RTE

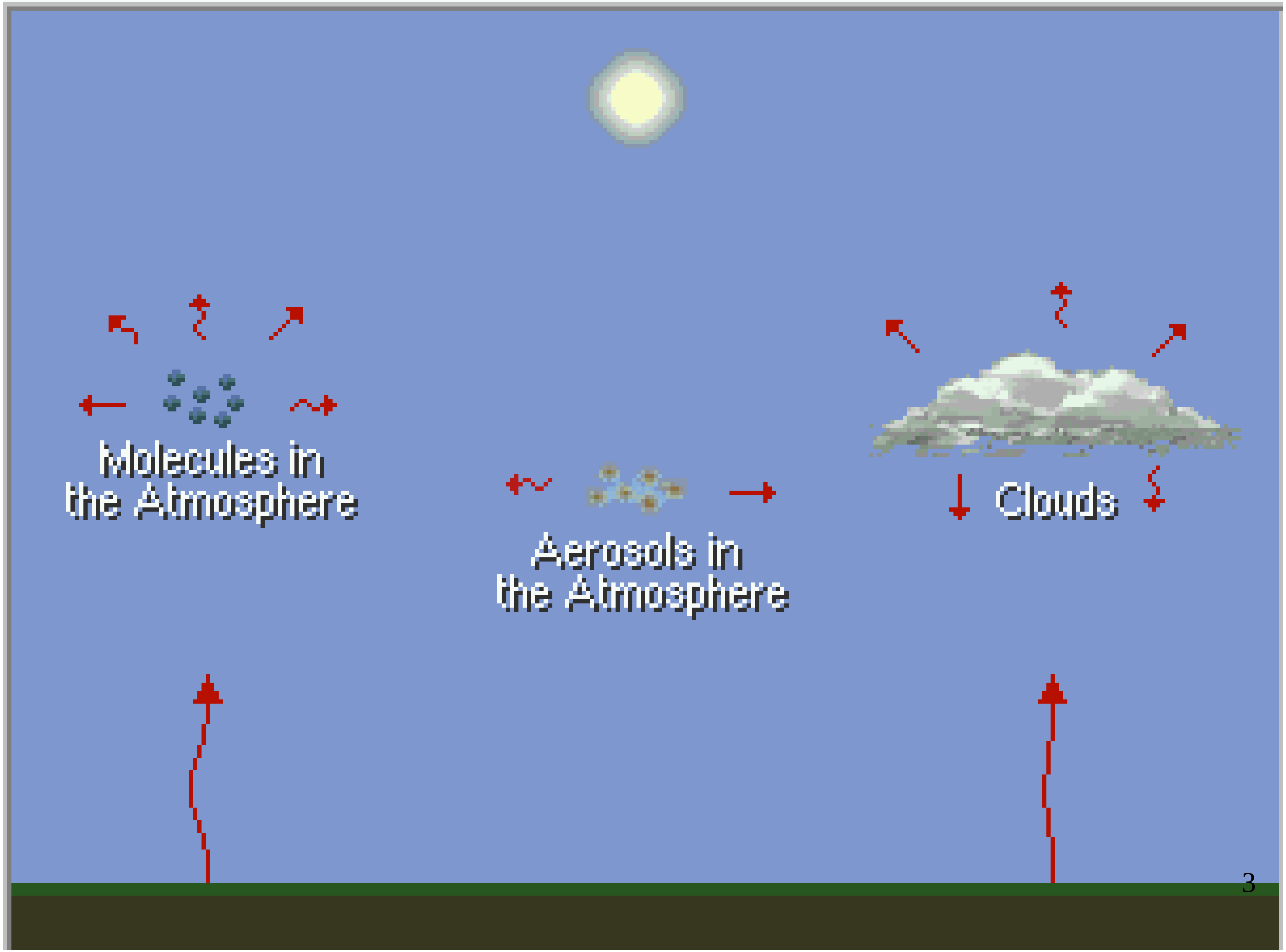
Lectures in Madison

26 Mar 2013

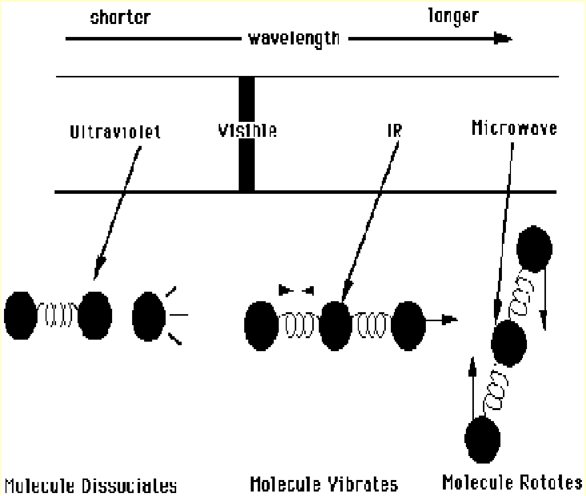
Paul Menzel
UW/CIMSS/AOS

Relevant Material in Applications of Meteorological Satellites

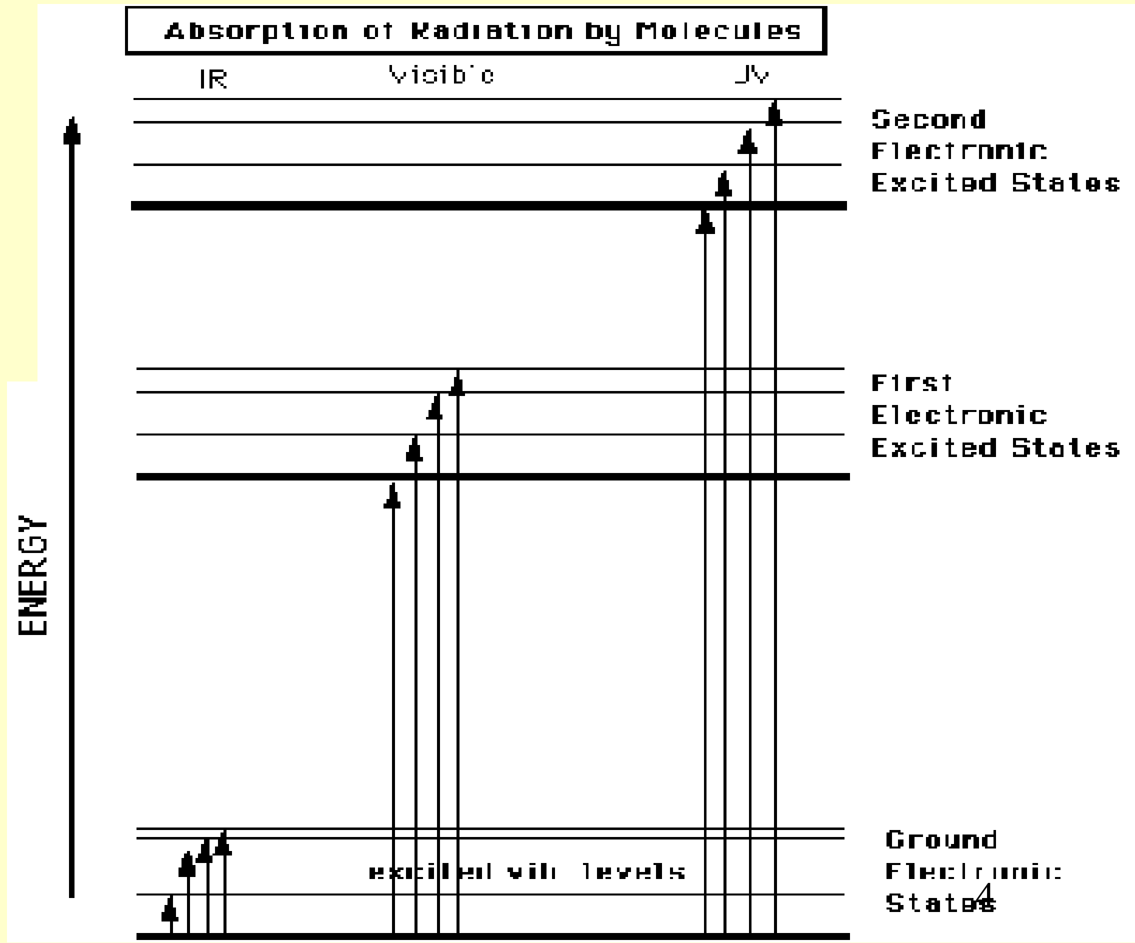
Re-emission of Infrared Radiation



Molecular Responses to Radiation



Molecular absorption of IR by vibrational and rotational excitation



CO2, H2O, and O3

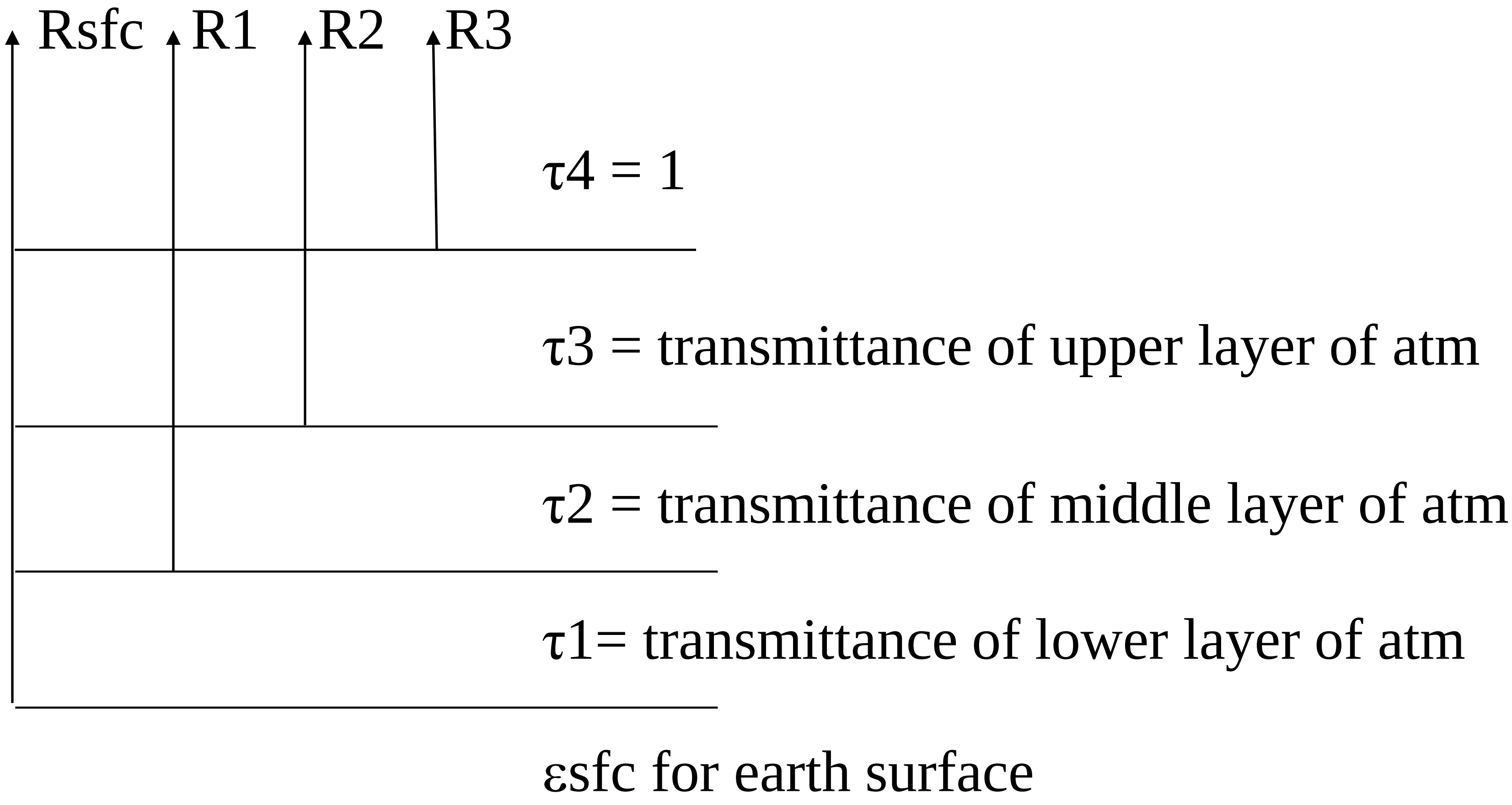
Radiative Transfer Equation

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.

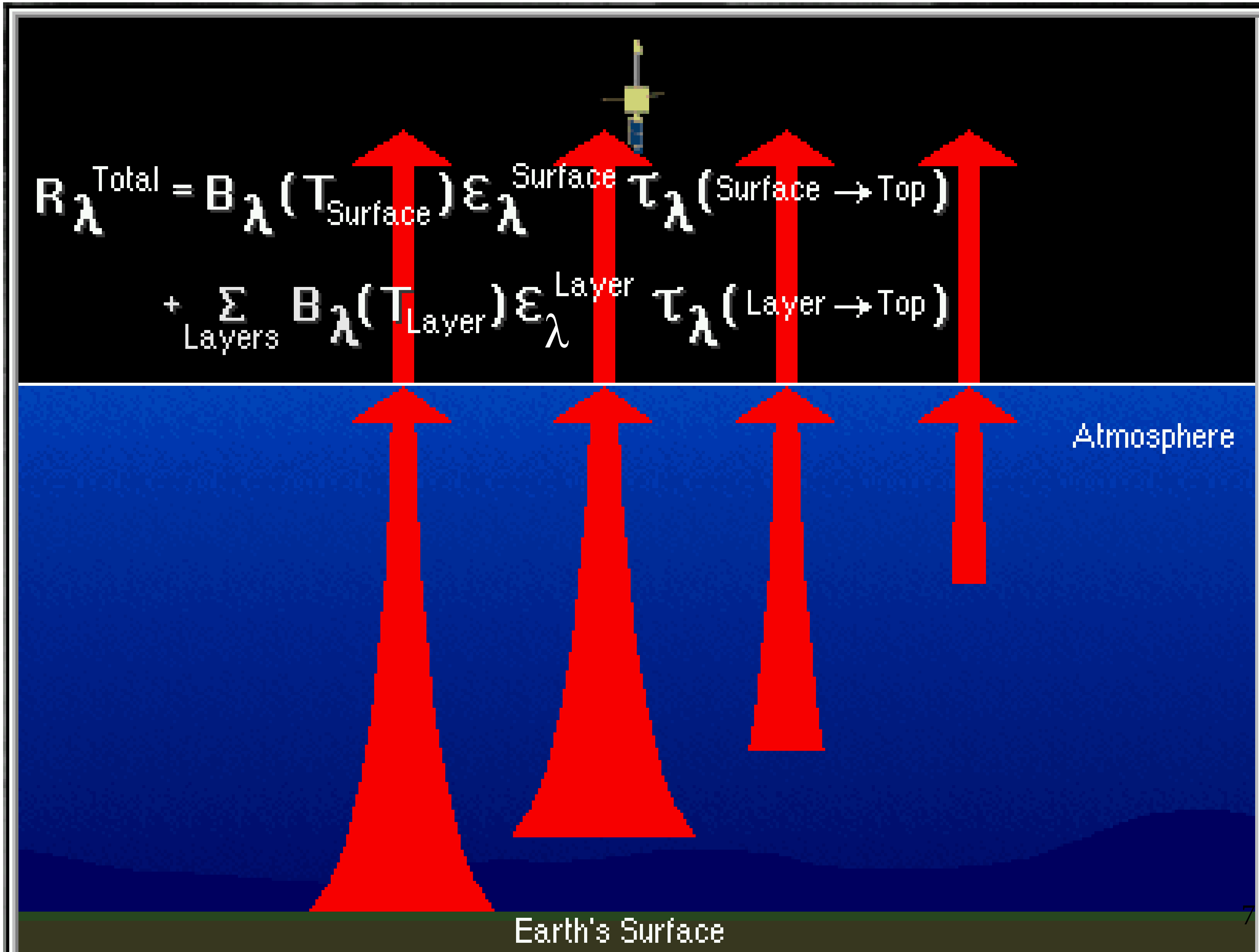
Satellite observation comes from the sfc and the layers in the atm



recalling that εi = 1- τi for each layer, then

$$R_{obs} = \varepsilon_{sfc} B_{sfc} \tau_1 \tau_2 \tau_3 + (1-\tau_1) B_1 \tau_2 \tau_3 + (1-\tau_2) B_2 \tau_3 + (1-\tau_3) B_3$$

Radiative Transfer through the Atmosphere



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

The emission of an infinitesimal layer of the atmosphere at pressure p is equal to the absorption (1 - transmission). So,

$$\varepsilon_\lambda(layer)\, \tau_\lambda(layer\ to\ top) = [1 - \tau_\lambda(layer)]\, \tau_\lambda(layer\ to\ top)$$

Since transmission is multiplicative

$$\tau_\lambda(layer\ to\ top) - \tau_\lambda(layer)\, \tau_\lambda(layer\ to\ top) = -\Delta\tau_\lambda(layer\ to\ top)$$

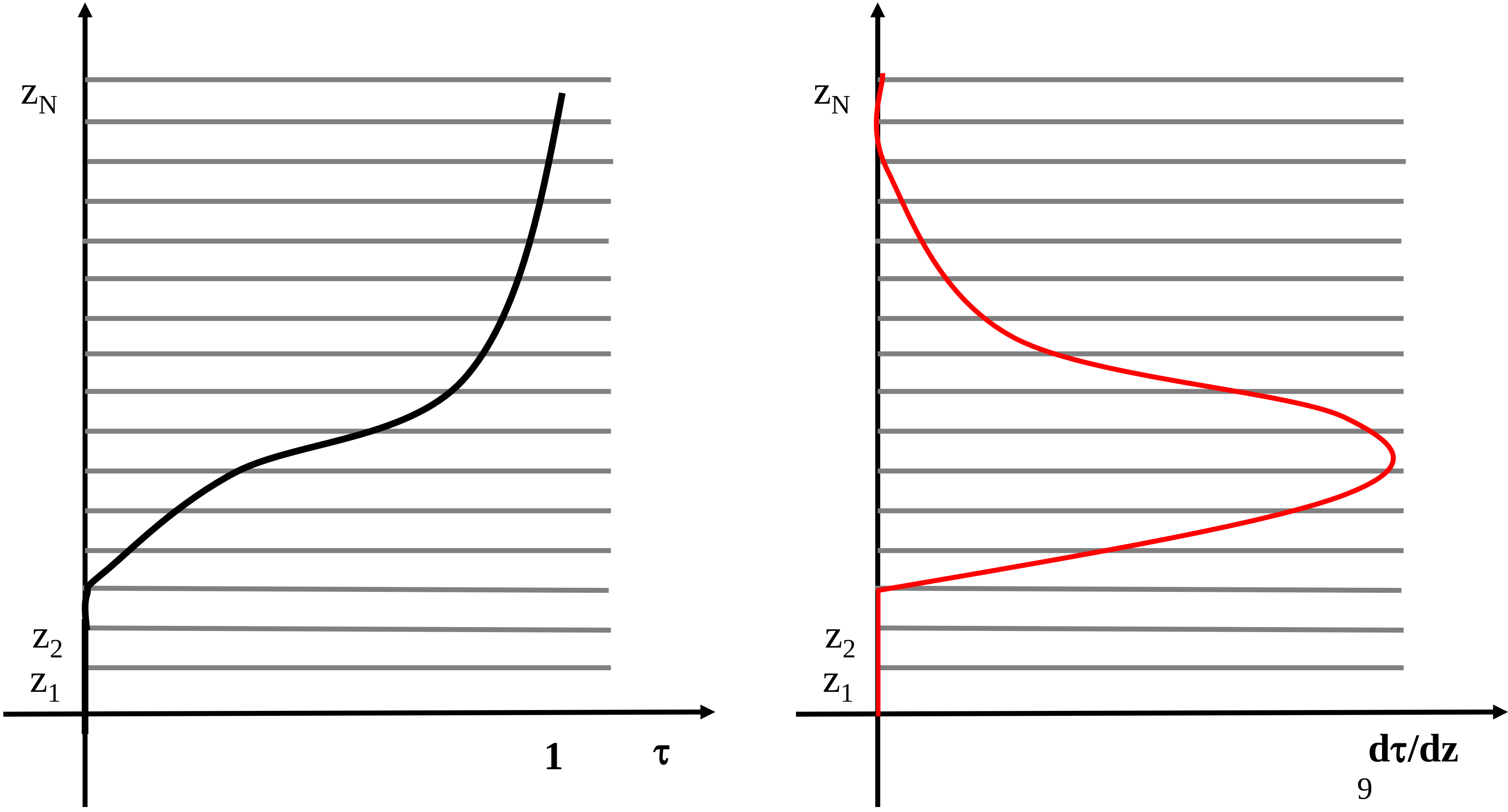
So we can write

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

which when written in integral form reads

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

Weighting Functions



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

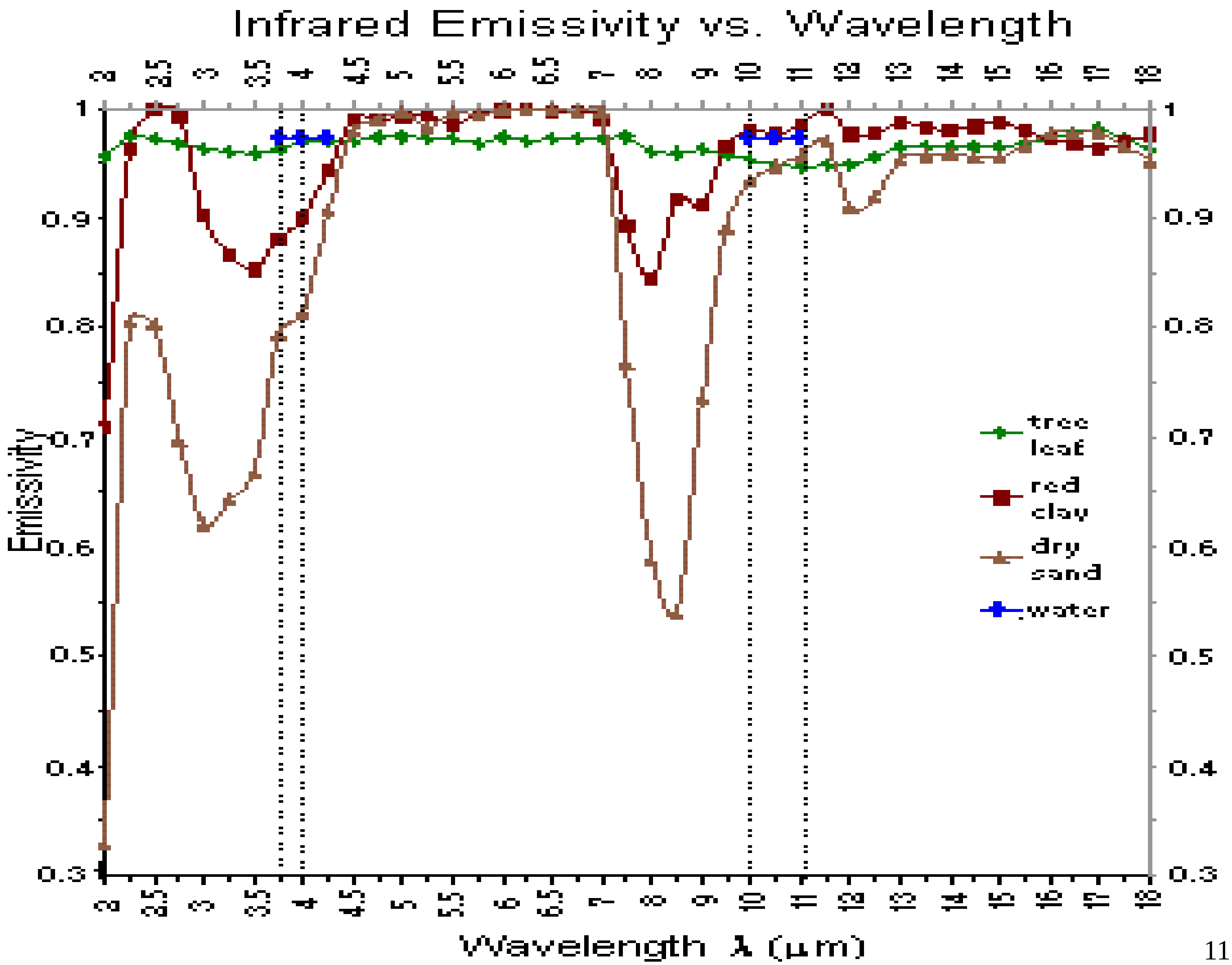
$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_s)\, \tau_\lambda(p_s) + \int_{p_s}^{o} B_\lambda(T(p))\, F_\lambda(p)\, [d\tau_\lambda(p)/\, dp]\, dp$$

where

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

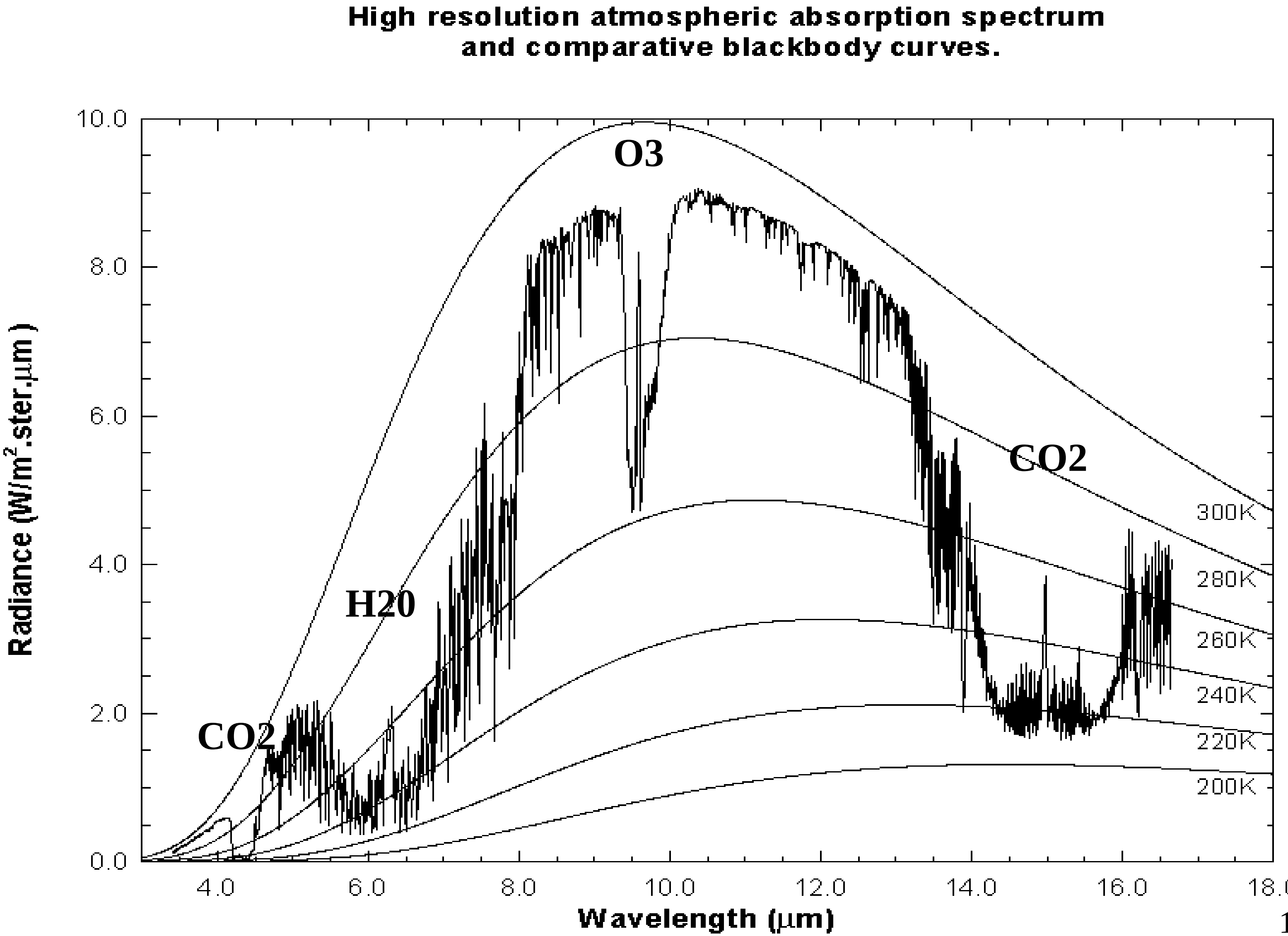
The first term is the spectral radiance emitted by the surface and attenuated by the atmosphere, often called the boundary term and the second term is the spectral radiance emitted to space by the atmosphere directly or by reflection from the earth surface.

