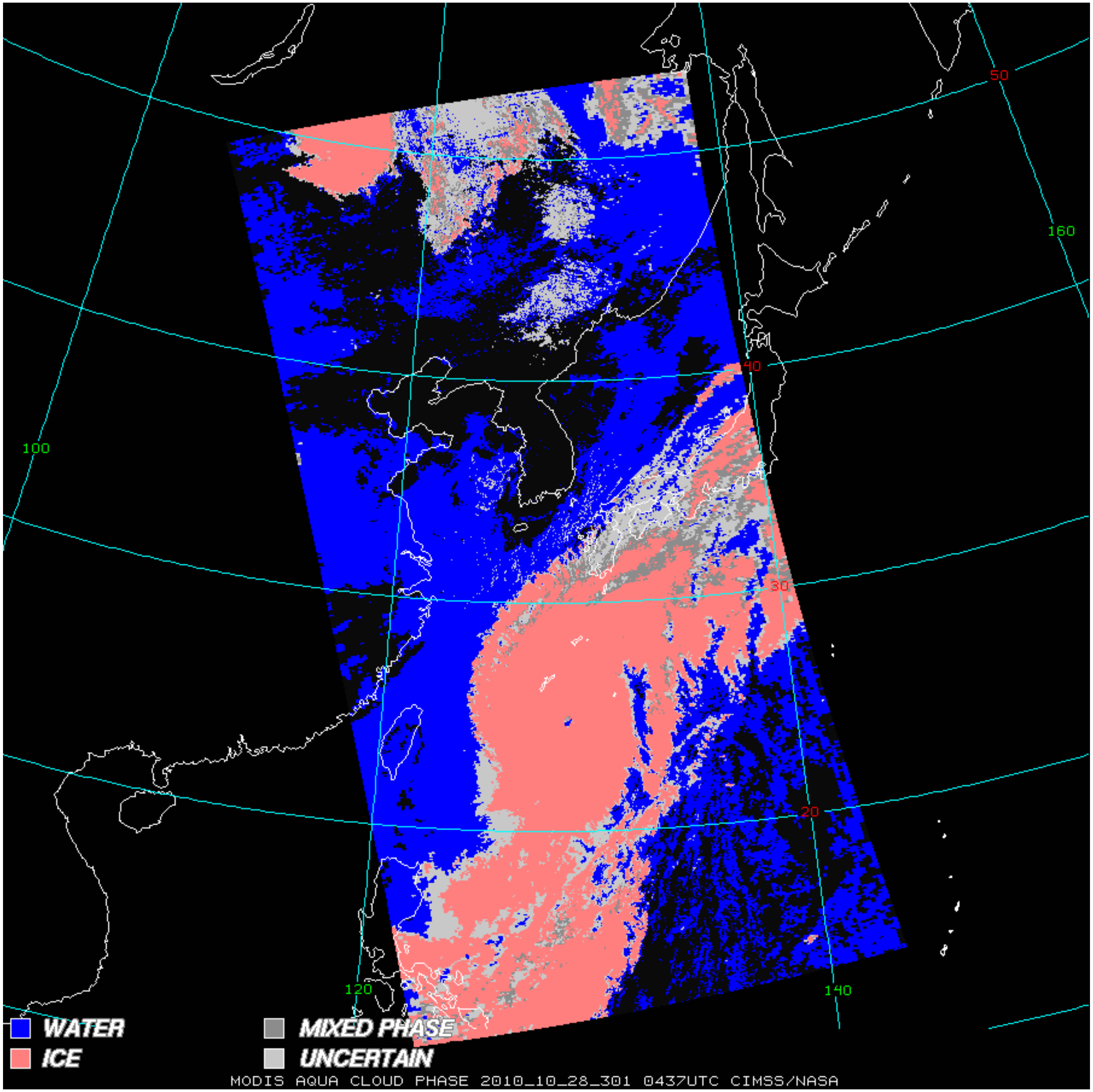
$$\frac{(I_{\lambda 1}-I_{\lambda 1}^{clr})}{(I_{\lambda 2}-I_{\lambda 2}^{clr})} = \frac{\eta \varepsilon_{\lambda 1} \int_{p_s}^{p_c} \tau_{\lambda 1}\, dB_{\lambda 1}}{\eta \varepsilon_{\lambda 2} \int_{p_s}^{p_c} \tau_{\lambda 2}\, dB_{\lambda 2}}$$

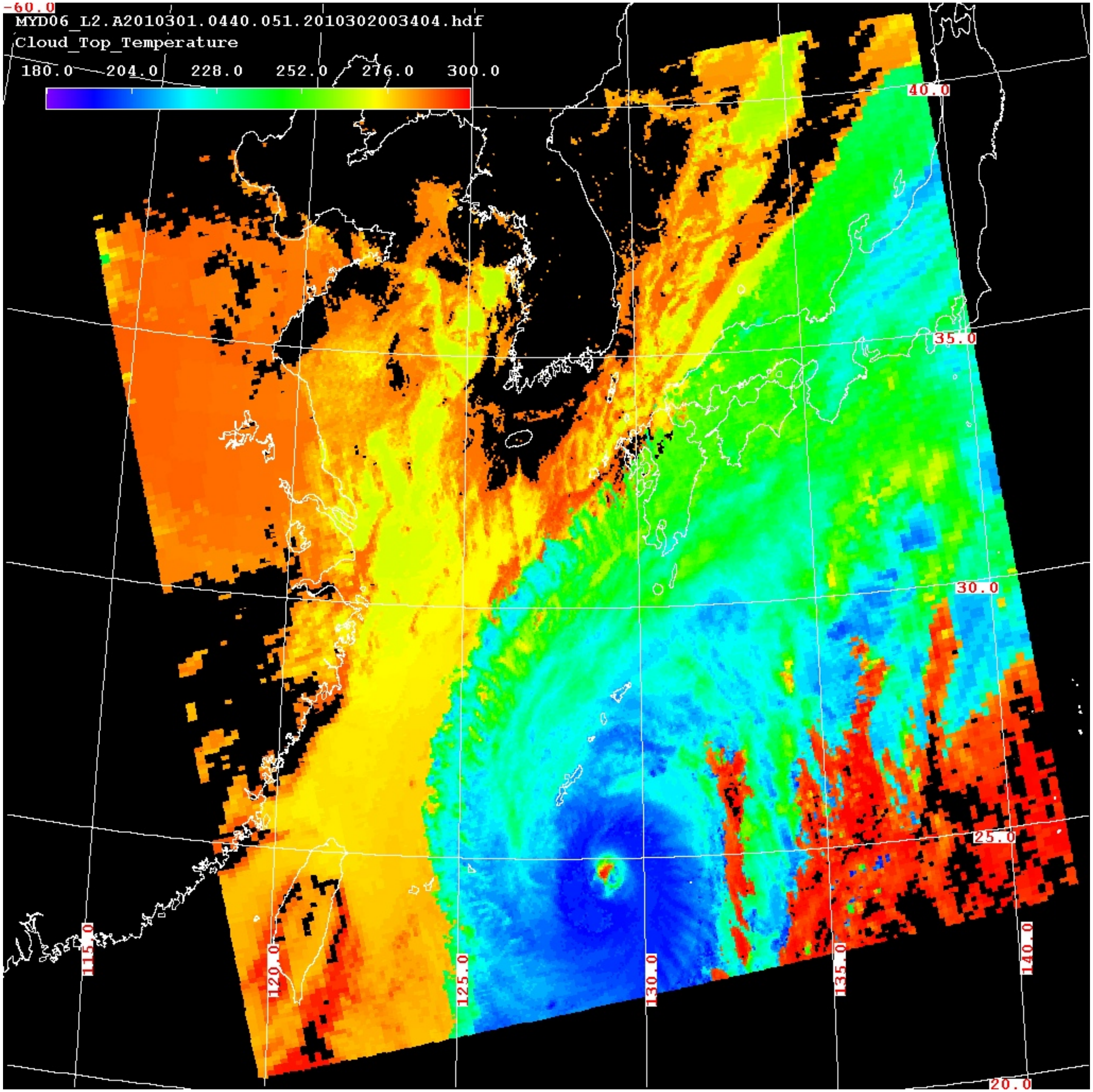



50
160
40
100
30
20
120
140
MODIS AQUA BAND 1 (.65 MICRON) 2010_10_28_301 0437UTC CIMSS/NASA



CTP
1100
1000
900
800
700
600
500
400
300
200
100
0
50
40
30
20
10
100
110
120
130
140
150
MODIS AQUA CLOUD TOP PRESSURES (HPA) 2010_10_28_301 0437UTC CIMSS/NASA


