Investigations with High Spectral Resolution IR Data

Lectures in Benevento
Jun 2007

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UW/CIMSS/AOS

Investigations with High Spectral Resolution Data from AIRS

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NOAA/NESDIS
in collaboration with
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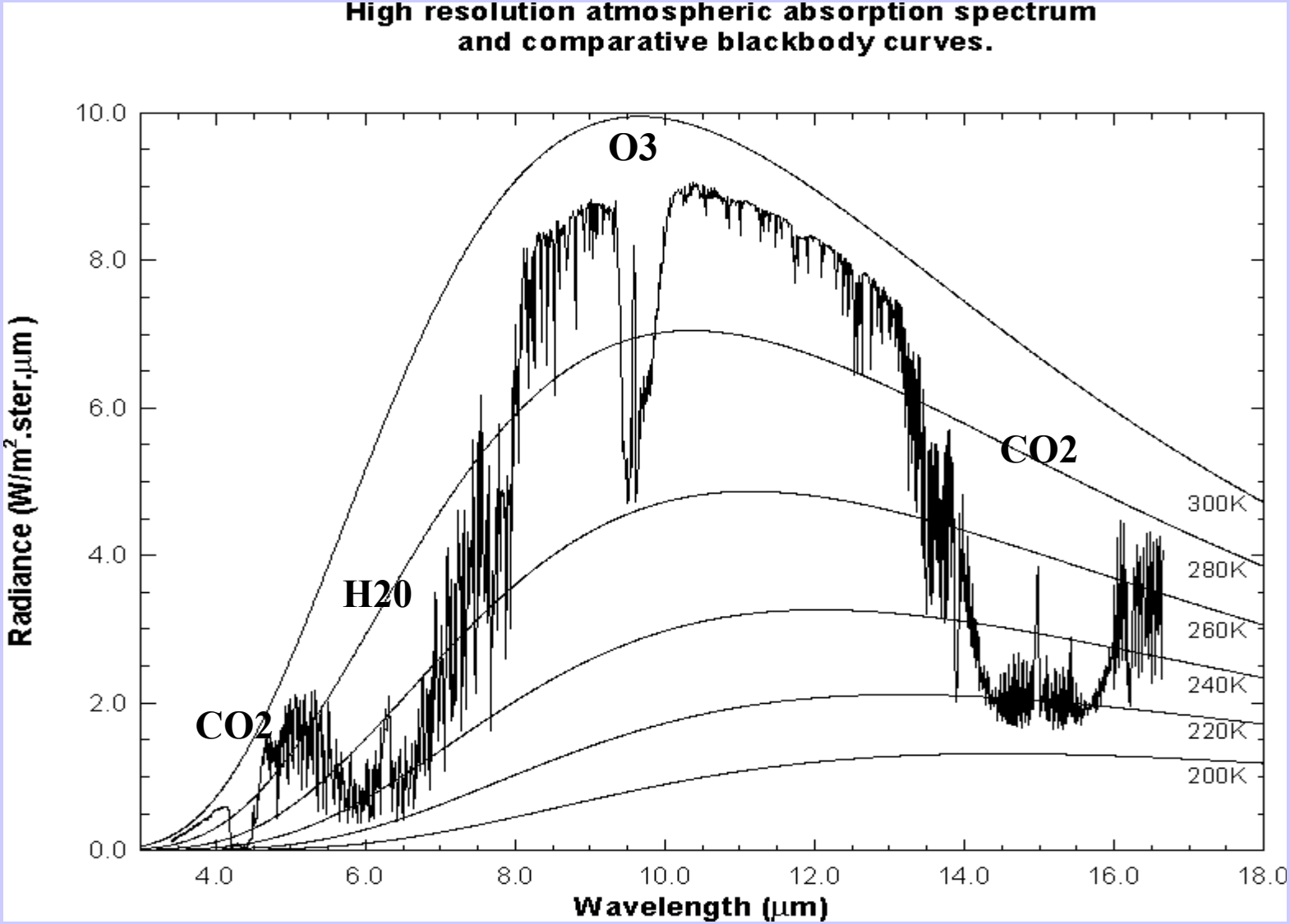
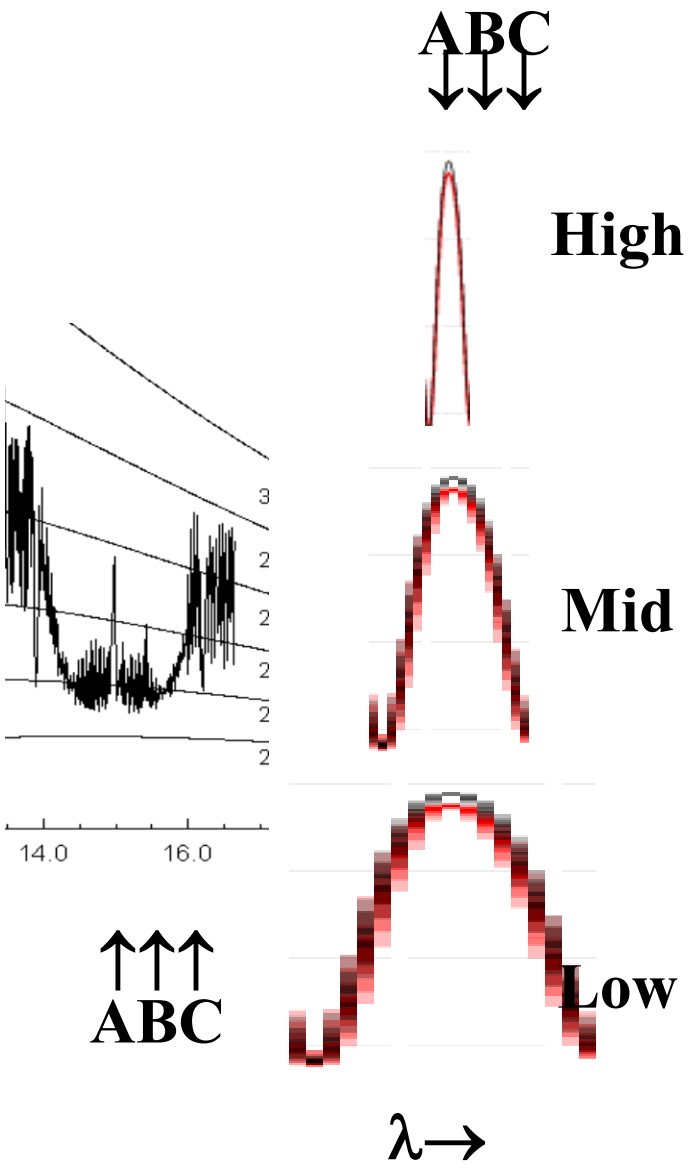
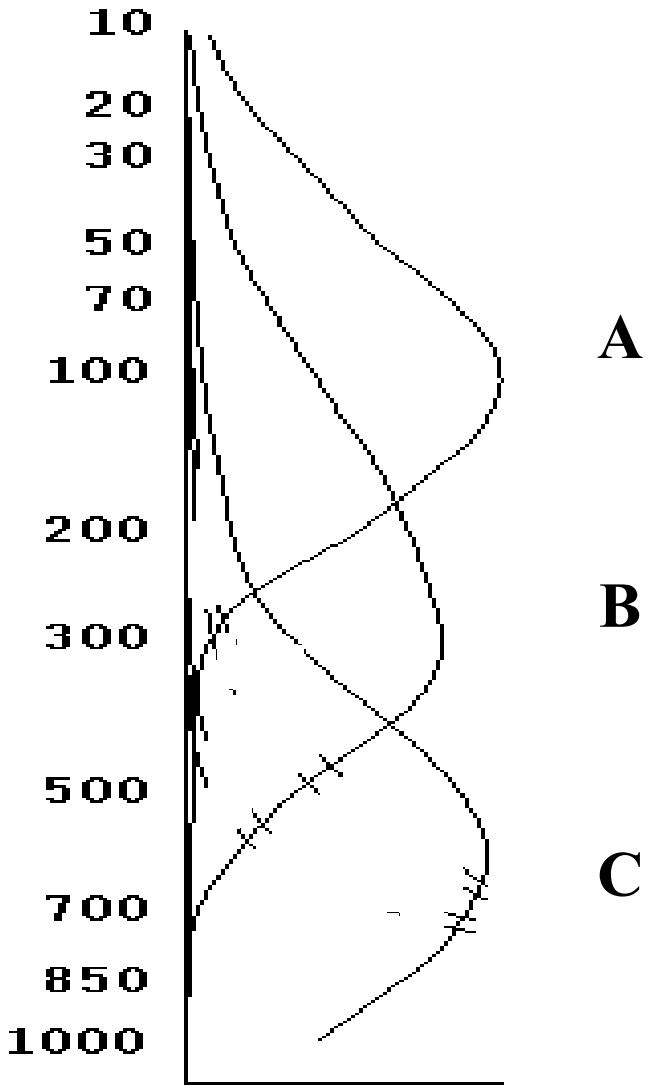
Earth emitted spectra overlaid on Planck function envelopes



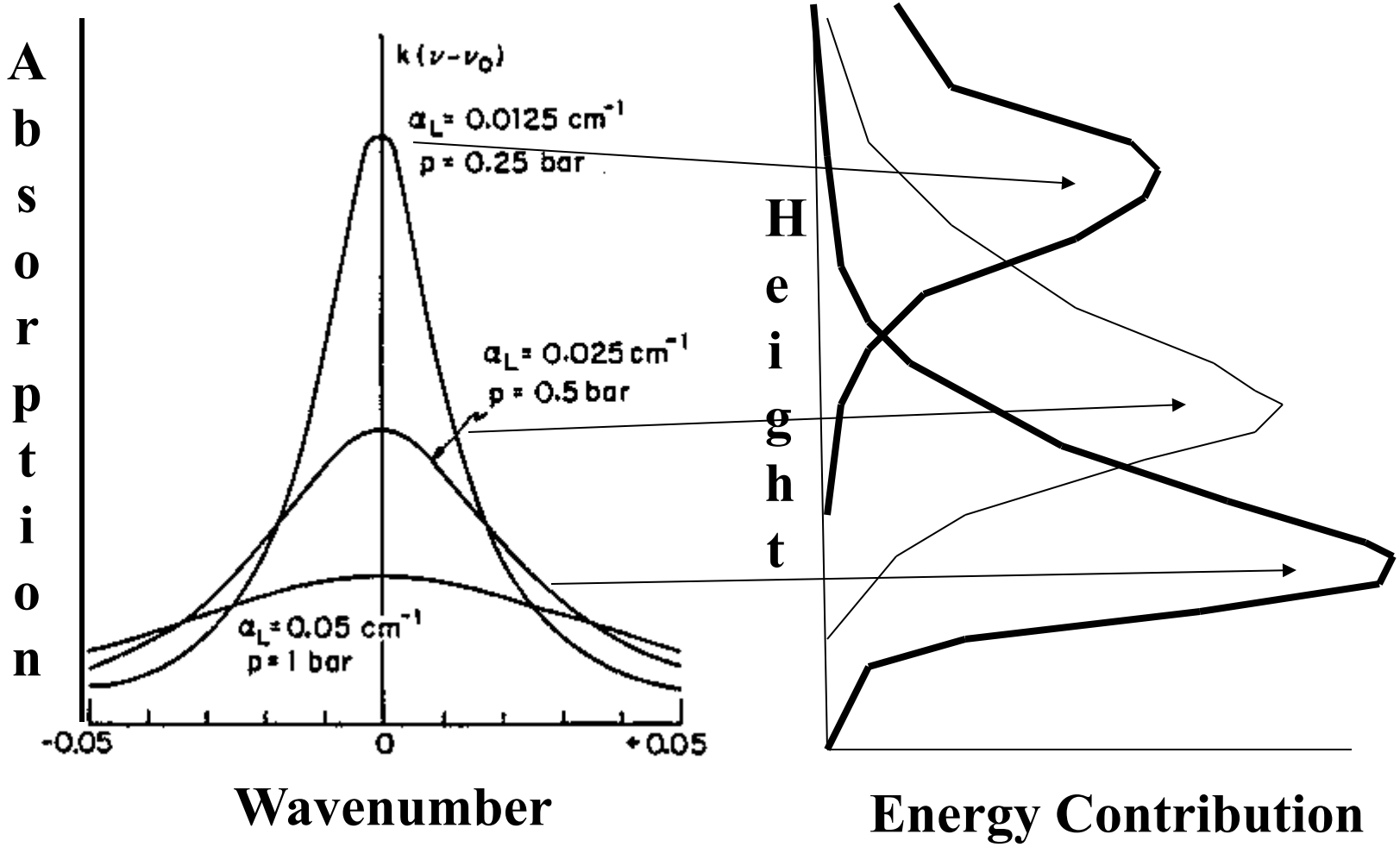
line broadening with pressure helps to explain weighting functions