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.

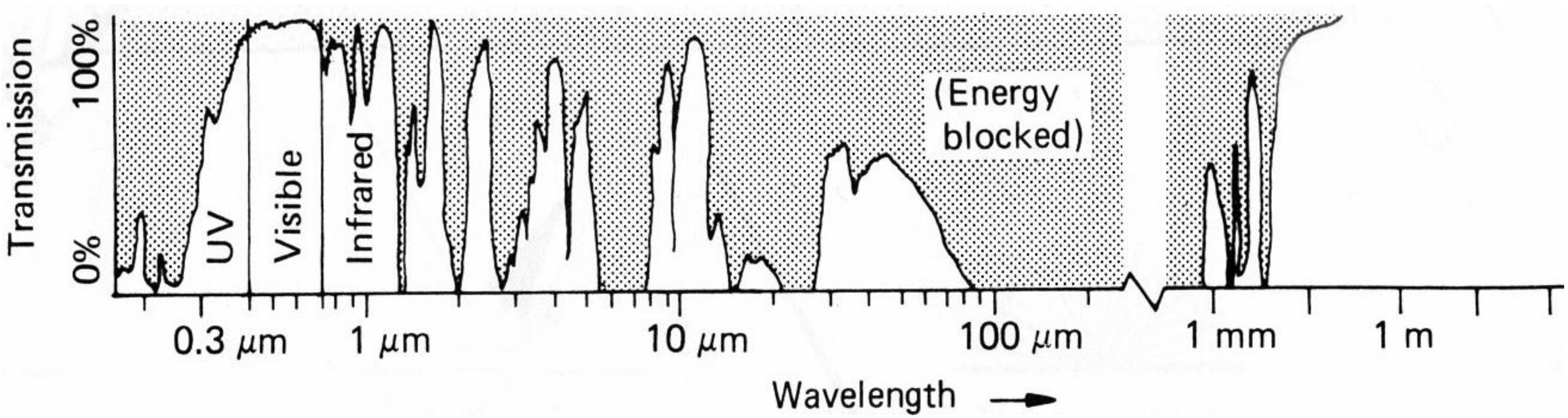


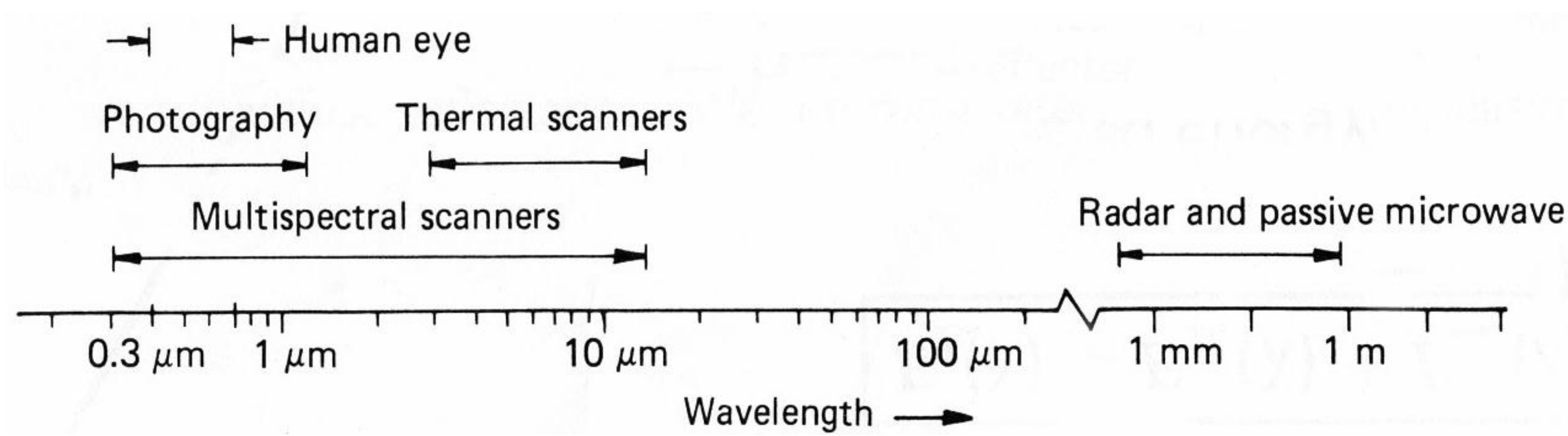
Infrared Emissivity vs. Wavelength
Emissivity
Wavelength λ (μm)
tree leaf
red clay
dry sand
water

Earth emitted spectra overlaid on Planck function envelopes

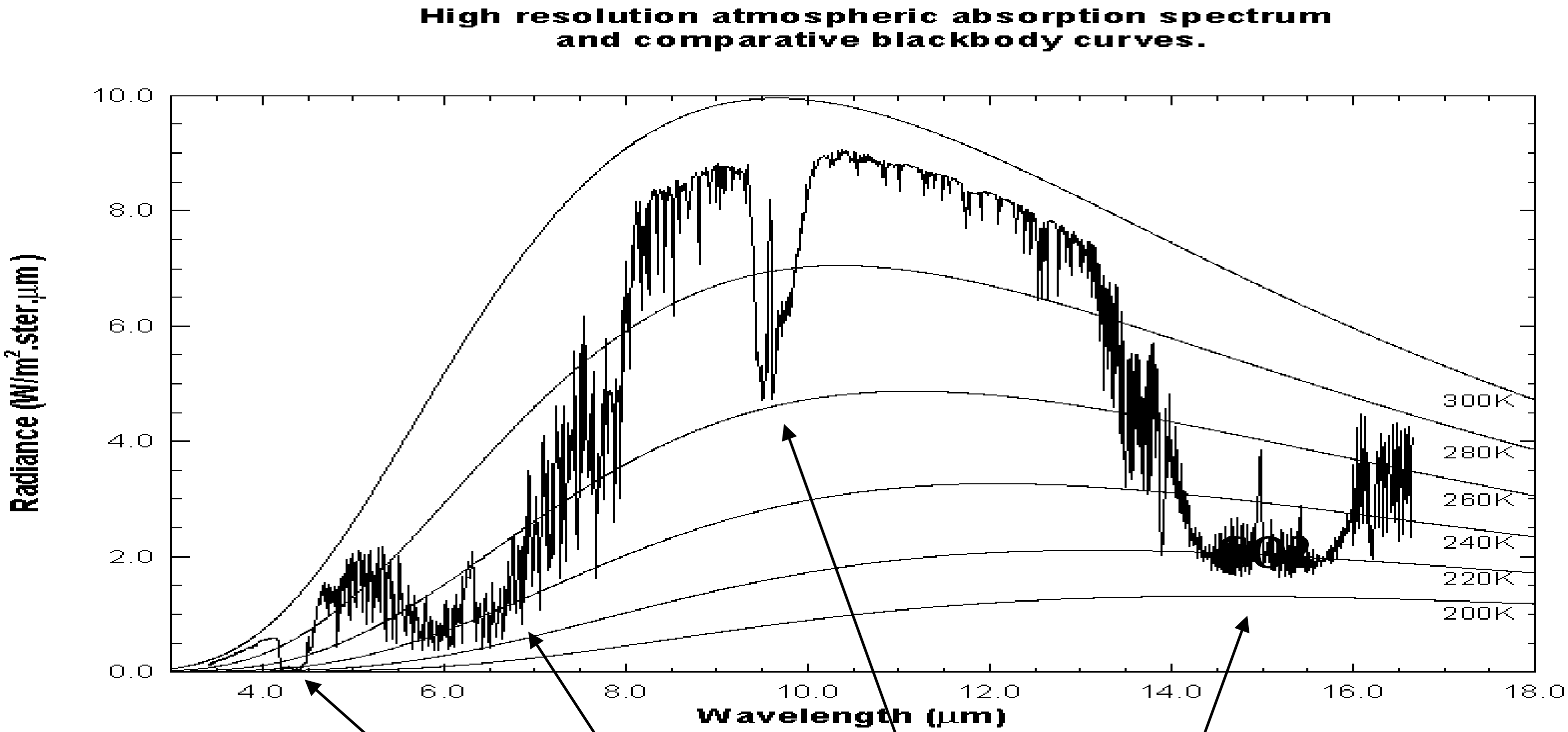


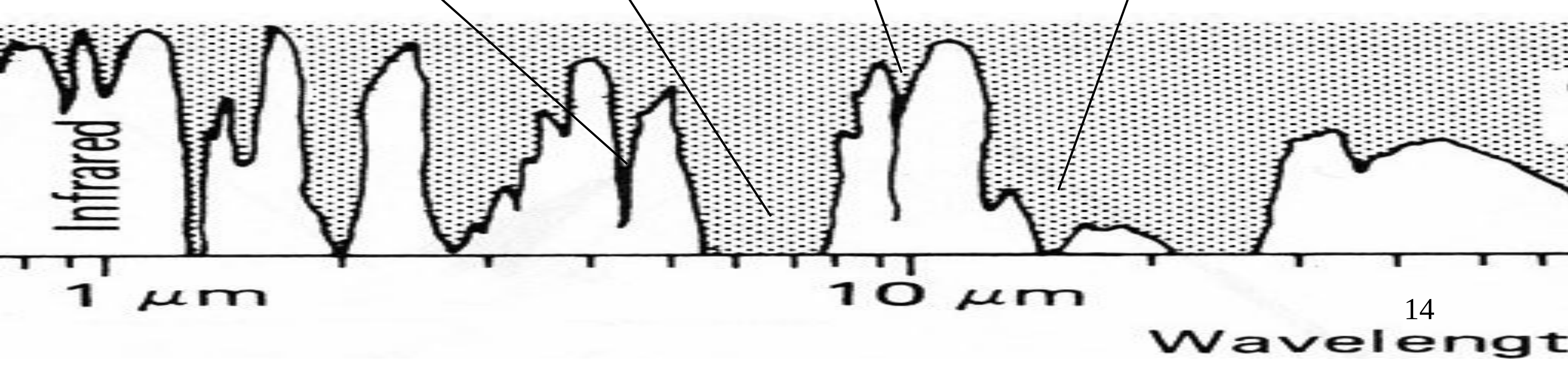
Spectral Characteristics of Atmospheric Transmission and Sensing Systems

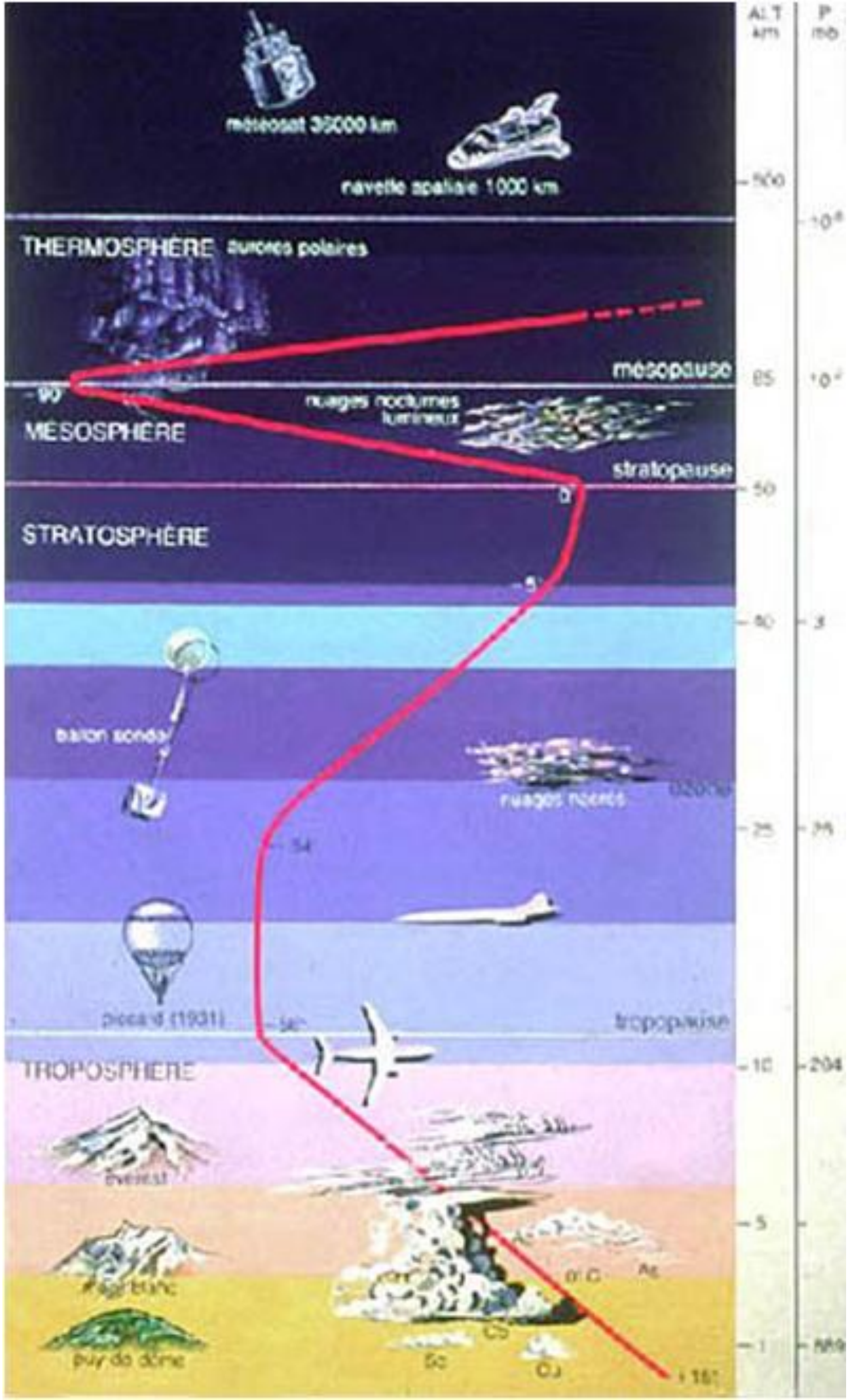


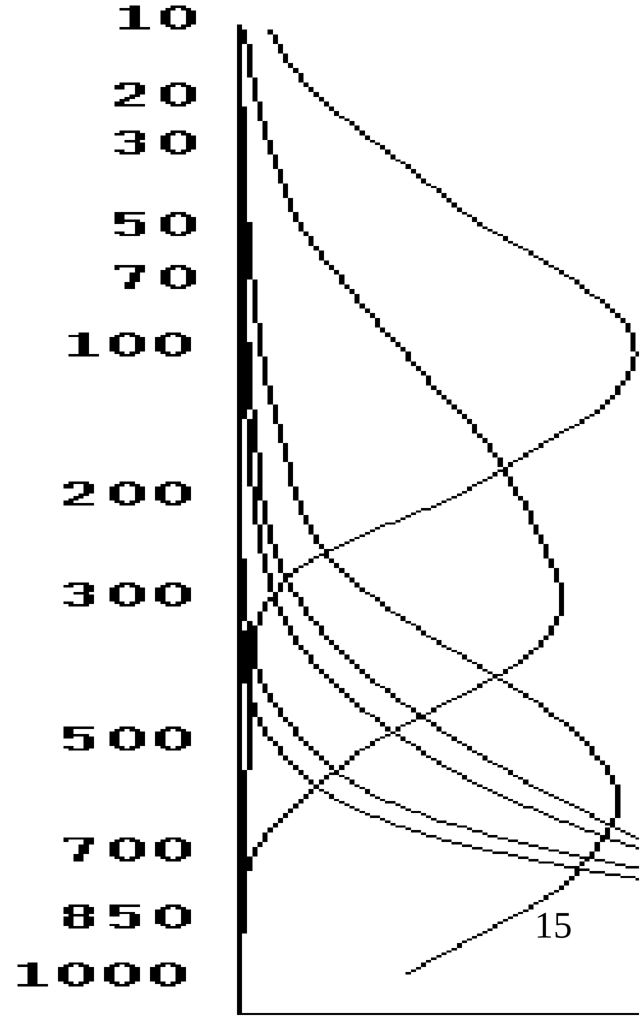


Earth emitted spectra overlaid on Planck function envelopes

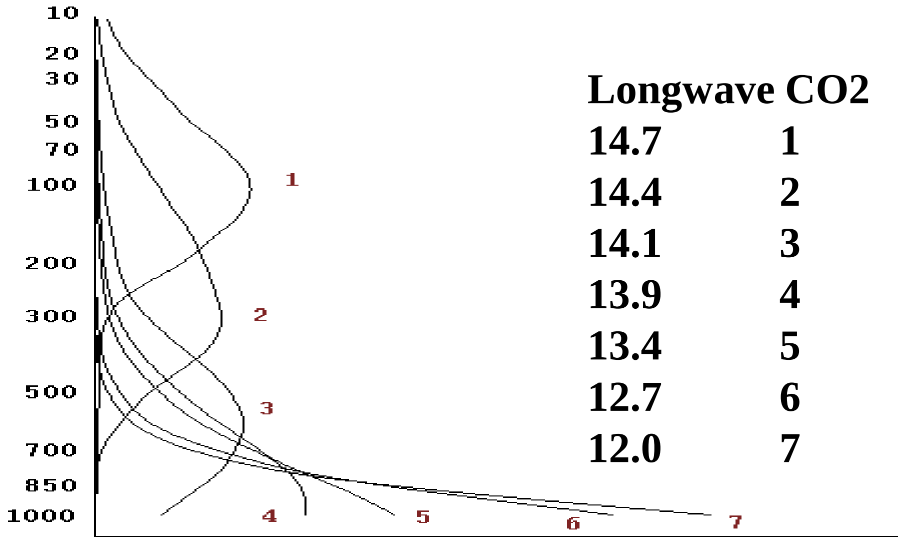




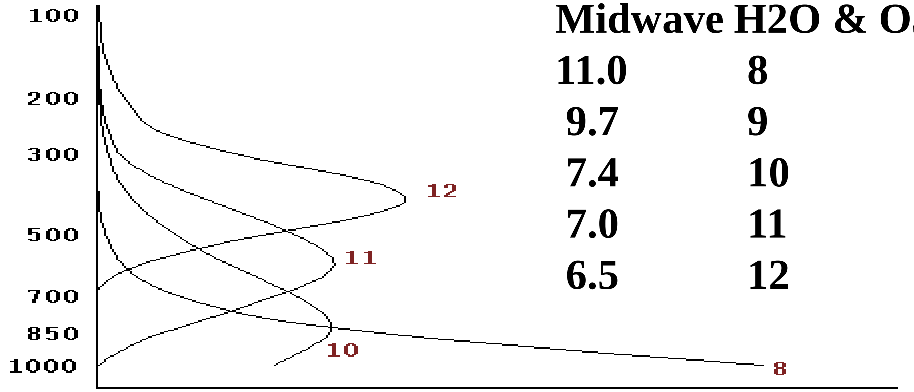

ALT km
P mb
THERMOSPHÈRE
aurores polaires
mésopause
MÉSOSPHÈRE
nuages nocturnes lumineux
stratopause
STRATOSPHÈRE
ballon sonde
tropopause
TROPOSPHÈRE
Everest
puy de dôme


10
20
30
50
70
100
200
300
500
700
850
1000

Weighting Functions



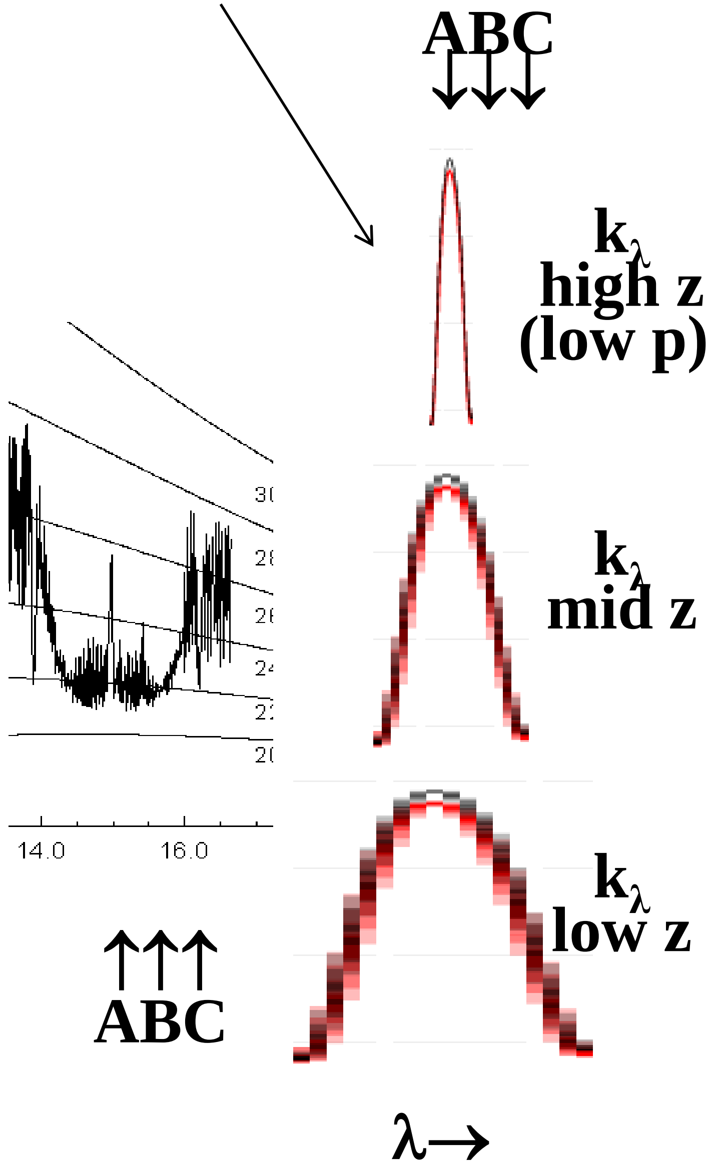
Longwave CO_2			
14.7	1	680	CO_2, strat temp
14.4	2	696	CO_2, strat temp
14.1	3	711	CO_2, upper trop temp
13.9	4	733	CO_2, mid trop temp
13.4	5	748	CO_2, lower trop temp
12.7	6	790	H_2O, lower trop moisture
12.0	7	832	H_2O, dirty window

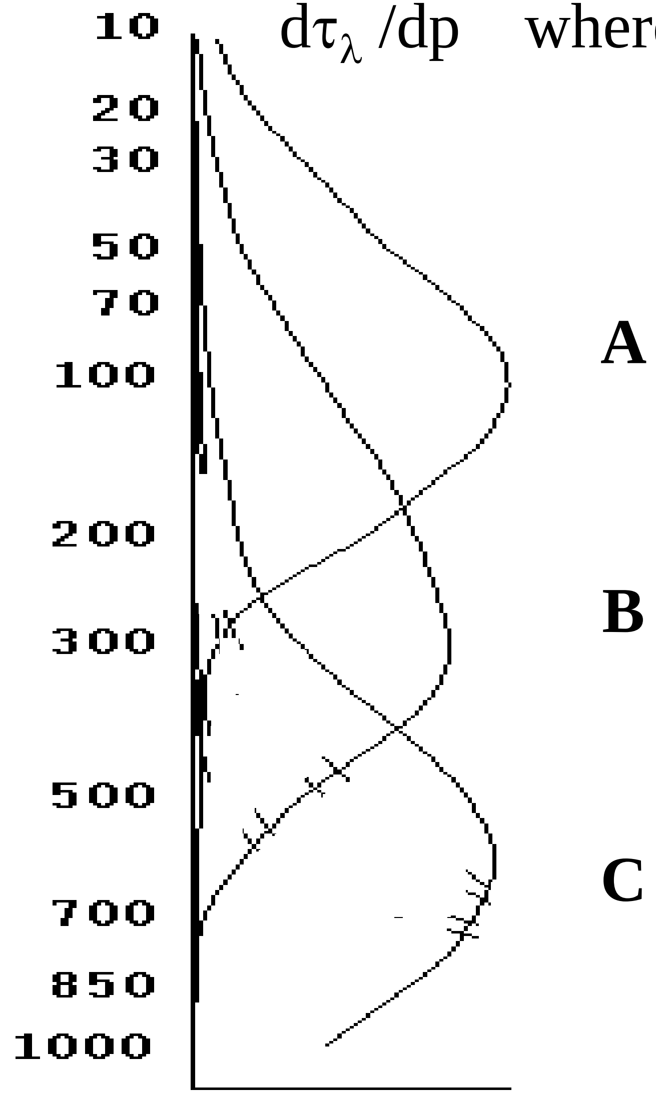


Midwave H_2O & O_3			
11.0	8	907	window
9.7	9	1030	O_3, strat ozone
7.4	10	1345	H_2O, lower mid trop moisture
7.0	11	1425	H_2O, mid trop moisture
6.5	12	1535	H_2O, upper trop moisture

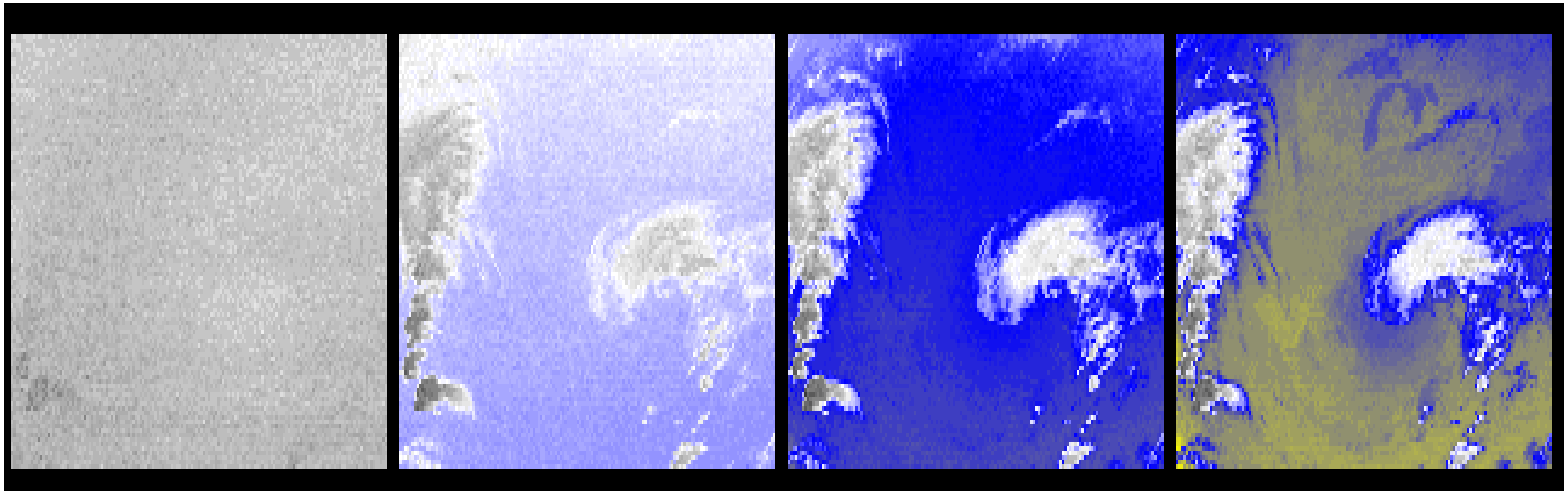
line broadening with pressure helps to explain weighting functions