50
160
40
100
30
20
120
140
WATER
ICE
MIXED PHASE
UNCERTAIN
MODIS AQUA CLOUD PHASE 2010_10_28_301 0437UTC CIMSS/NASA


-60.0
MYD06_L2.A2010301.0440.051.2010302003404.hdf
Cloud_Top_Temperature
180.0
204.0
228.0
252.0
276.0
300.0
40.0
35.0
30.0
25.0
20.0
115.0
120.0
125.0
130.0
135.0
140.0

MOD06 Key Output Parameters

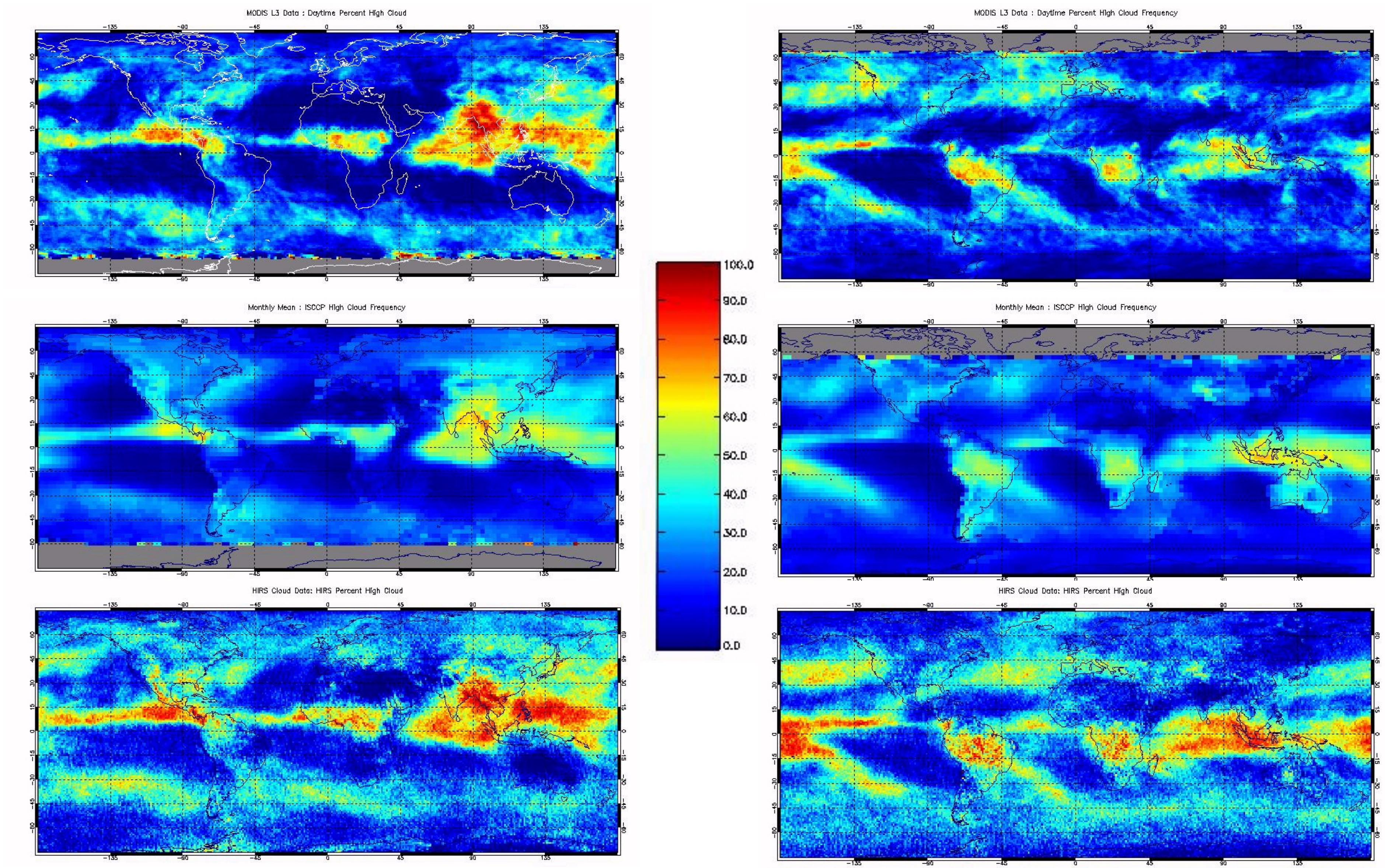
5x5 pixel (1km) resolution

- **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
- Cloud_Phase_Infrared
- Cloud Optical Depth (daytime – 1 km product)
- Cloud Effective Radius (daytime – 1km)

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

References

Menzel, W. P., F. Richard, H. Zhang, D. P. Wylie, C. Moeller, R. E. Holz, B. Maddux, K. I. Strabala, and L. E. Gumley (2008), MODIS global cloud-top pressure and amount estimation: Algorithm description and results, J. Appl. Meteorol. Climatol., 47, 1175 – 1198, doi: 10.1175/2007JAMC1705.1.

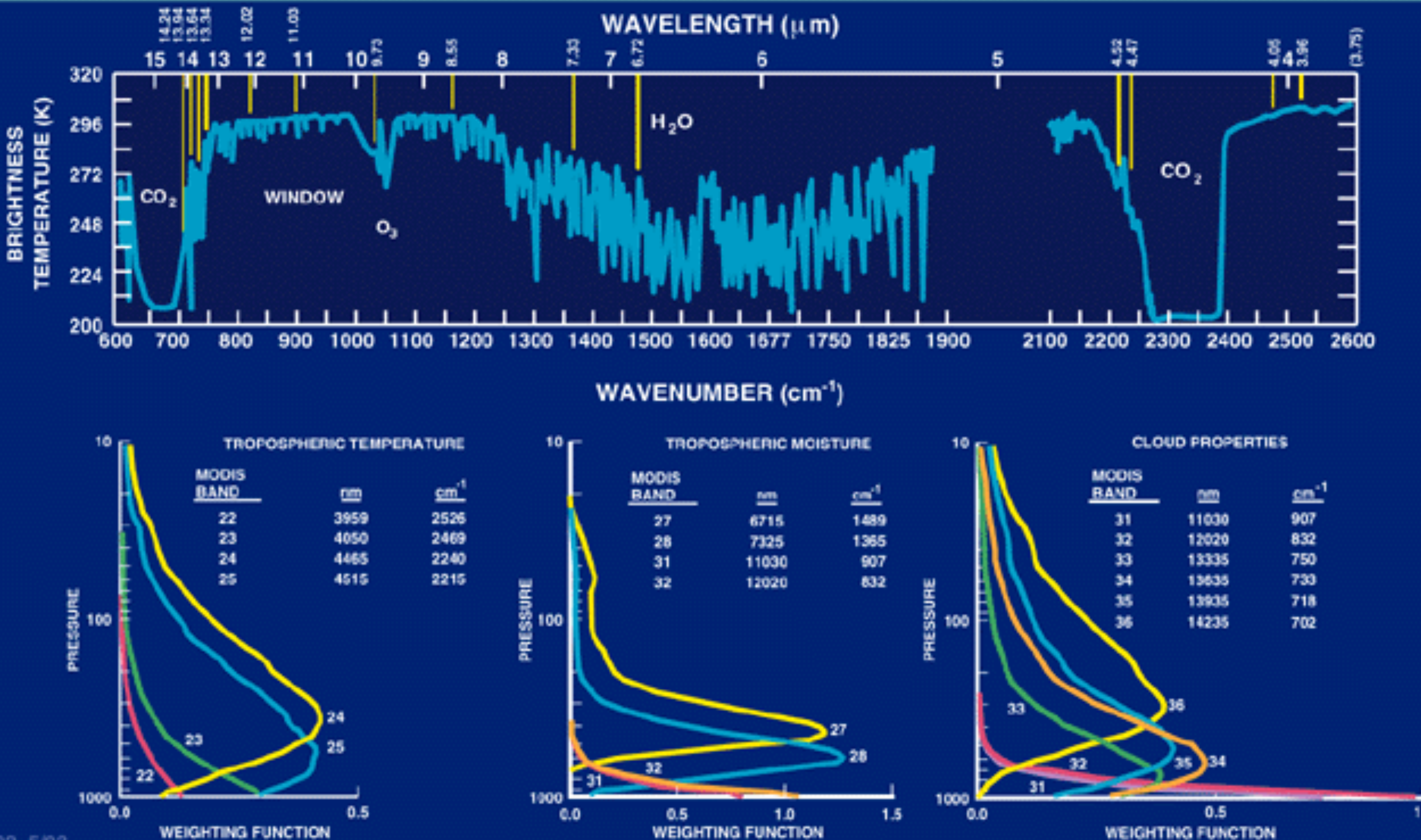
MODIS Atmospheric Profiles (MOD07)