Fourier Transform Spectrocopy

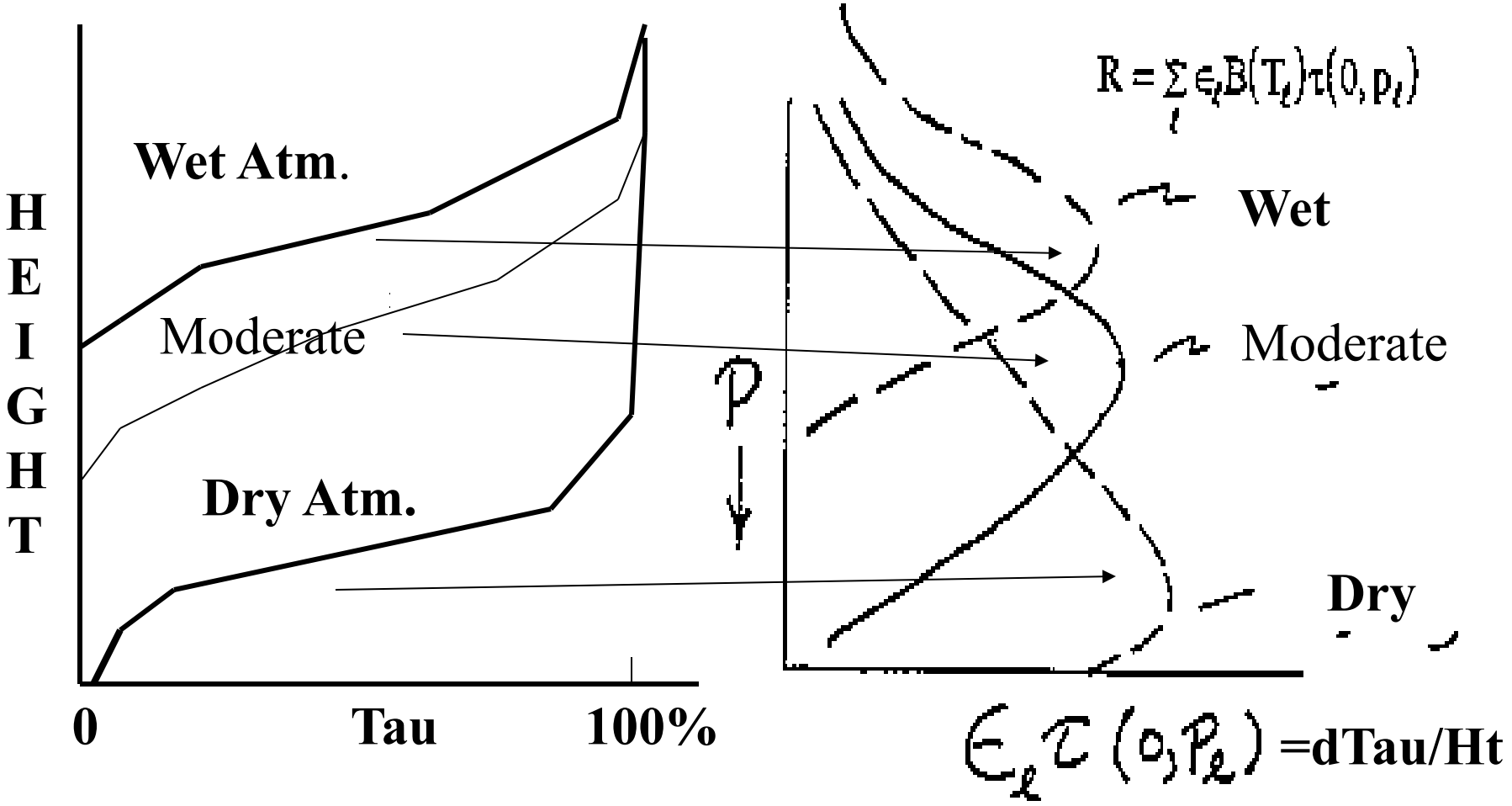
Infrared Atmospheric Sounding



Fourier Transform Spectroscopy

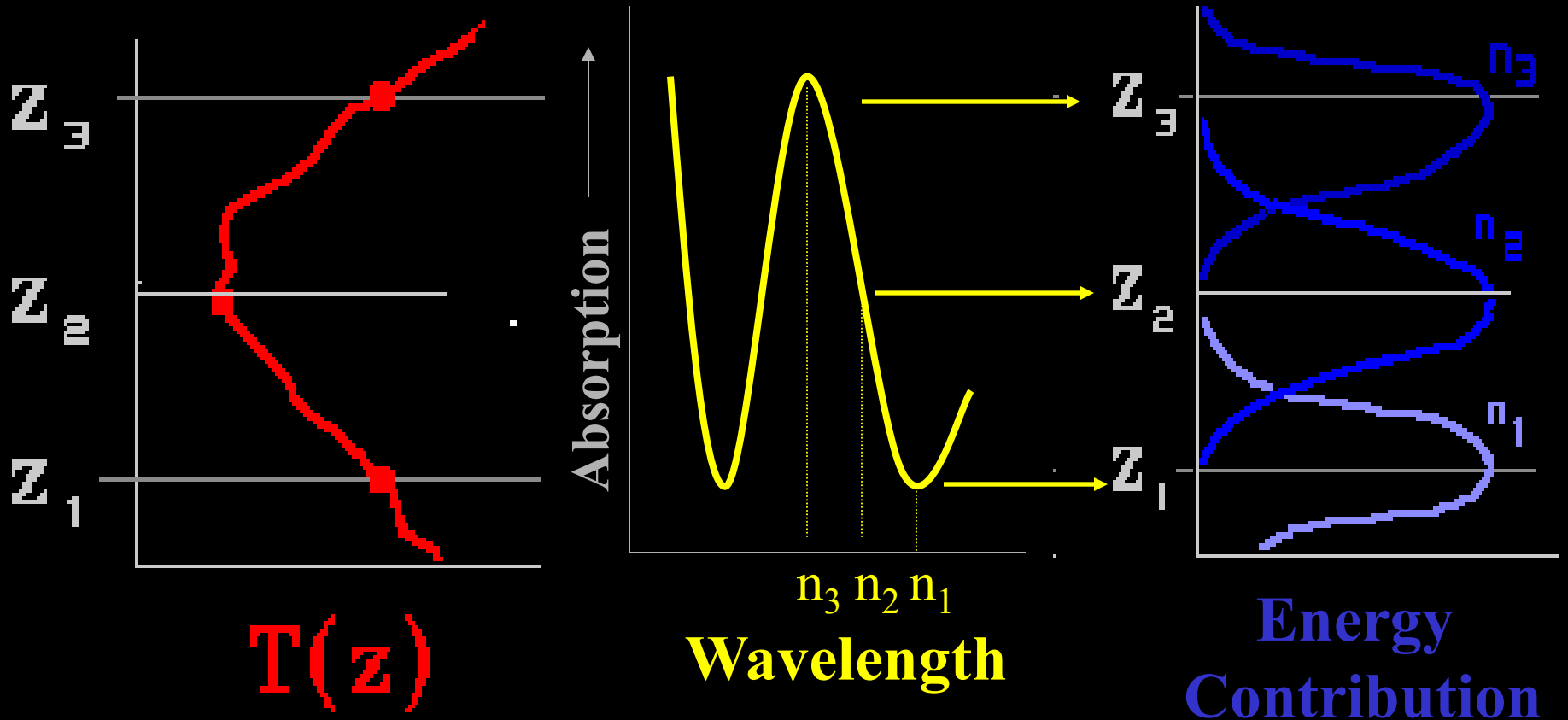
Infrared Atmospheric Sounding

For a given water vapor spectral channel

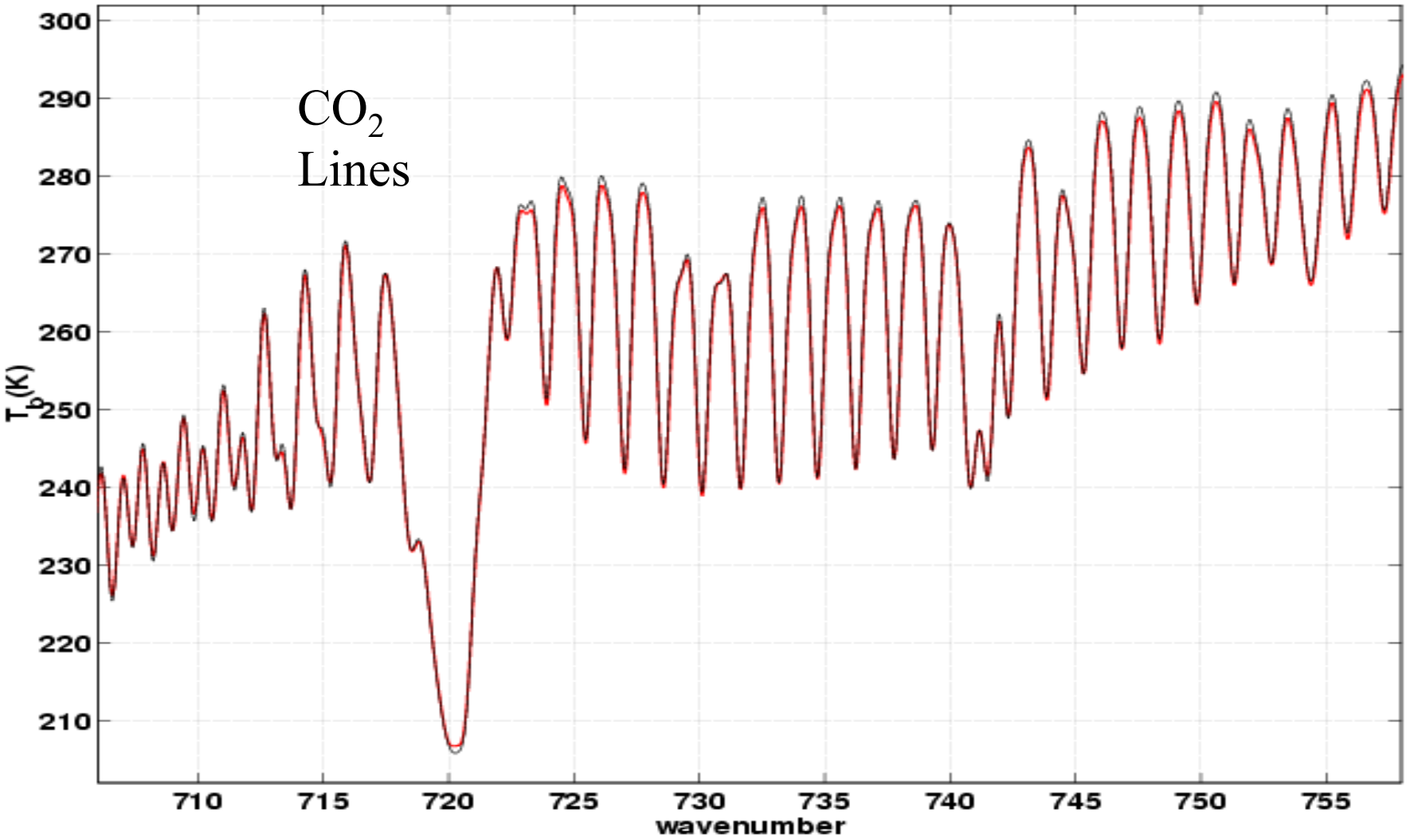


Fourier Transform Spectroscopy
Infrared Atmospheric Sounding

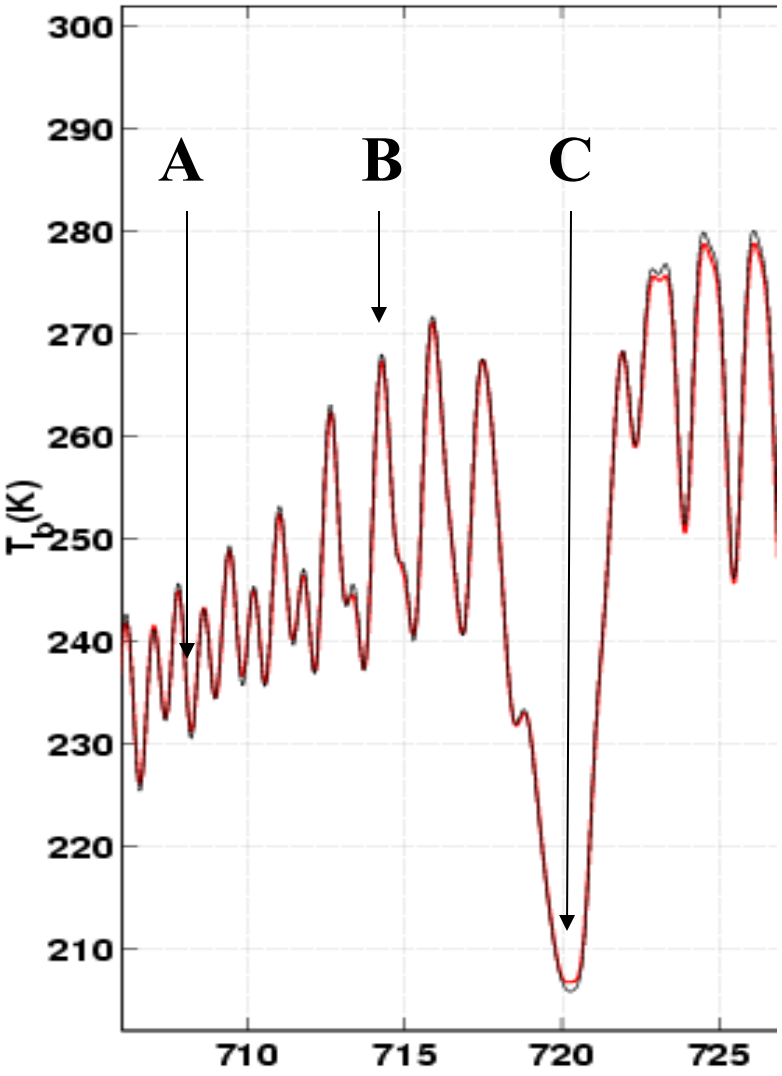
Wavelength Converts to Altitude



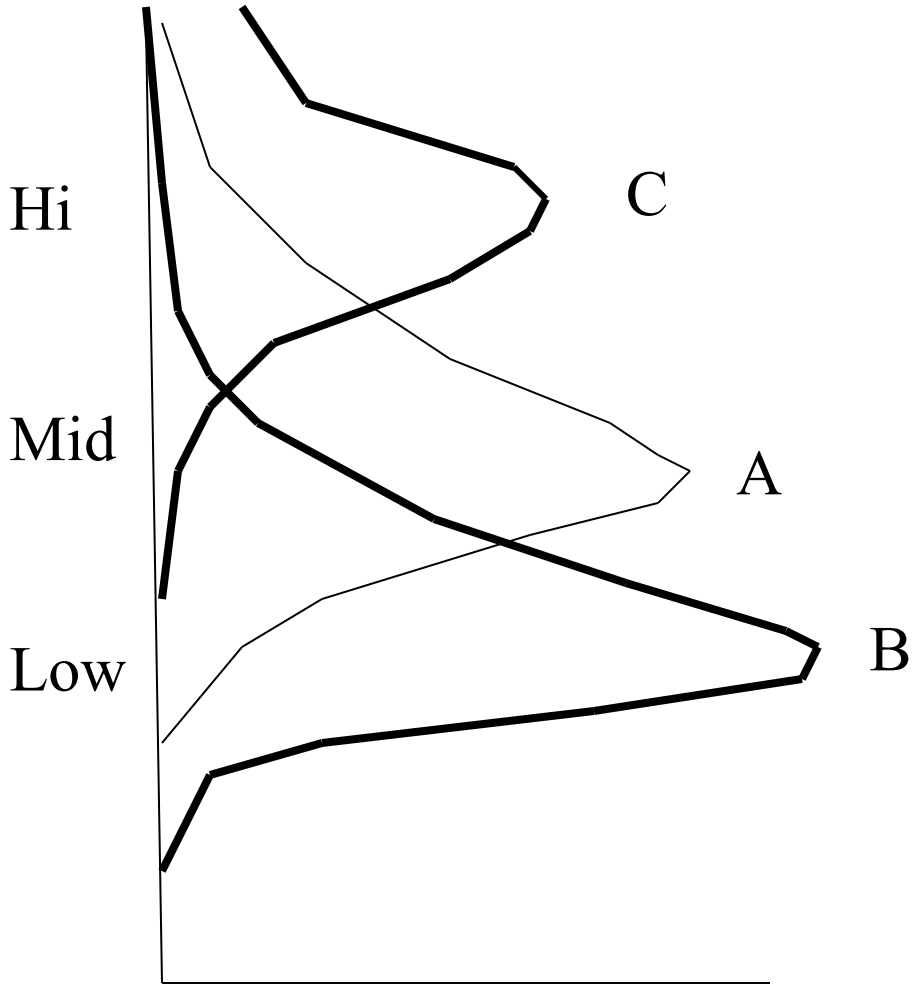
Earth emitted spectrum in CO2 sensitive 705 to 760 cm-1



Associating relative weighting functions with the CO2 rotational bands

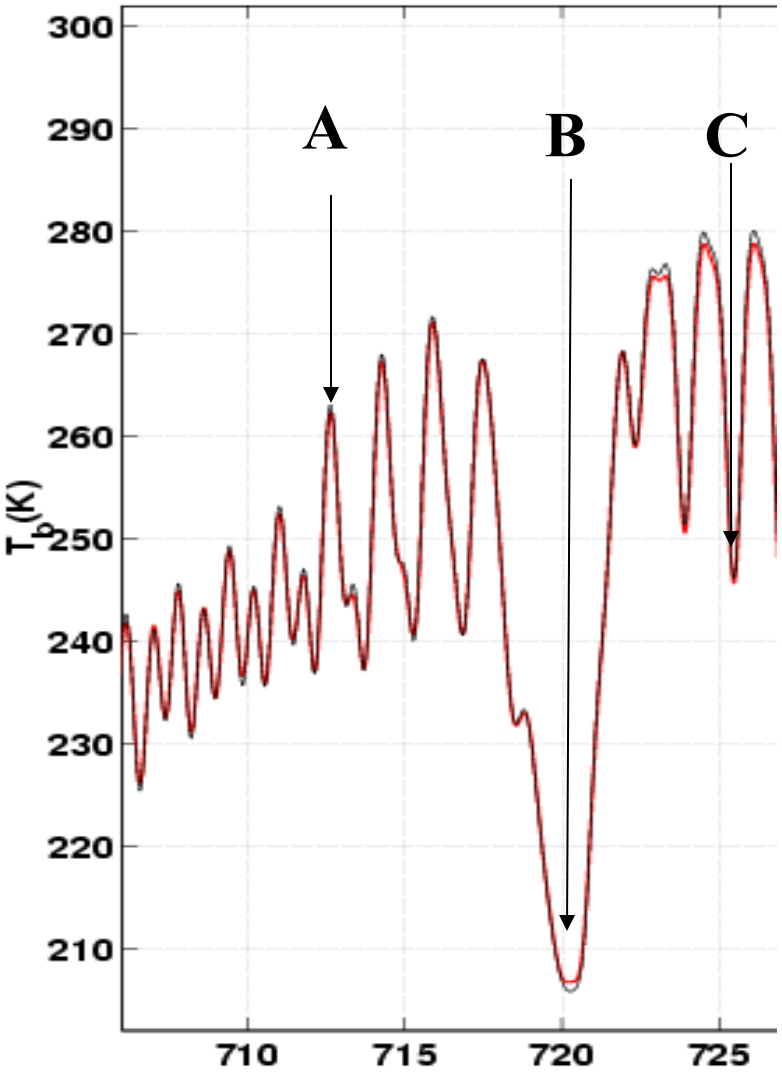


Wavenumber

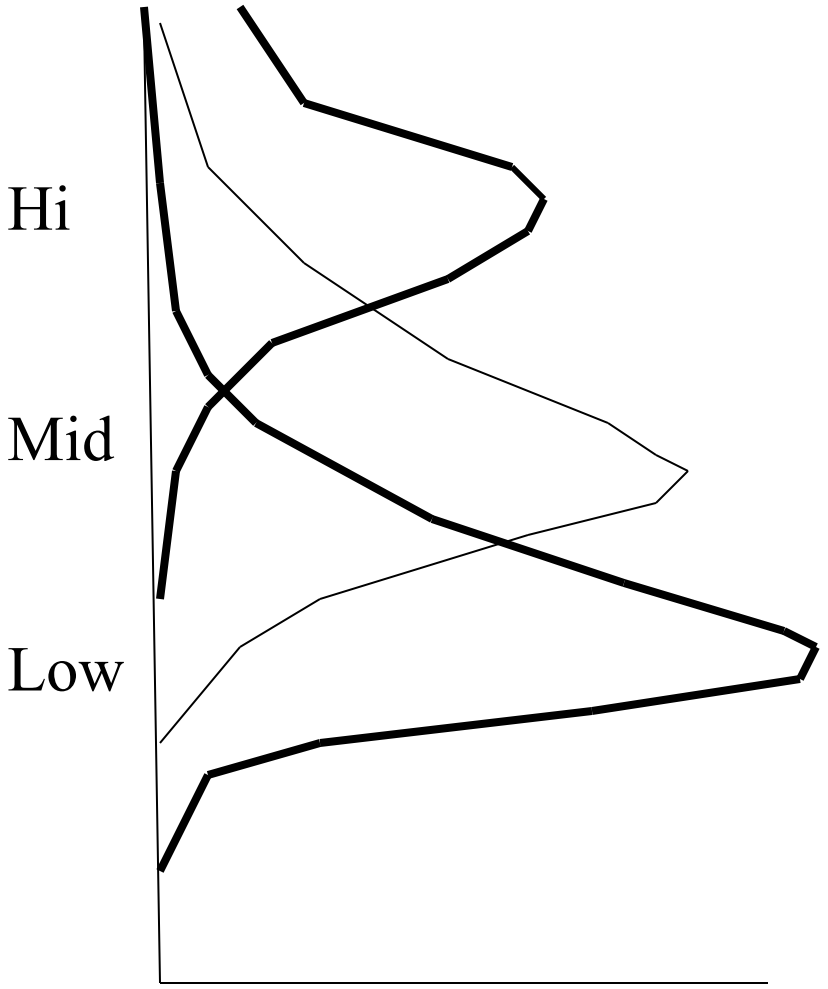


Weighting Function

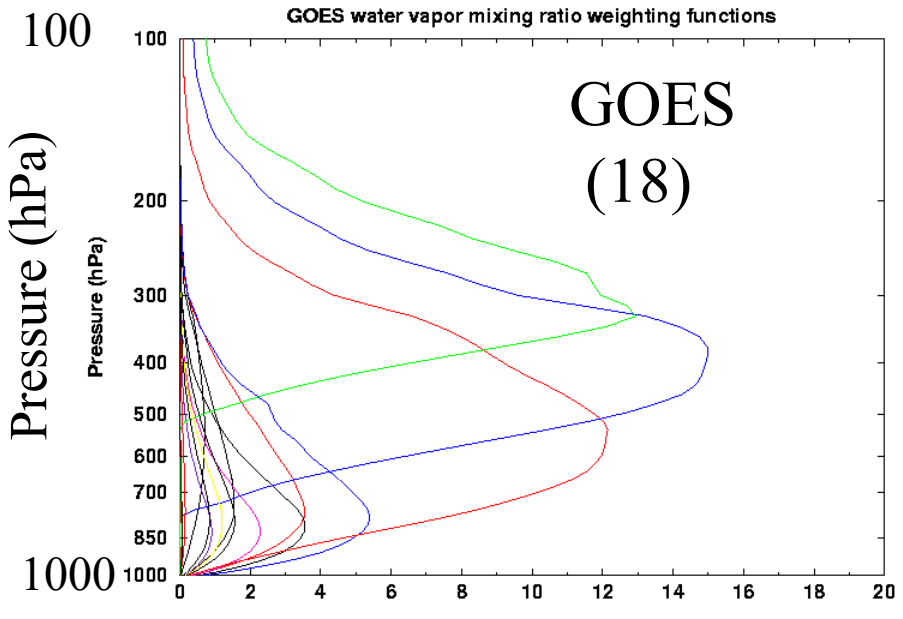
Associating relative weighting functions with the CO2 rotational bands