$d\tau_\lambda / dp$ where $\tau_\lambda = e^{-k_\lambda u}$





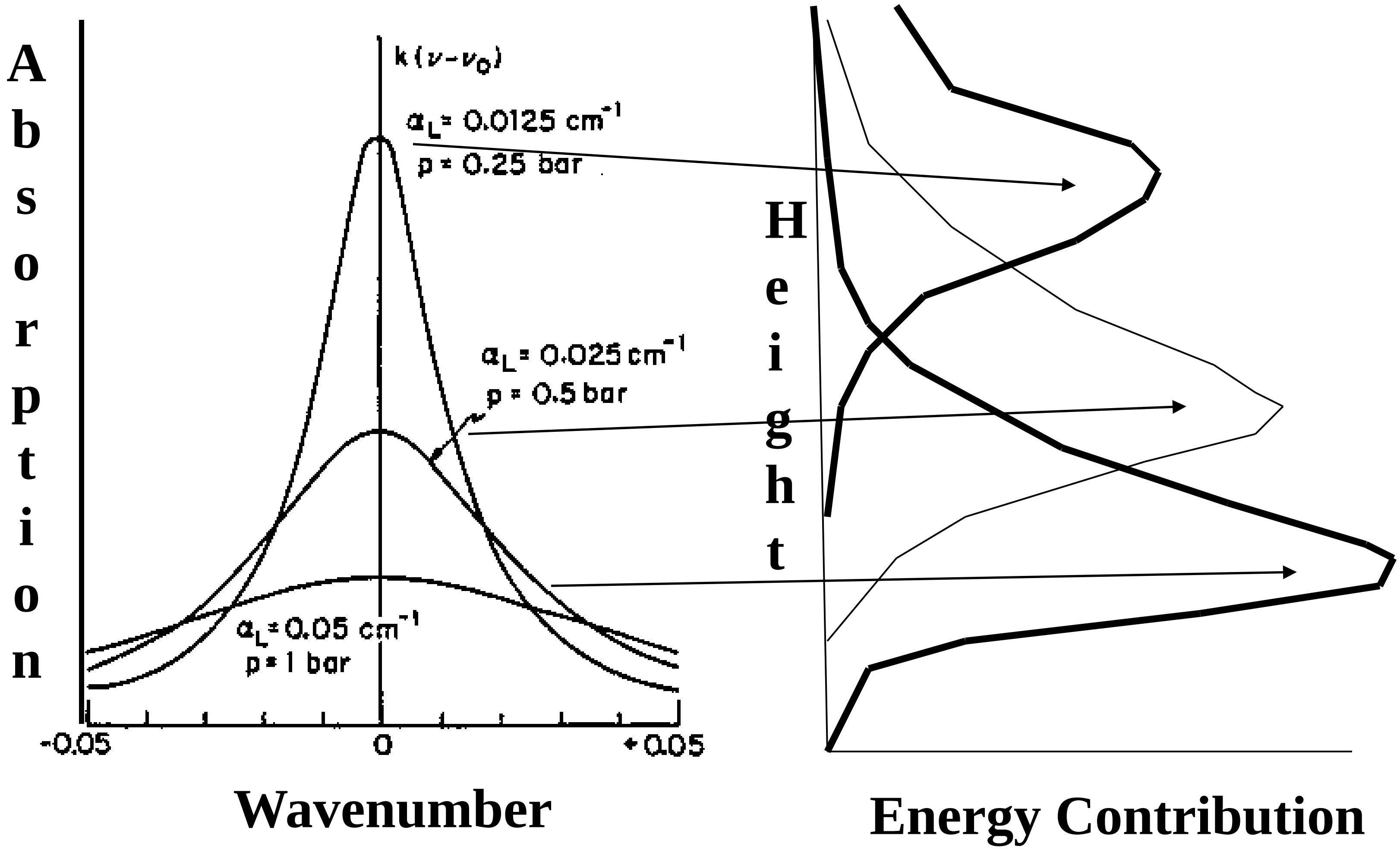
CO_2 channels see to different levels in the atmosphere



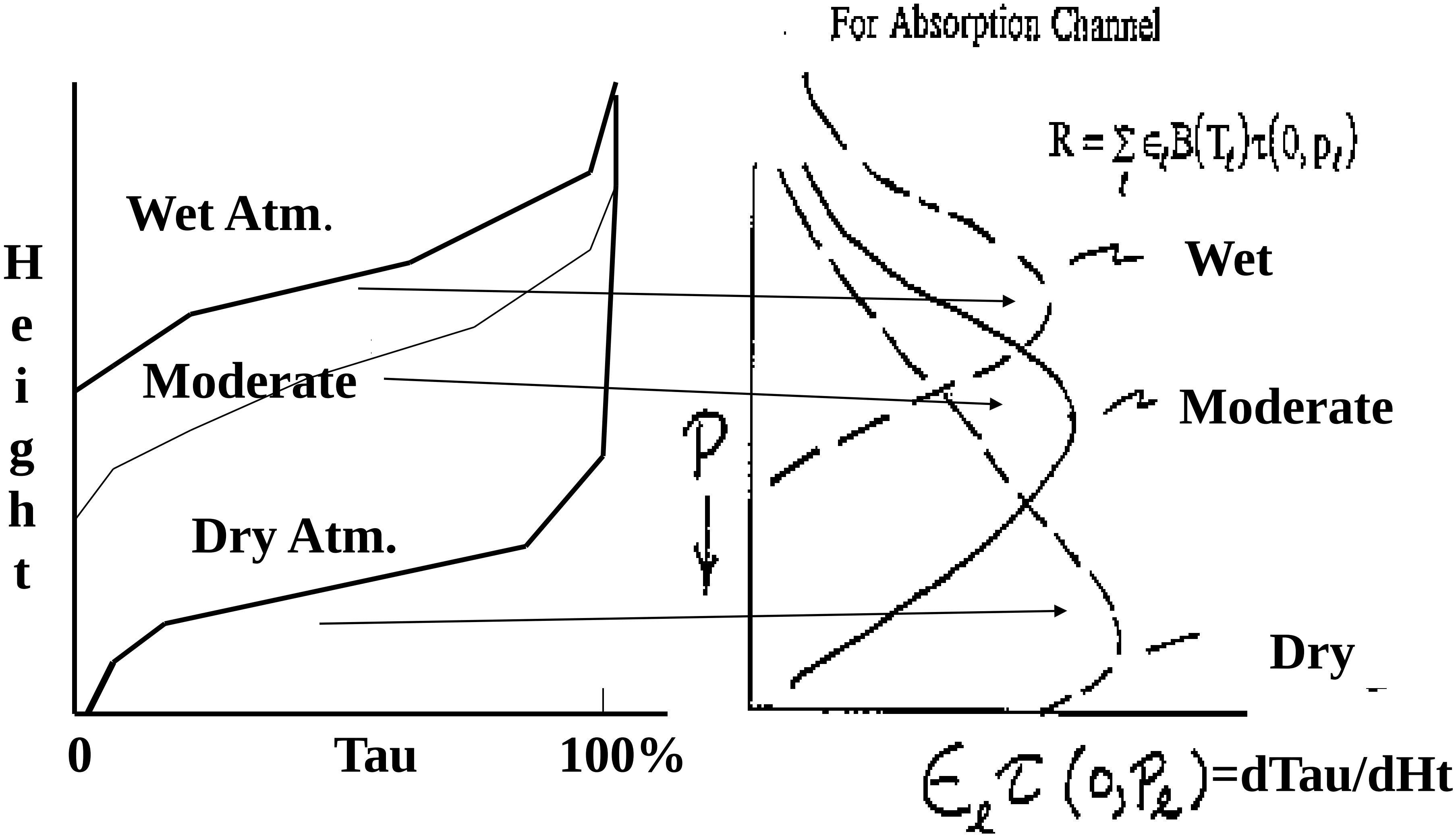
14.2 um 13.9 um 13.6 um 13.3 um

line broadening with pressure helps to explain weighting functions

$$\tau_\nu (z \to \infty) = e^{-k_\nu u(z)}$$

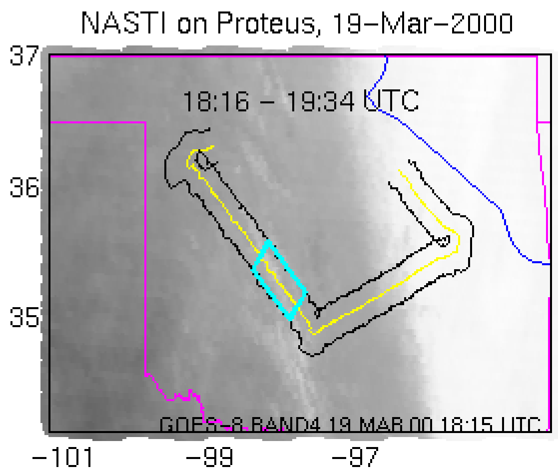


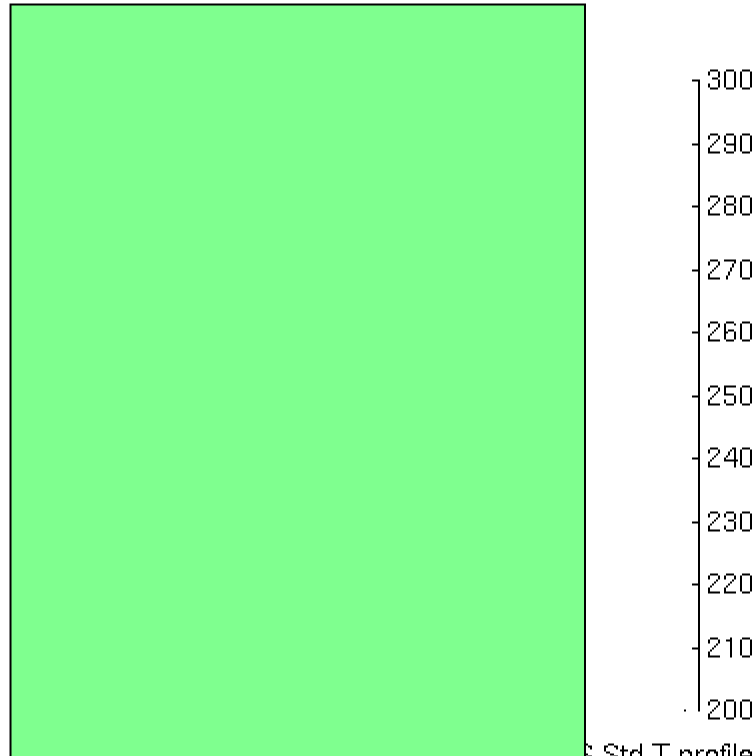
For a given water vapor spectral channel the weighting function depends on the amount of water vapor in the atmospheric column

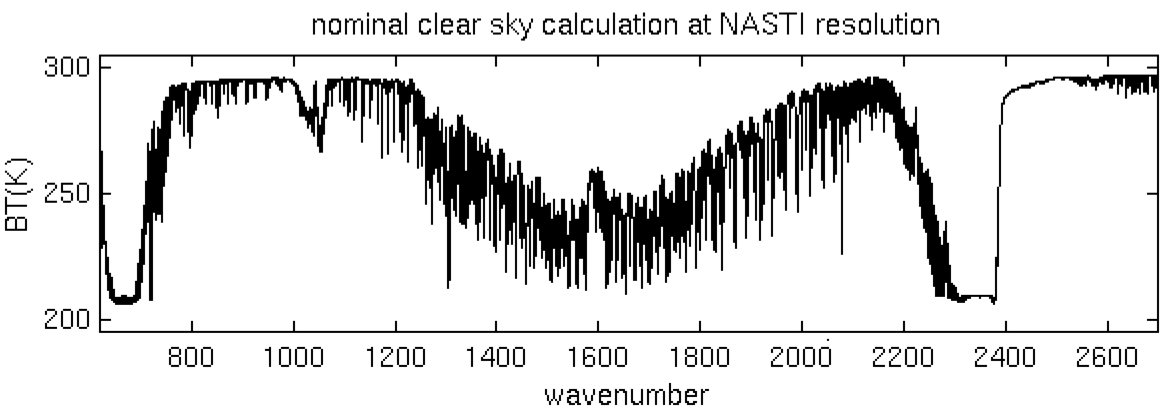


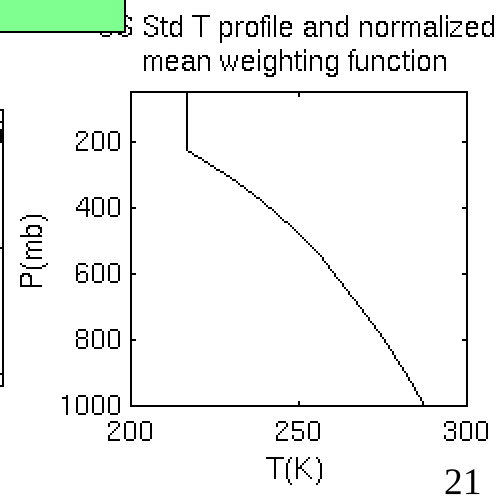
CO2 is about the same everywhere, the weighting function for a given CO2 spectral channel is the same everywhere

Improvements with Hyperspectral IR Data

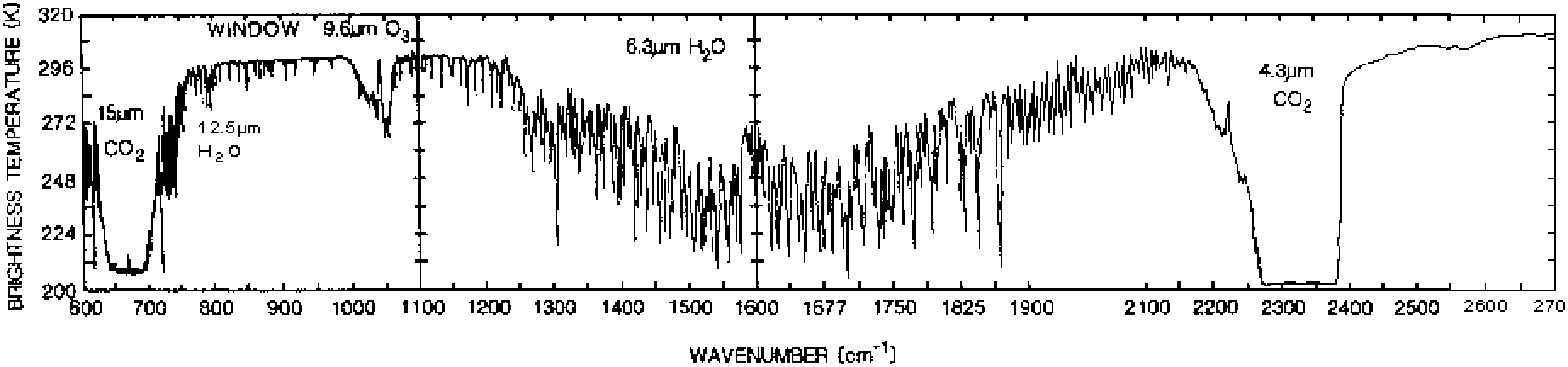


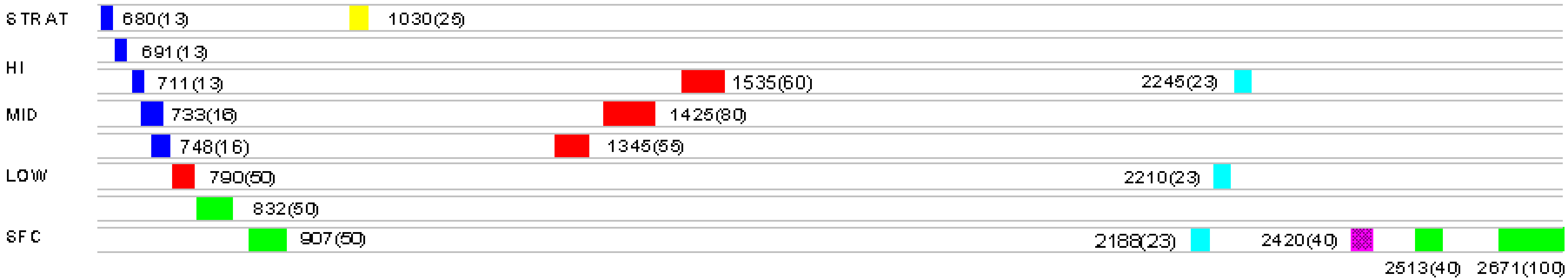






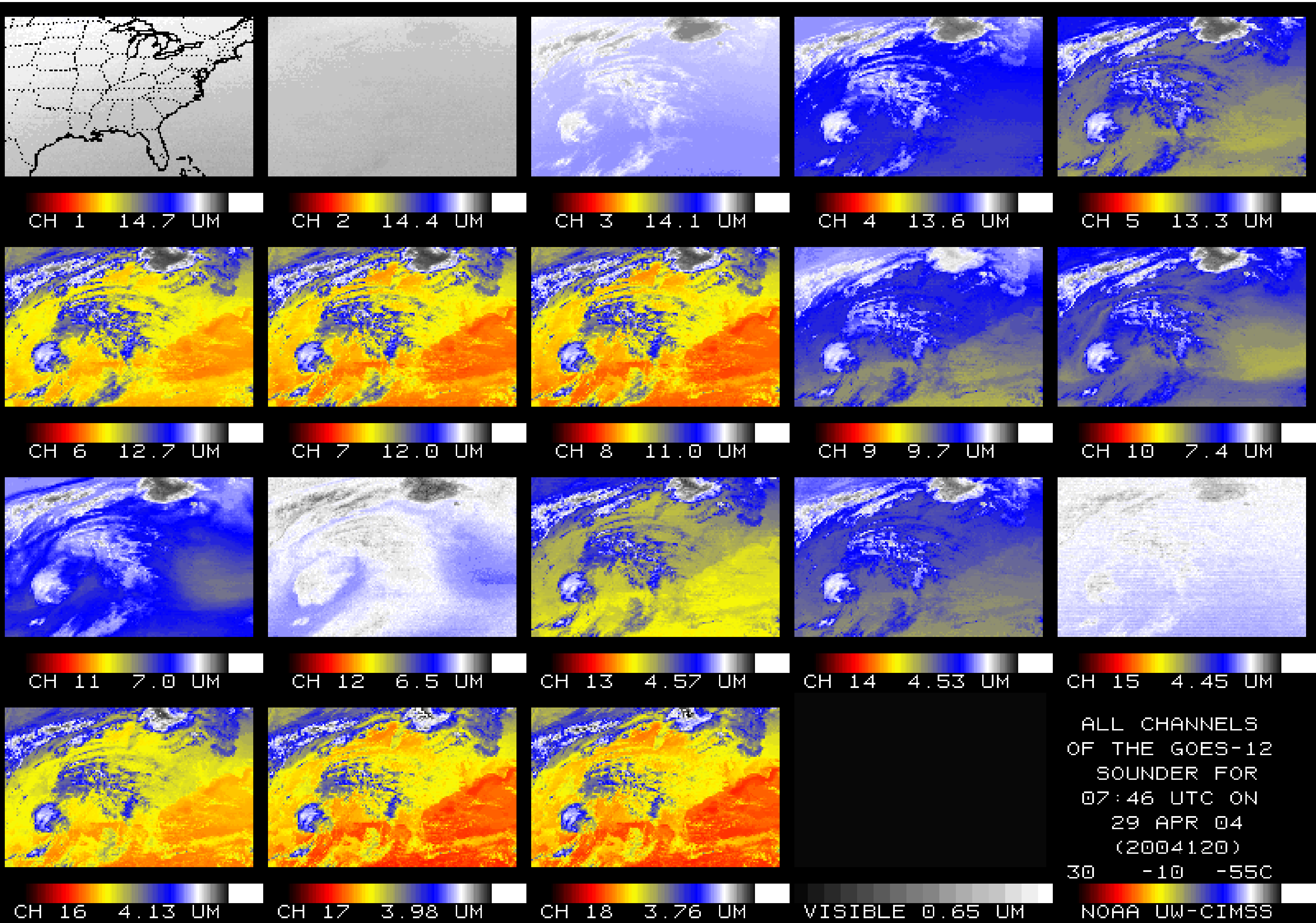
EARTH EMITTED SPECTRA





GOES-I SOUNDER SPECTRAL BANDS

GOES-12 Sounder – Brightness Temperature (Radiances) – 12 bands



Characteristics of RTE

* Radiance arises from deep and overlapping layers

* The radiance observations are not independent

* There is no unique relation between the spectrum of the outgoing radiance and T(p) or Q(p)

* T(p) is buried in an exponent in the denominator in the integral

* Q(p) is implicit in the transmittance

* Boundary conditions are necessary for a solution; the better the first guess the better the final solution

Profile Retrieval from Sounder Radiances

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

I1, I2, I3, ... , In are measured with the sounder

P(sfc) and T(sfc) come from ground based conventional observations

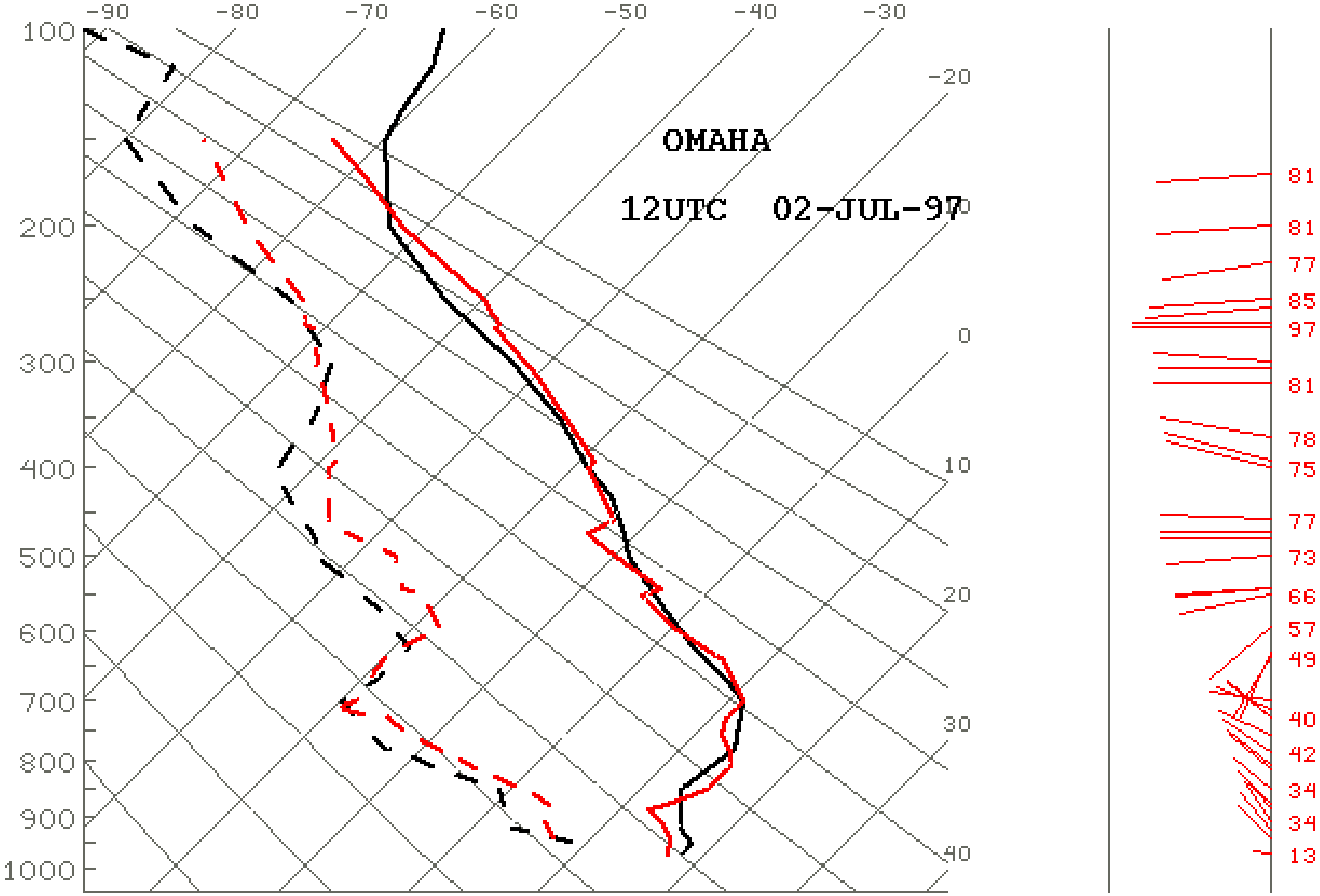
$\tau_\lambda(p)$ are calculated with physics models (using for CO_2 and O_3)

$\varepsilon_\lambda^{sfc}$ is estimated from a priori information (or regression guess)

First guess solution is inferred from (1) in situ radiosonde reports, (2) model prediction, or (3) blending of (1) and (2)

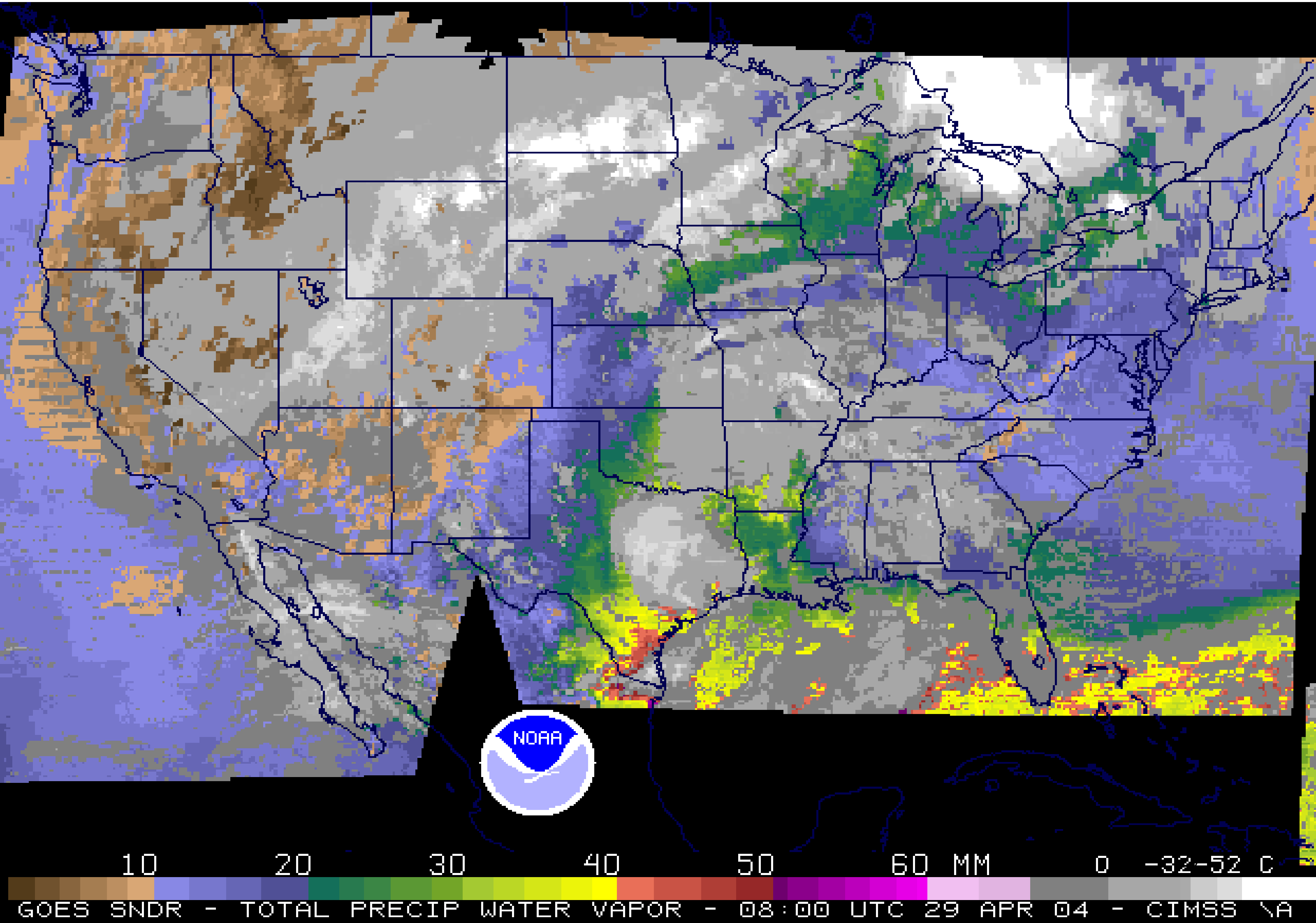
Profile retrieval from perturbing guess to match measured sounder radiances