MODIS Atmospheric Profiles

Eva Borbas, Suzanne Wetzel-Seemann SSEC

- Retrievals are performed in 5x5 FOV (approximately 5km resolution) clear-sky radiances over land and ocean for both day and night.
- Algorithm is a statistical regression and has the option for a subsequent nonlinear physical retrieval.
- Regression predictors include MODIS infrared radiances from bands 25, 27-36 (4.4 - 14.2mm).
- Clear sky determined by MODIS cloud mask (MOD35).

ATMOSPHERE - THERMAL RADIATION



E351.002 5/93

Atmospheric Profile Output

- Atmospheric precipitable water
  short Water_Vapor
  short Water_Vapor_Low
  short Water_Vapor_High
- Profiles of temperature and moisture (20 levels)
  short Retrieved_Moisture_Profile
  short Retrieved_Temperature_Profile
- Total column ozone
  short Total_Ozone

Pressure_Level = 05., 10., 20., 30., 50., 70., 100., 150., 200., 250., 300., 400., 500., 620., 700., 780., 850., 920., 950., 1000. ;

Algorithm Discussion

Clear radiance exiting the atmosphere for a MODIS IR band with wavelength λ:

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

I_λ is measured by MODIS for λ = 4.4 - 14.2μm (I_{25}, I_{27}, … I_{36})

I_λ can be considered a nonlinear function of the atmospheric properties including T, q, ozone, surface pressure, skin temperature, and emissivity.

We can infer a statistical regression relationship using calculated radiances from a global set of radiosonde profiles and surface data.

Relationship is inverted to retrieve atmospheric properties from observed MODIS radiances.

Algorithm Discussion

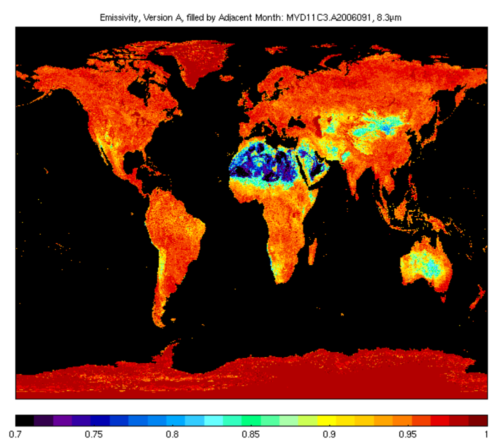
Global radiosondes: data set drawn from NOAA-88, TIGR-3, ozonesondes, ECMWF, desert radiosondes containing 12000+ global radiosonde profiles of temperature, moisture, and ozone used for training data set.

RT model: RT Model used is the CRTM (Community Radiative Transfer Model distributed by the Joint Center for Satellite Data Assimilation (JCSDA)

- Radiosonde temperature-moisture-ozone profile / calculated MODIS radiance pairs are used to create the statistical regression relationship.

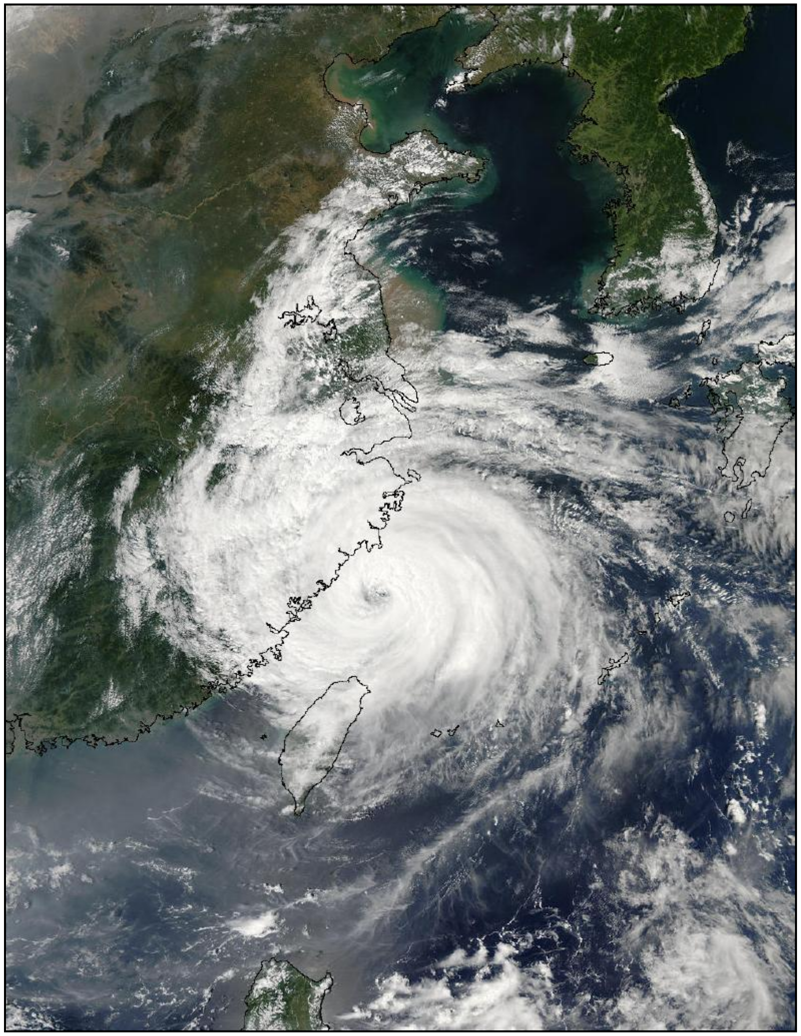
Recent improvements to the algorithm:

- Global database of infrared (IR) land surface emissivity
- Distributed for use in the retrieval of atmospheric temperature and moisture profiles is introduced.
- Emissivity is derived using input from the MODIS operational land surface emissivity product (called MYD11).
- MODIS MOD07 retrieval algorithm requires a surface emissivity value corresponding to each of the global training profiles
- Improvement is evident over retrievals made with a typical assumption of constant emissivity.