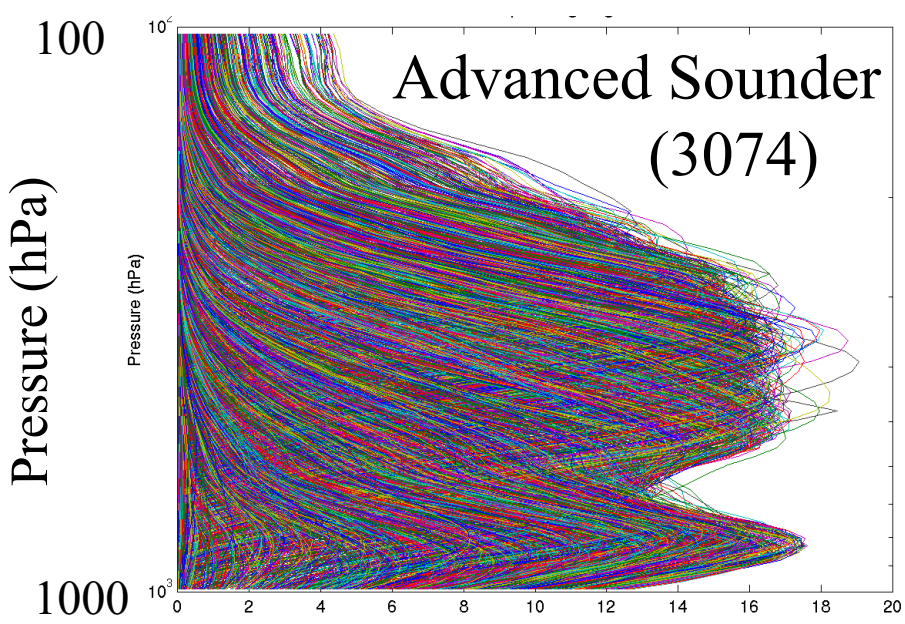


Wavenumber



Weighting Function

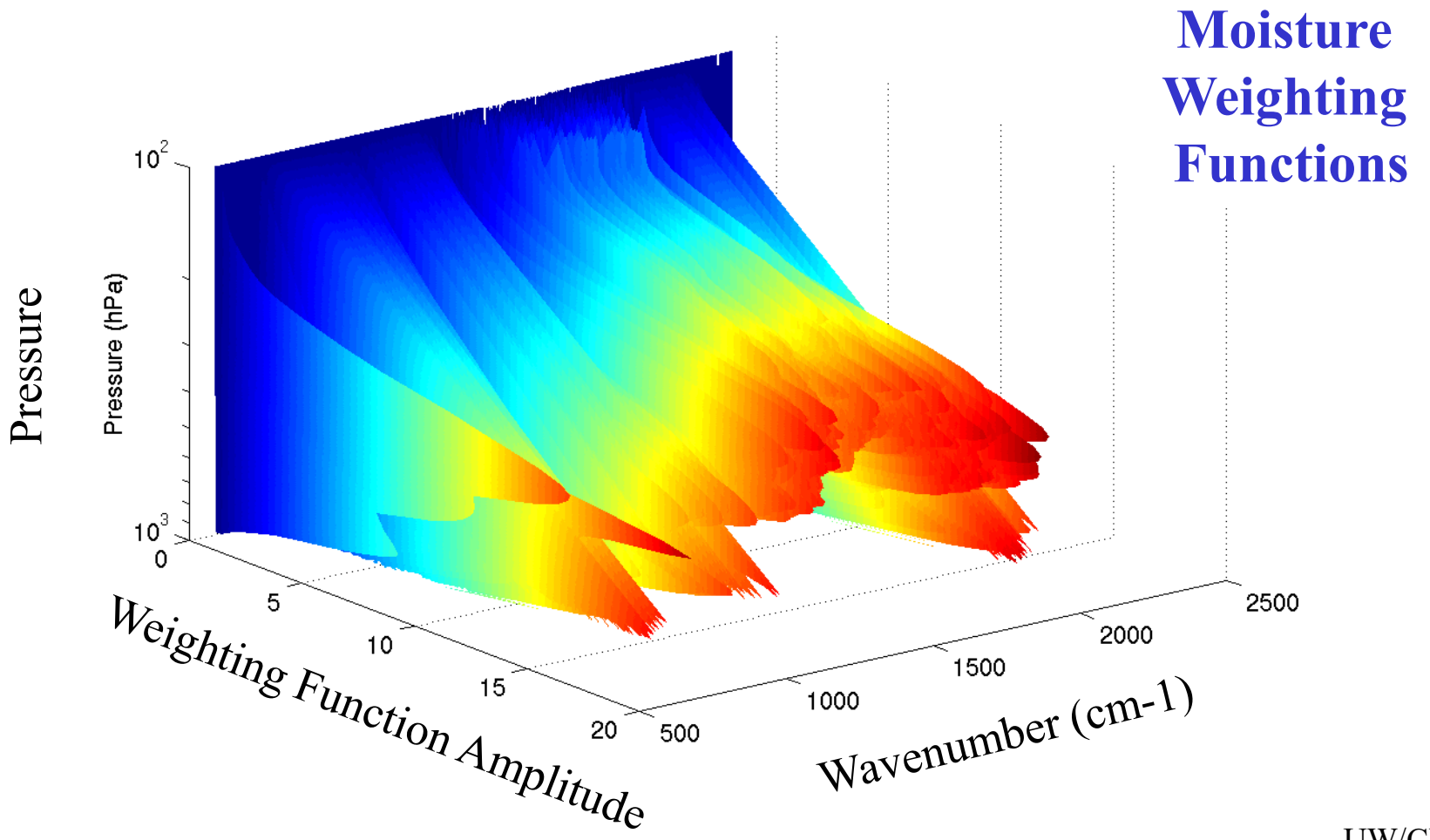




Moisture Weighting Functions

High spectral resolution advanced sounder will have more and sharper weighting functions compared to current GOES sounder. Retrievals will have better vertical resolution.

These water vapor weighting functions reflect the radiance sensitivity of the specific channels to a water vapor % change at a specific level (equivalent to dR/dlnq scaled by dlnp).



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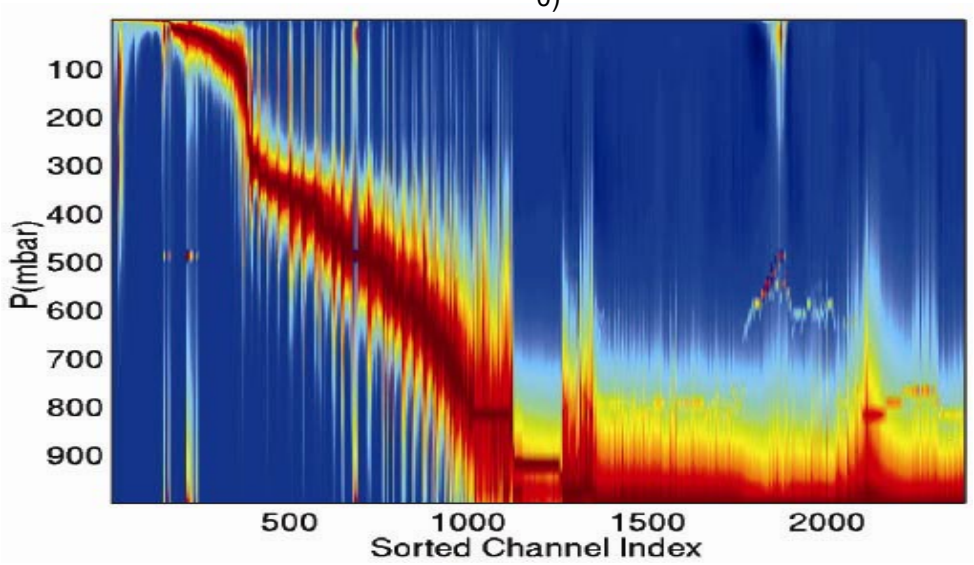
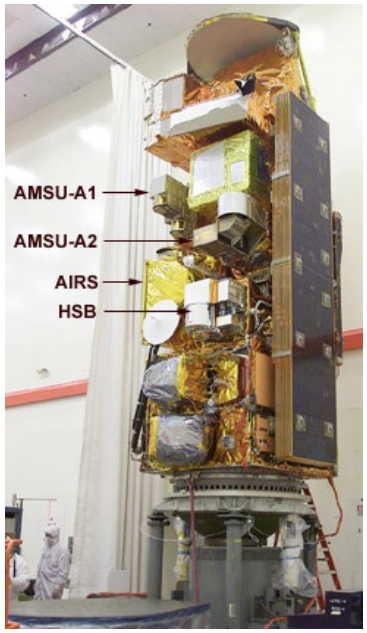
The advanced sounder has more and sharper weighting functions

temperature weighting functions sorted by pressure of their peak (blue = 0)



AIRS On Aqua

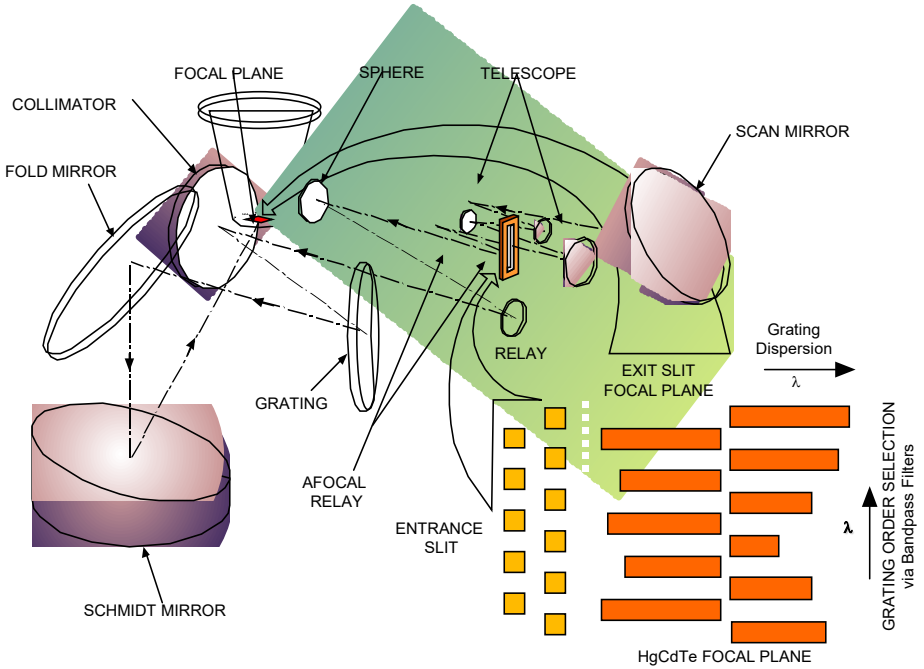


Instrument

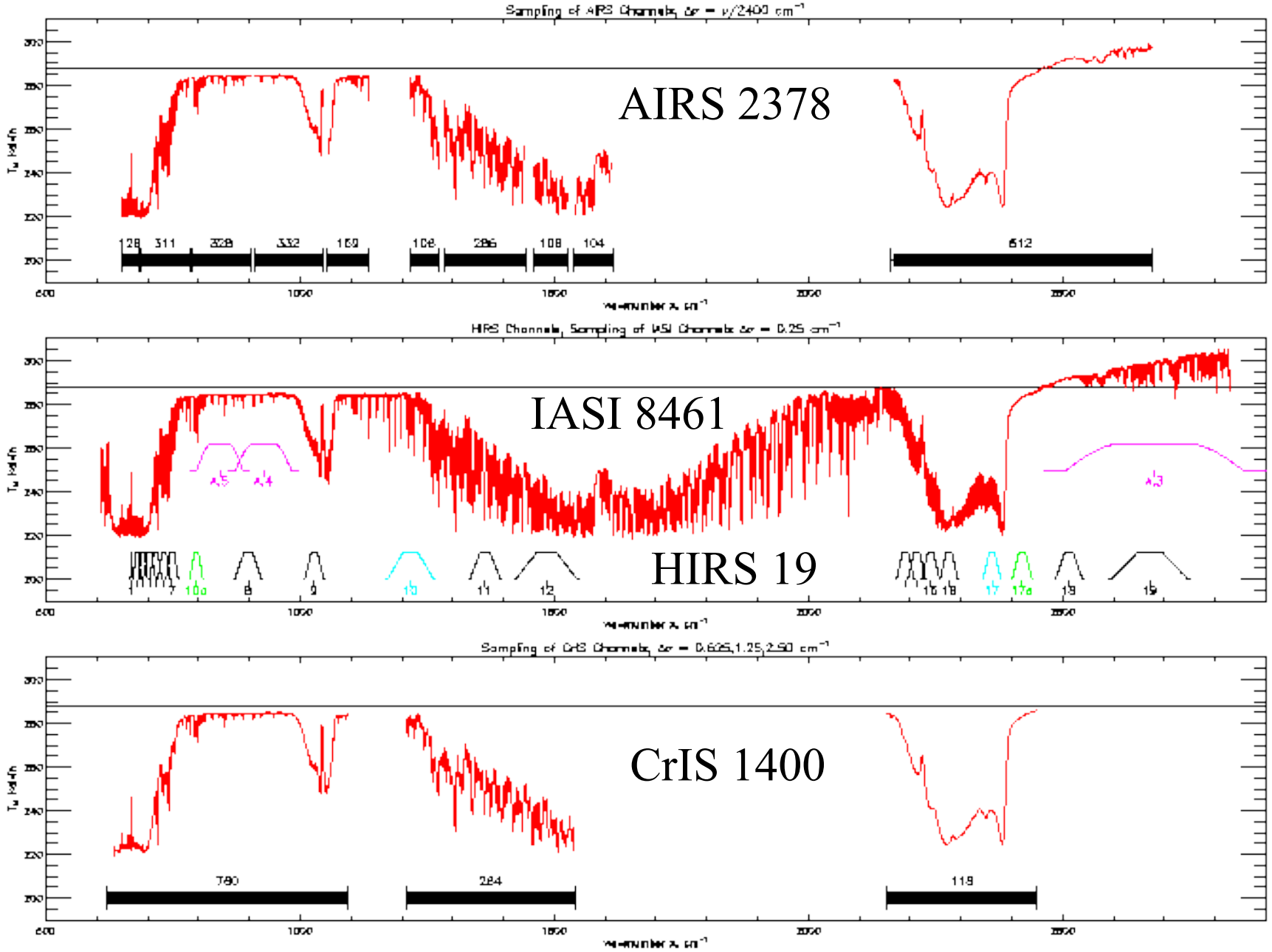
- Hyperspectral radiometer with **resolution of 0.5 – 2 cm^{-1}**
- Extremely well calibrated pre-launch
- **Spectral range: 650 – 2700 cm^{-1}**
- Associated microwave instruments (AMSU, HSB)

Design

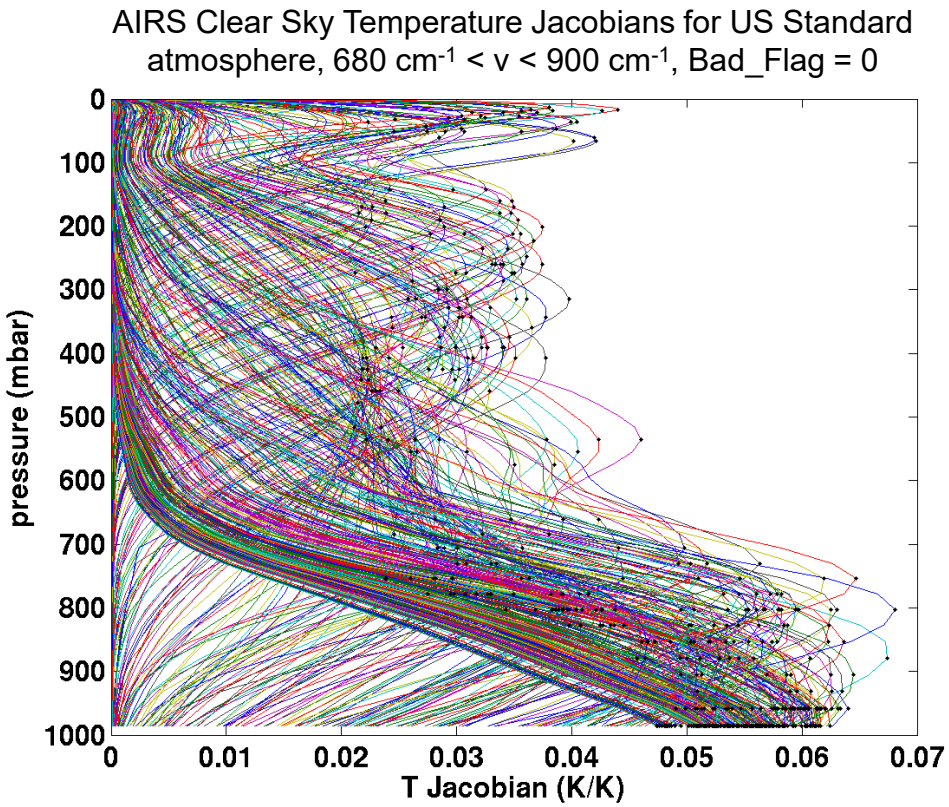
- Grating Spectrometer passively cooled to 160K, stabilized to 30 mK
- **PV and PC HdCdTe focal plane cooled to 60K** with redundant active pulse tube cryogenic coolers
- **Focal plane has ~5000 detectors,** 2378 channels. PV detectors (all below 13 microns) are doubly redundant. Two channels per resolution element (n/Dn = 1200)
- 310 K Blackbody and space view provides radiometric calibration
- Paralyene coating on calibration mirror and upwelling radiation provides spectral calibration
- **NEDT (per resolution element) ranges from 0.05K to 0.5K**