Example GOES Sounding

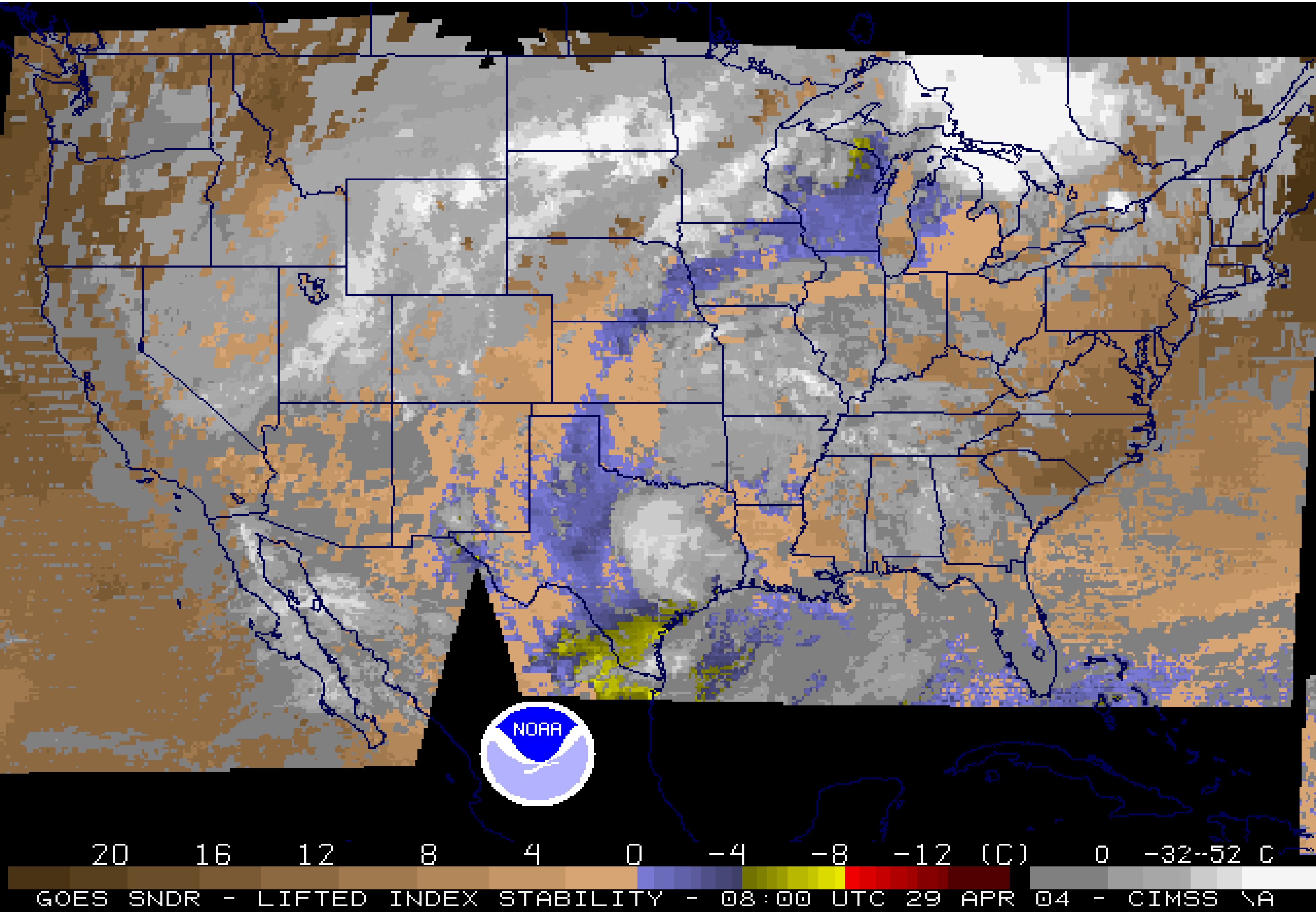


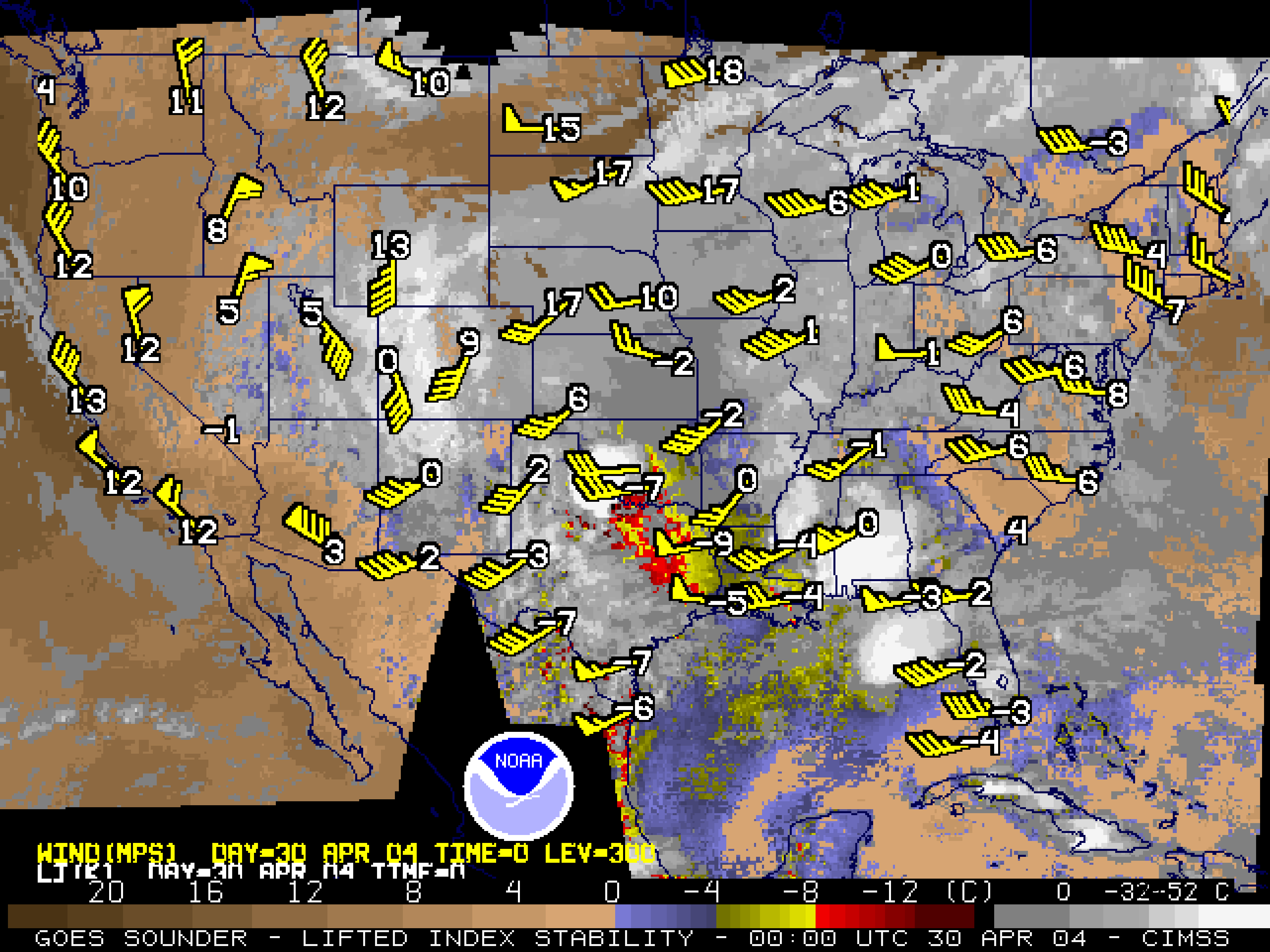
GMT	ID	TOTAL	EQUIP	FMAX	CVT	L.I.	KINX	PW	
021153	267	30				11	-10	12	GOES-8 RTVL
021200	72558	36				10	-4	14	RAOB

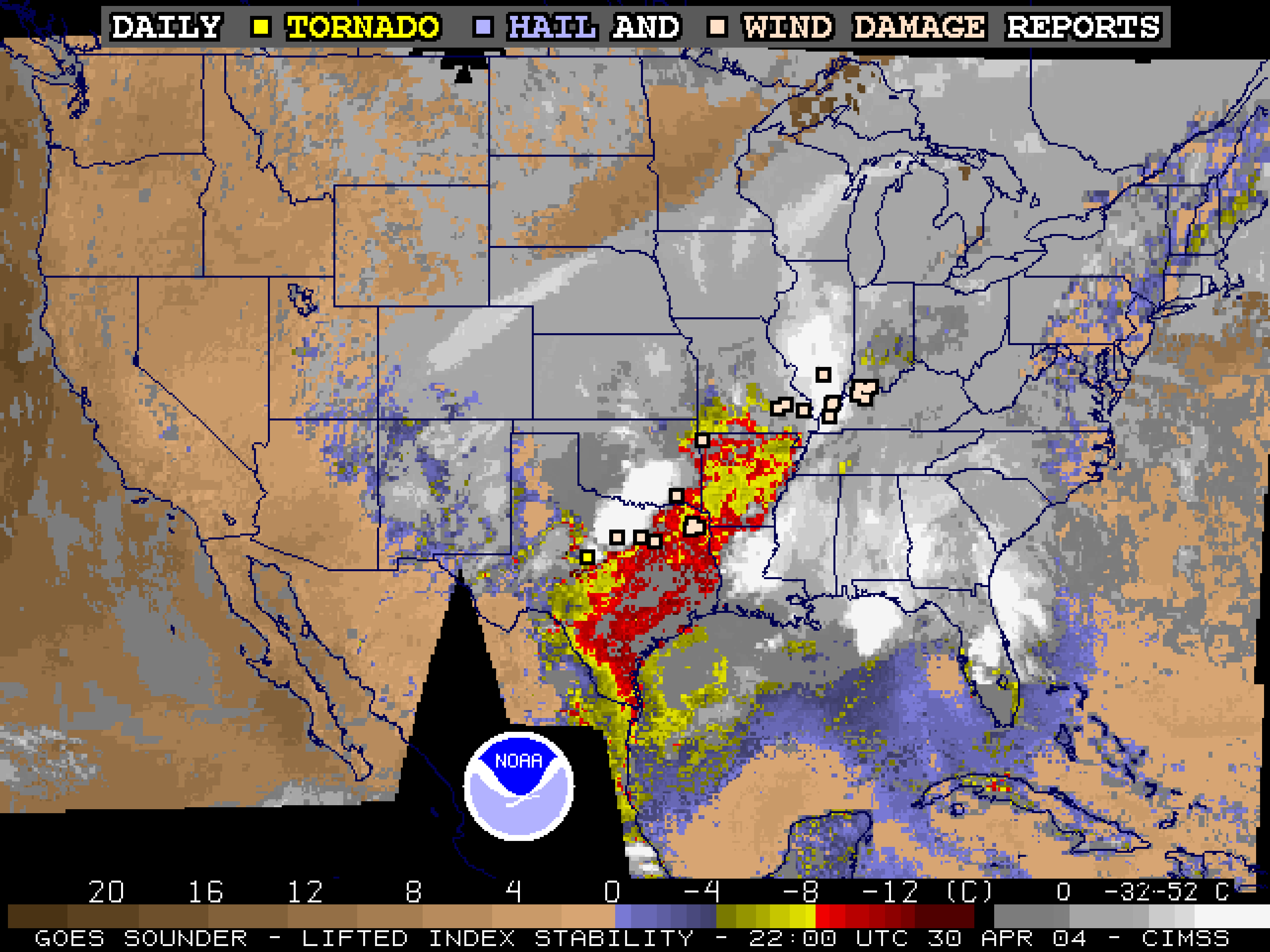
GOES Sounders –Total Precipitable Water



GOES Sounders –Lifted Index Stability




NOAA
WIND(MPS) DAY=30 APR 04 TIME=0 LEV=300
20 16 12 8 4 0 -4 -8 -12 (C) 0 -32 -52 C
GOES SOUNDER - LIFTED INDEX STABILITY - 00:00 UTC 30 APR 04 - CIMSS



DAILY ■ TORNADO ■ HAIL AND ■ WIND DAMAGE REPORTS
NOAA
20 16 12 8 4 0 -4 -8 -12 (C) 0 -32 -52 C
GOES SOUNDER - LIFTED INDEX STABILITY - 22:00 UTC 30 APR 04 - CIMSS

Sounder Retrieval Products

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

Direct

brightness temperatures

Derived in Clear Sky

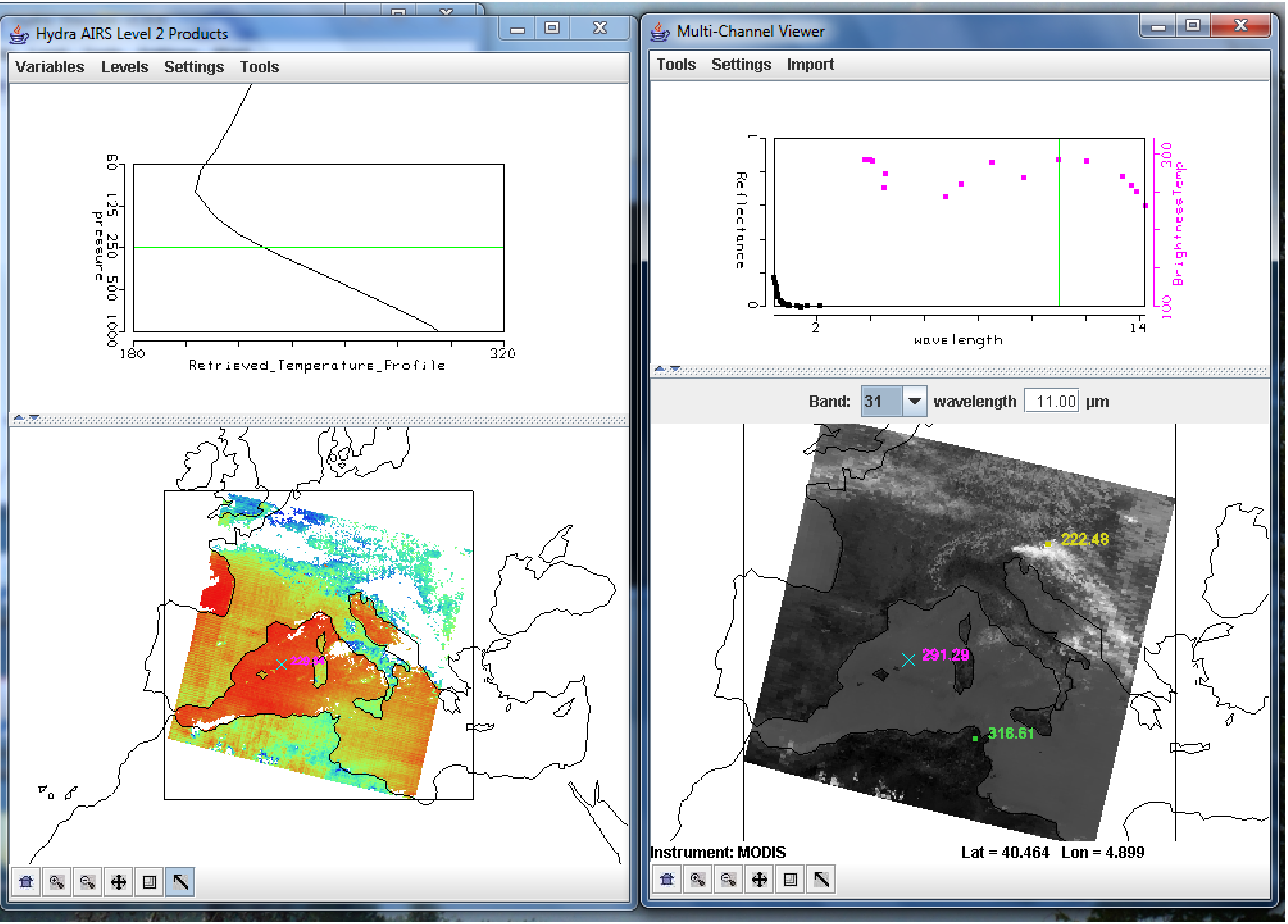
20 retrieved temperatures (at mandatory levels)
20 geo-potential heights (at mandatory levels)
11 dewpoint temperatures (at 300 hPa and below)
3 thermal gradient winds (at 700, 500, 400 hPa)
1 total precipitable water vapor
1 surface skin temperature
2 stability index (lifted index, CAPE)

Derived in Cloudy conditions

3 cloud parameters (amount, cloud top pressure, and cloud top temperature)

Mandatory Levels (in hPa)

sfc	780	300	70
1000	700	250	50
950	670	200	30
920	500	150	20
850	400	100	10


Hydra AIRS Level 2 Products
Variables
Levels
Settings
Tools
pressure
60
125
250
500
1000
180
320
Retrieved_Temperature_Profile
Multi-Channel Viewer
Tools
Settings
Import
Reflectance
BrightnessTemp
100
300
0
1
2
14
wavelength
Band:
31
wavelength
11.00
μm
222.48
291.29
318.61
Instrument: MODIS
Lat = 40.464
Lon = 4.899

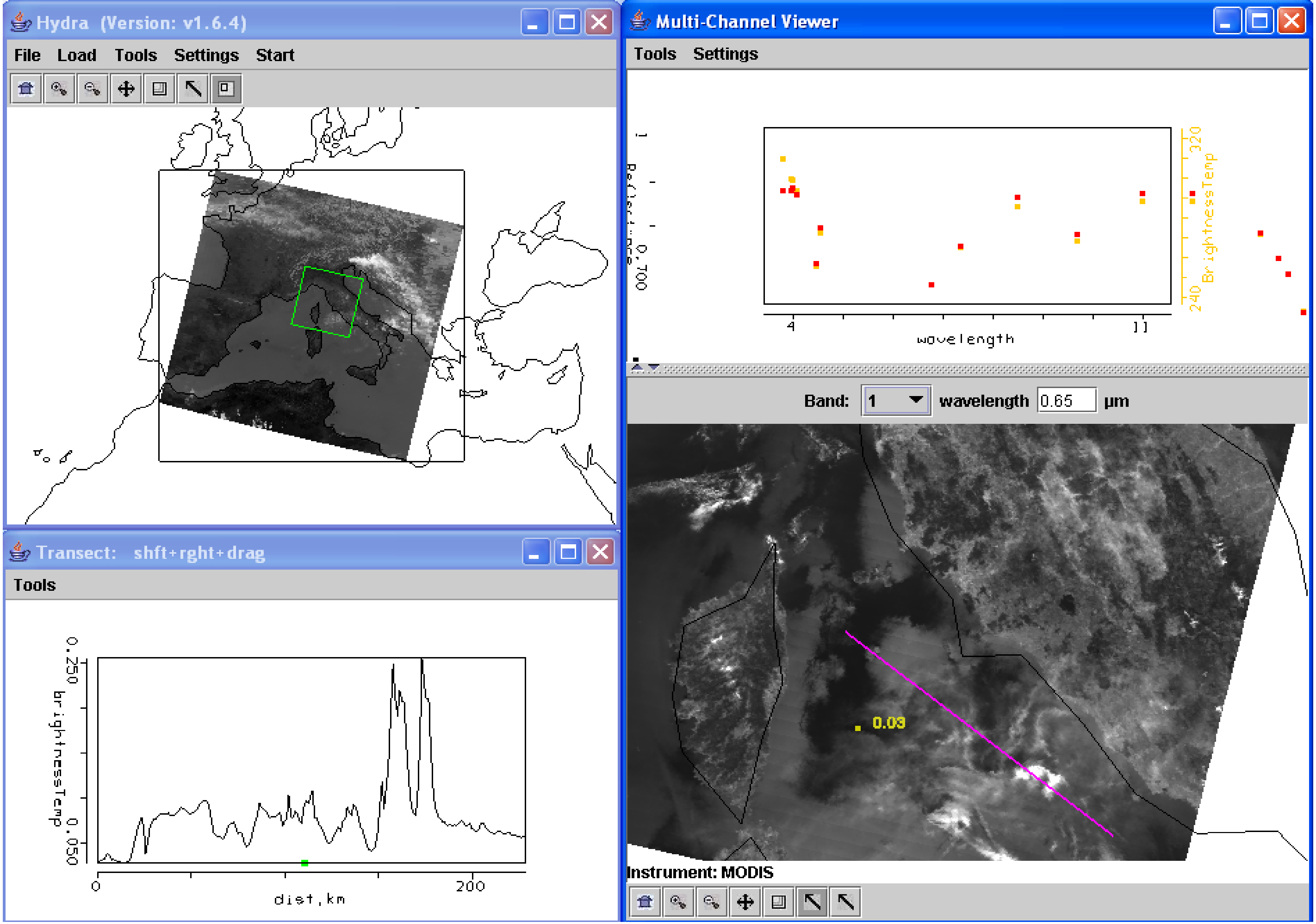
Intro to Land-Ocean-Atmosphere Remote Sensing

Lectures in Madison

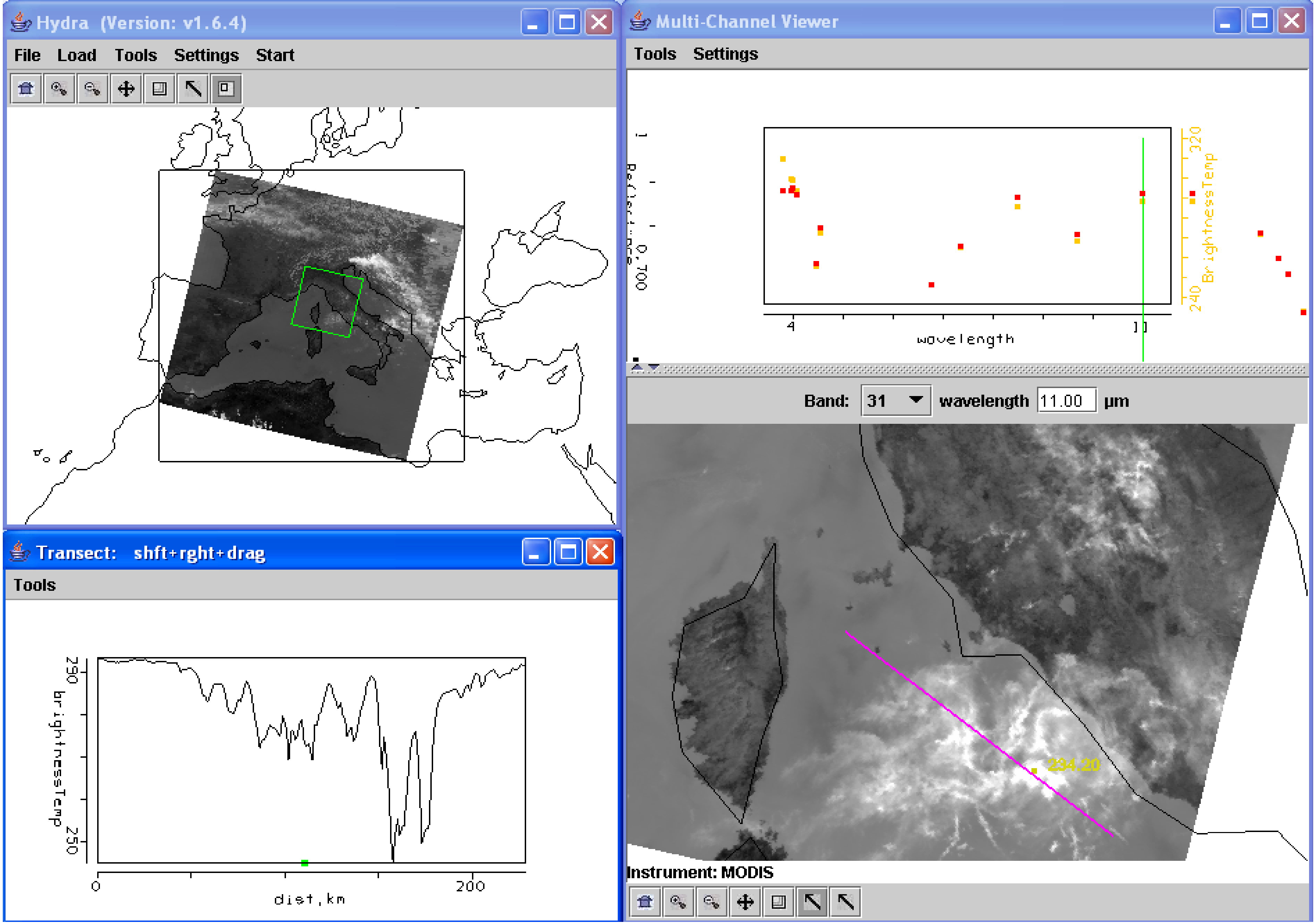
26 March 2013

Paul Menzel
UW/CIMSS/AOS

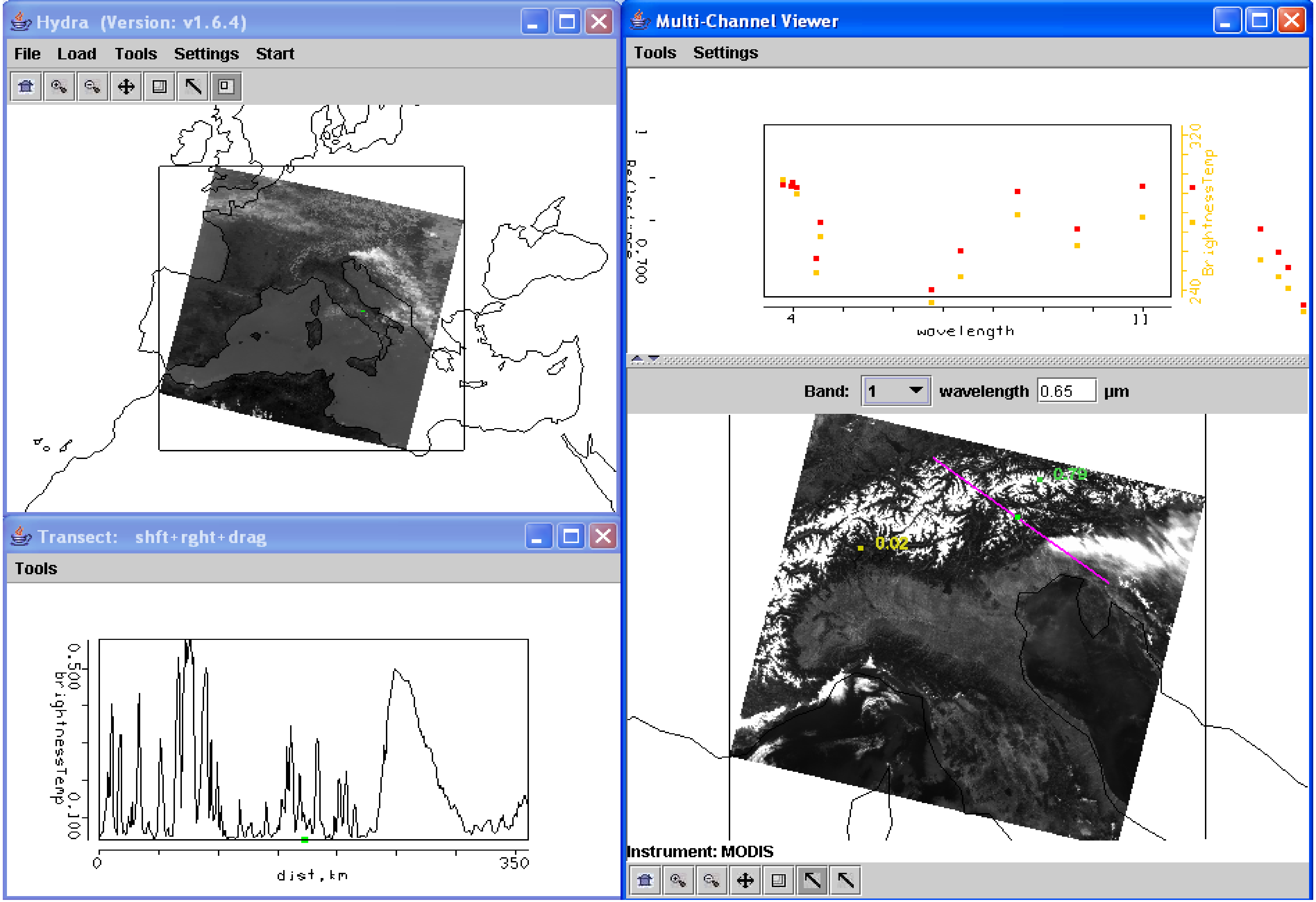
Relevant Material in Applications of Meteorological Satellites