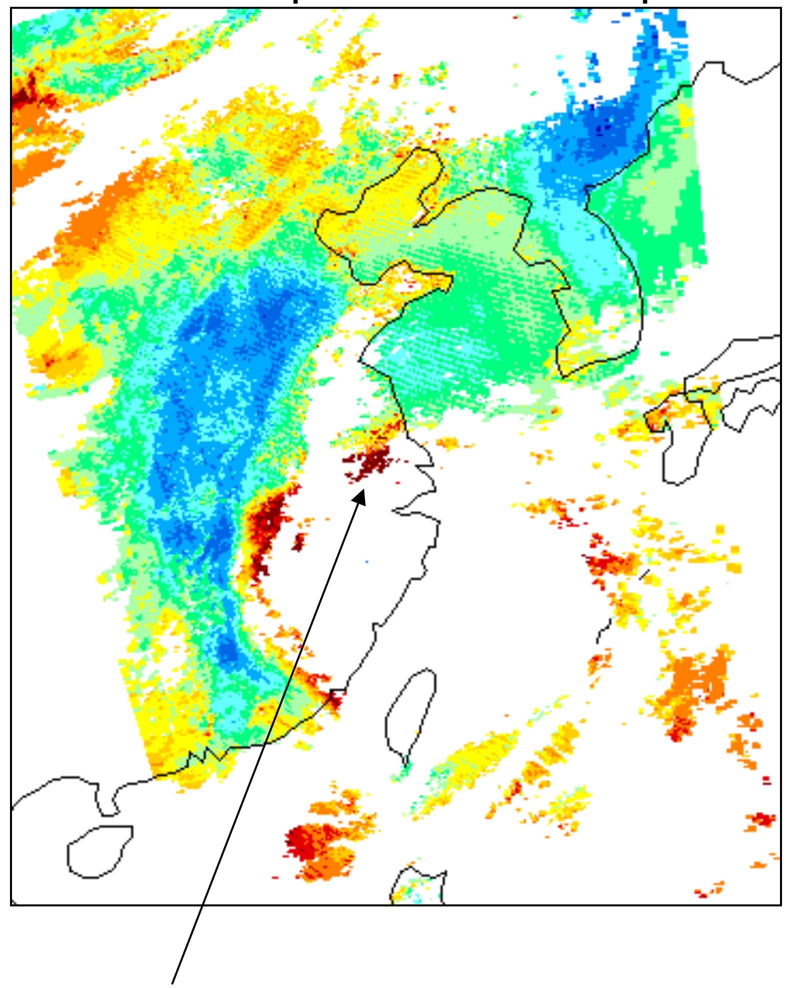
Database available from:
http://cimss.ssec.wisc.edu/iremis/