Spectral filters at each entrance slit and over each FPA array isolate color band (grating order) of interest

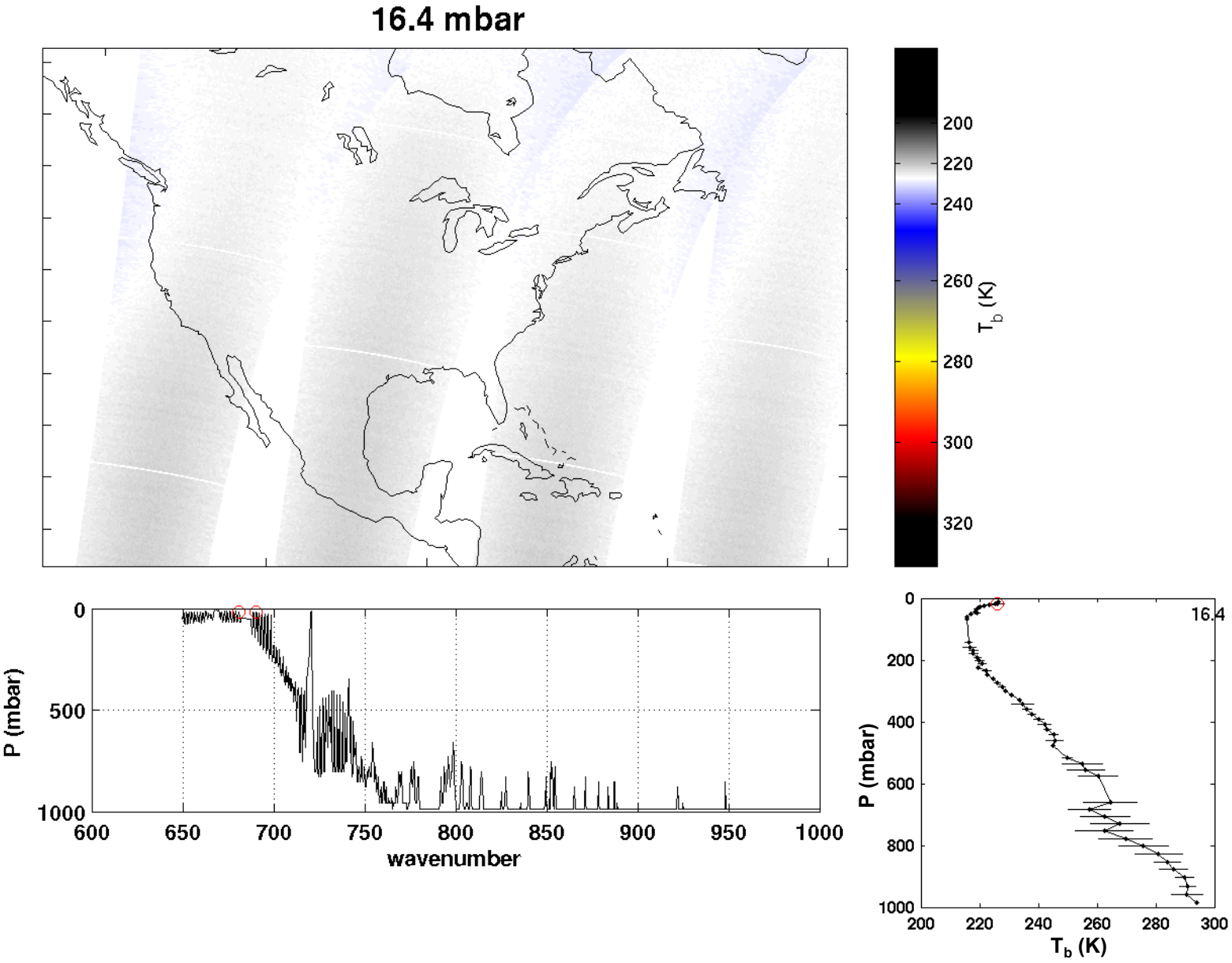

AIRS 2378
IASI 8461
HIRS 19
CrIS 1400

AIRS movie

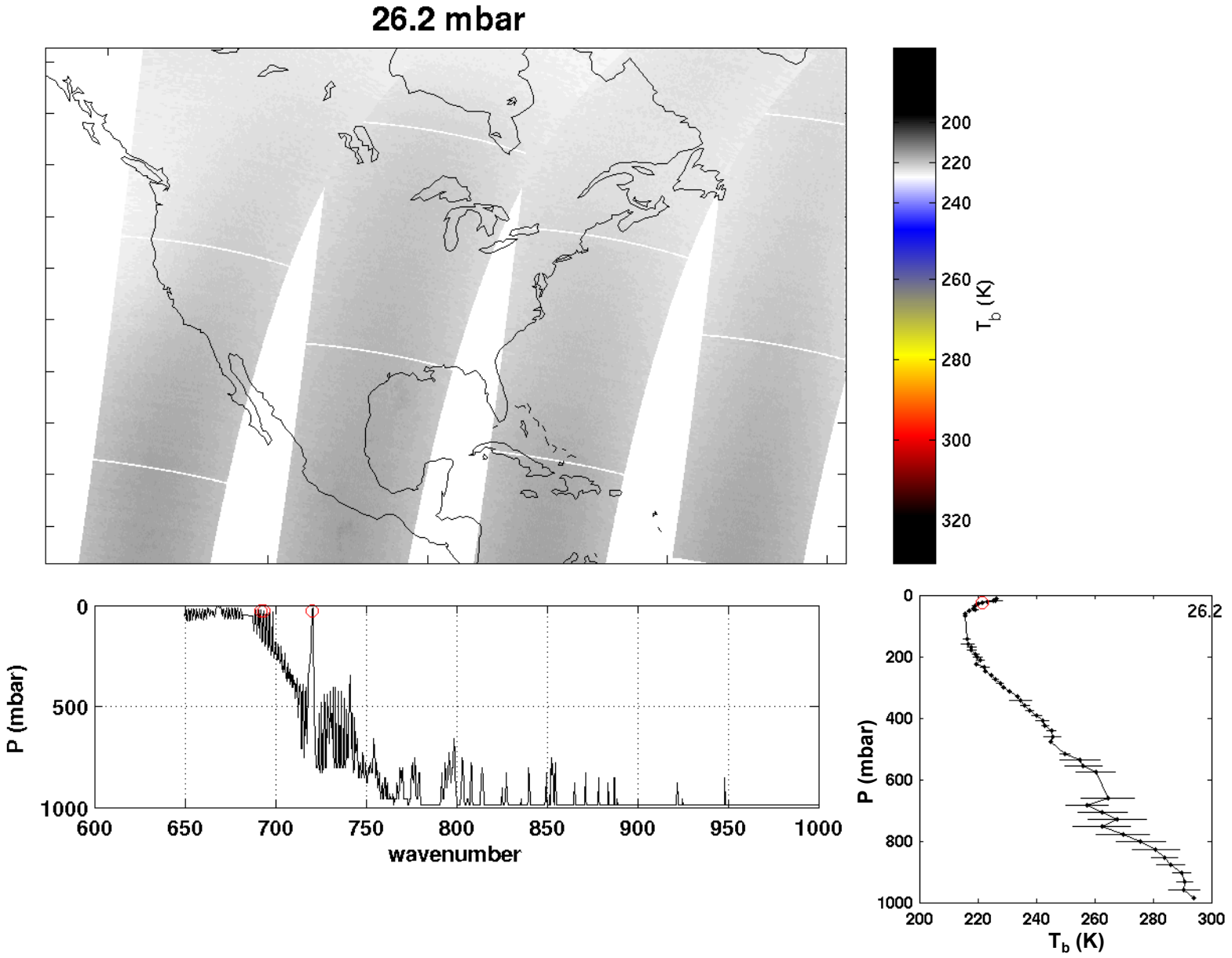


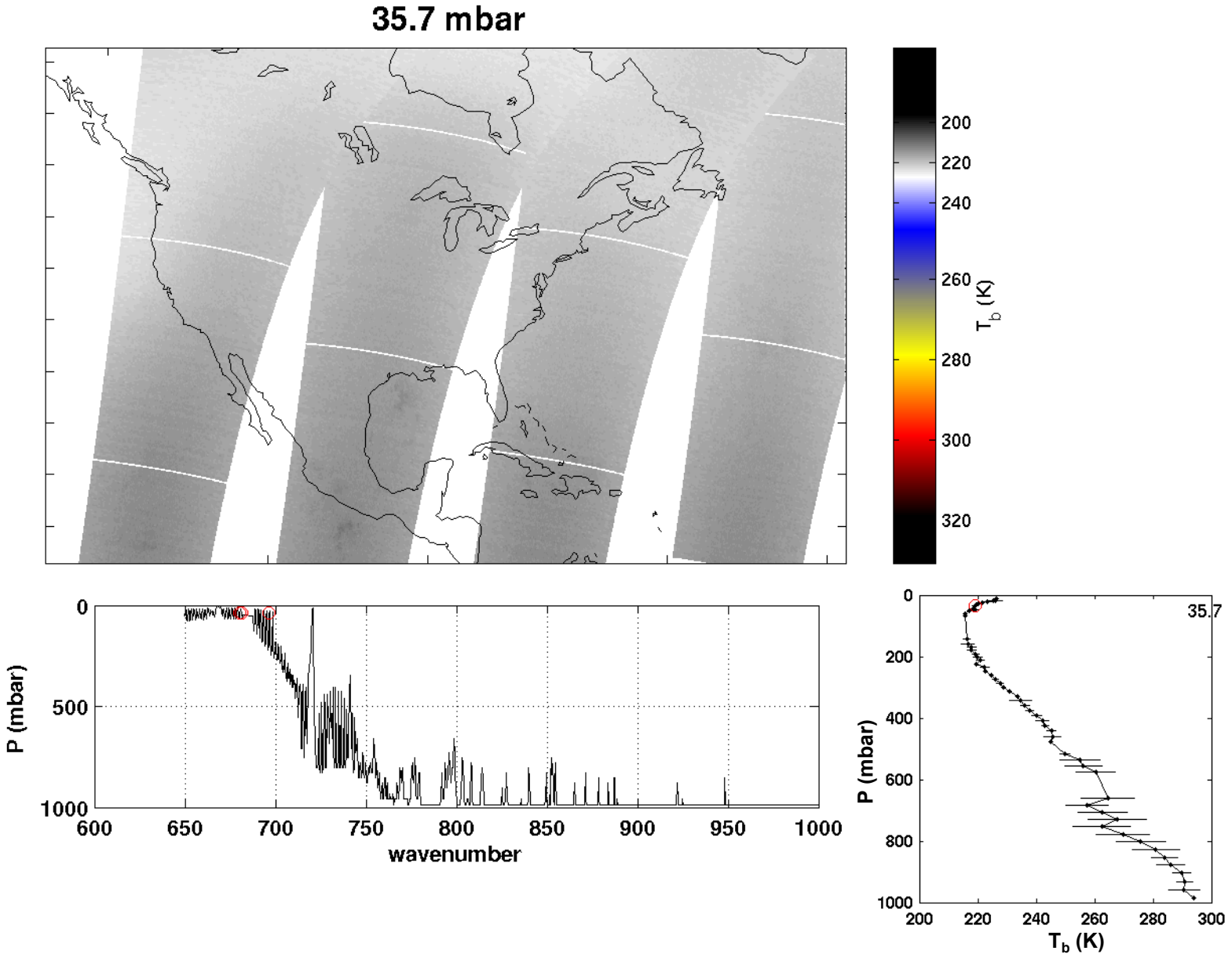
↙ Sort channels by pressure of Jacobian peaks

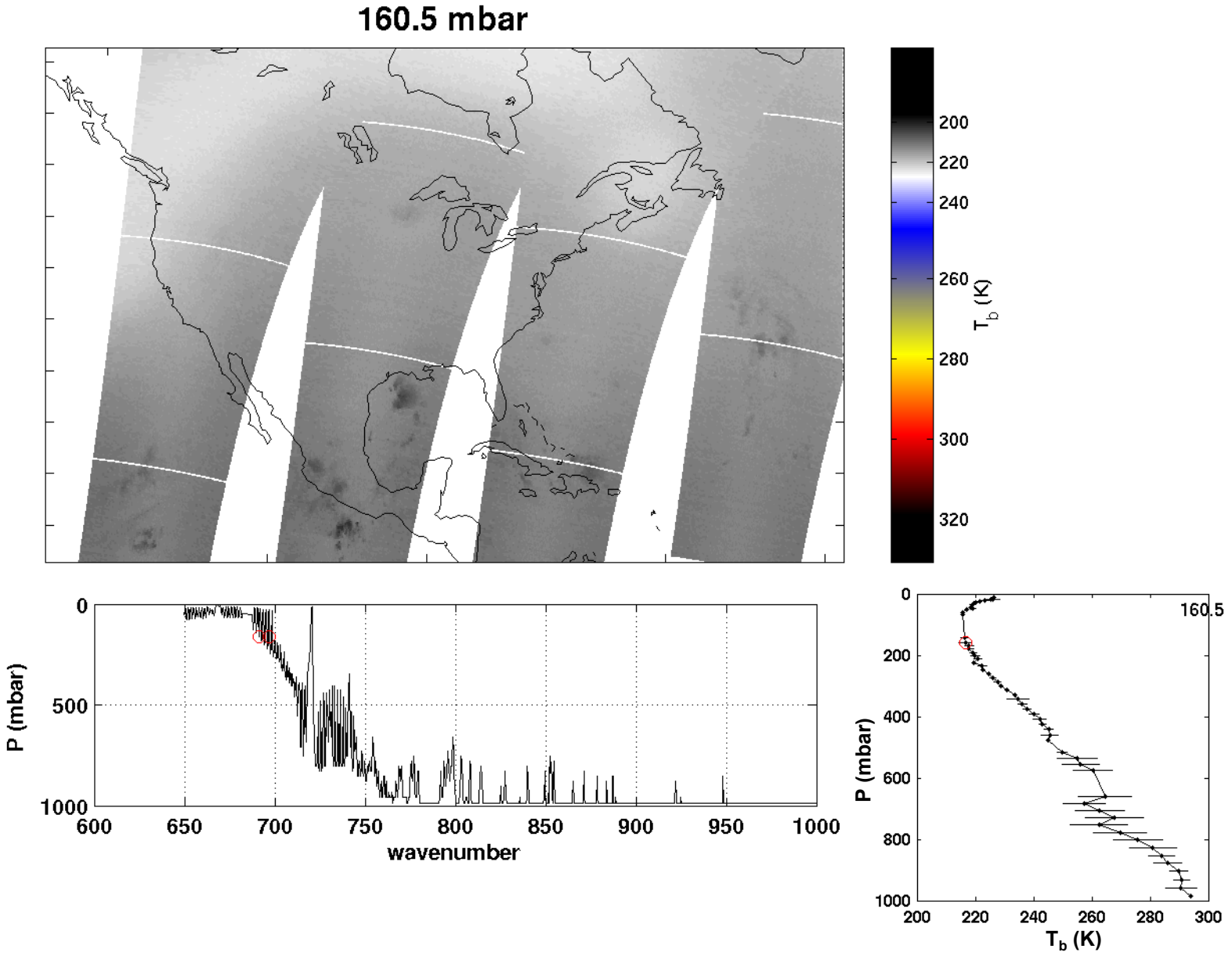
AIRS nighttime granules over CONUS, 6 Sept 2002

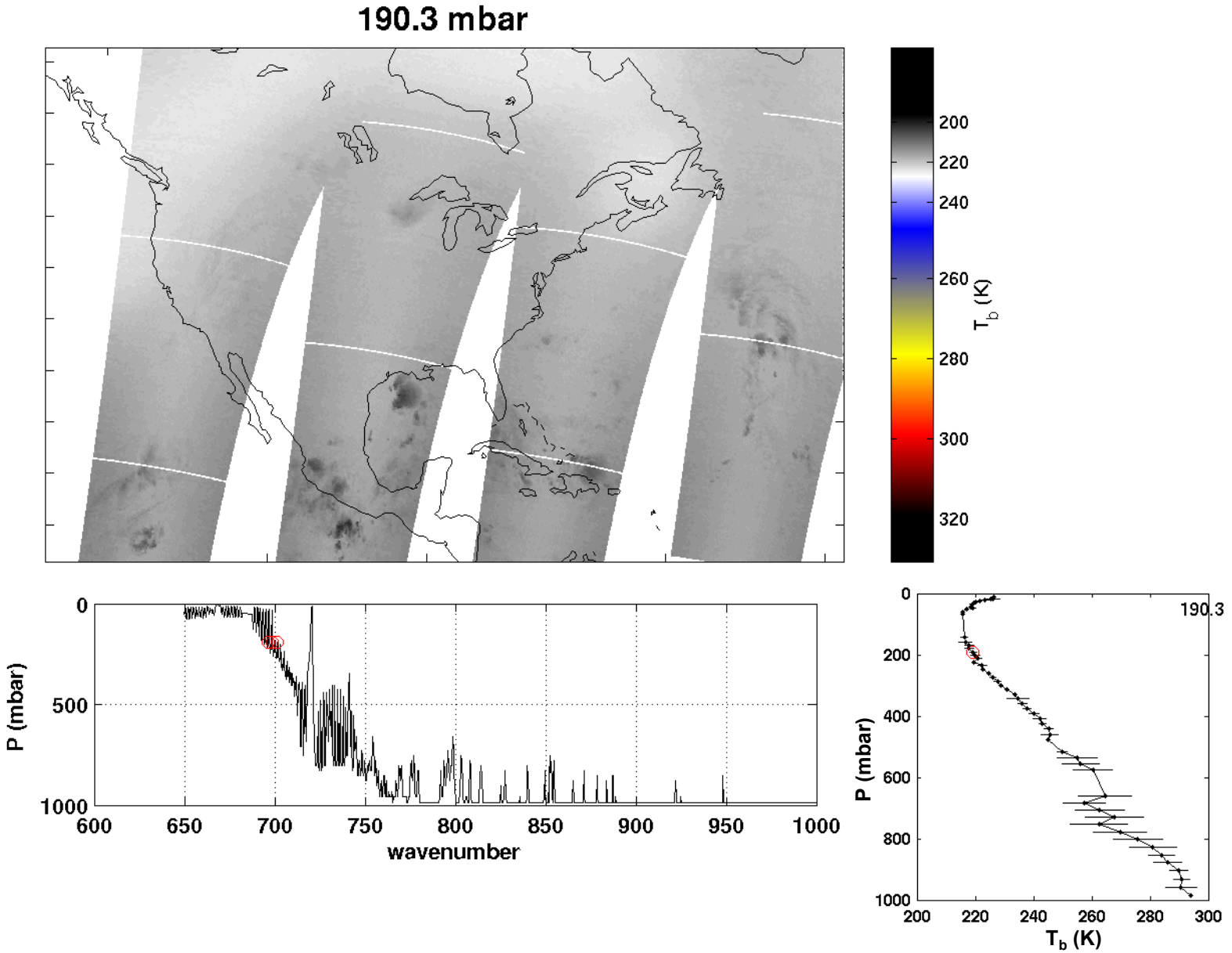


Mouse click or page down to start movie


26.2 mbar
200
220
240
260
280
300
320
T_b (K)
P (mbar)
0
500
1000
600
650
700
750
800
850
900
950
1000
wavenumber
26.2
200
400
600
800
1000
220
240
260
280
300
T_b (K)