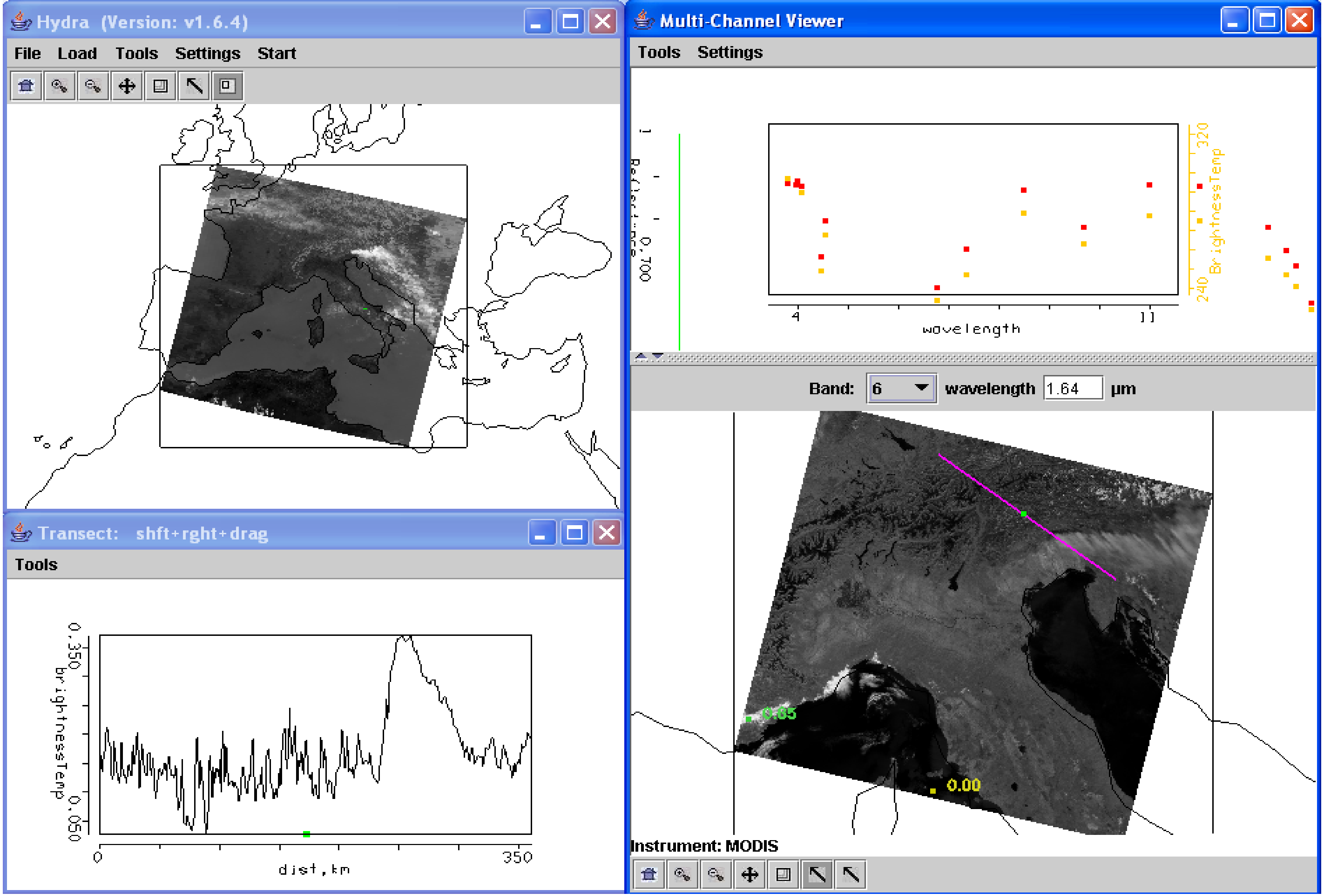
High clouds reflect more than surface at 0.65 µm



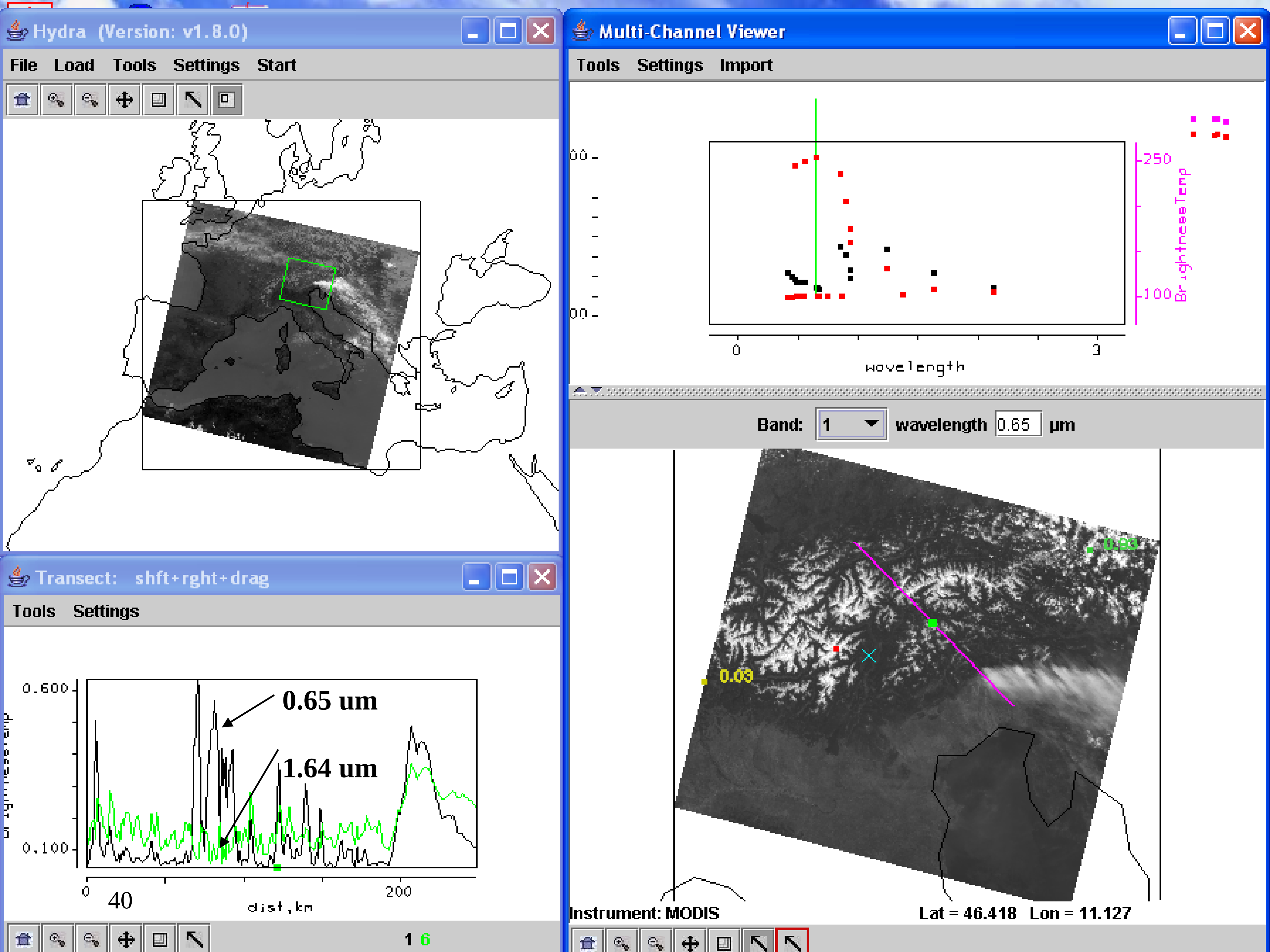
High clouds, cooler than surface, create lower 11 μm BTs



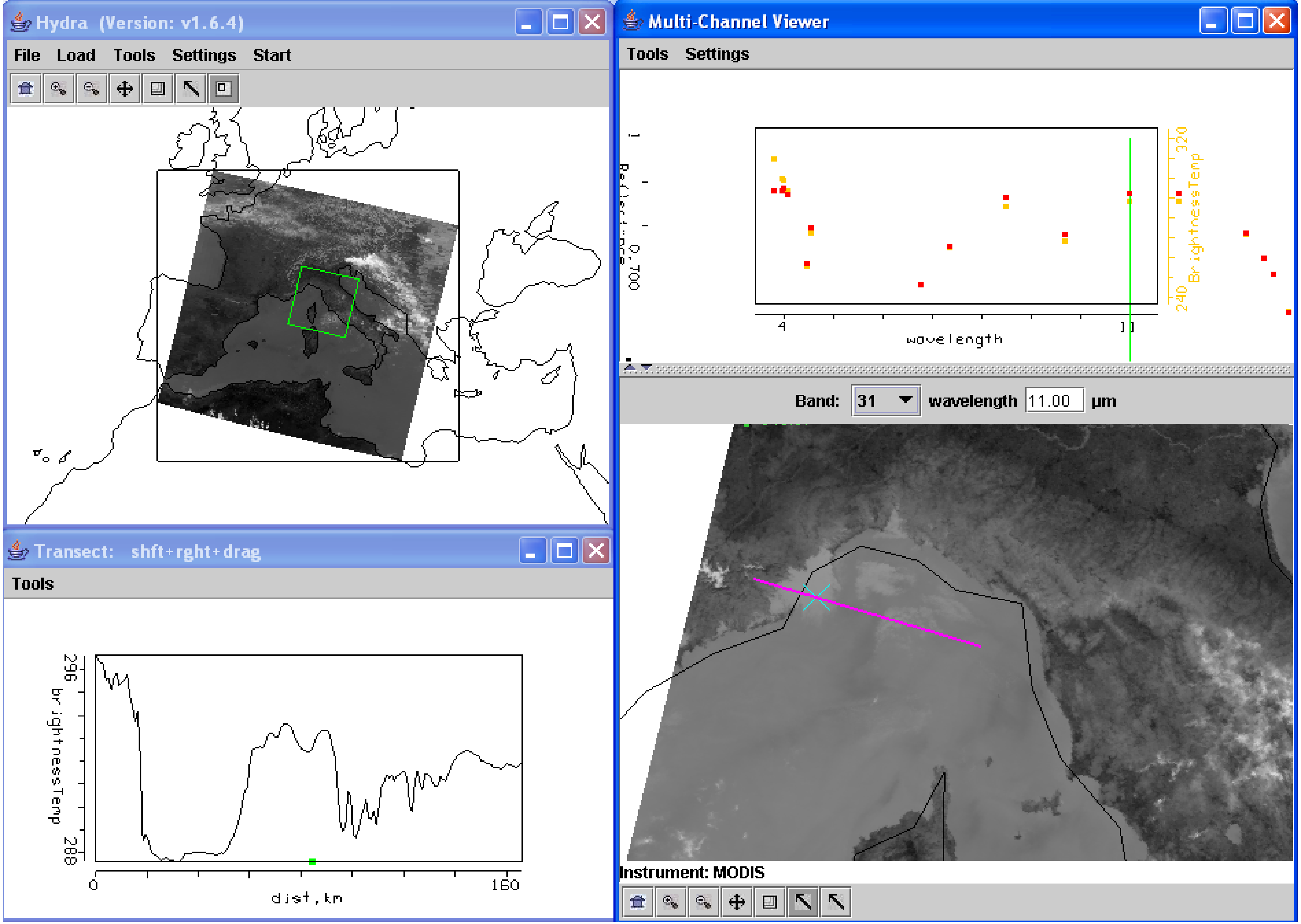
High clouds and snow both reflect a lot at 0.65 µm



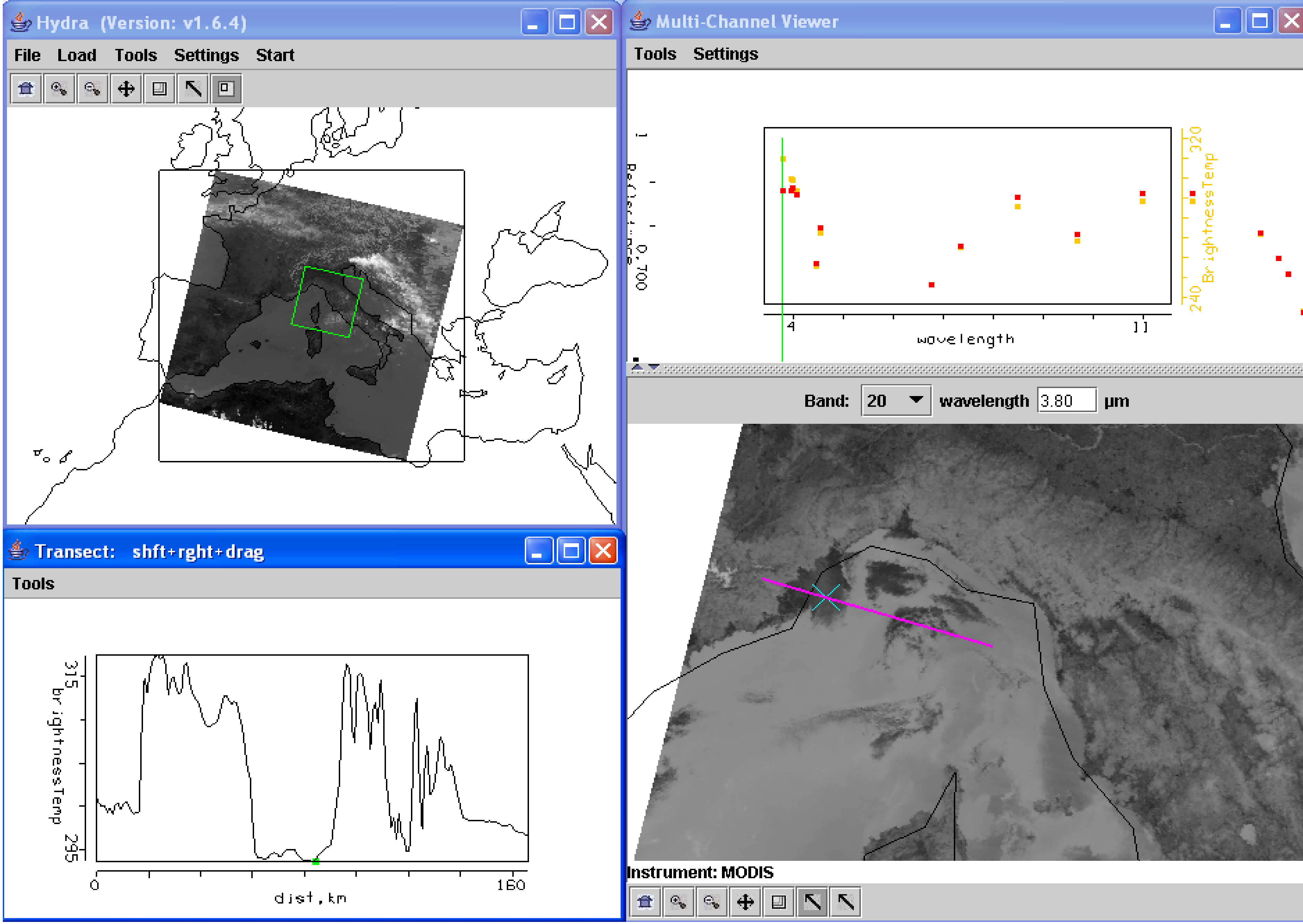
High clouds reflect but snow doesn't at 1.64 µm



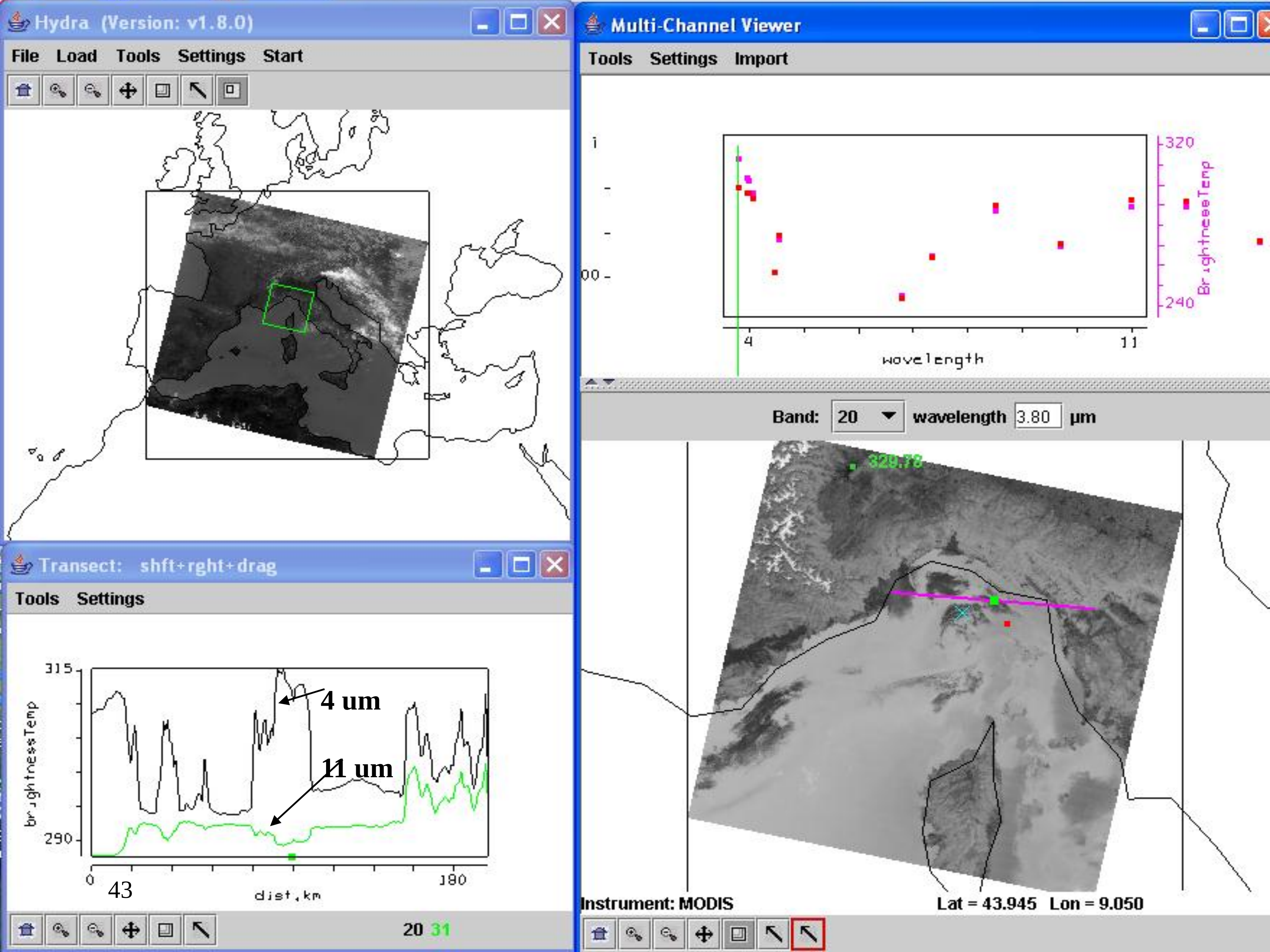
Hydra (Version: v1.8.0)
File Load Tools Settings Start
Multi-Channel Viewer
Tools Settings Import
250
100
BrightnessTemp
0
3
wavelength
Band:
1
wavelength
0.65
µm
0.03
0.03
Instrument: MODIS
Lat = 46.418 Lon = 11.127
Transect: shft+rght+drag
Tools Settings
0.600
0.100
0.65 um
1.64 um
0
200
40
dist,km
1 6

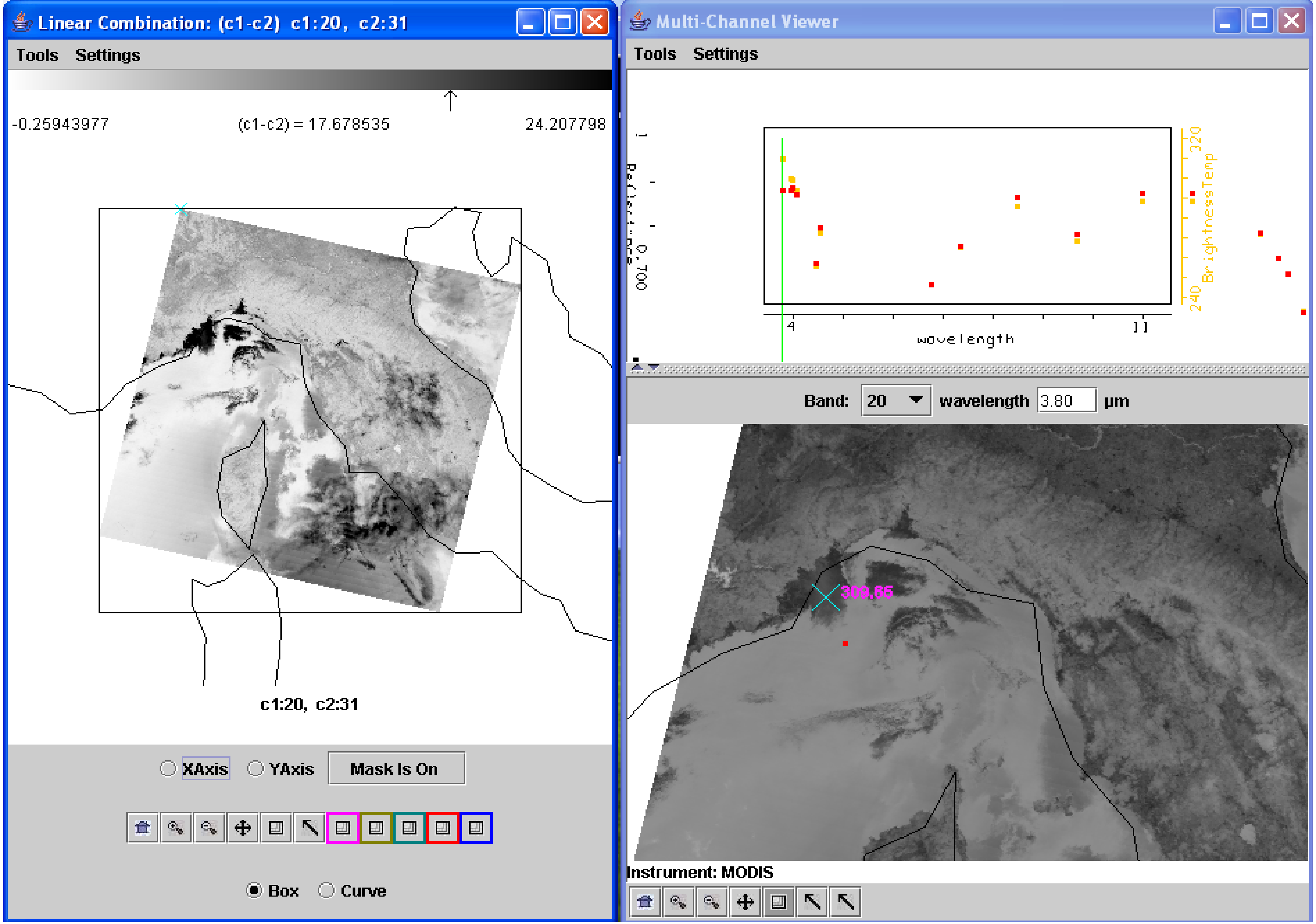


Low clouds, cooler than surface, create lower 11 µm BTs

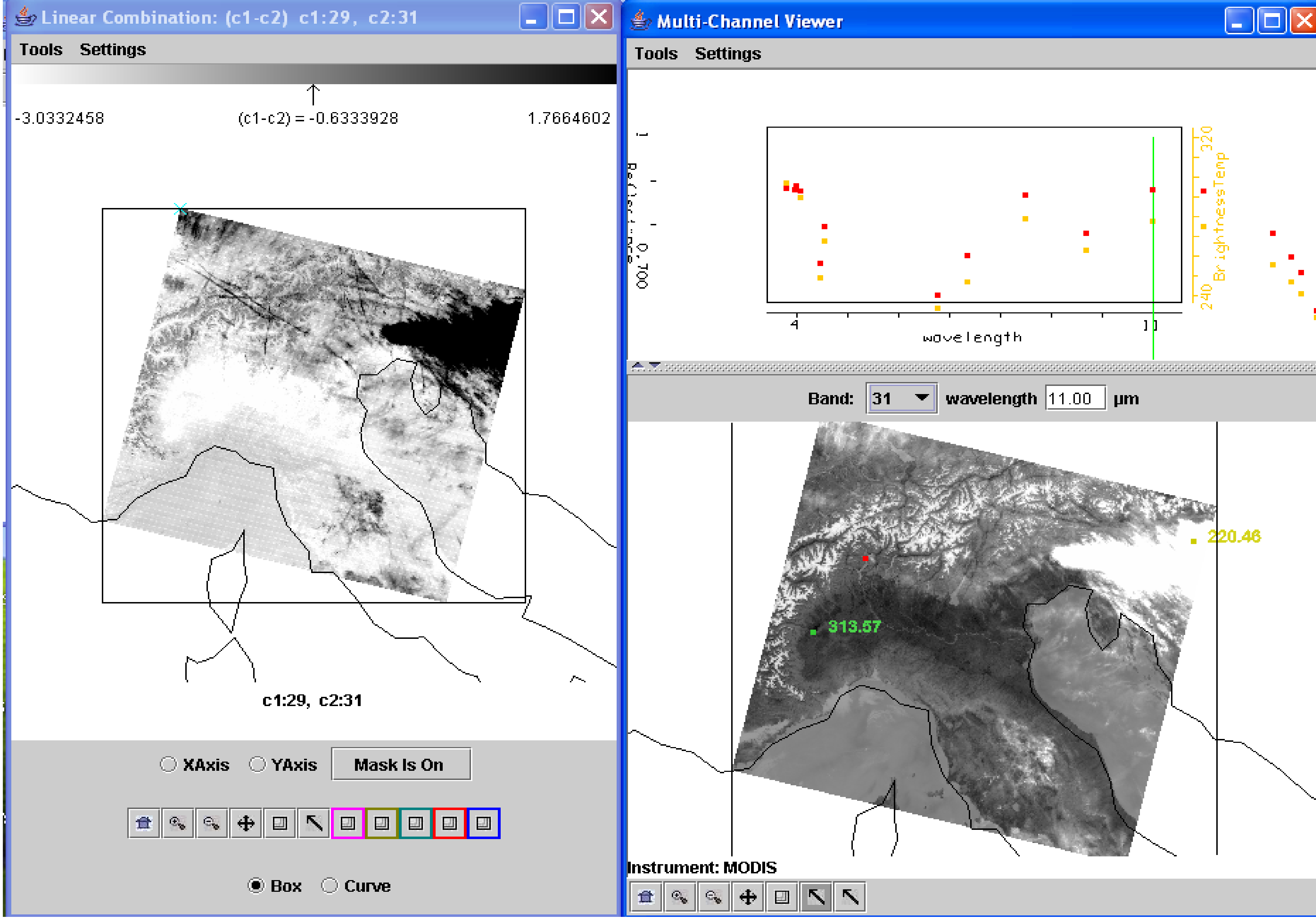


Low clouds reflecting create larger 4 µm brightness temperatures


Hydra (Version: v1.8.0)
File Load Tools Settings Start
Multi-Channel Viewer
Tools Settings Import
320
240
BrightnessTemp
4
11
wavelength
Band: 20 wavelength 3.80 µm
Instrument: MODIS
Lat = 43.945 Lon = 9.050
Transect: shft+rght+drag
Tools Settings
315
290
brightnessTemp
4 um
11 um
0
180
dist,km
20 31