Typhoon Sinlaku, 7 September 2002
Aqua MODIS



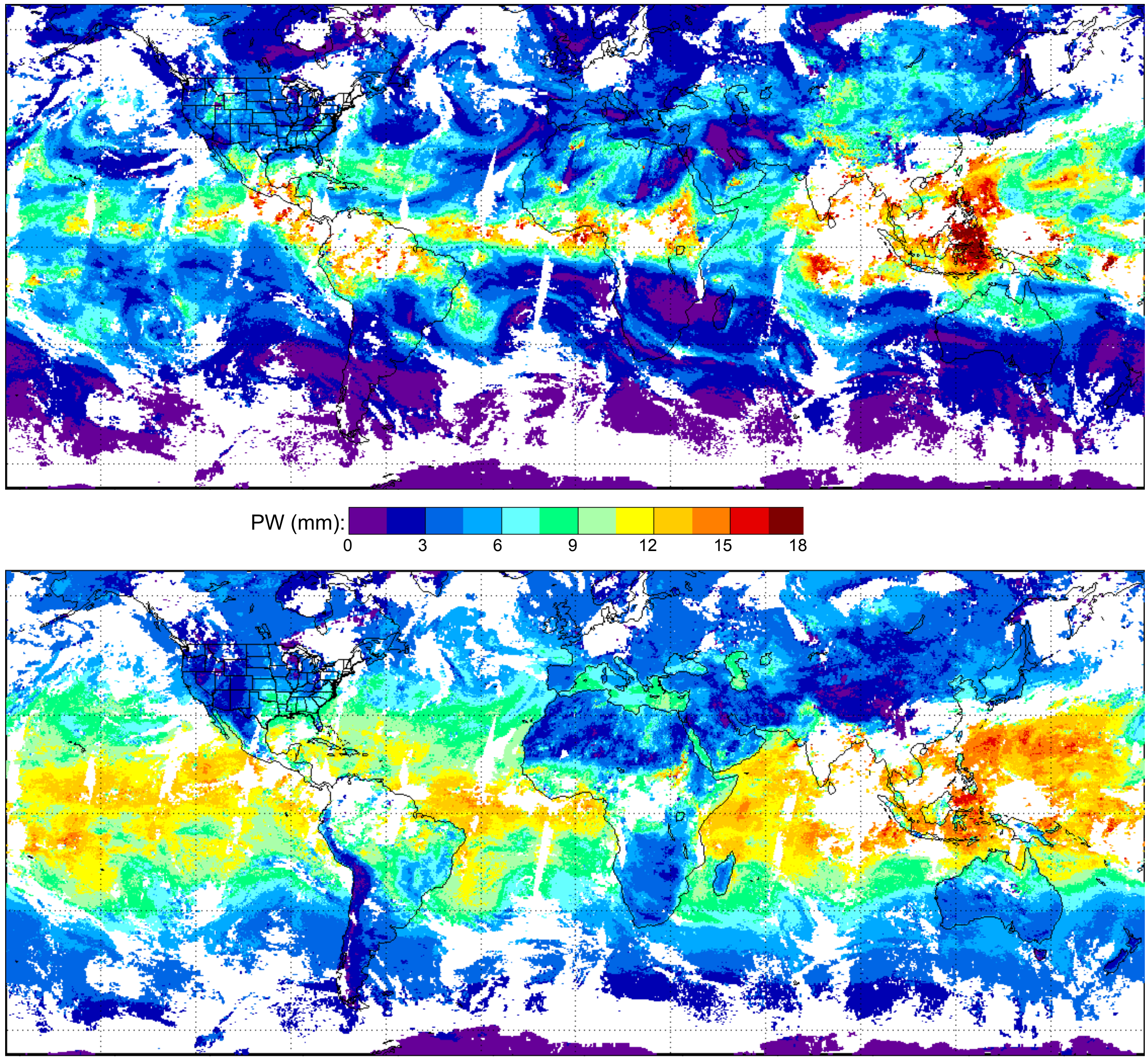
Aqua MODIS true color image

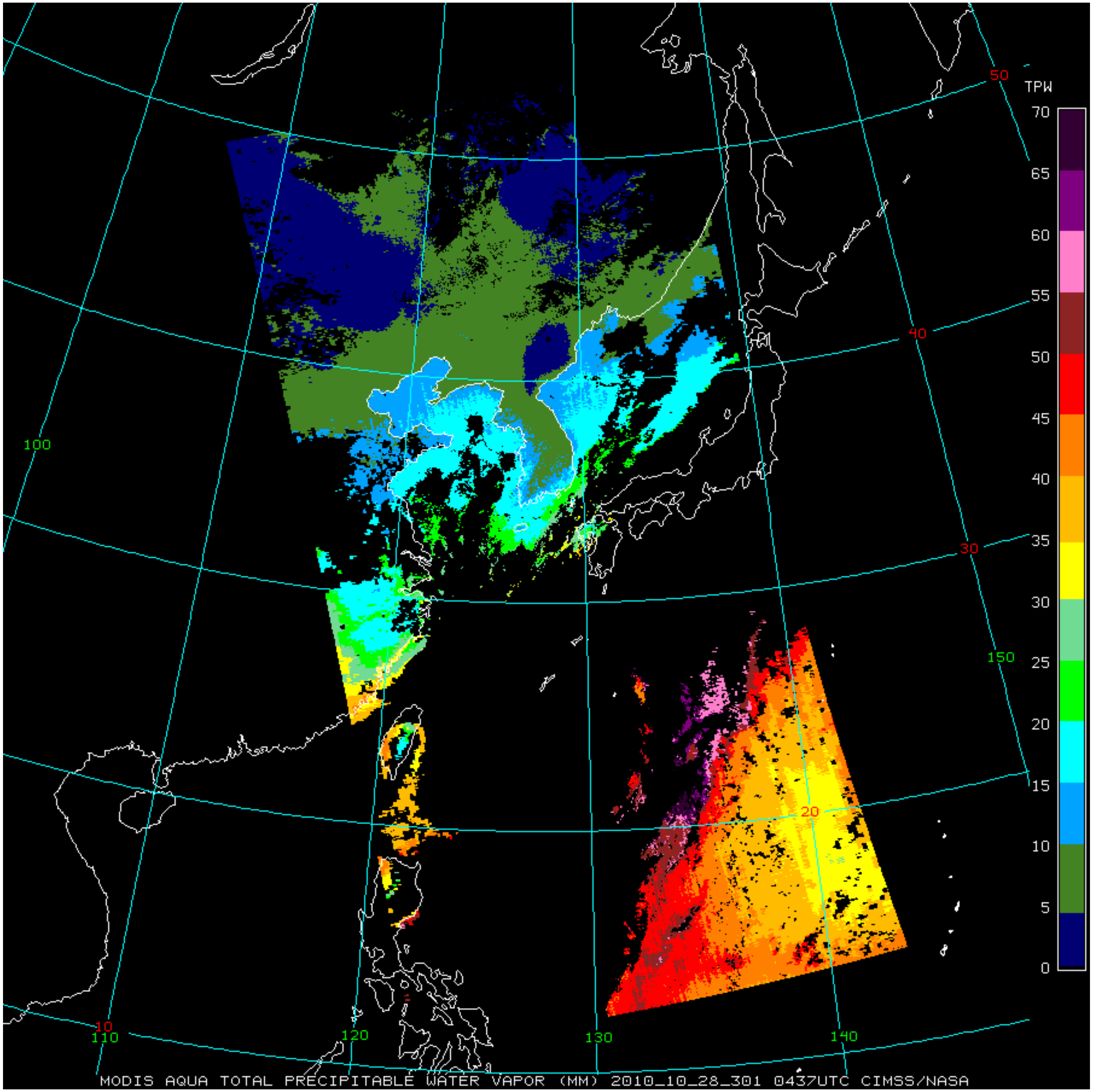
Total Precipitable Water Vapor

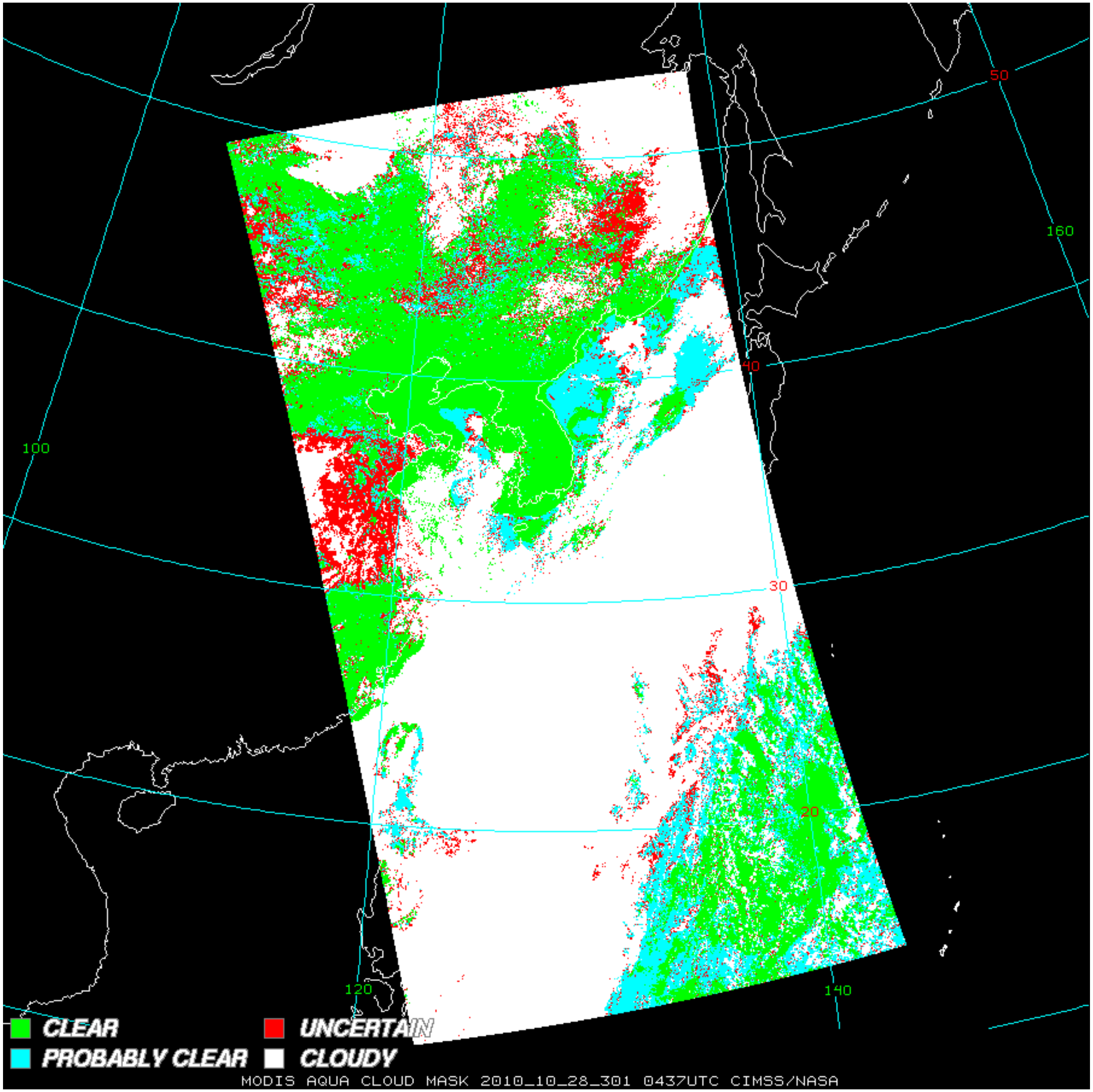


PW High
700-300 hPa

PW Low
920 hPa - sfc

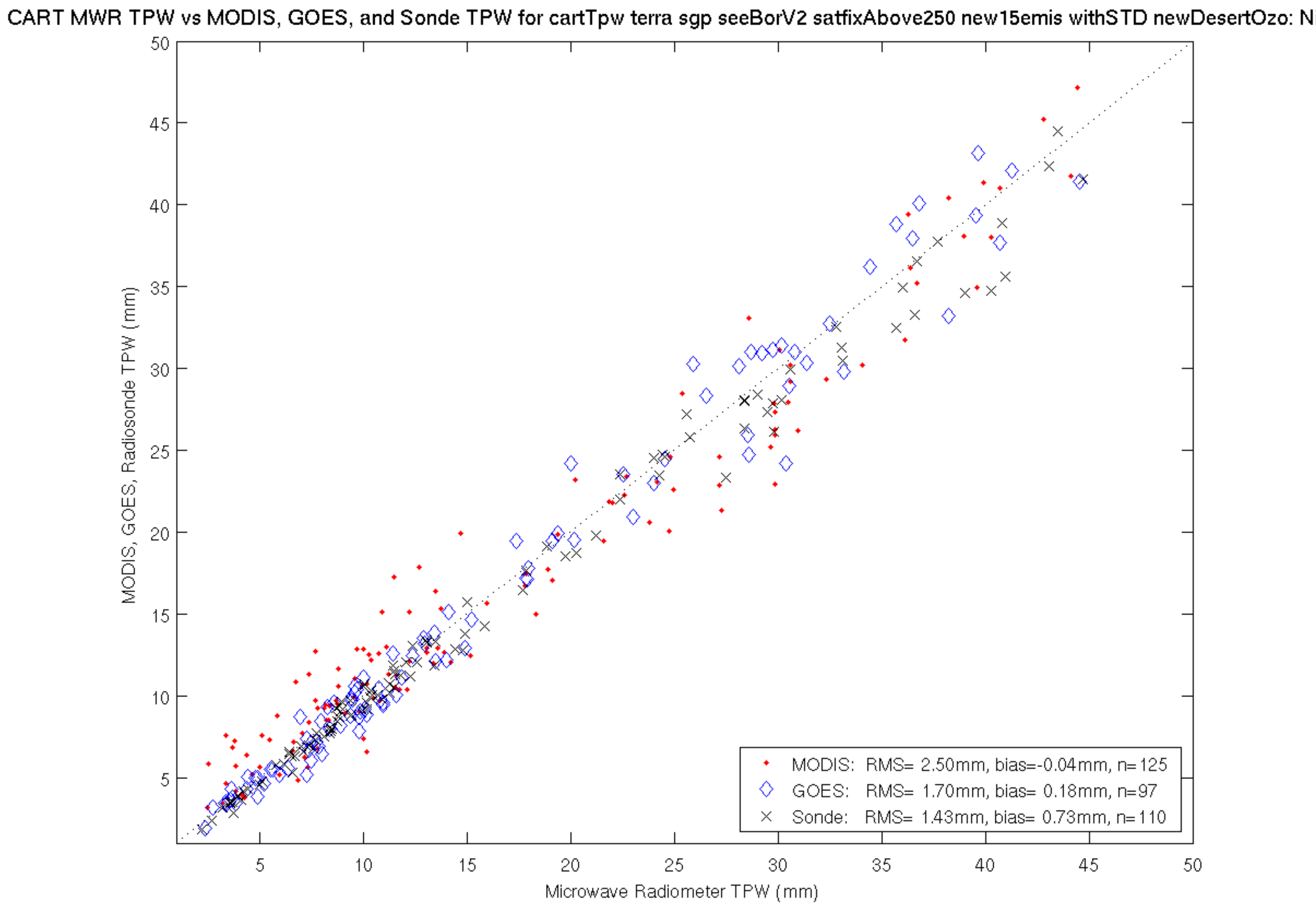



TPW
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
50
40
30
20
10
100
110
120
130
140
150
MODIS AQUA TOTAL PRECIPITABLE WATER VAPOR (MM) 2010_10_28_301 0437UTC CIMSS/NASA



50
160
40
100
30
20
120
140
CLEAR
UNCERTAIN
PROBABLY CLEAR
CLOUDY
MODIS AQUA CLOUD MASK 2010_10_28_301 0437UTC CIMSS/NASA