35.7 mbar
200
220
240
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
0
200
400
600
800
1000
P (mbar)
35.7
200
220
240
260
280
300
T_b (K)


160.5 mbar
200
220
240
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
160.5
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)


190.3 mbar
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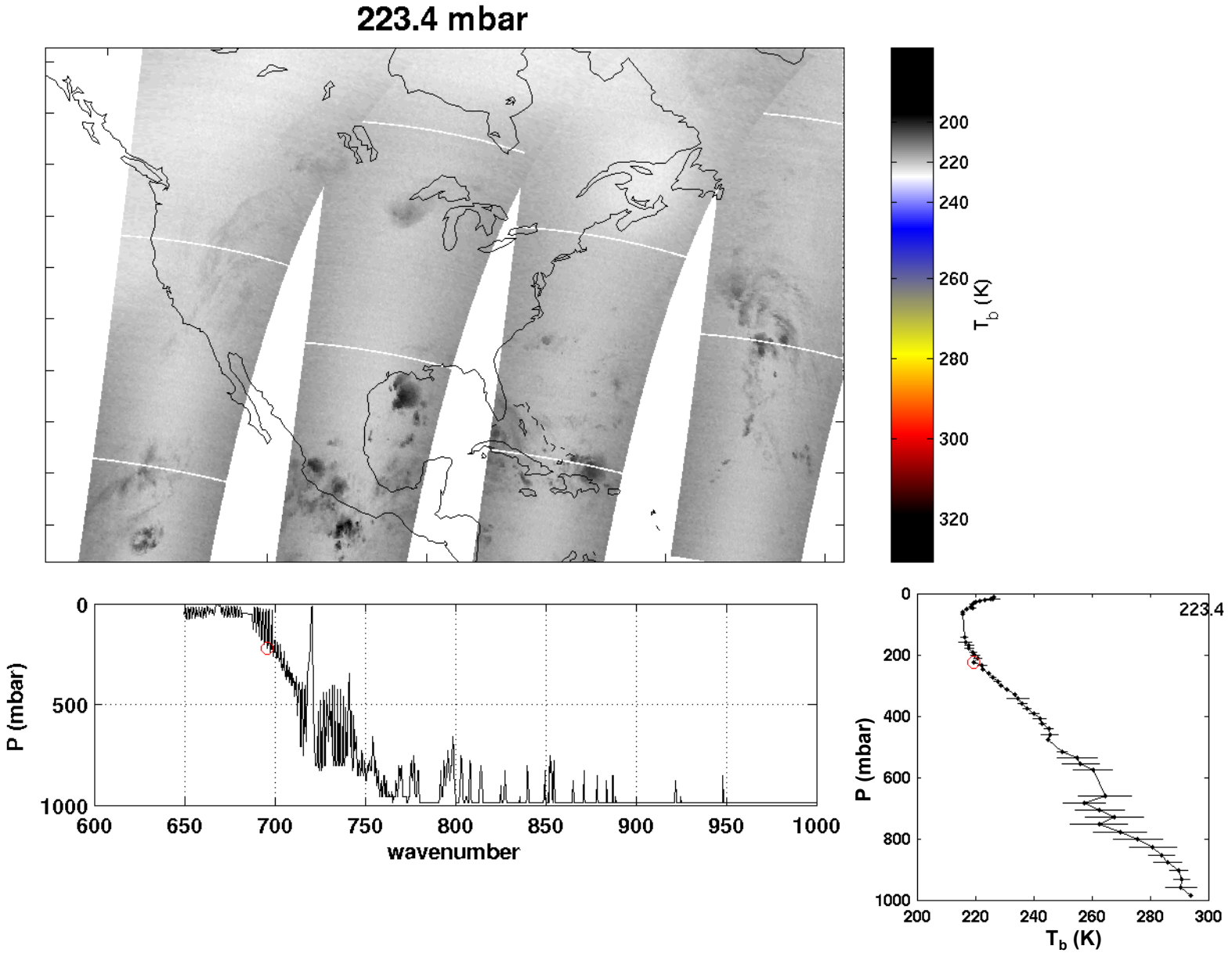
220
240
260
280
300
320
T_b (K)
P (mbar)
0
500
1000
600
650
700
750
800
850
900
950
1000
wavenumber
190.3
P (mbar)
0
200
400
600
800
1000
200
220
240
260
280
300
T_b (K)


223.4 mbar
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240
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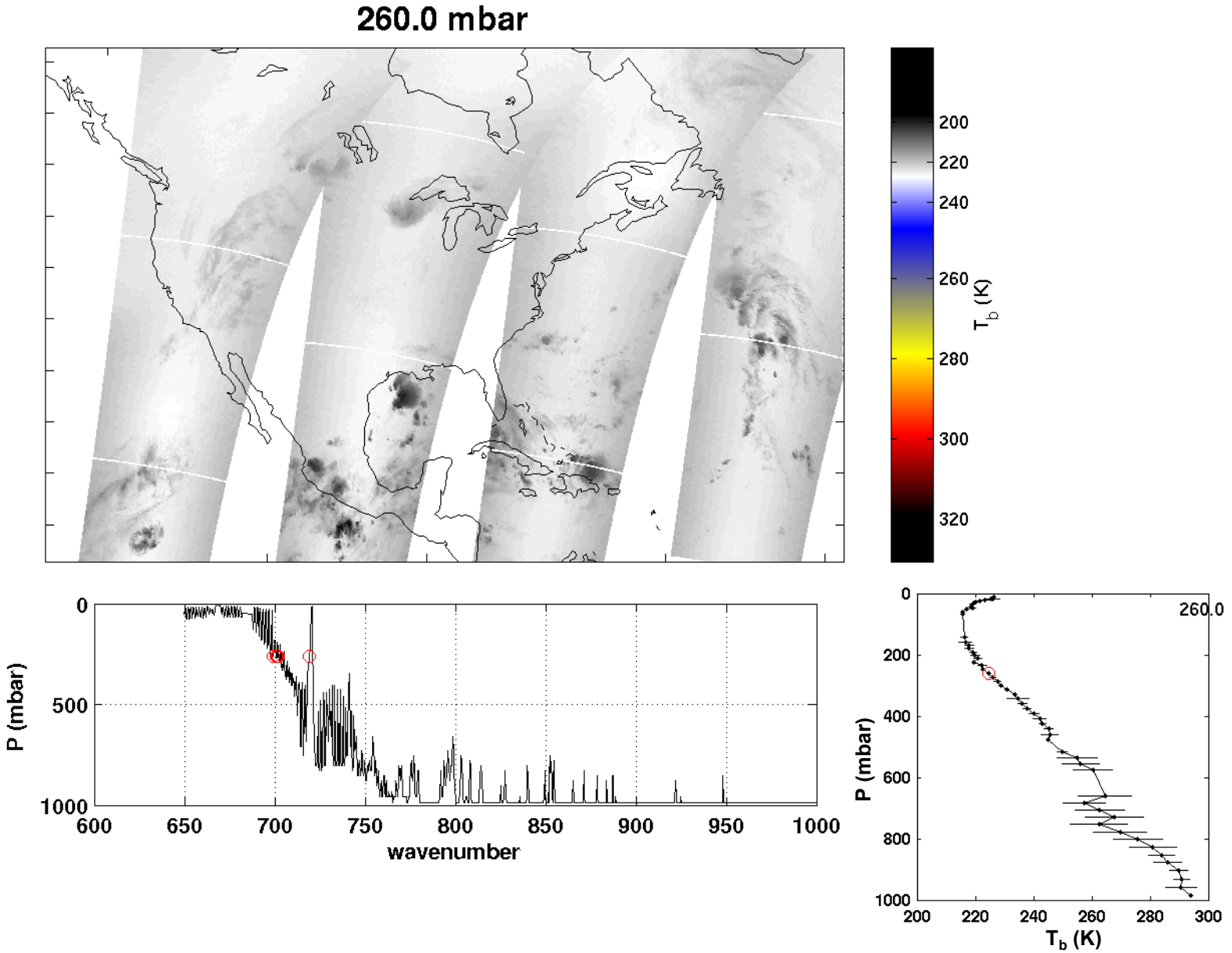
280
300
320
T_b (K)
P (mbar)
0
500
1000
600
650
700
750
800
850
900
950
1000
wavenumber
223.4
P (mbar)
0
200
400
600
800
1000
200
220
240
260
280
300
T_b (K)


260.0 mbar
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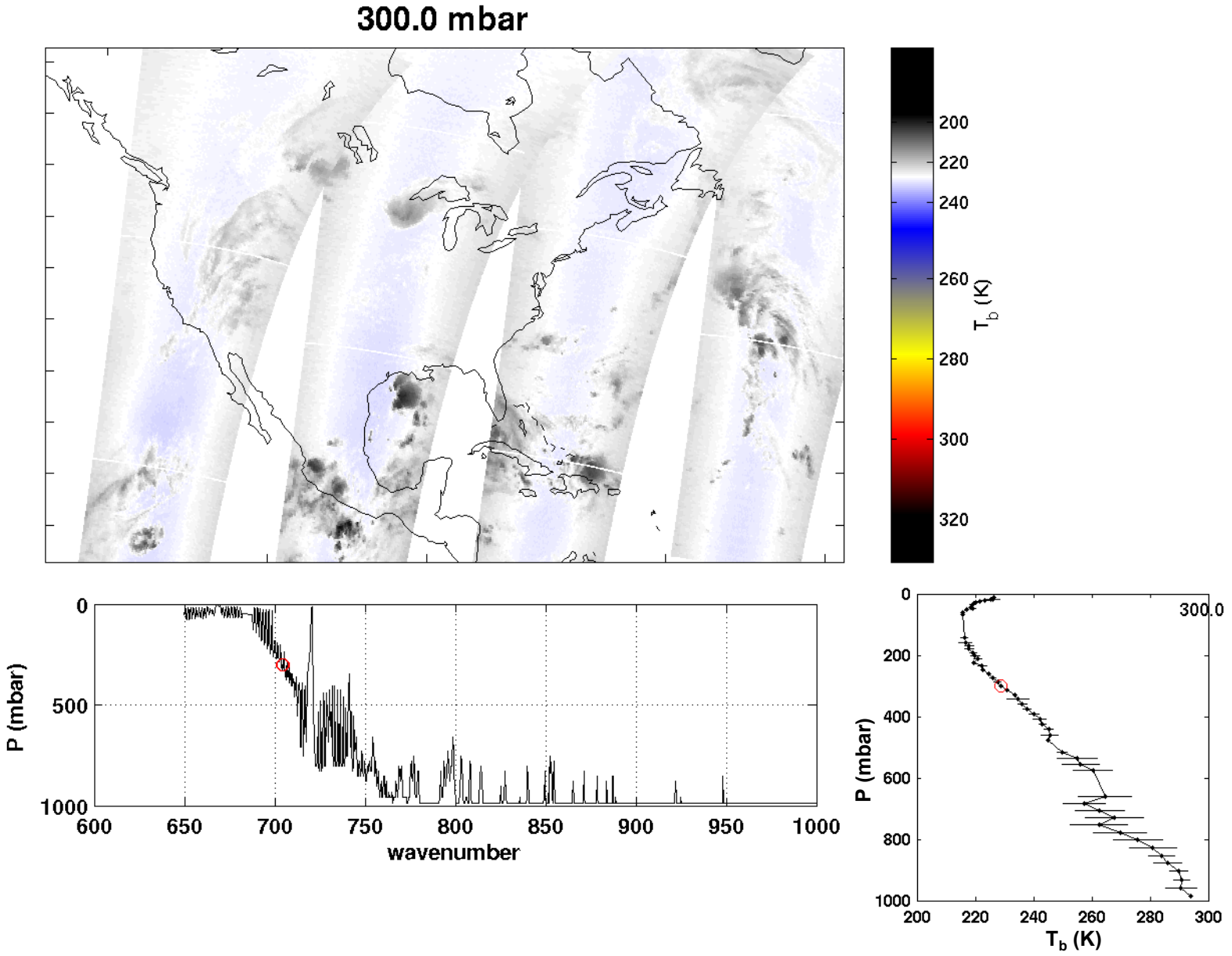
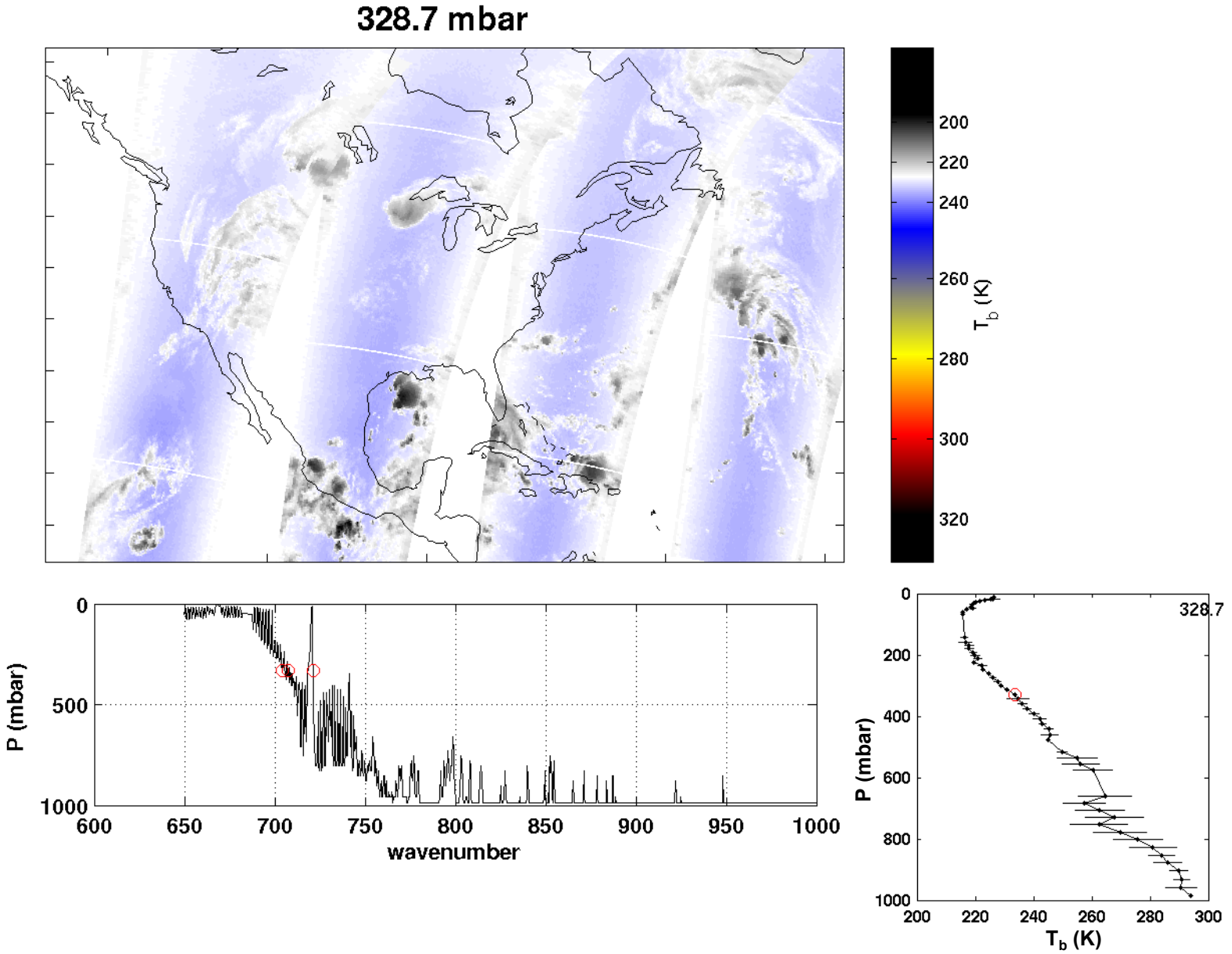
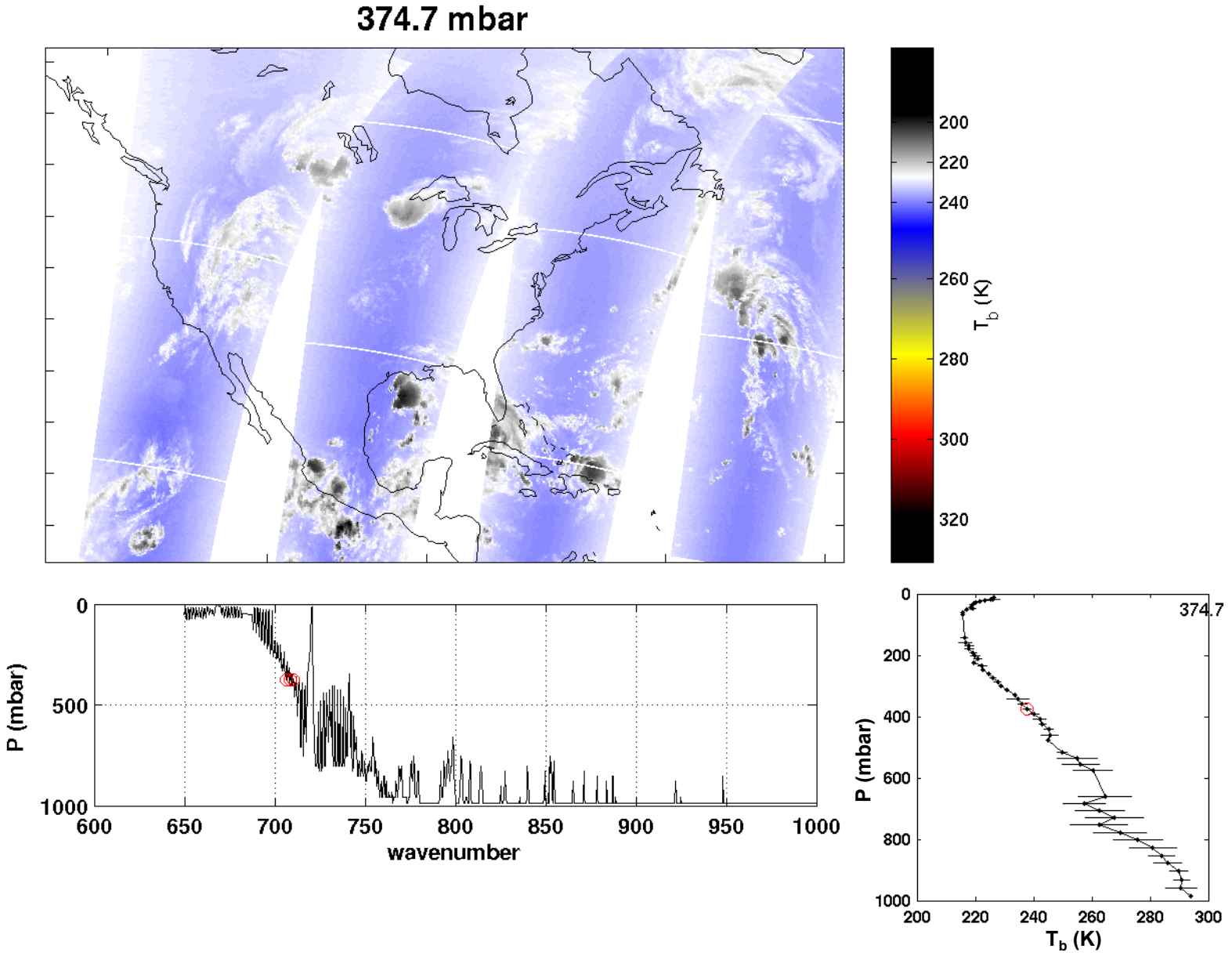
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
260.0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)