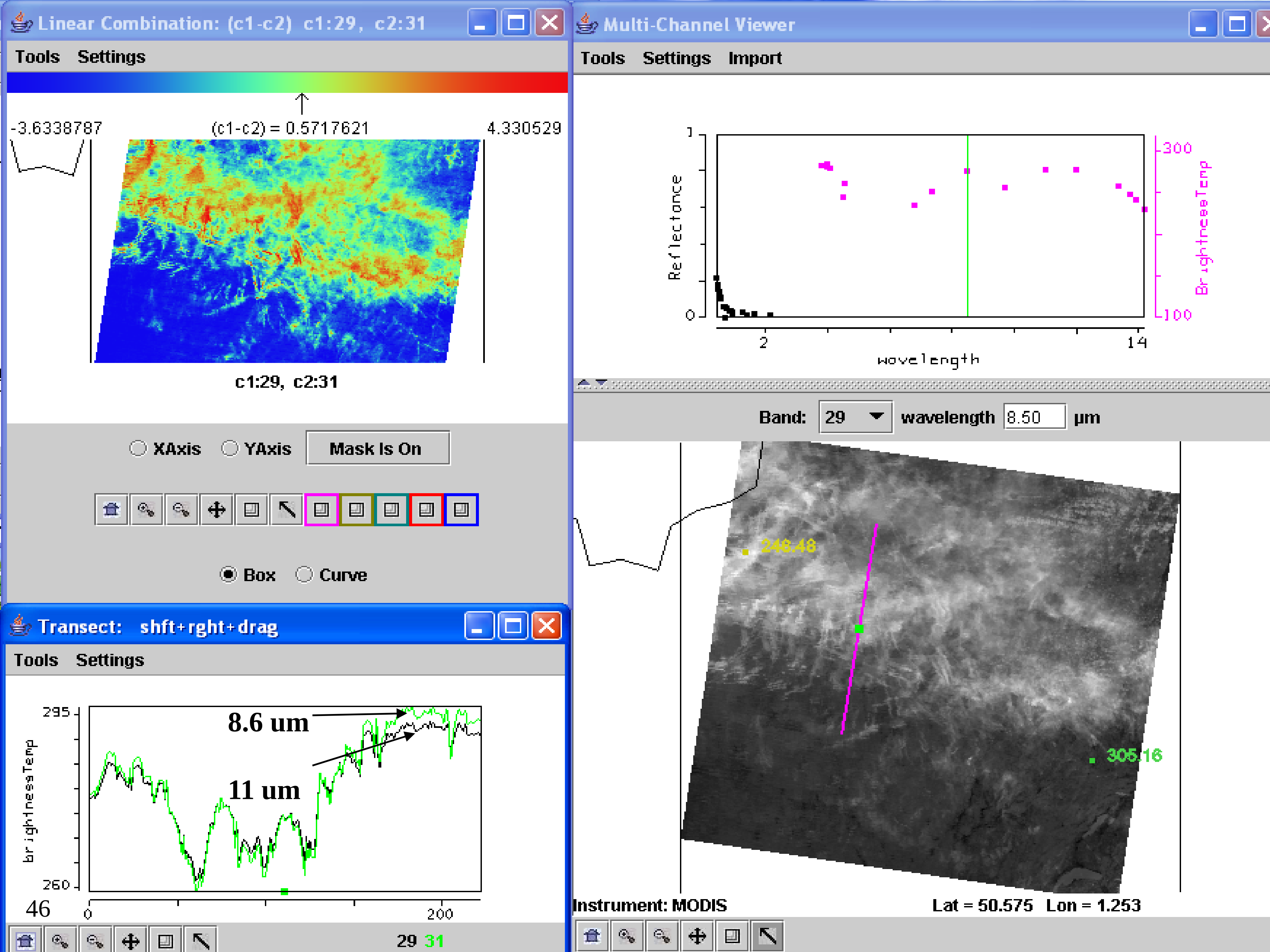


Detecting low clouds in 4-11 µm brightness temperature differences

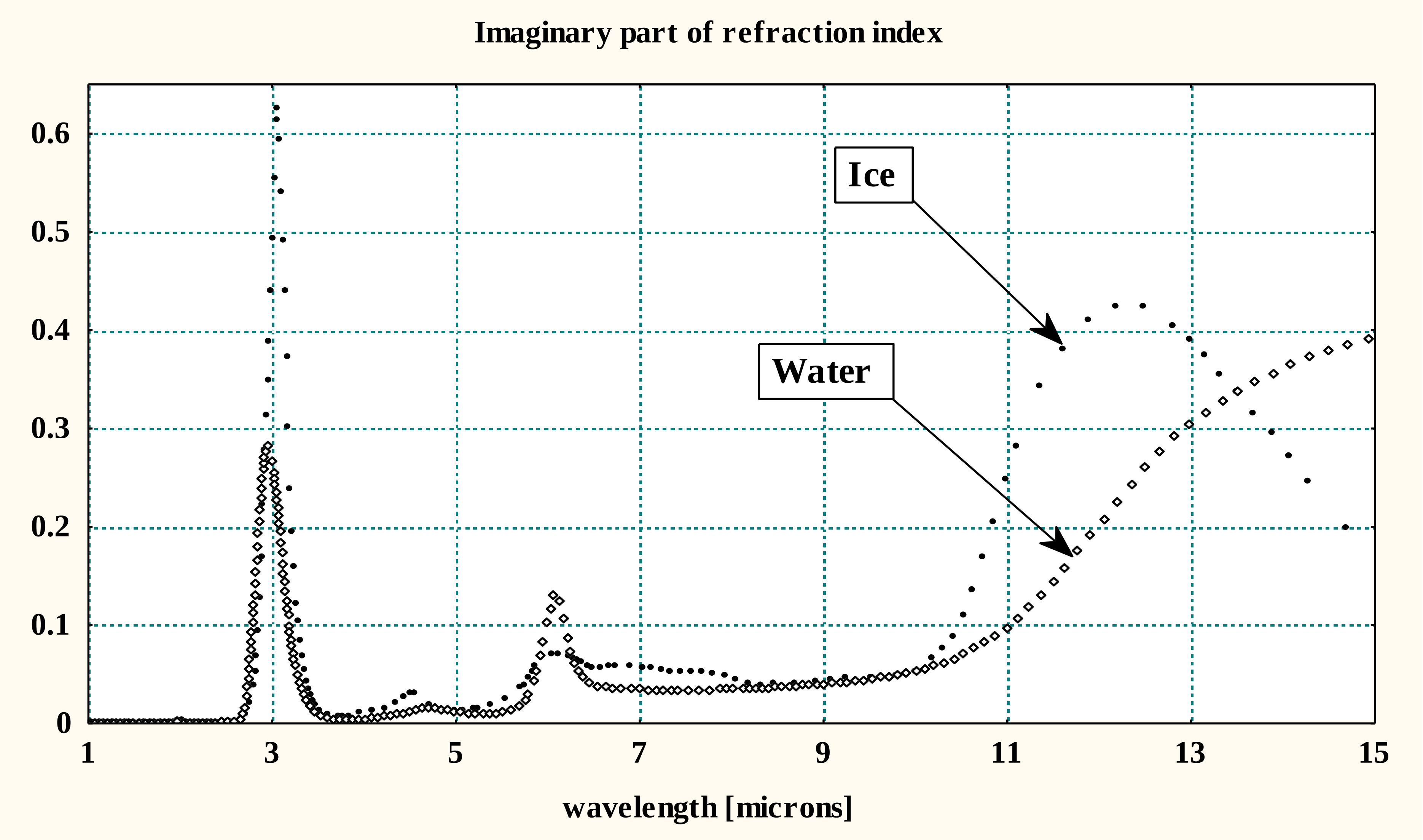


45

Detecting ice clouds in 8.6-11 μm brightness temperature differences

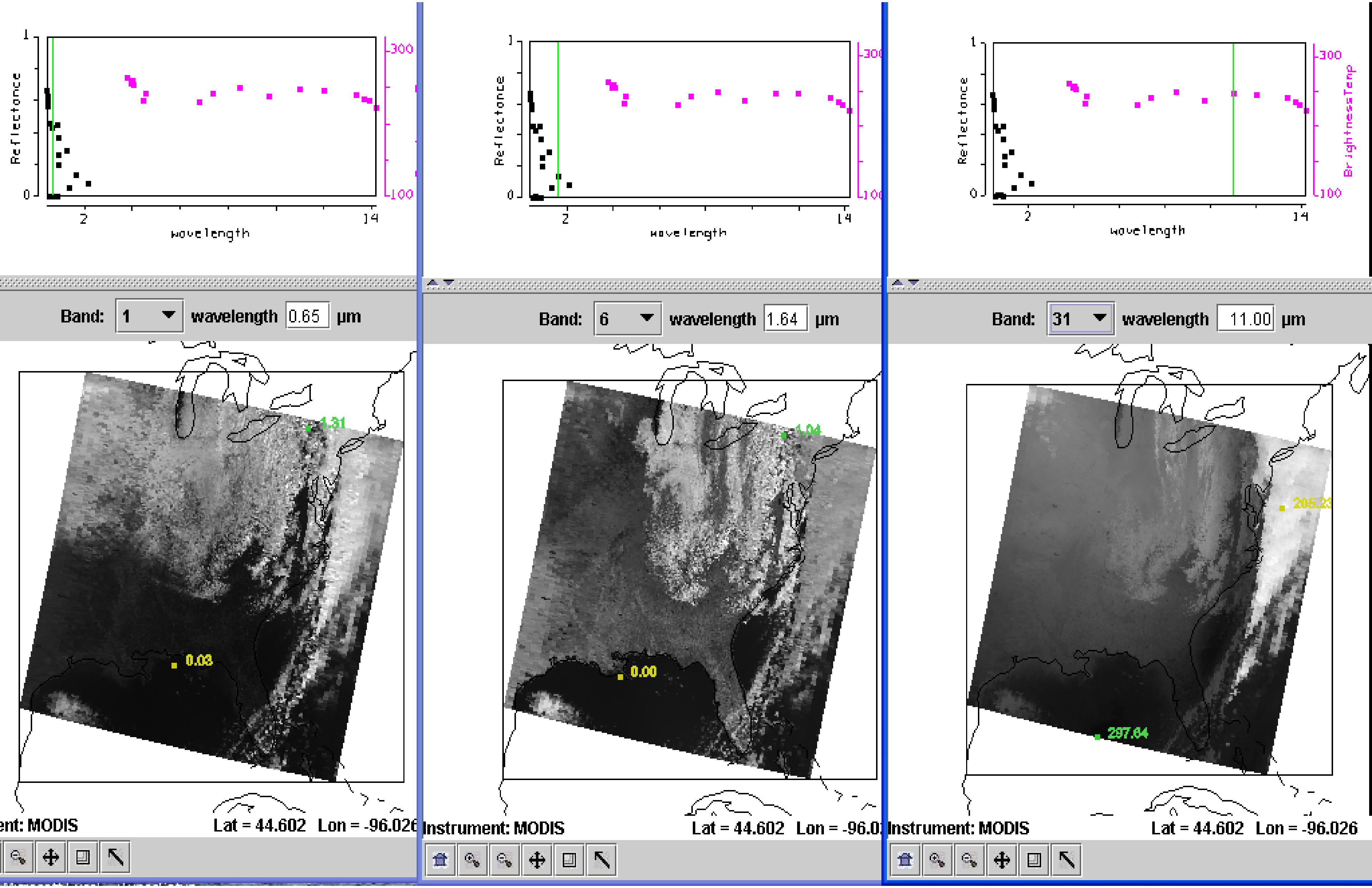

Linear Combination: (c1-c2) c1:29, c2:31
Tools Settings
-3.6338787
(c1-c2) = 0.5717621
4.330529
c1:29, c2:31
XAxis
YAxis
Mask Is On
Box
Curve
Transect: shft+rght+drag
Tools Settings
295
260
brightnessTemp
8.6 um
11 um
0
200
29 31
Multi-Channel Viewer
Tools Settings Import
Reflectance
1
0
300
100
BrightnessTemp
2
14
wavelength
Band: 29
wavelength 8.50 µm
248.48
305.16
Instrument: MODIS
Lat = 50.575 Lon = 1.253

Optical properties of cloud particles: imaginary part of refraction index

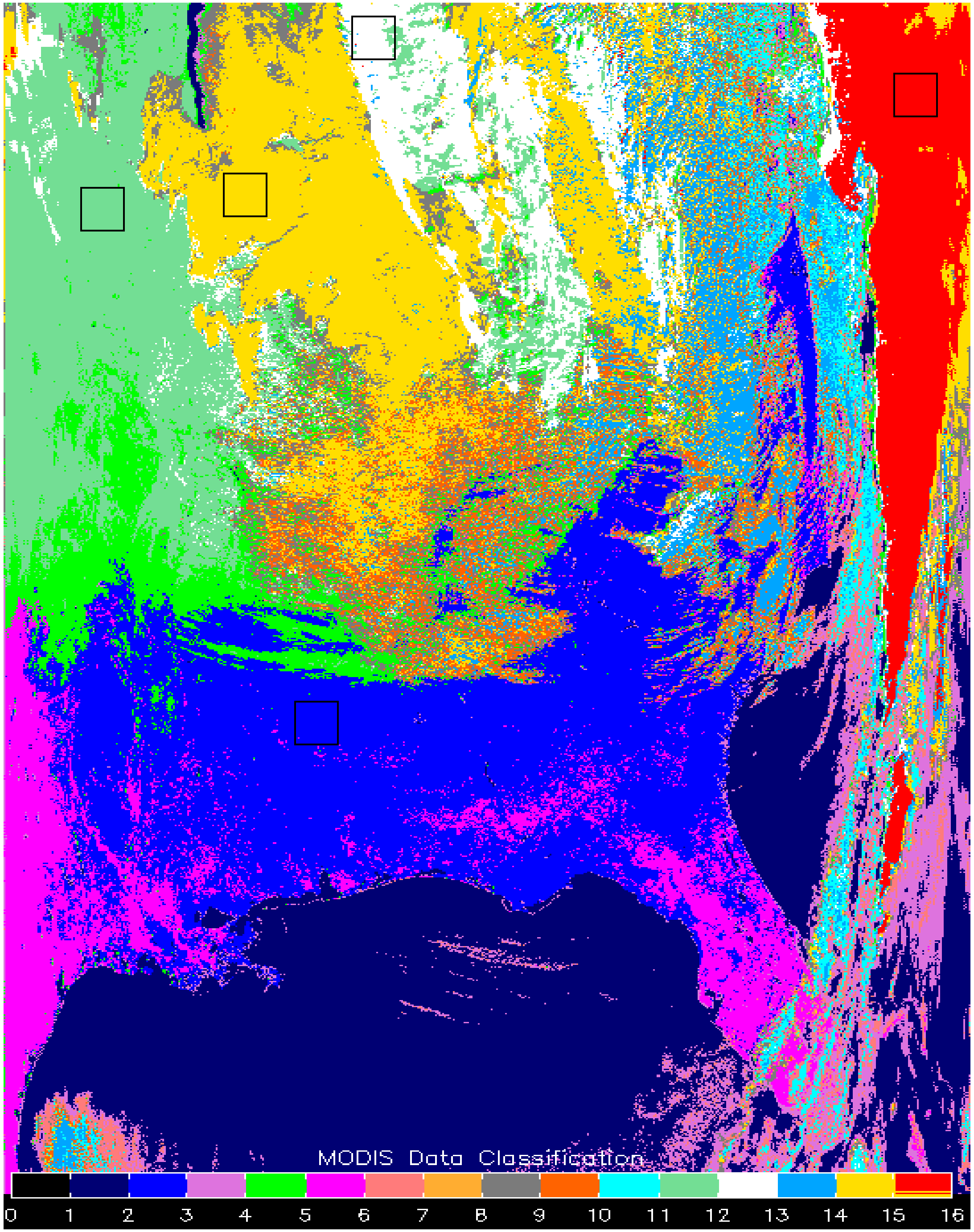


47

BT[8.6] – BT[11] will be positive for transmissive ice clouds


Reflectance
wavelength
Band: 1
wavelength 0.65 µm
0.03
ent: MODIS
Lat = 44.602 Lon = -96.026
Reflectance
wavelength
Band: 6
wavelength 1.64 µm
0.00
Instrument: MODIS
Lat = 44.602 Lon = -96.0
Reflectance
BrightnessTemp
wavelength
Band: 31
wavelength 11.00 µm
297.64
Instrument: MODIS
Lat = 44.602 Lon = -96.026

MODIS identifies cloud classes



Hi cld

Mid cld

Lo cld

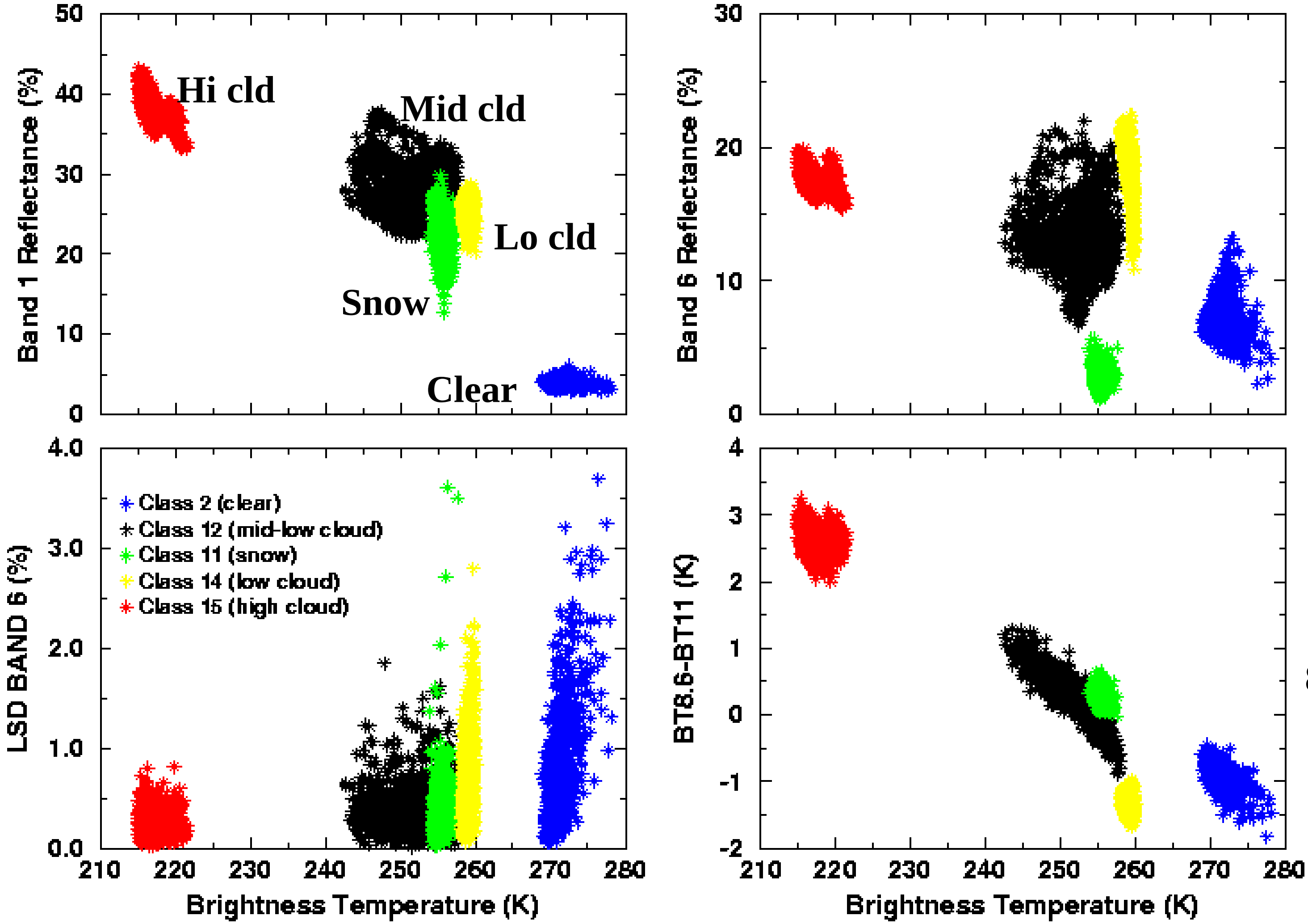
Snow

clr

Clouds separate into classes when multispectral radiance information is viewed

vis

1.6 um



LSD
1.6 um

8.6-11 um

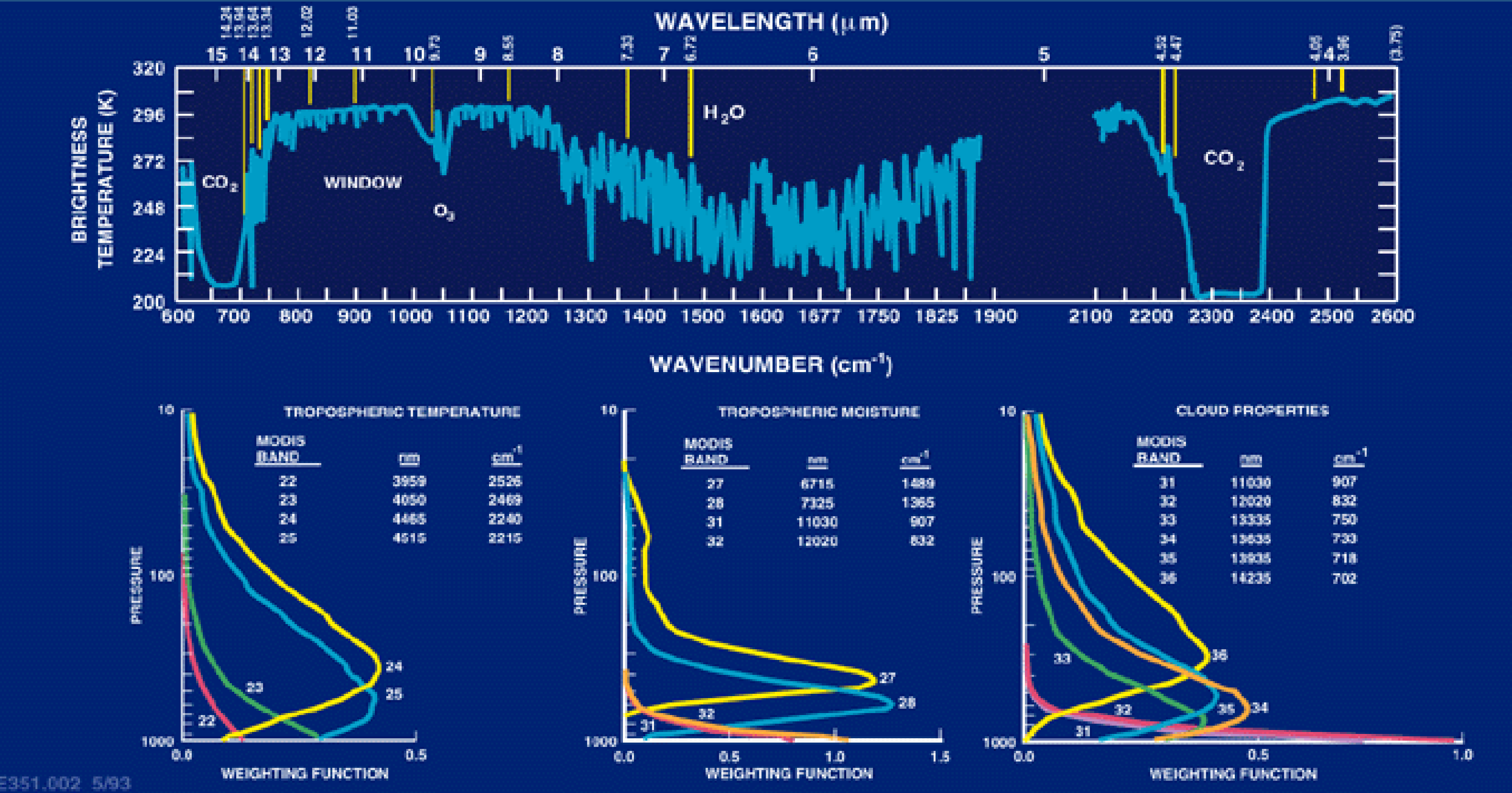
11 um

11 um

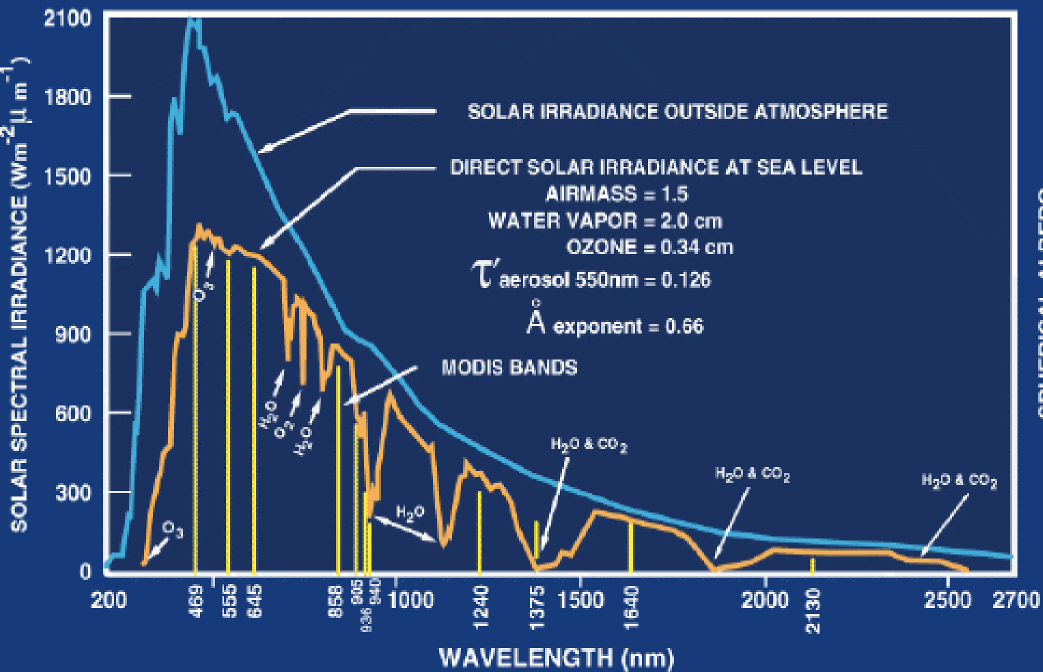
Cloud Mask Tests

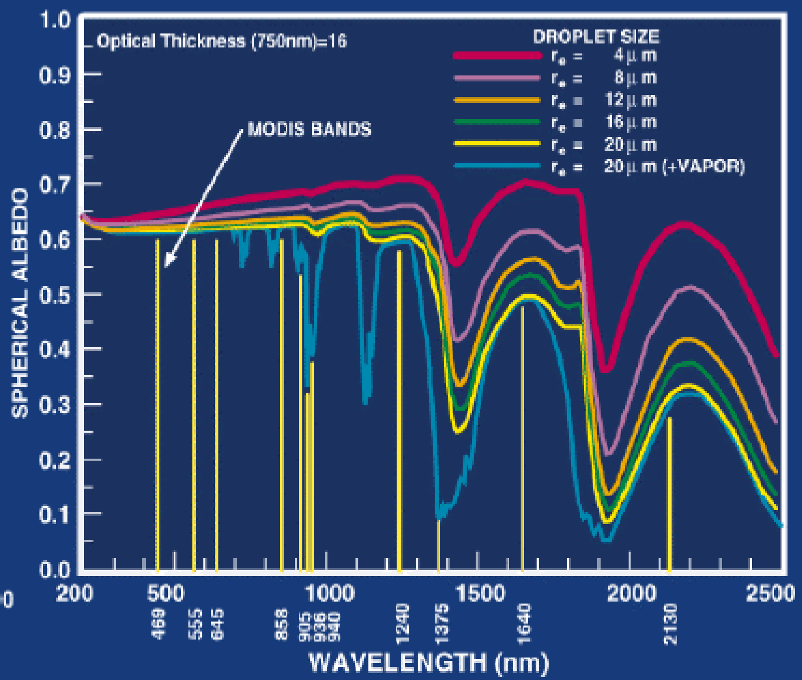
• BT11	clouds over ocean
• BT13.9	high clouds
• BT6.7	high clouds
• BT3.9-BT11	broken or scattered clouds
• BT11-BT12	high clouds in tropics
• BT8.6-BT11	ice clouds
• BT6.7-BT11 or BT13.9-BT11	clouds in polar regions
• BT11+aPW(BT11-BT12)	clouds over ocean
• r0.65	clouds over land
• r0.85	clouds over ocean
• r1.38	thin cirrus
• r1.6	clouds over snow, ice cloud
• r0.85/r0.65 or NDVI	clouds over vegetation
• σ(BT11)	clouds over ocean