ARM CART Site Comparison

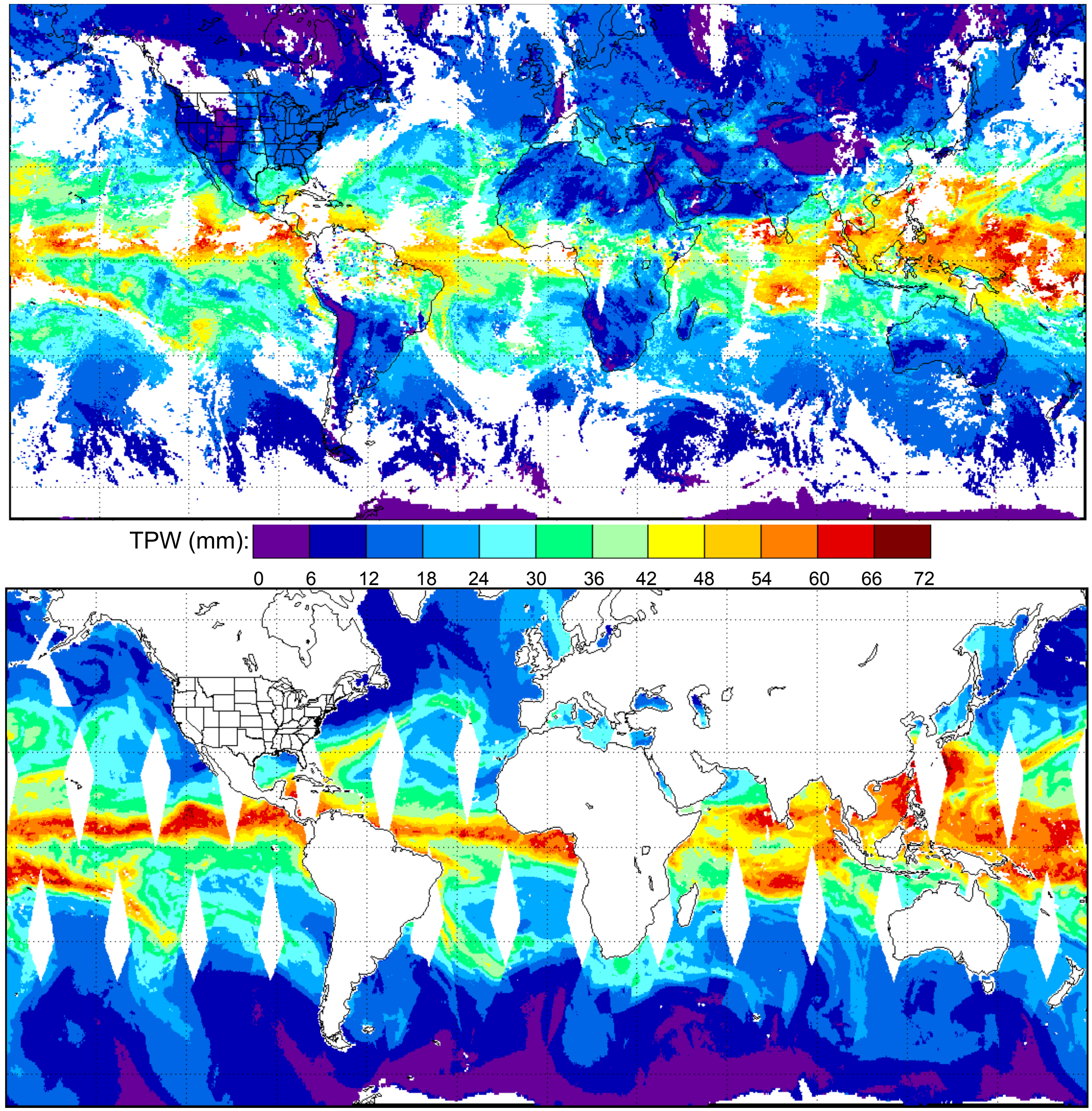


Global Total Precipitable Water Comparison 22 May 2002

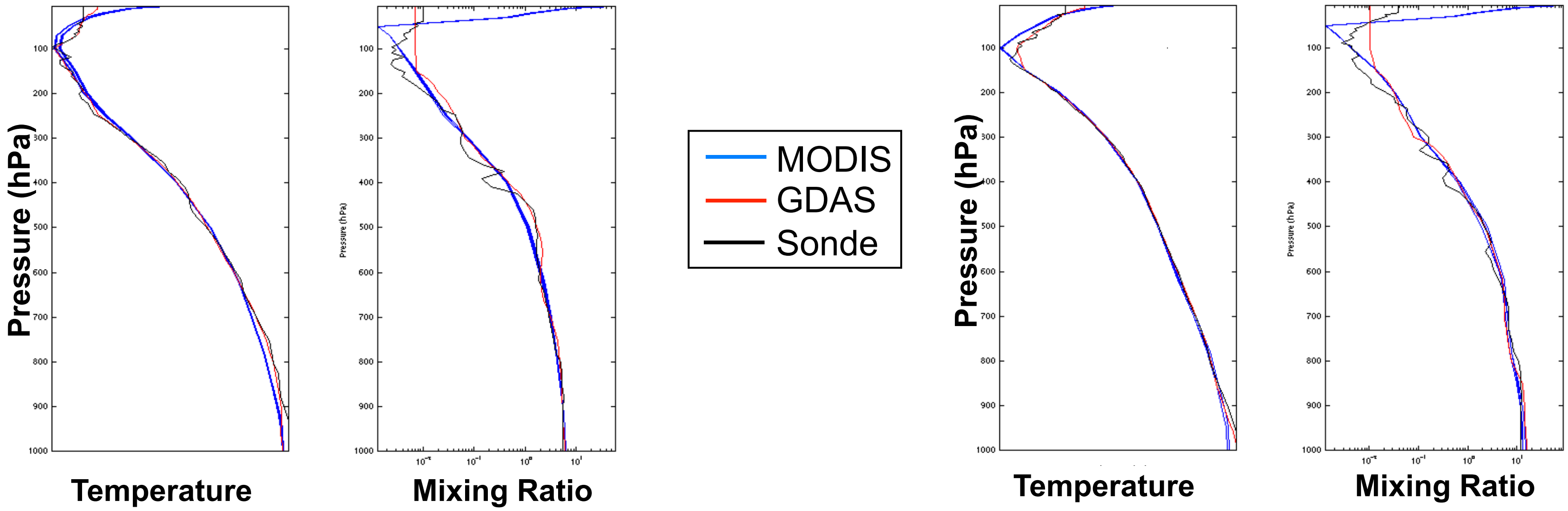
MODIS TPW

SSM/I f-14 TPW

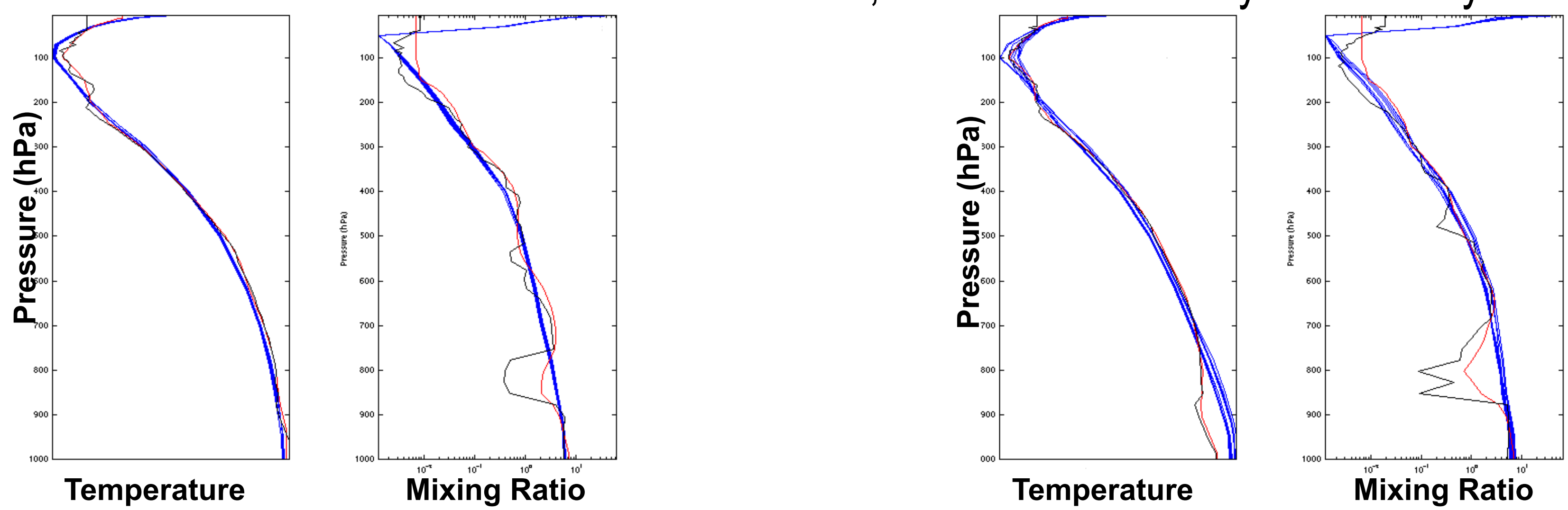
Ascending and descending passes were averaged



MODIS profiles agree well with radiosondes and NCEP-GDAS when the atmospheric temperature and moisture is fairly smooth and monotonic:



But not so well with smaller-scale features, such as isolated dry or moist layers:

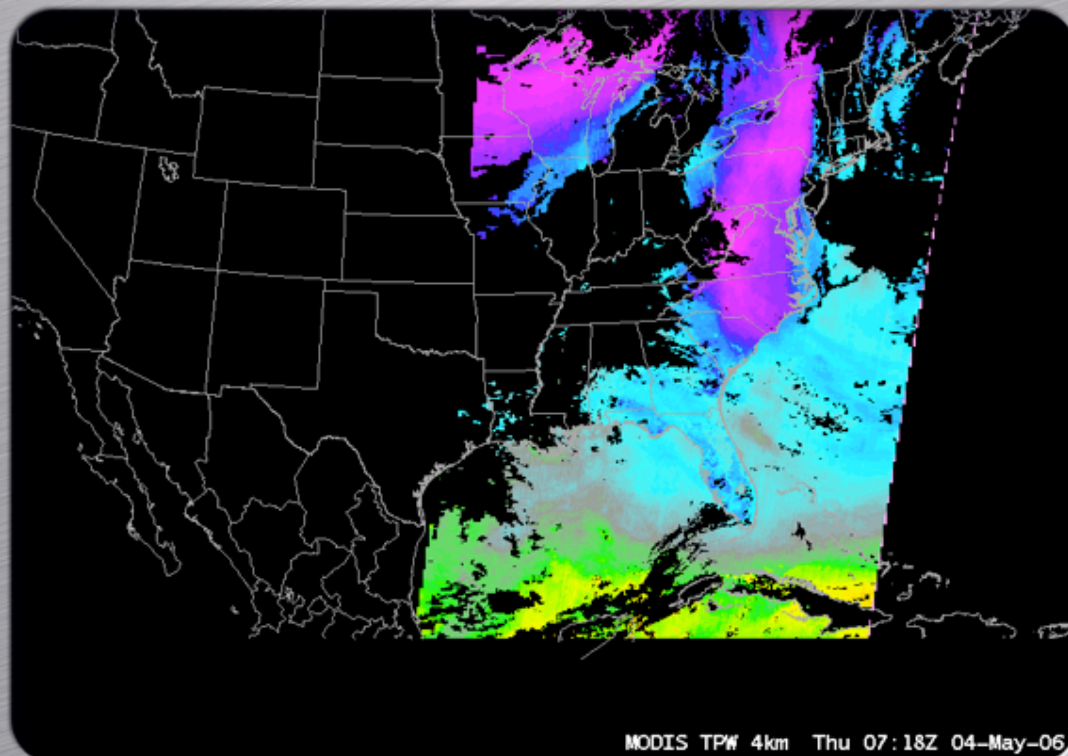


Applications

1. Meteorological
   - 3 dimensional view of atmosphere in clear sky
   - Dry Line
   - Humidity
   - Convection
   - Instability
   - Severe Weather
   - Precipitation Potential