300.0 mbar
200
220
240
260
280
300
320
T_b (K)
P (mbar)
0
500
1000
600
650
700
750
800
850
900
950
1000
wavenumber
300.0
200
400
600
800
1000
200
220
240
260
280
300
T_b (K)


328.7 mbar
200
220
240
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
328.7
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)


374.7 mbar
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T_b (K)
P (mbar)
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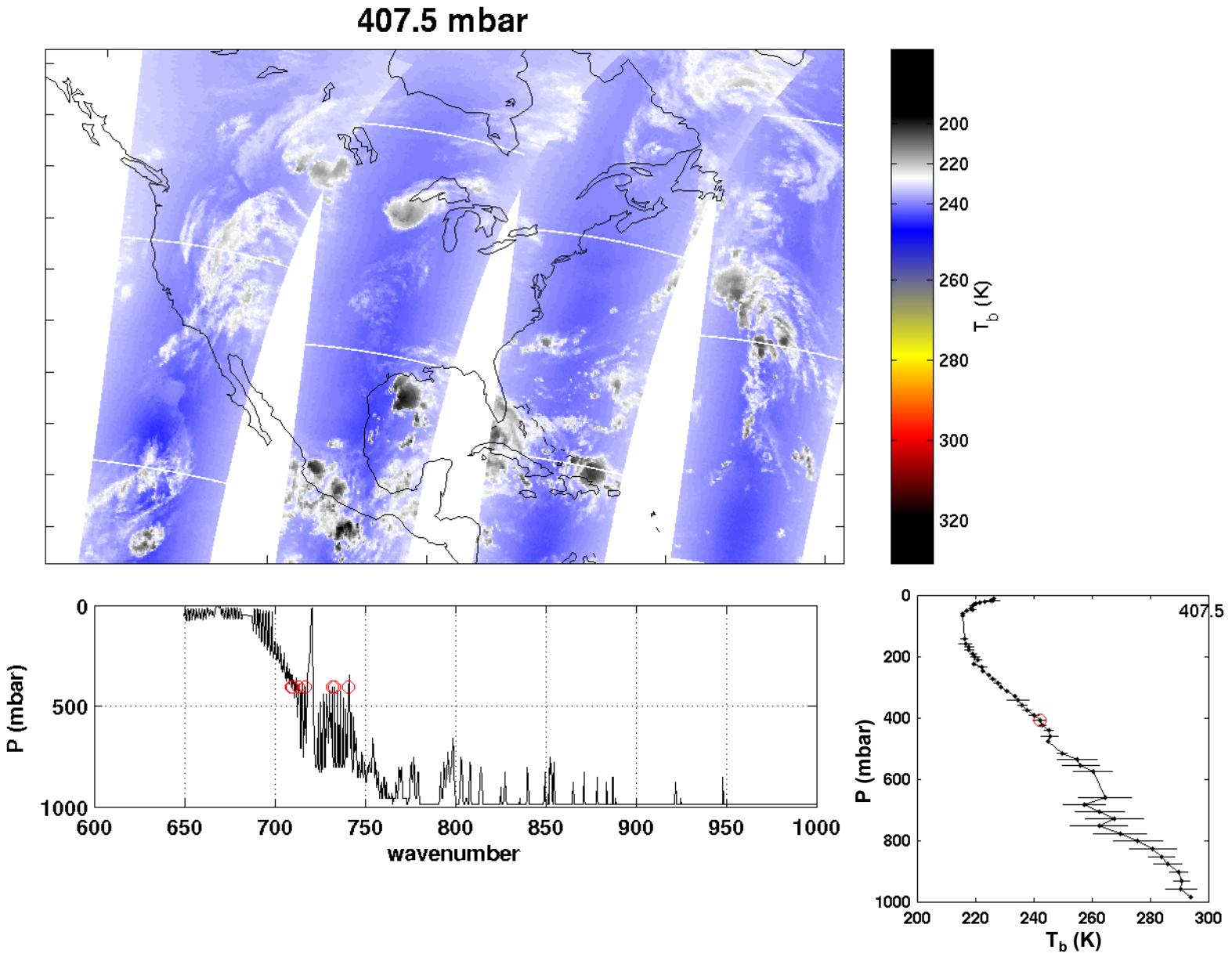
500
1000
600
650
700
750
800
850
900
950
1000
wavenumber
374.7
P (mbar)
0
200
400
600
800
1000
200
220
240
260
280
300
T_b (K)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300
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T_b (K)
P (mbar)
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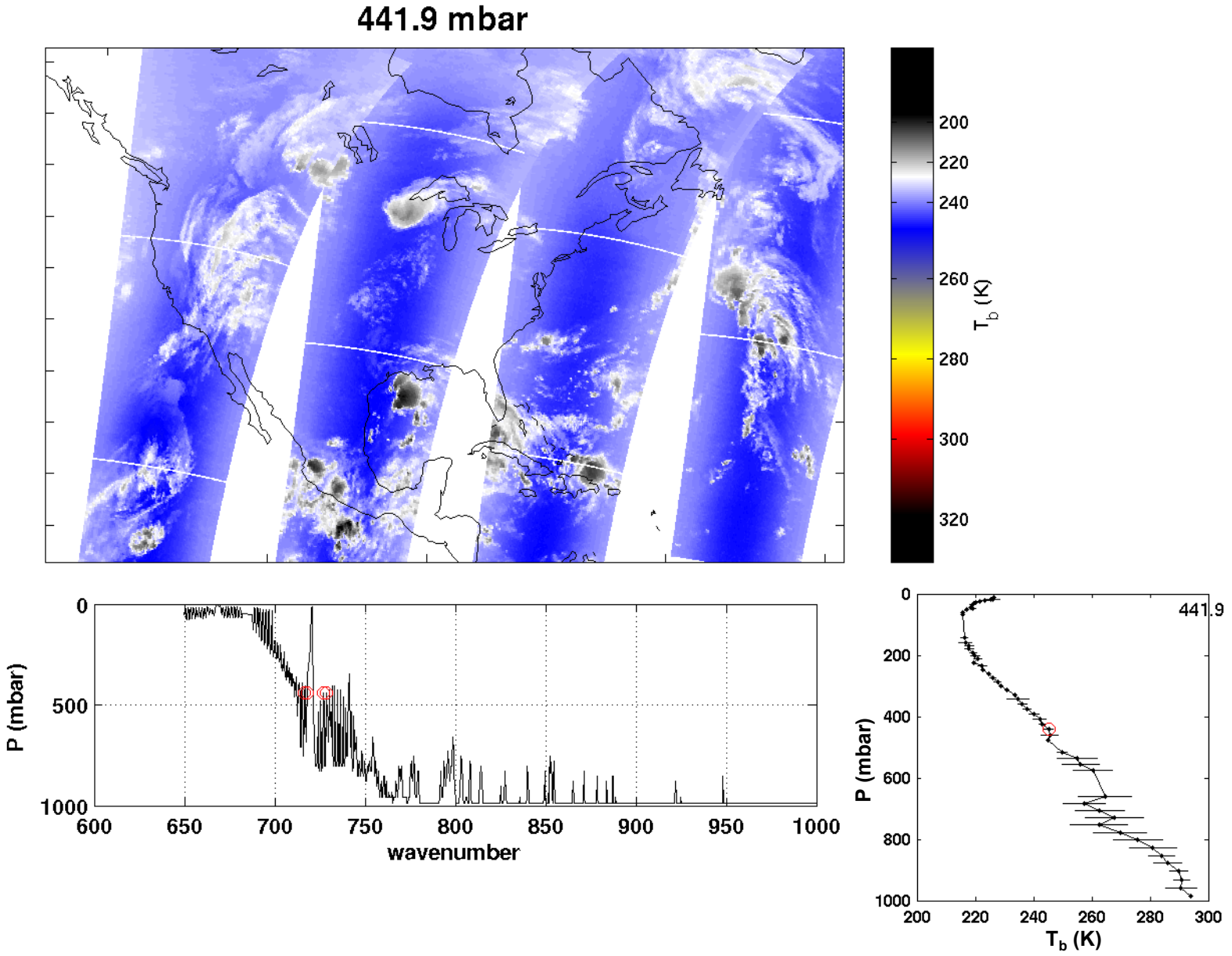
500
1000
600
650
700
750
800
850
900
950
1000
wavenumber
407.5
P (mbar)
0
200
400
600
800
1000
200
220
240
260
280
300
T_b (K)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T_b (K)
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1000
P (mbar)
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650
700
750
800
850
900
950
1000
wavenumber
441.9
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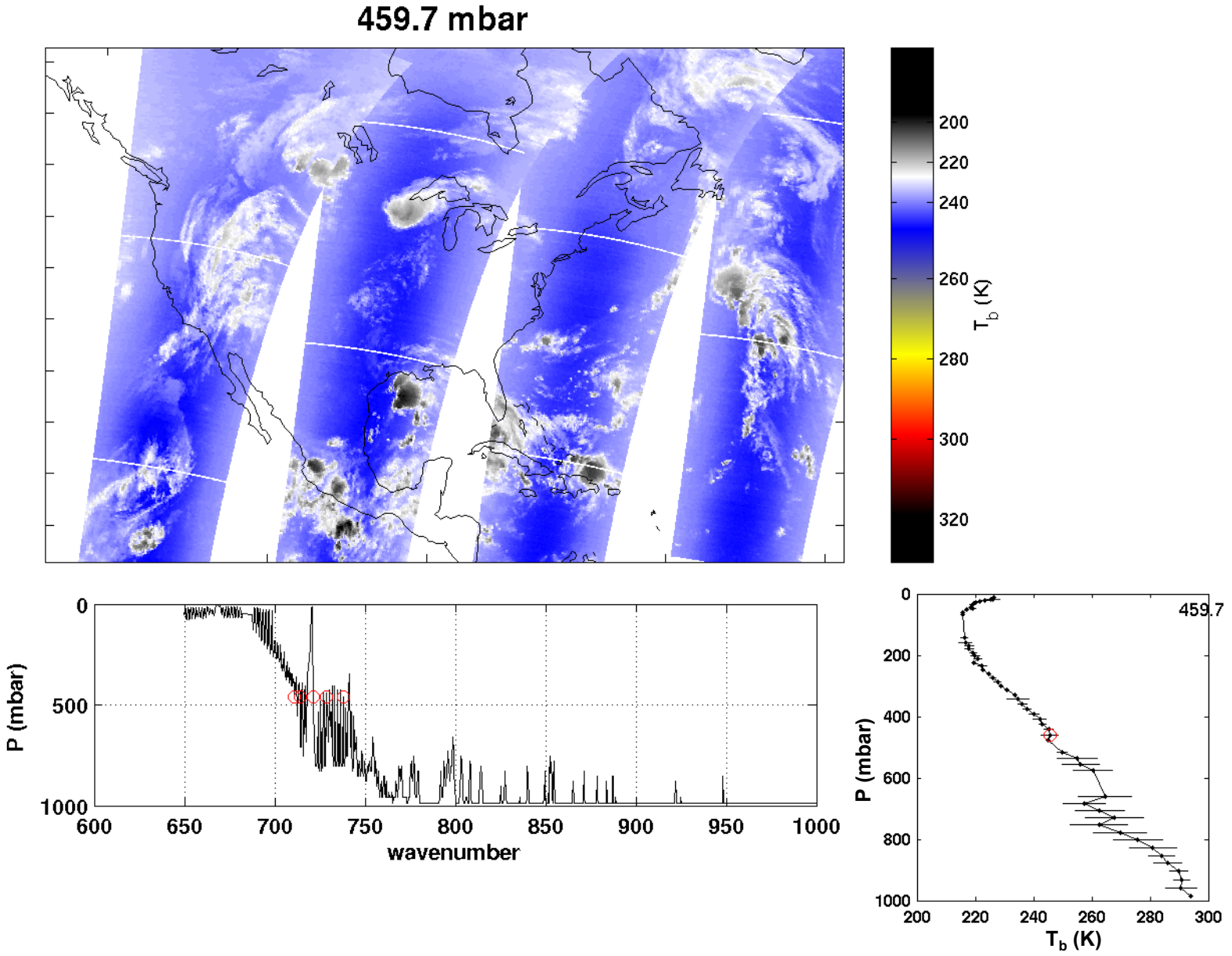
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)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T_b (K)
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1000
P (mbar)
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750
800
850
900
950
1000
wavenumber
459.7
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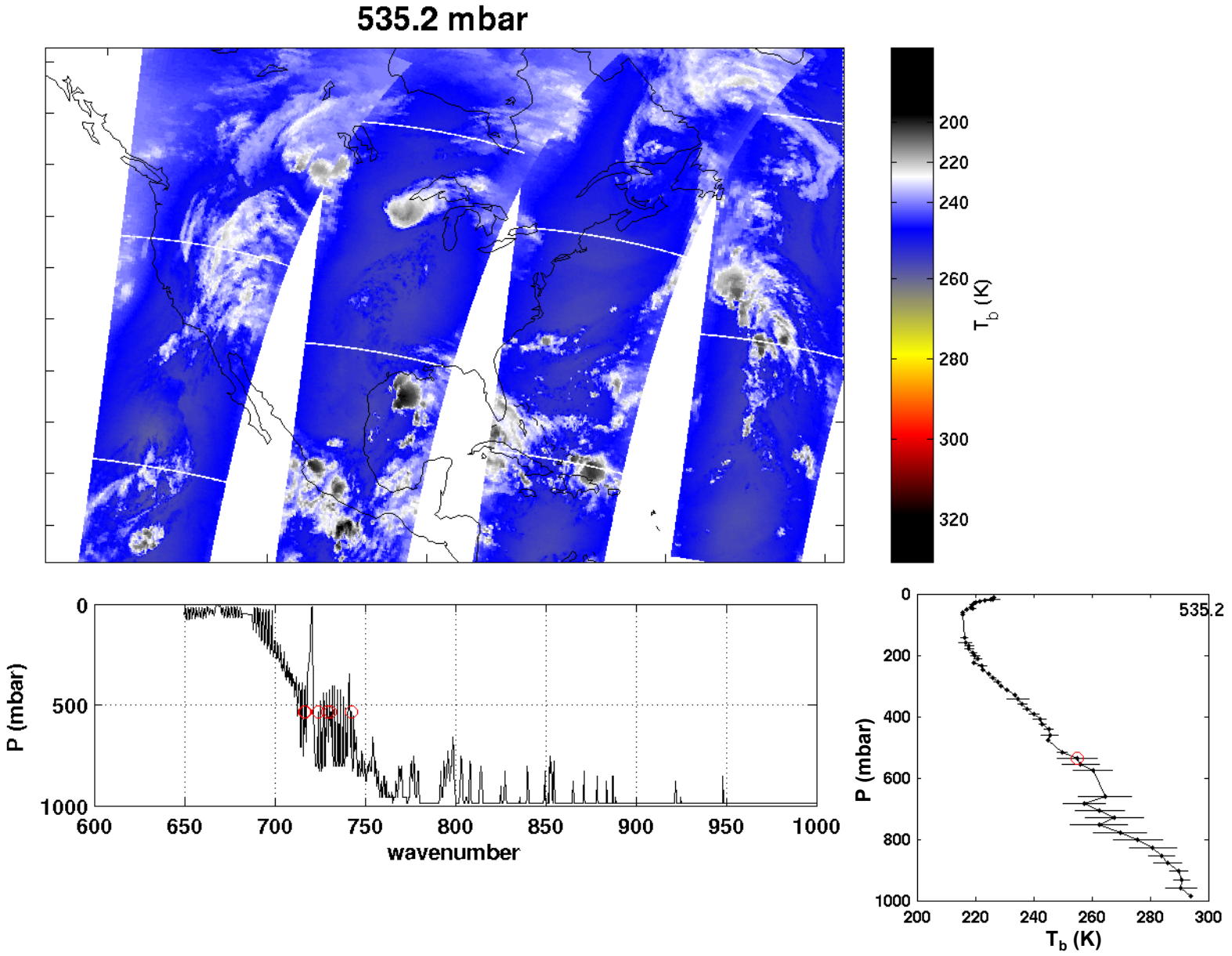
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)