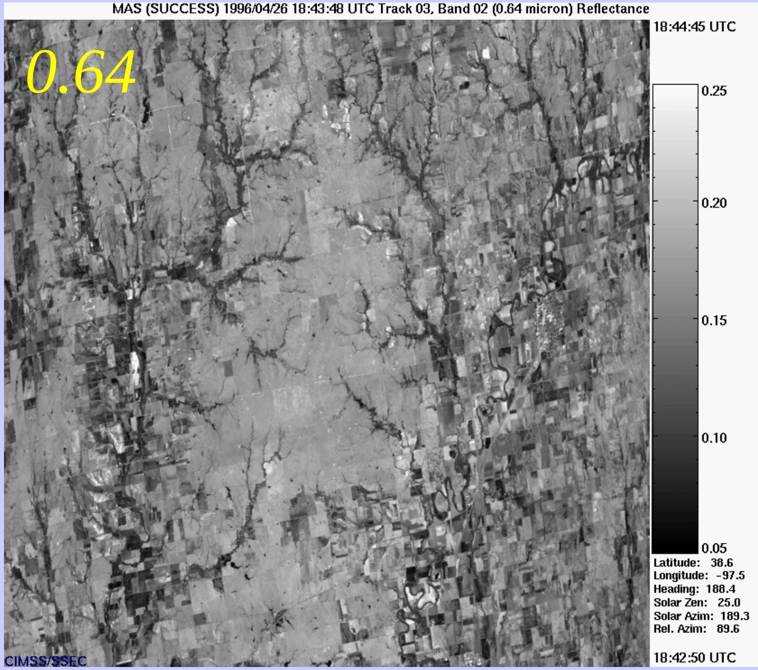
ATMOSPHERE - THERMAL RADIATION

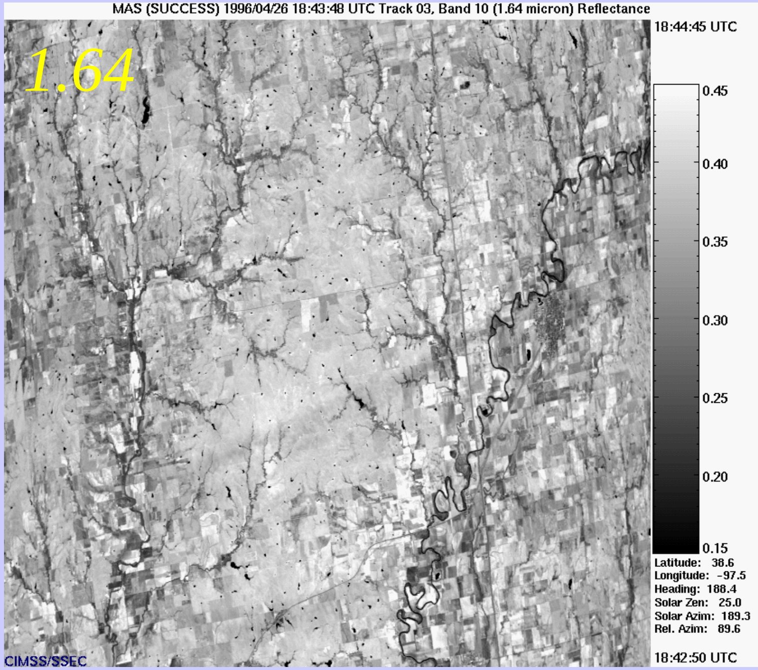


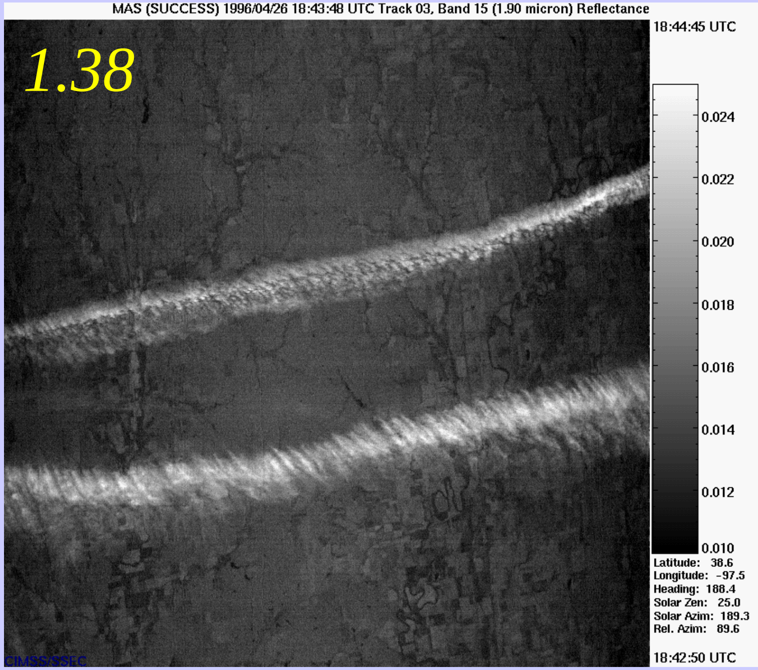
ATMOSPHERE-SOLAR RADIATION

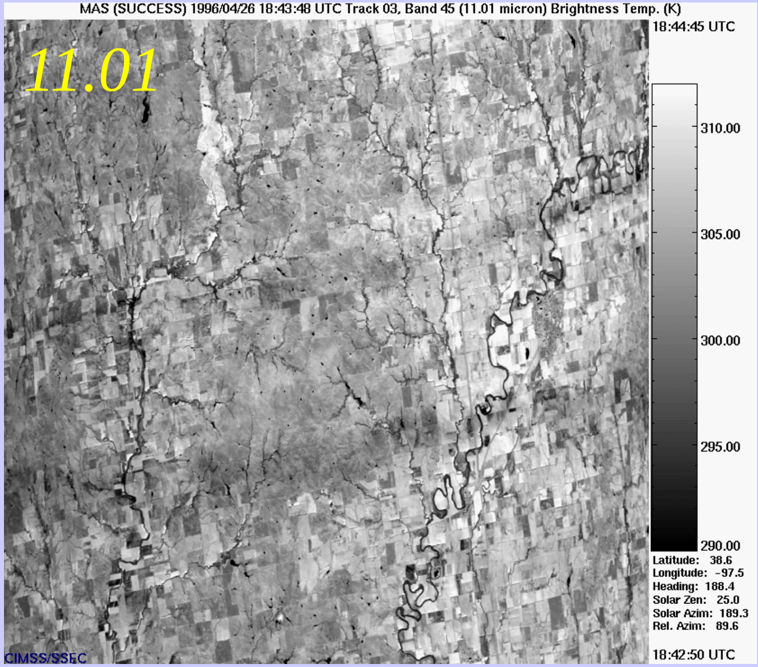




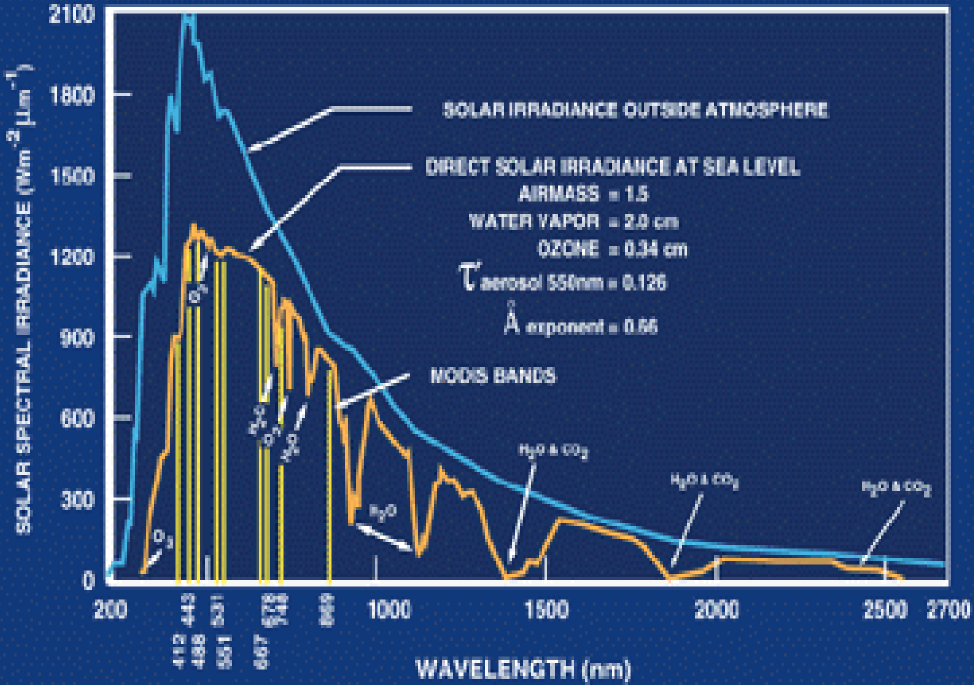

MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 02 (0.64 micron) Reflectance
0.64
18:44:45 UTC
0.25
0.20
0.15
0.10
0.05
Latitude: 38.6
Longitude: -97.5
Heading: 188.4
Solar Zen: 25.0
Solar Azim: 189.3
Rel. Azim: 89.6
CIMSS/SSEC
18:42:50 UTC

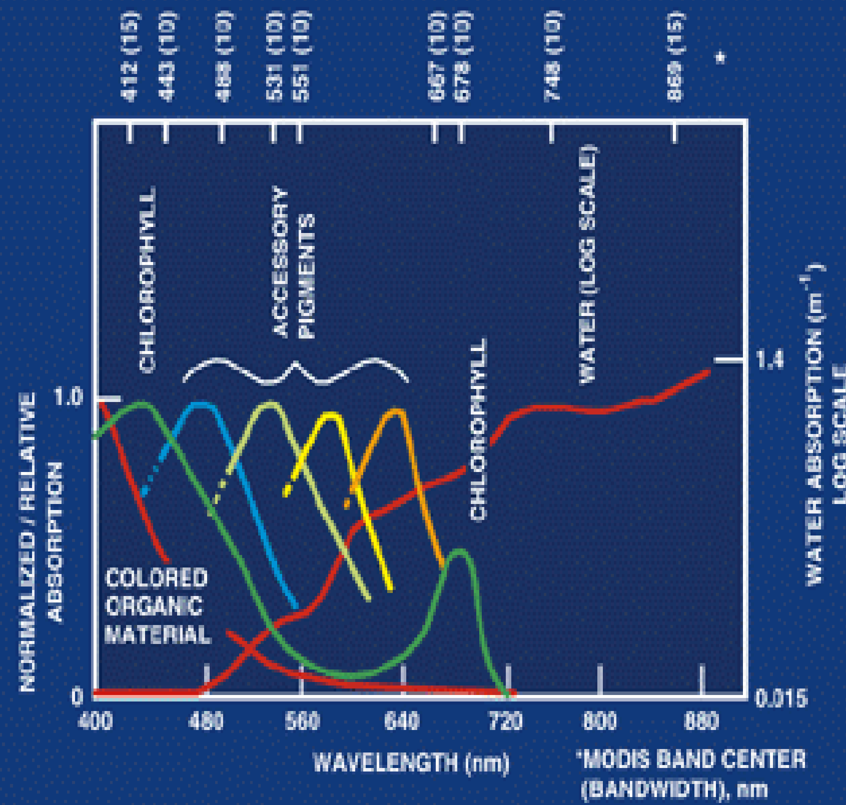

MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 10 (1.64 micron) Reflectance
1.64
18:44:45 UTC
0.45
0.40
0.35
0.30
0.25
0.20
0.15
Latitude: 38.6
Longitude: -97.5
Heading: 188.4
Solar Zen: 25.0
Solar Azim: 189.3
Rel. Azim: 89.6
CIMSS/SSEC
18:42:50 UTC


MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 15 (1.90 micron) Reflectance
1.38
18:44:45 UTC
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
Latitude: 38.6
Longitude: -97.5
Heading: 188.4
Solar Zen: 25.0
Solar Azim: 189.3
Rel. Azim: 89.6
CIMSS/SSEC
18:42:50 UTC

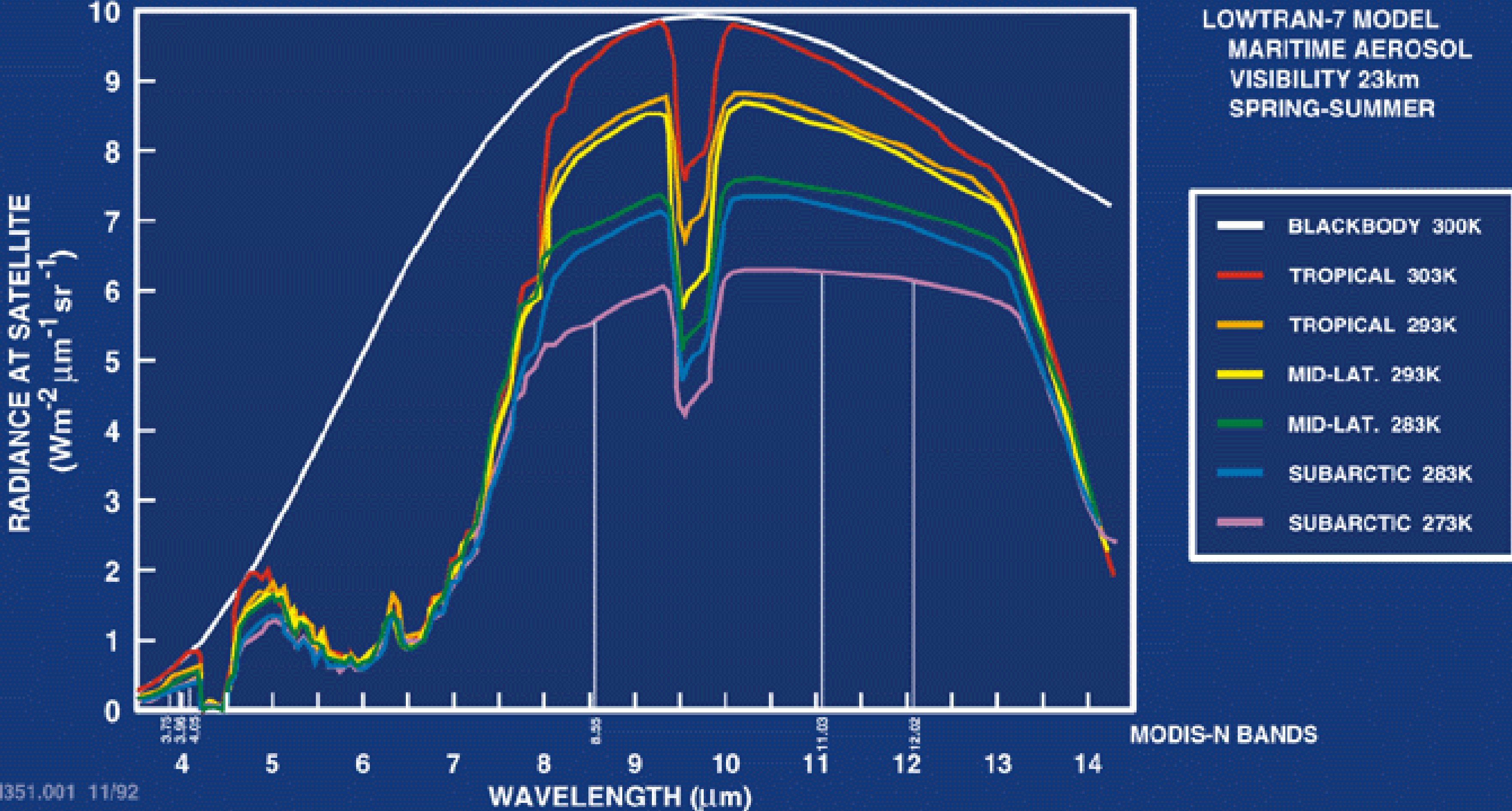

MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 45 (11.01 micron) Brightness Temp. (K)
11.01
18:44:45 UTC
310.00
305.00
300.00
295.00
290.00
Latitude: 38.6
Longitude: -97.5
Heading: 188.4
Solar Zen: 25.0
Solar Azim: 189.3
Rel. Azim: 89.6
CIMSS/SSEC
18:42:50 UTC