2. Climatological
   - Global Circulations Monitoring
   - Greenhouse Gas Measure

MODIS Imagery in AWIPS



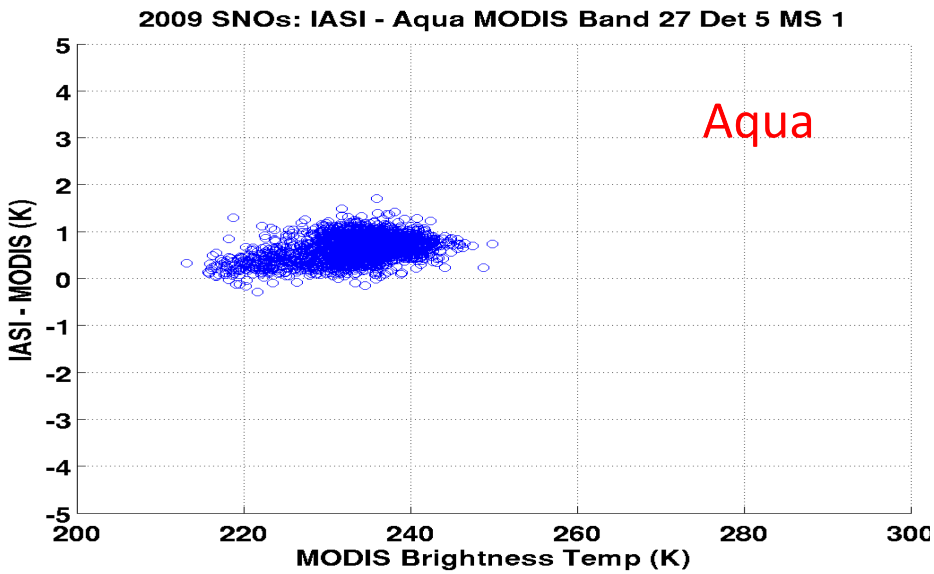
Total Precipitable Water

AREA FORECAST DISCUSSION
NATIONAL WEATHER SERVICE MILWAUKEE/SULLIVAN WI
409 AM CDT FRI JUL 6 2007

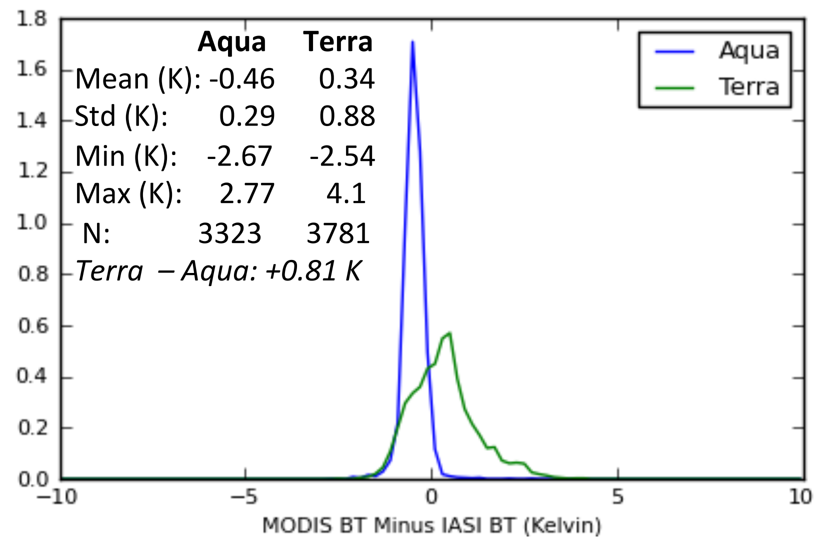
.DISCUSSION...FORECAST FOCUS ON POTENTIAL FOR ISOLATED TSTM ACTIVITY TODAY...THEN HOW HIGH WILL THE MERCURY SOAR THIS WEEKEND?

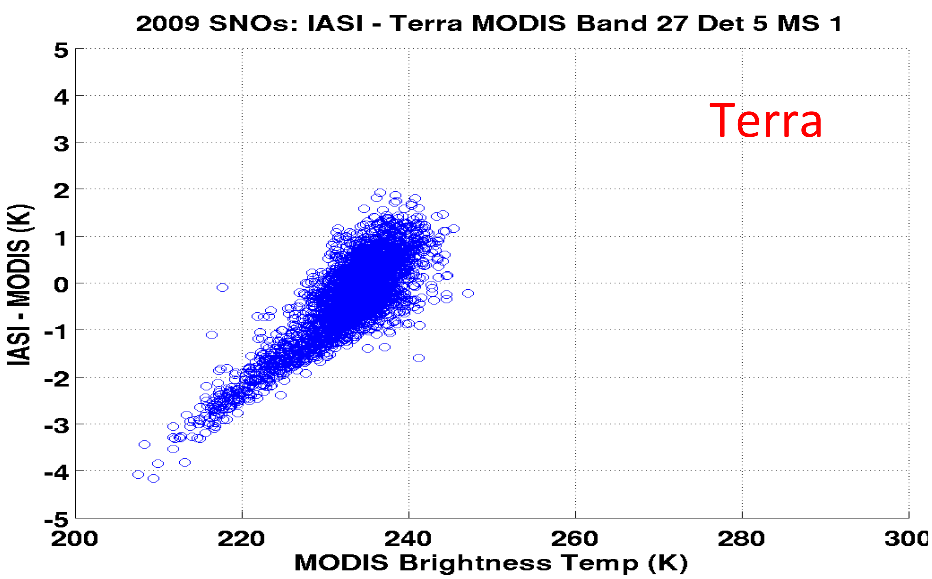
00Z 500/250MB ANALYSIS INDICATED UPPER TROUGHING OVER THE GREAT LAKES/ERN CONUS WITH IMPRESSIVE RIDGING OVER THE WRN CONUS. 500MB HEIGHTS IN THE 596-598DM RANGE FROM AZ NWD INTO WA/ID YIELDING BLISTERING TEMPS WELL INTO THE 100S IN MANY LOCALES ACROSS THE INTERMOUNTAIN WEST. THIS BLOB OF HEAT WILL GRADUALLY ADVECT EWD TOWARD INTO OUR AREA THIS WEEKEND...MORE ON THIS LATER. OTWR NWLY FLOW IN THE LOWER LEVELS OF THE AMS TRYING TO ADVECT SOME DRIER AIR INTO GREAT LAKES WITH GOES/MODIS TOTAL PRECIP WATER PRODUCTS SHOWING PWS DIPPING AOB 0.75 INCHES...WITH SFC TDS GNRLY IN THE 50S UPSTREAM. IR IMAGERY EARLY THIS MORNING SHOWING CLEAR SKIES OVER ALL OF SRN WI.

SRF Investigation using IASI – MODIS BT Comparison for 2009
by C. Moeller, G. Quinn and D. Tobin



Band 27





References

Seemann, S., J. Li, W. P. Menzel, and L. Gumley, 2003: Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances. Journal of Applied Meteorology and Climatology, 42, 1072-1091.

Aniko Kern, Judit Bartholy, Eva E. Borbas, Zoltan Barcza, Rita Pongracz, Csaba Ferencz, 2008: Estimation of vertically integrated water vapor in Hungary using MODIS imagery. Advances in Space Research, 41, 1933-1945.

S. W. Seemann , E. E. Borbas , R. O. Knuteson , G. R. Stephenson and H.-L. Huang, 2008: Development of a global infrared land surface emissivity database for application to clear sky sounding retrievals from multispectral satellite radiance measurements. Journal of Applied Meteorology, vol. 47, p. 108.