535.2 mbar
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300
320
T_b (K)
P (mbar)
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500
1000
600
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700
750
800
850
900
950
1000
wavenumber
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P (mbar)
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400
600
800
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200
220
240
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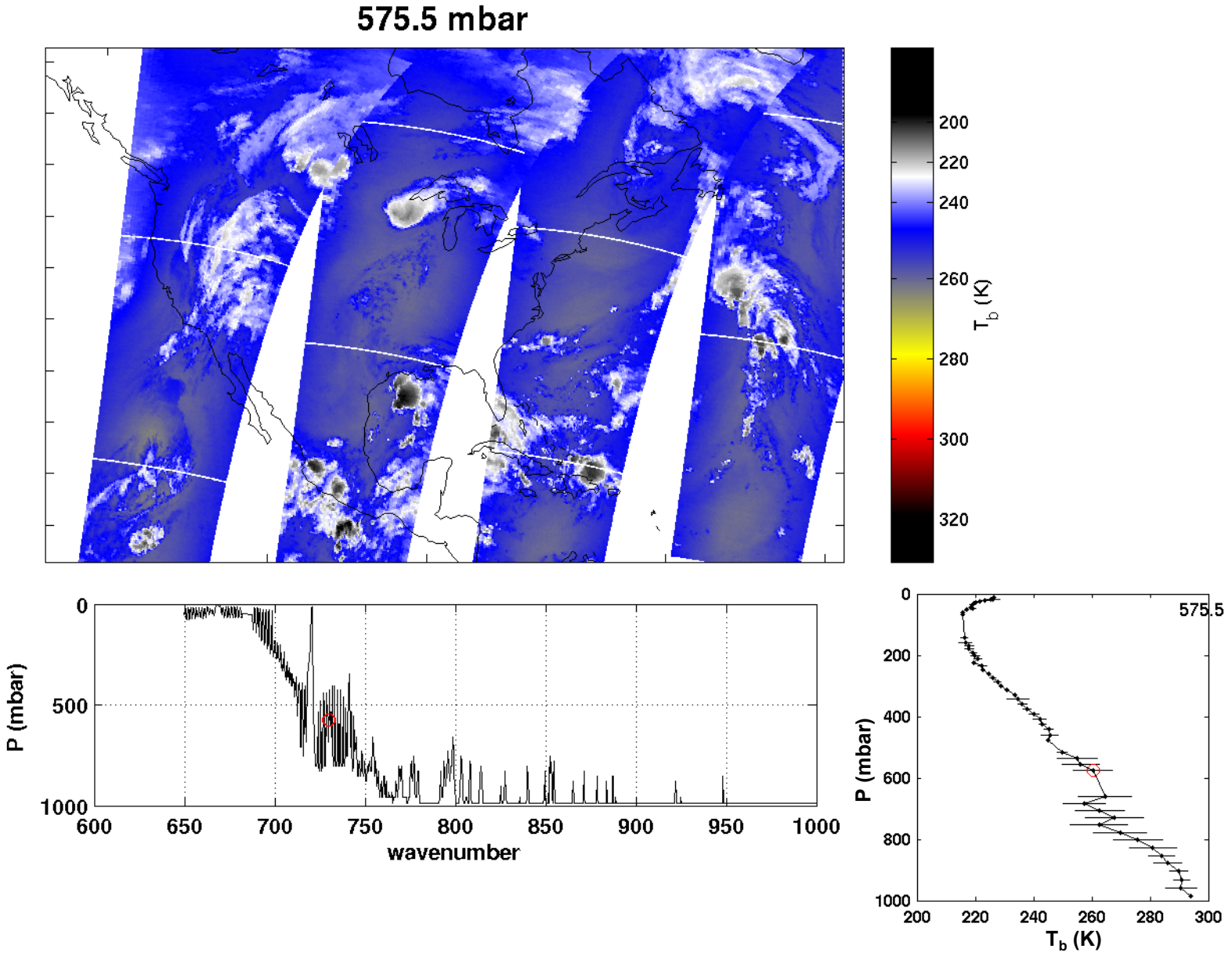
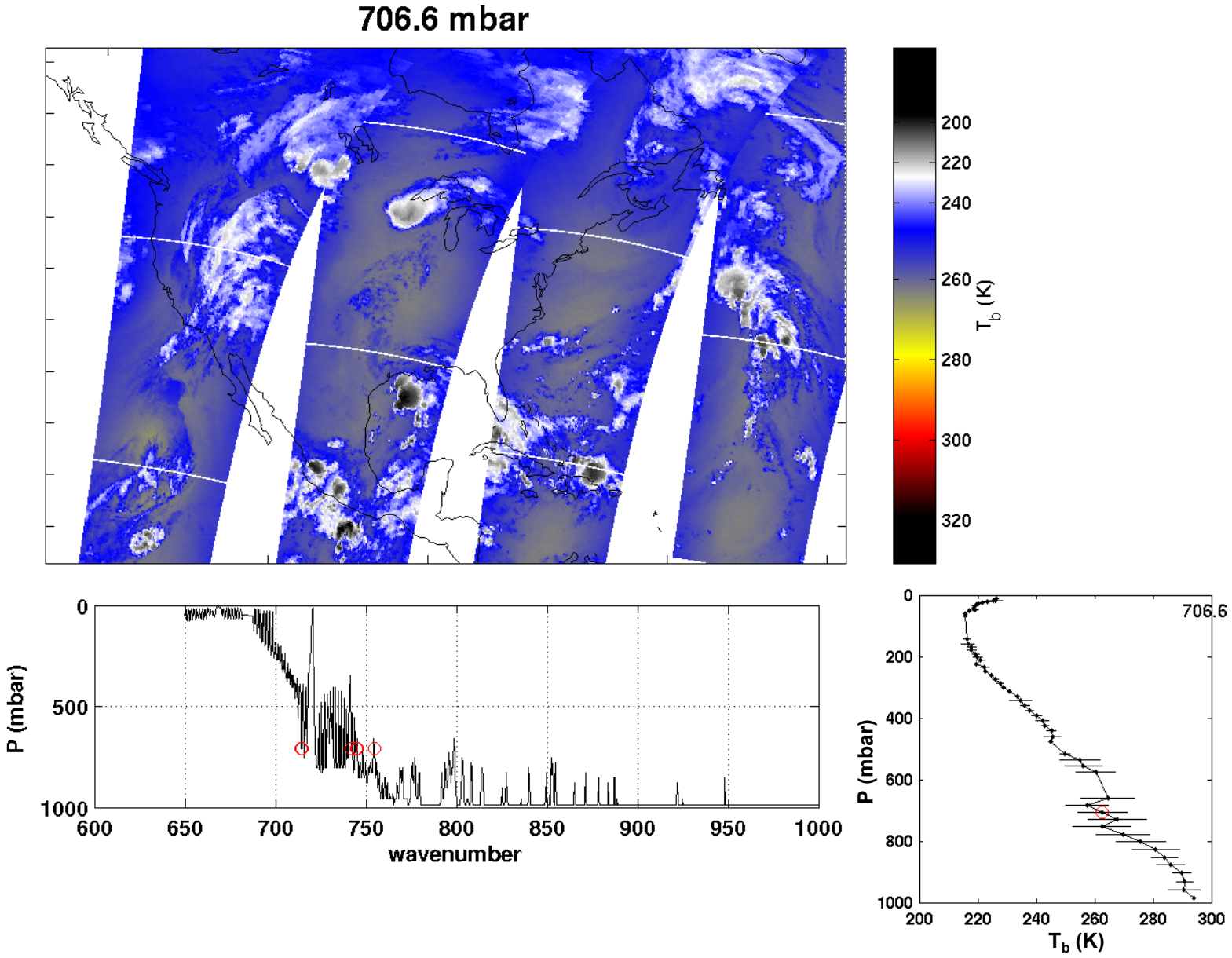
300
T_b (K)


575.5 mbar
200
220
240
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
575.5
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)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300
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T_b (K)
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1000
P (mbar)
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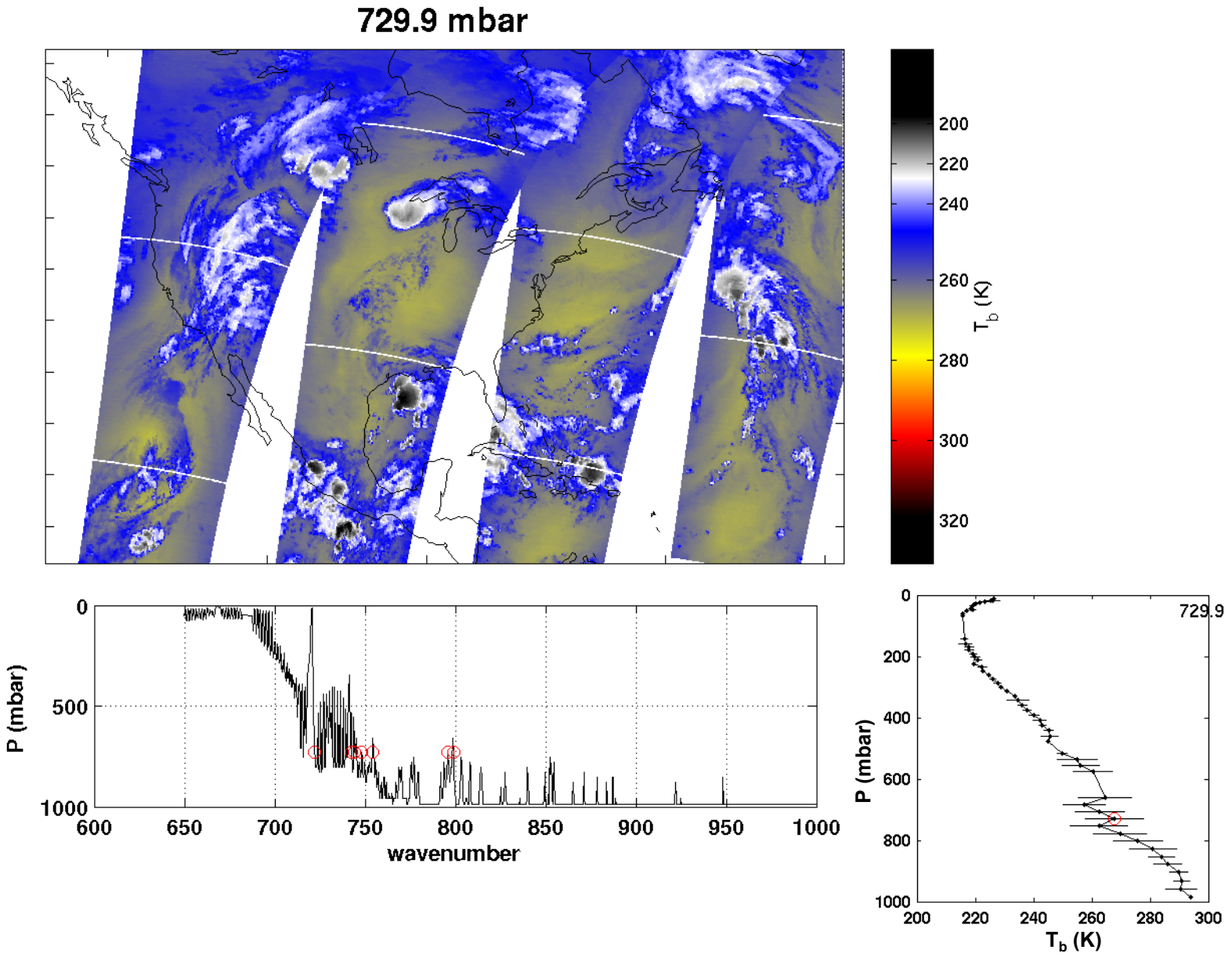
650
700
750
800
850
900
950
1000
wavenumber
706.6
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)


729.9 mbar
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240
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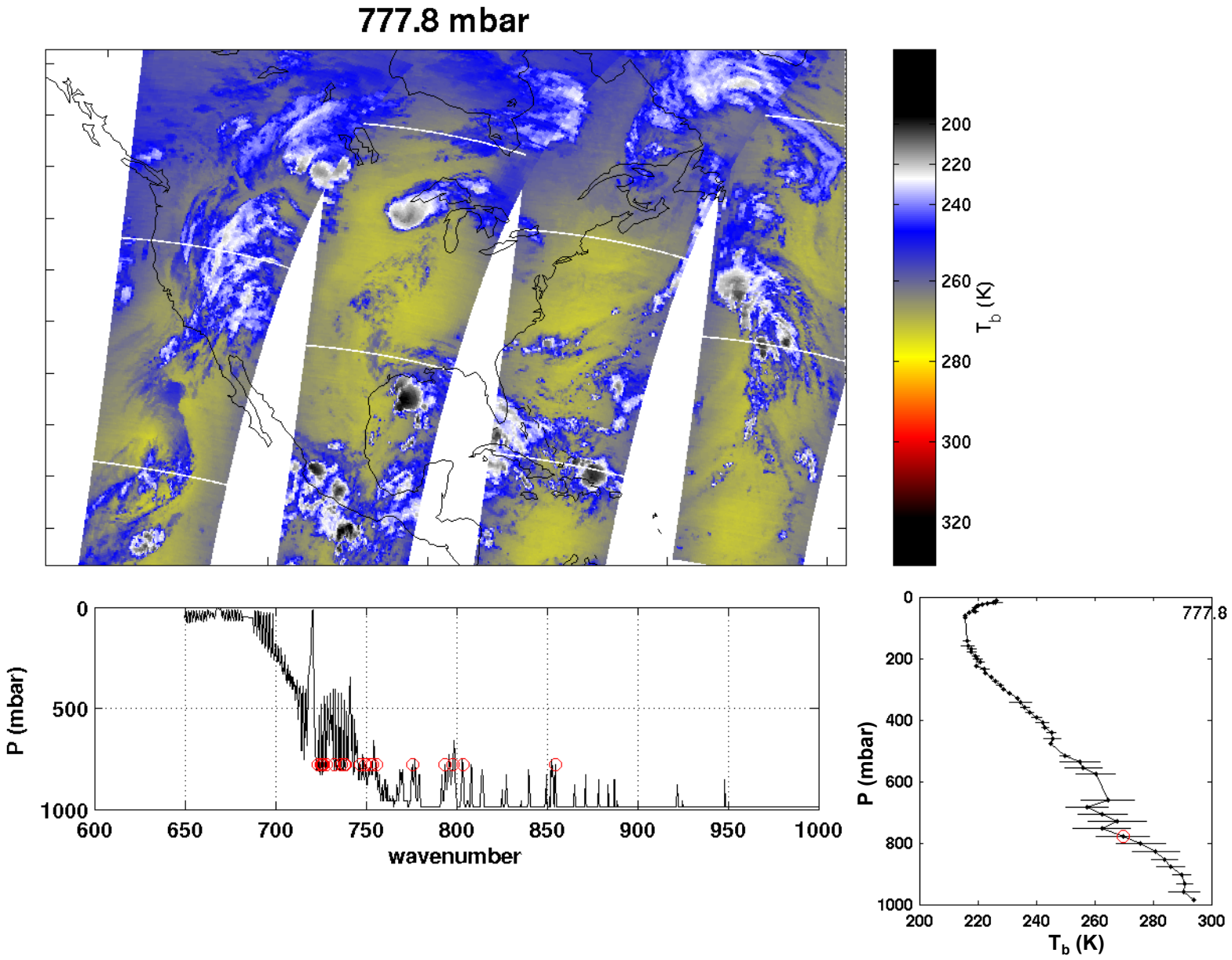
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
729.9
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)