OCEAN-SOLAR RADIATION

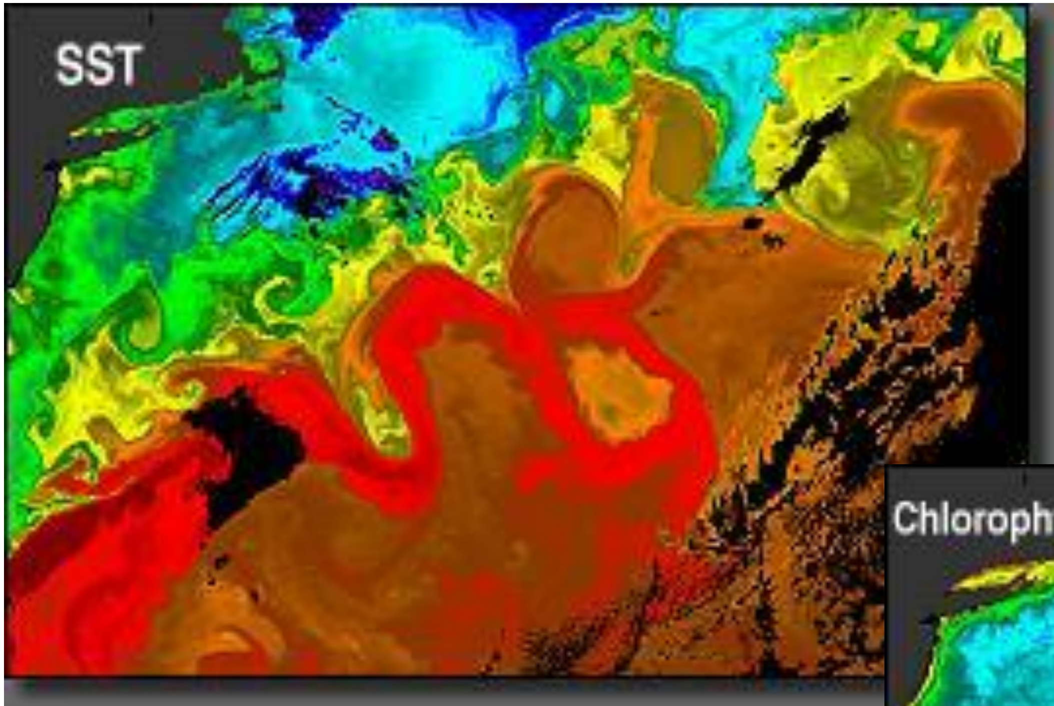


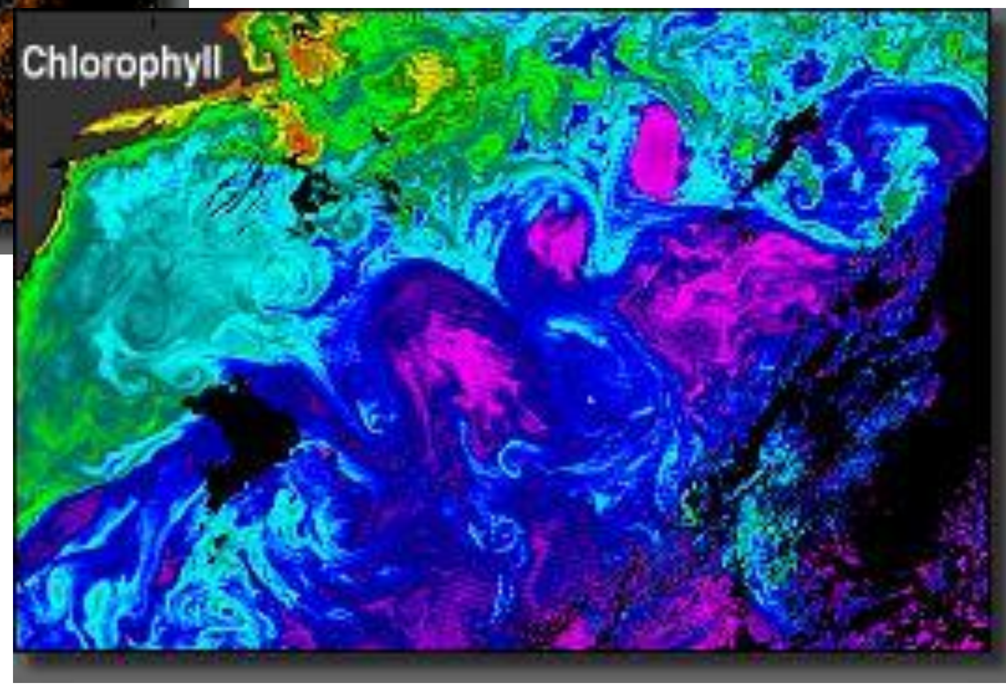


MODIS SEA SURFACE TEMPERATURE



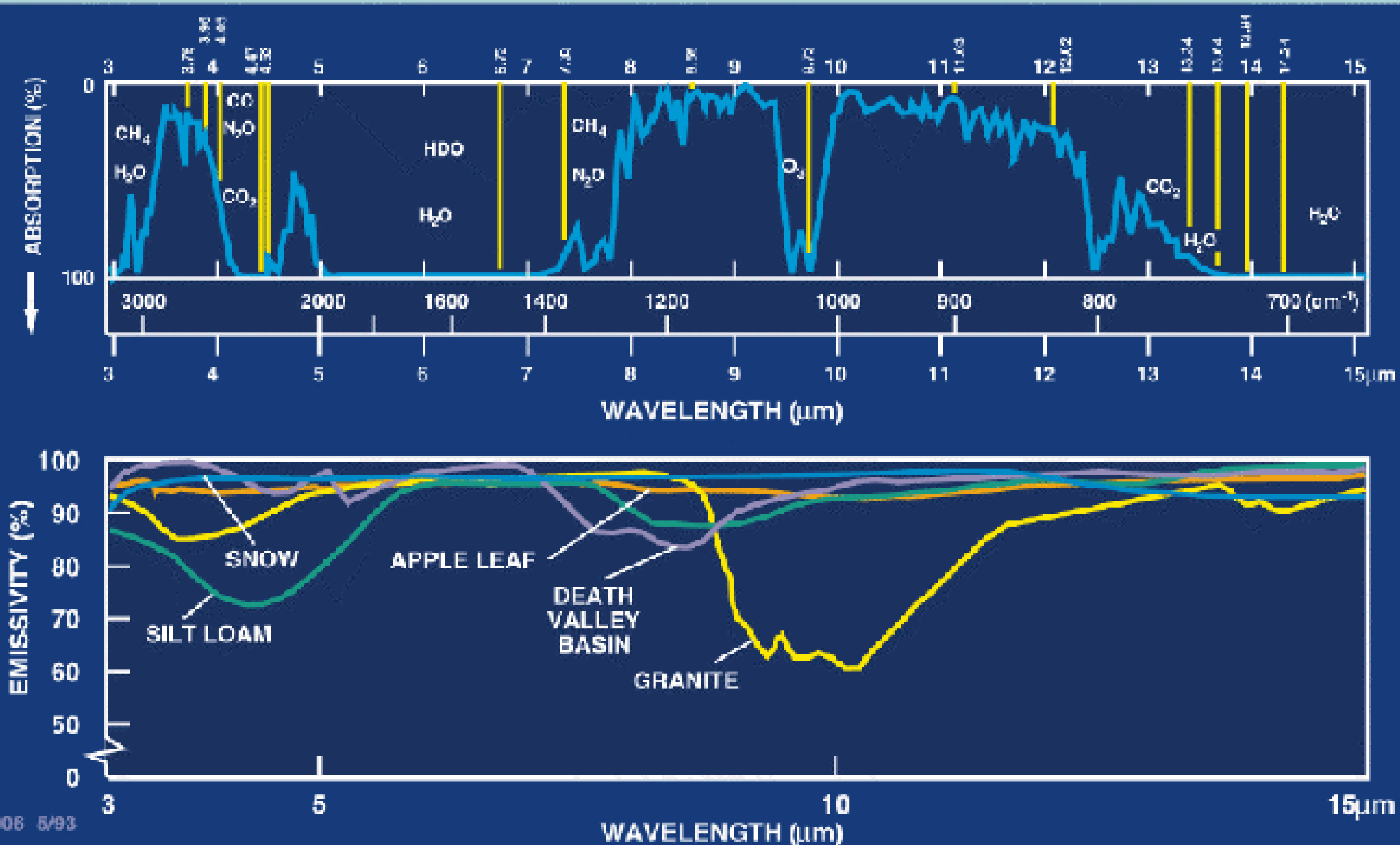
H351.001 11/92



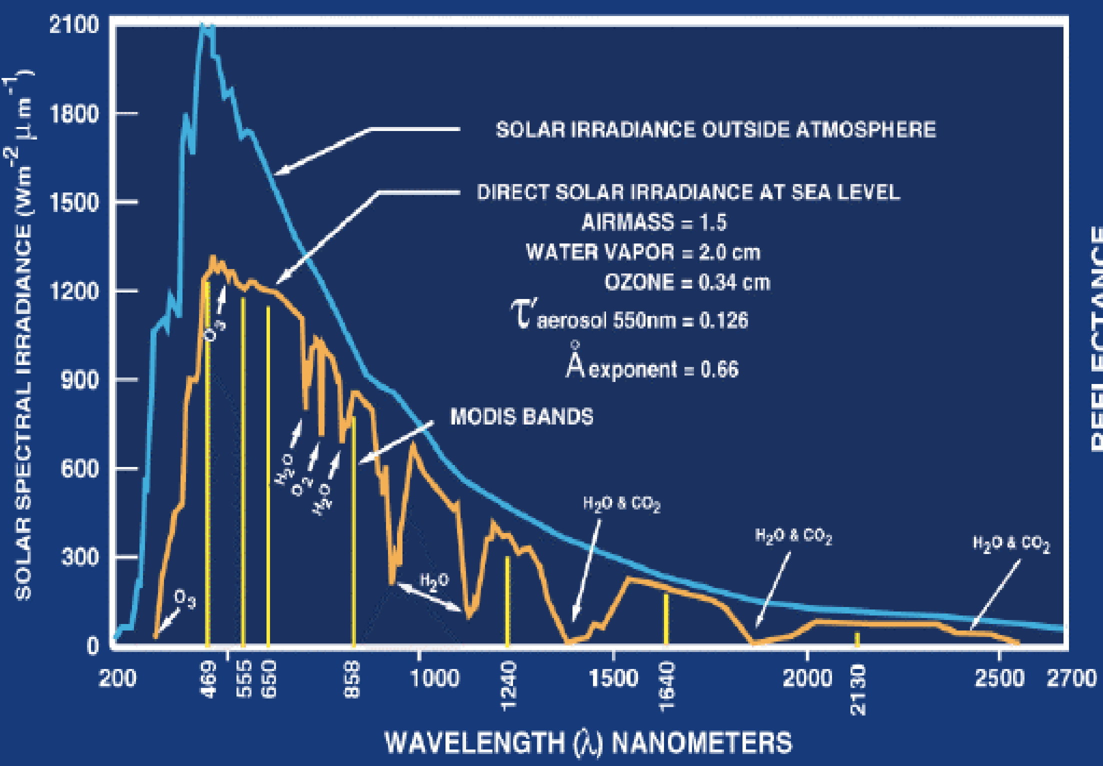


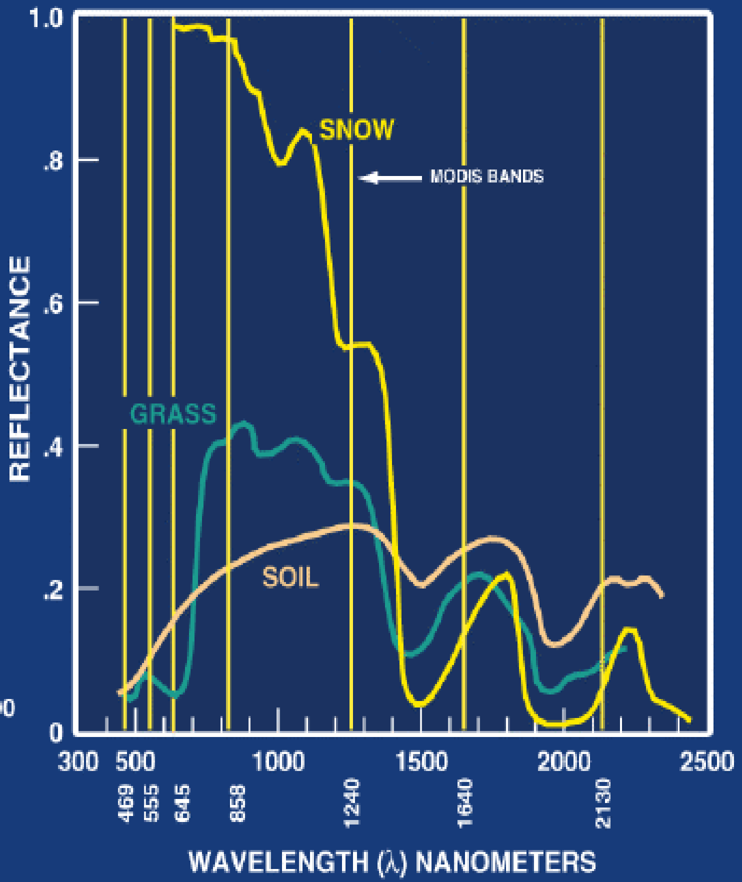
The warm heart of the Gulf Stream is readily apparent in the top SST image. As the current flows toward the northeast it begins to meander and pinch off eddies that transport warm water northward and cold water southward. The current also divides the local ocean into a low-biomass region to the south and a higher-biomass region to the north. The data were collected by MODIS aboard Aqua on April 18, 2005.

LAND - THERMAL RADIATION

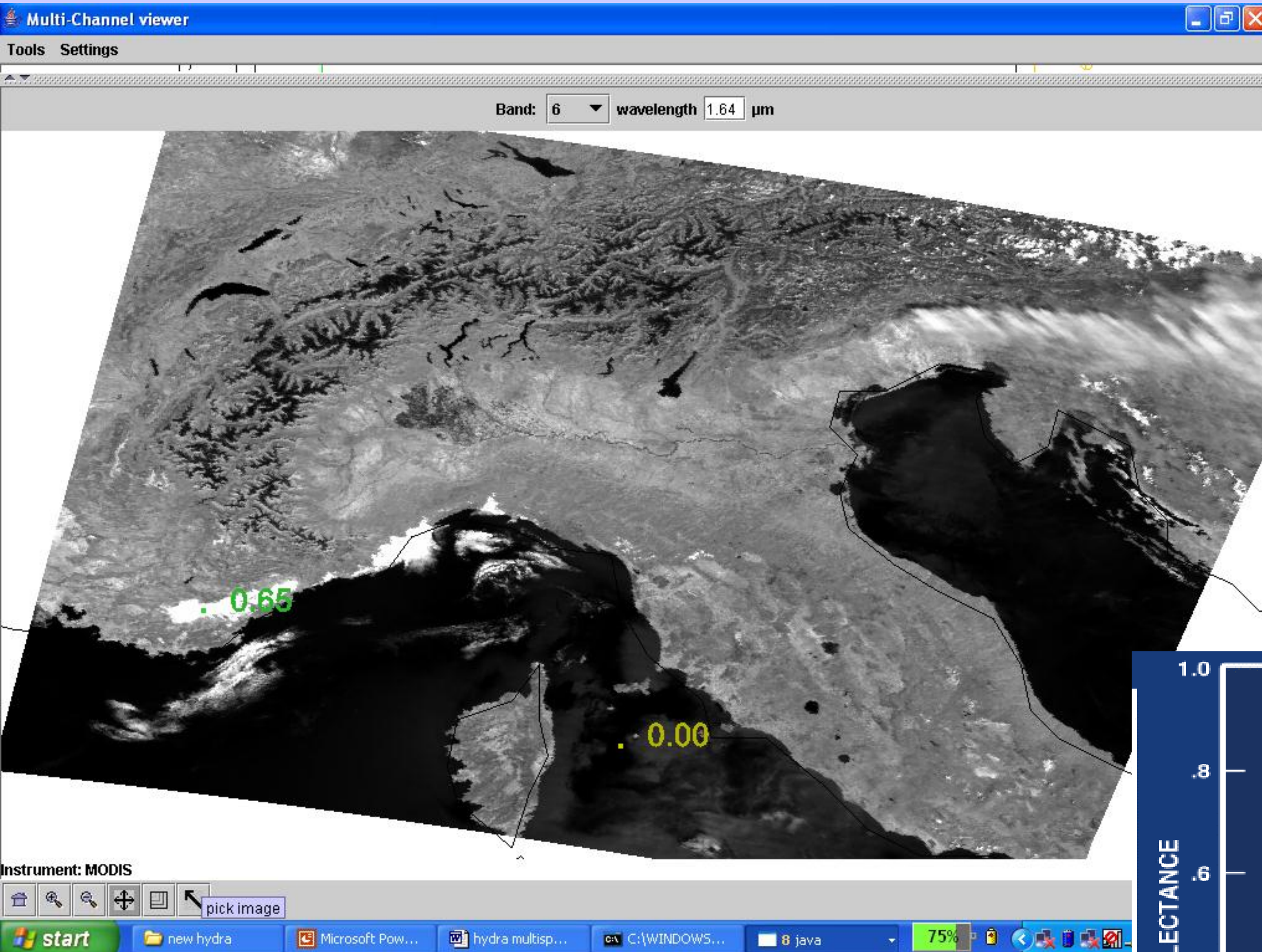


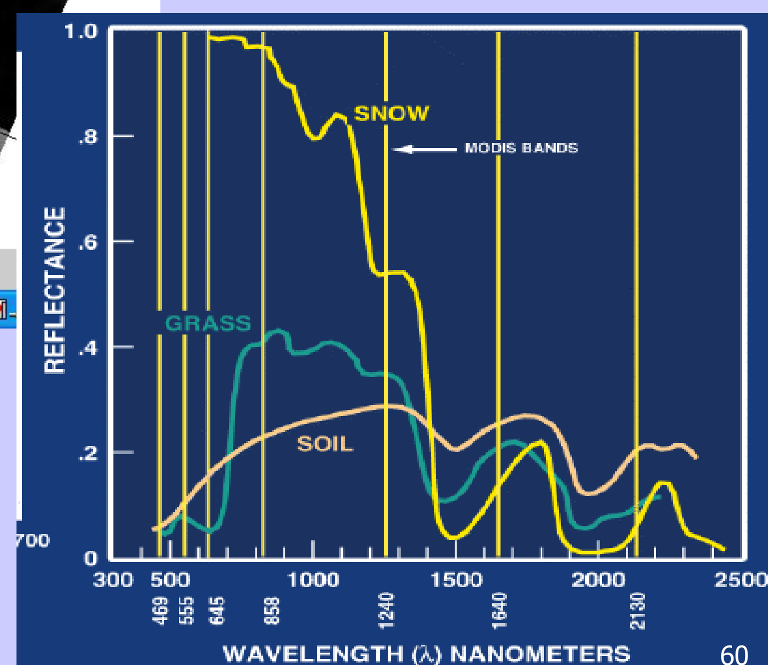
LAND-SOLAR RADIATION



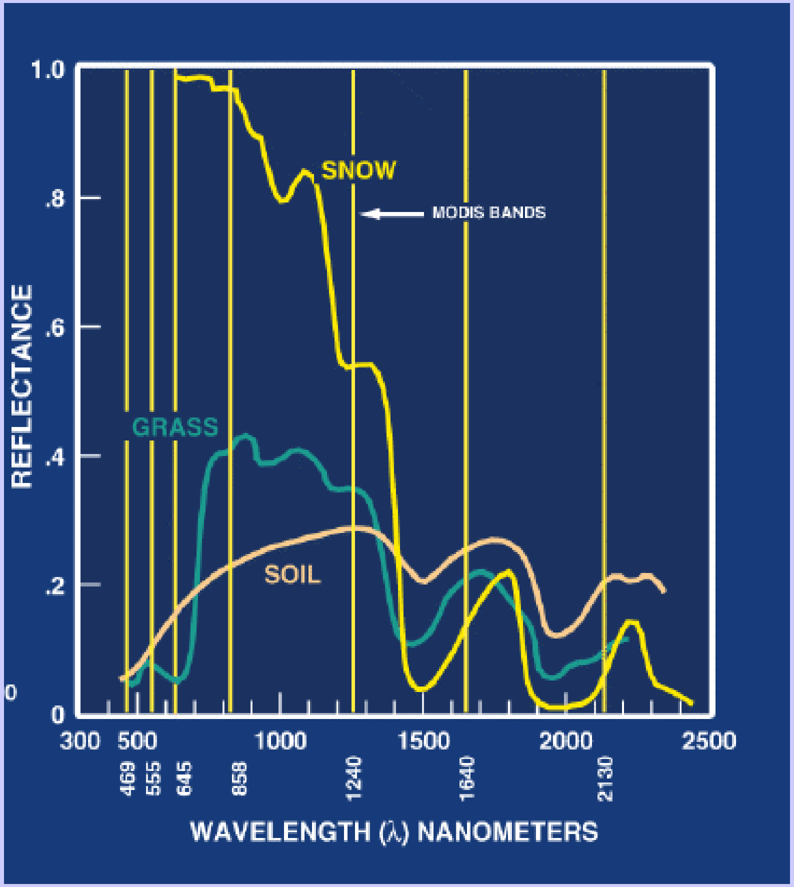


Example with MODIS





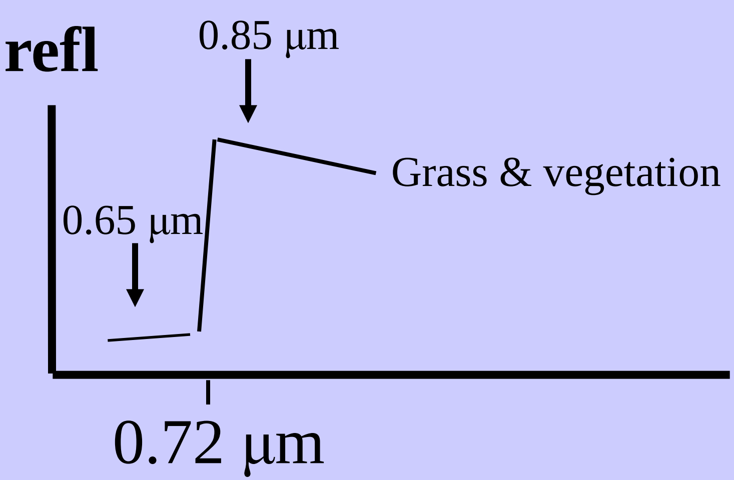
low refl at 1.6 um from snow in mountains



Investigating with Multi-spectral Combinations

Given the spectral response of a surface or atmospheric feature

Select a part of the spectrum where the reflectance or absorption changes with wavelength

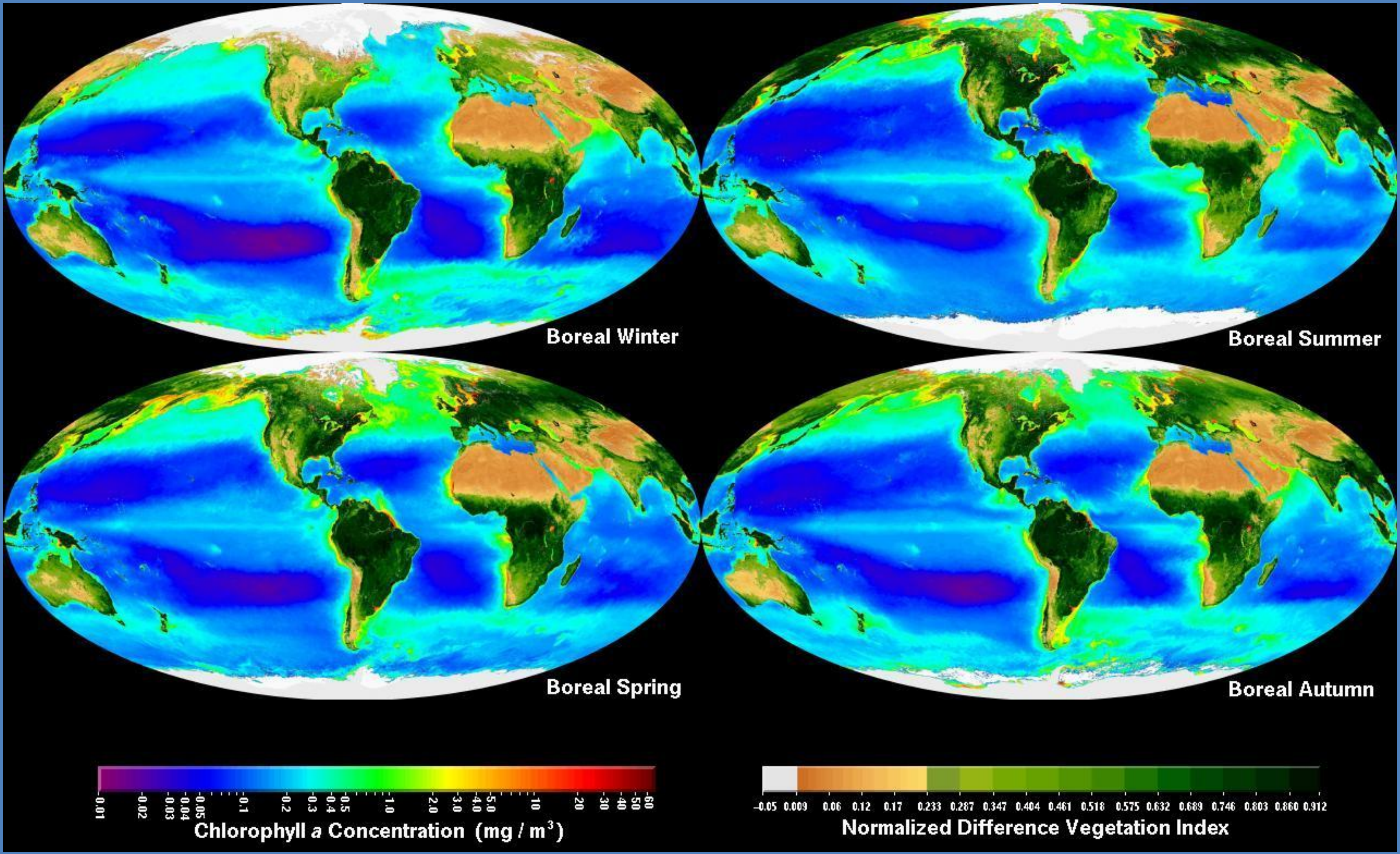


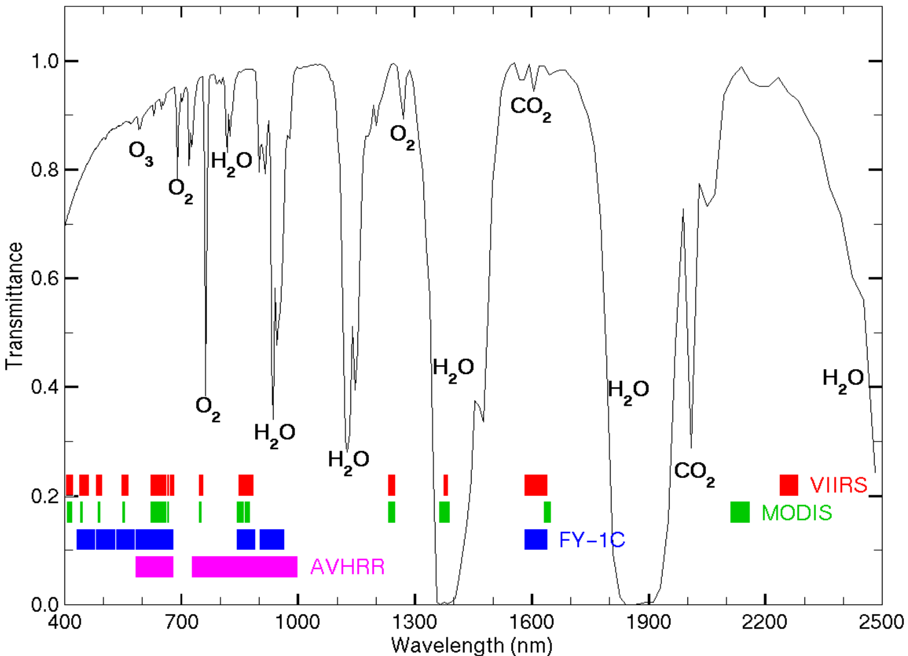
e.g. reflection from grass

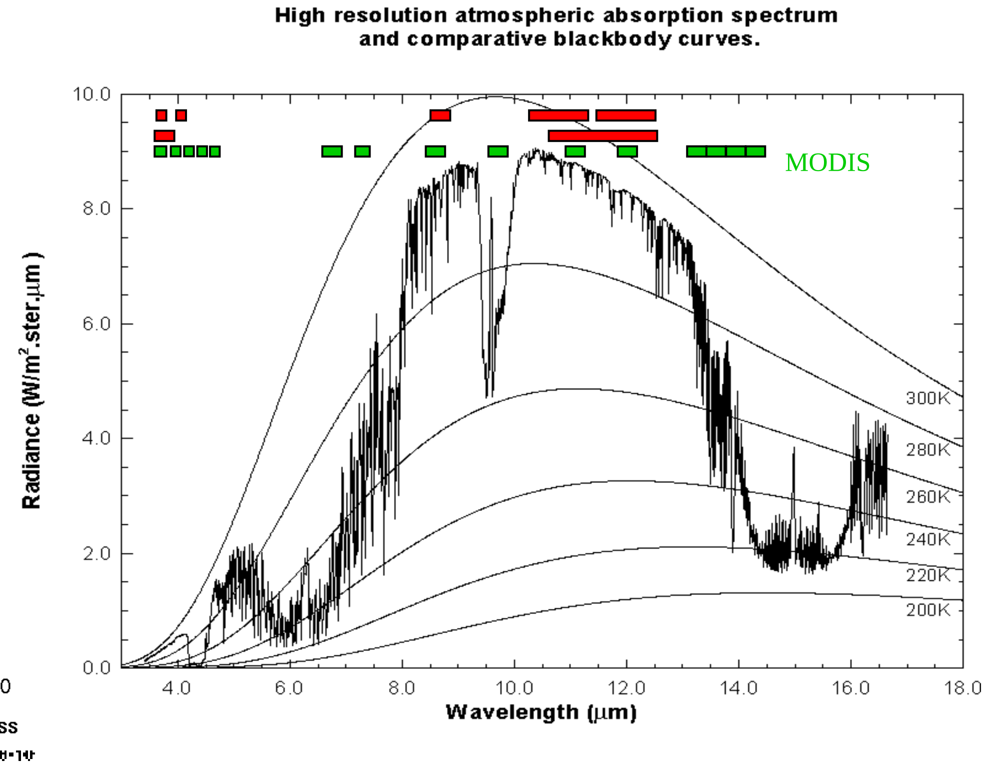
If 0.65 µm and 0.85 µm channels see the same reflectance than surface viewed is not grass;
if 0.85 µm sees considerably higher reflectance than 0.65 µm then surface might be grass

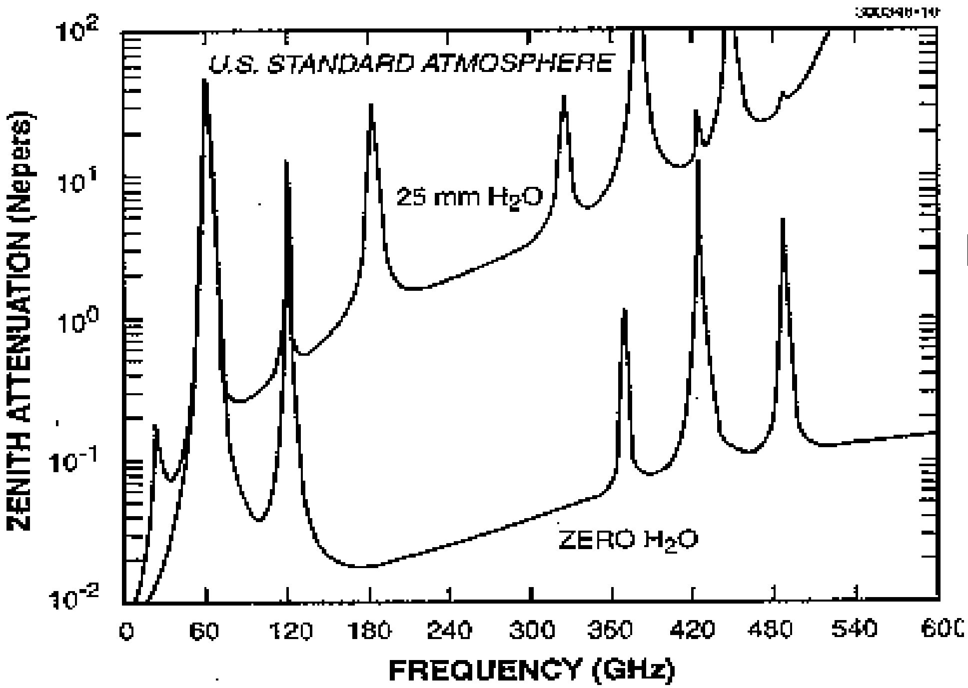
Seasonal Biosphere

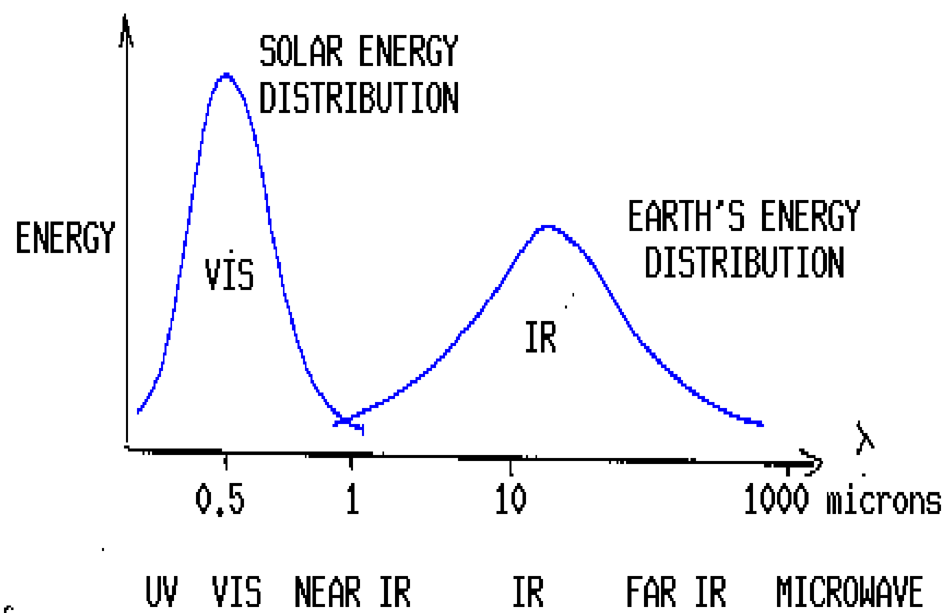
Ocean Chlorophyll-a & Terrestrial NDVI




Transmittance
Wavelength (nm)
O_3
O_2
H_2O
CO_2
VIIRS
MODIS
FY-1C
AVHRR


High resolution atmospheric absorption spectrum
and comparative blackbody curves.
Radiance (W/m^2.ster.μm)
Wavelength (μm)
MODIS
300K
280K
260K
240K
220K
200K
UW/CIMSS


U.S. STANDARD ATMOSPHERE
25 mm H_2O
ZERO H_2O
ZENITH ATTENUATION (Nepers)
FREQUENCY (GHz)


SOLAR ENERGY
DISTRIBUTION
EARTH'S ENERGY
DISTRIBUTION
ENERGY
VIS
IR
λ
0.5
1
10
1000 microns
UV
VIS
NEAR IR
IR
FAR IR
MICROWAVE