777.8 mbar
200
220
240
260
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300
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T_b (K)
P (mbar)
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500
1000
600
650
700
750
800
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wavenumber
777.8
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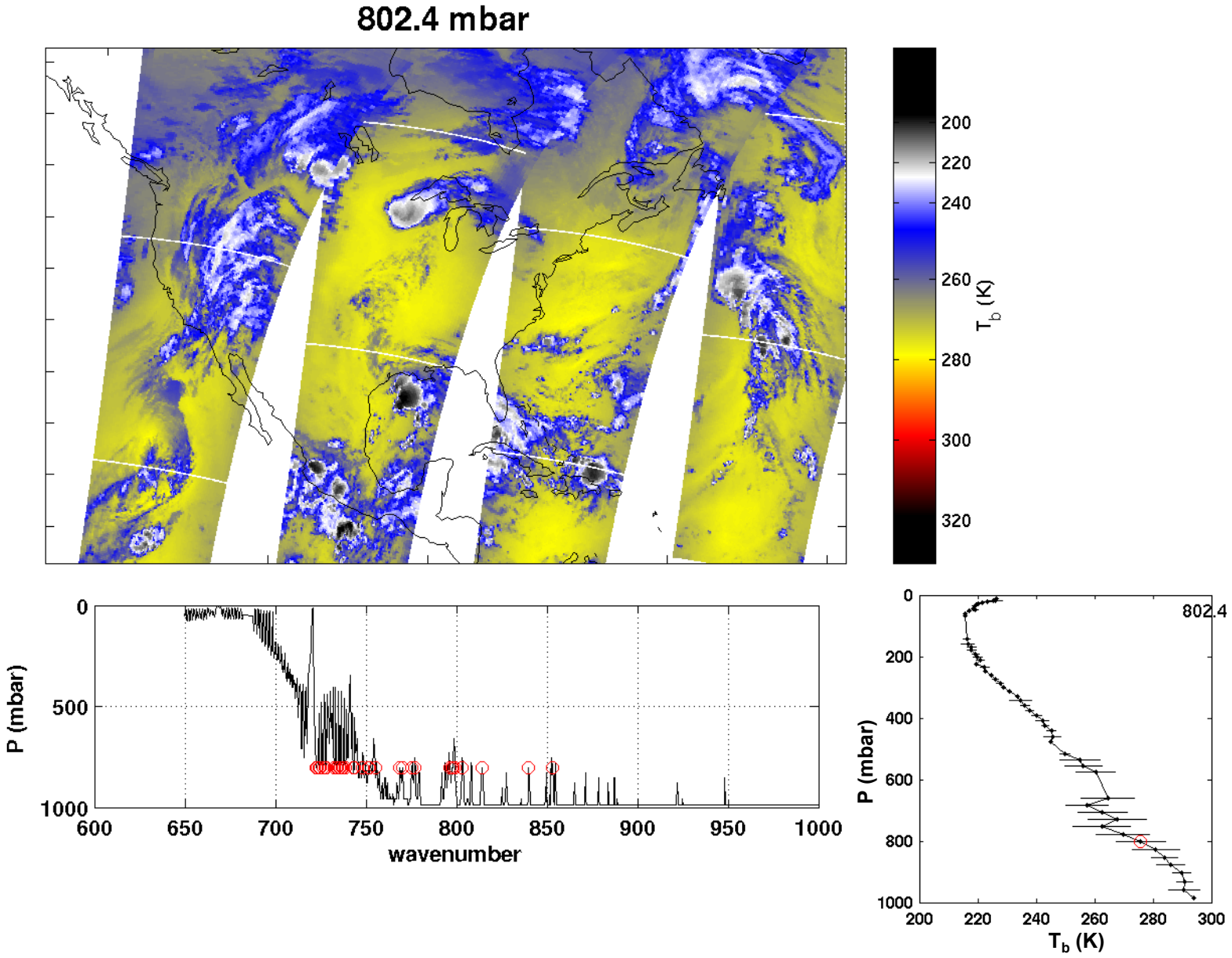
280
300
T_b (K)


802.4 mbar
200
220
240
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280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
802.4
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800
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P (mbar)
200
220
240
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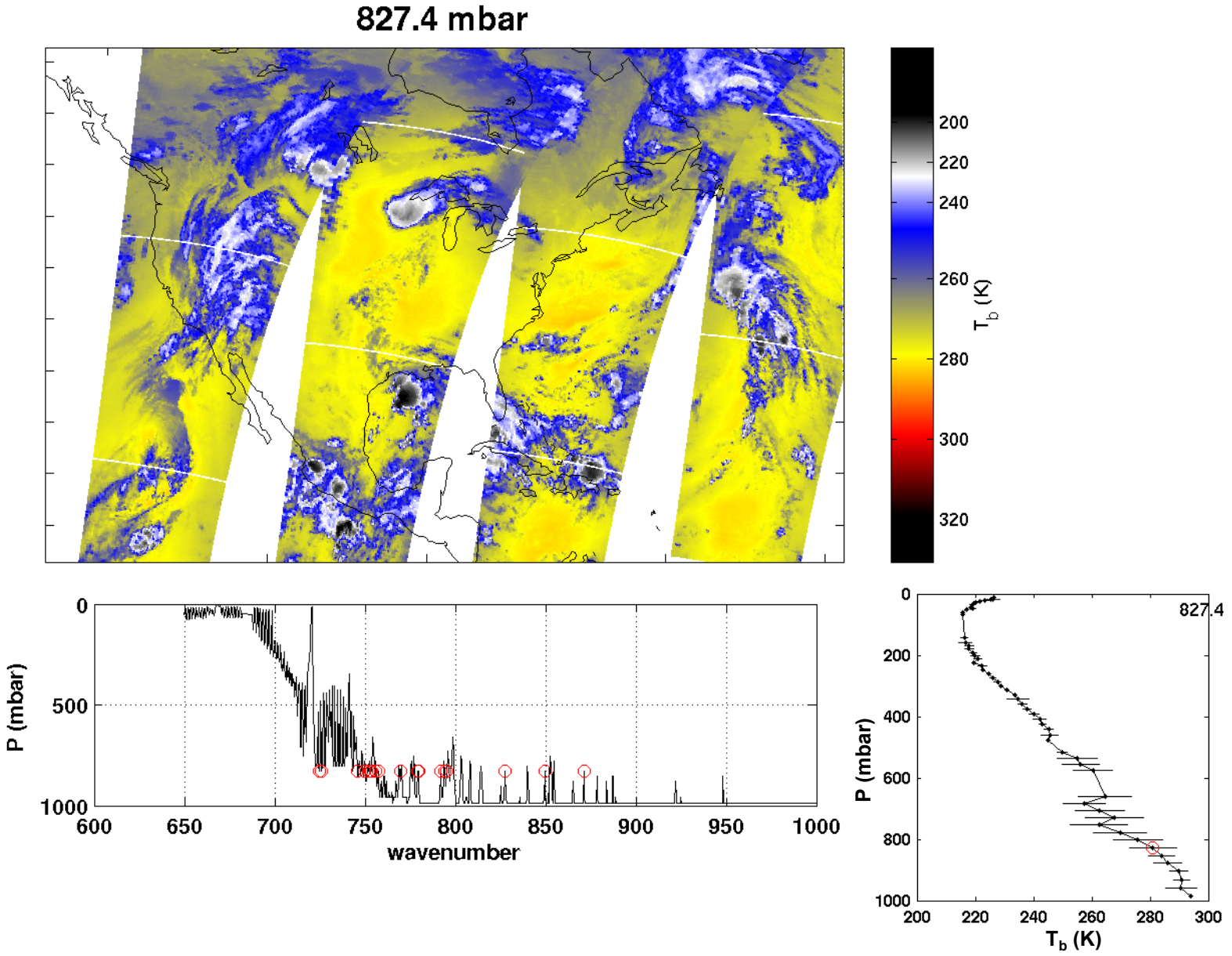
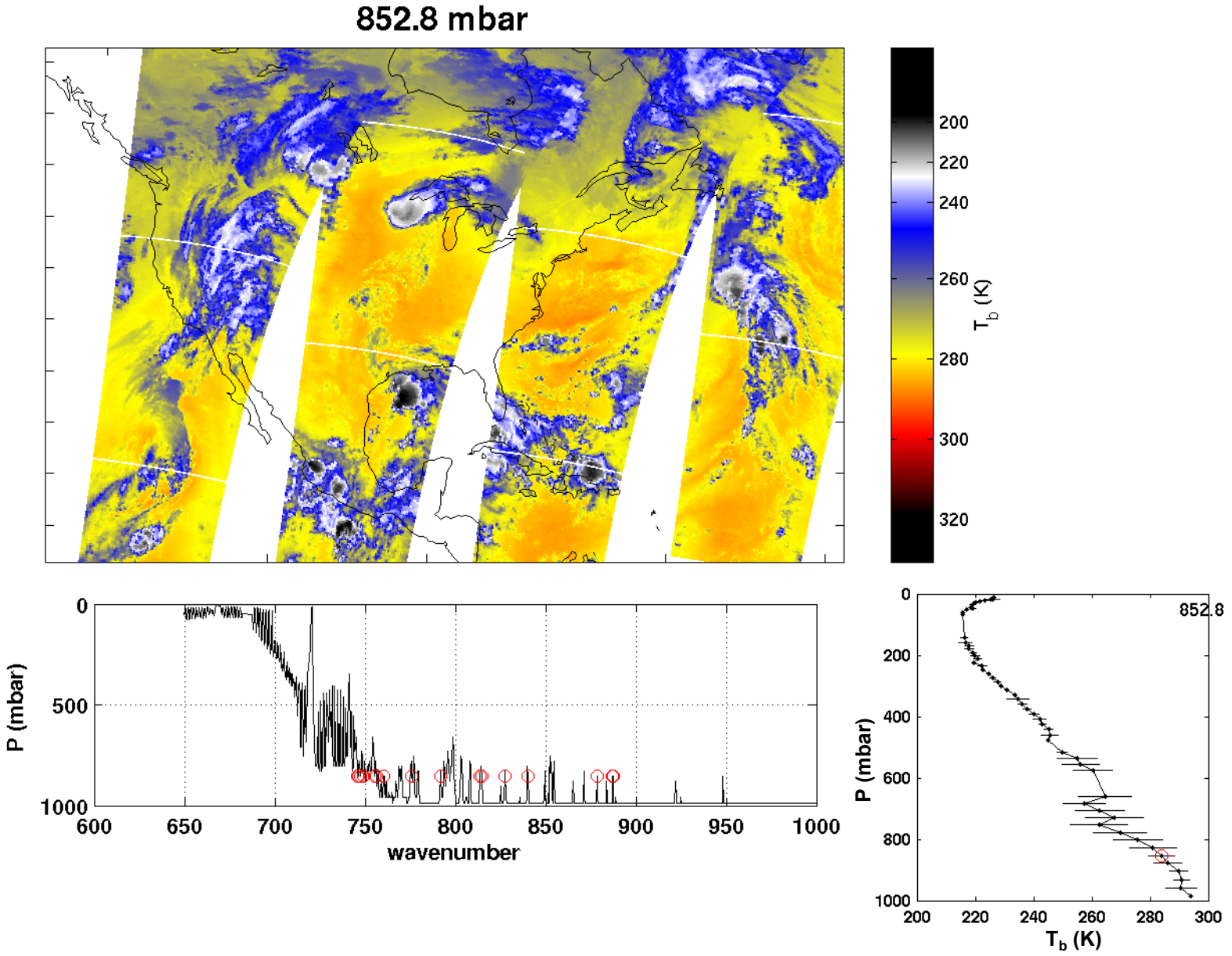
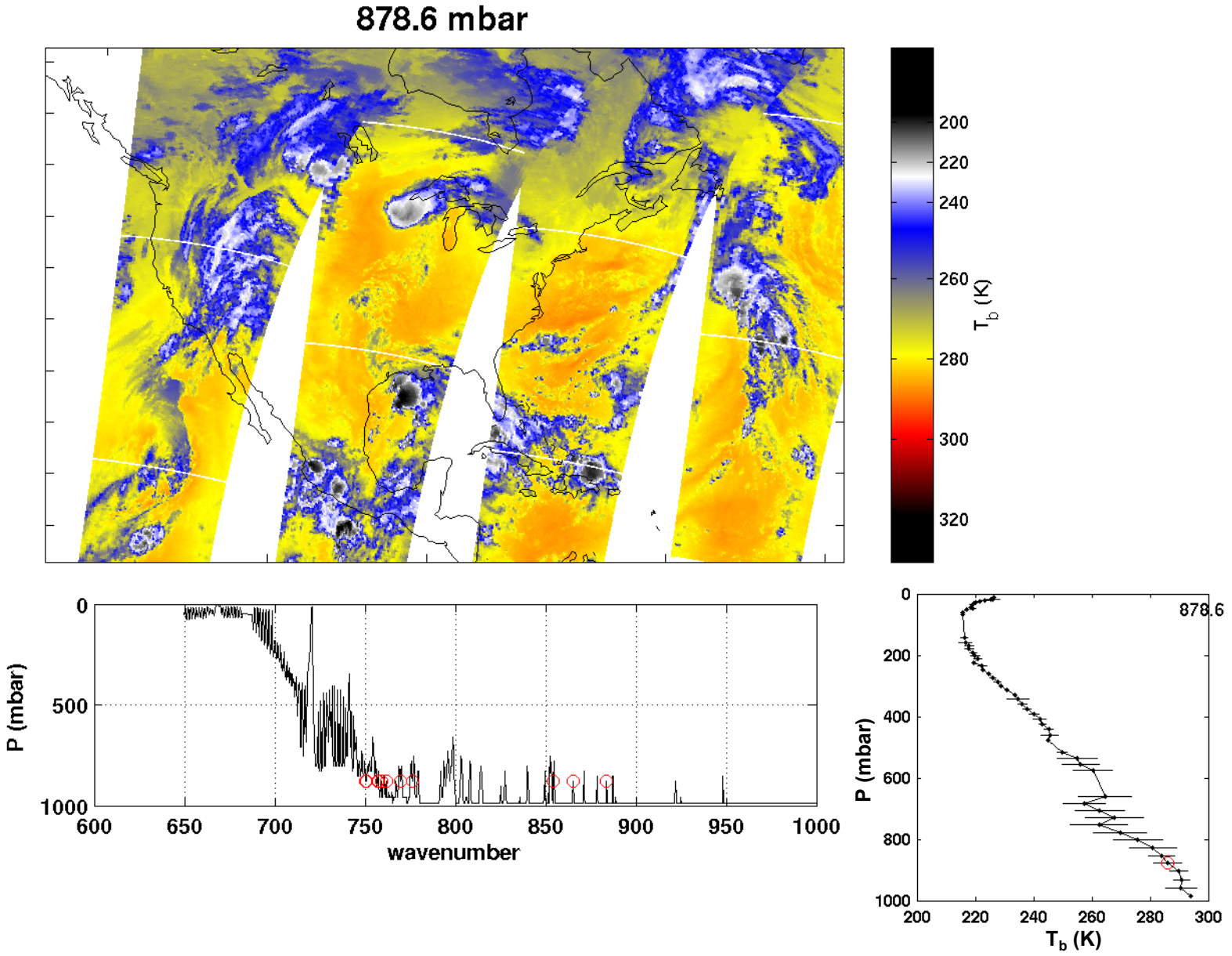
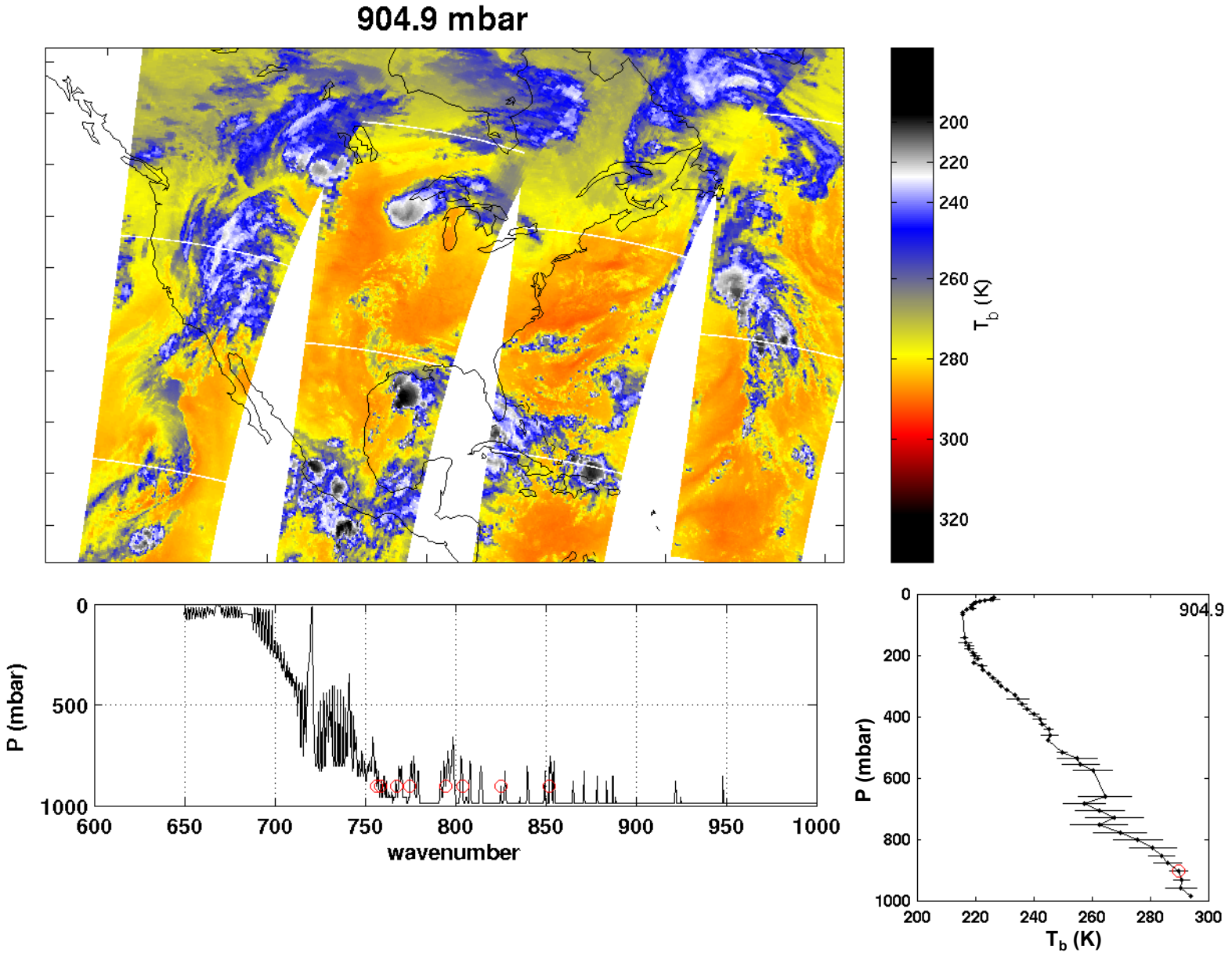
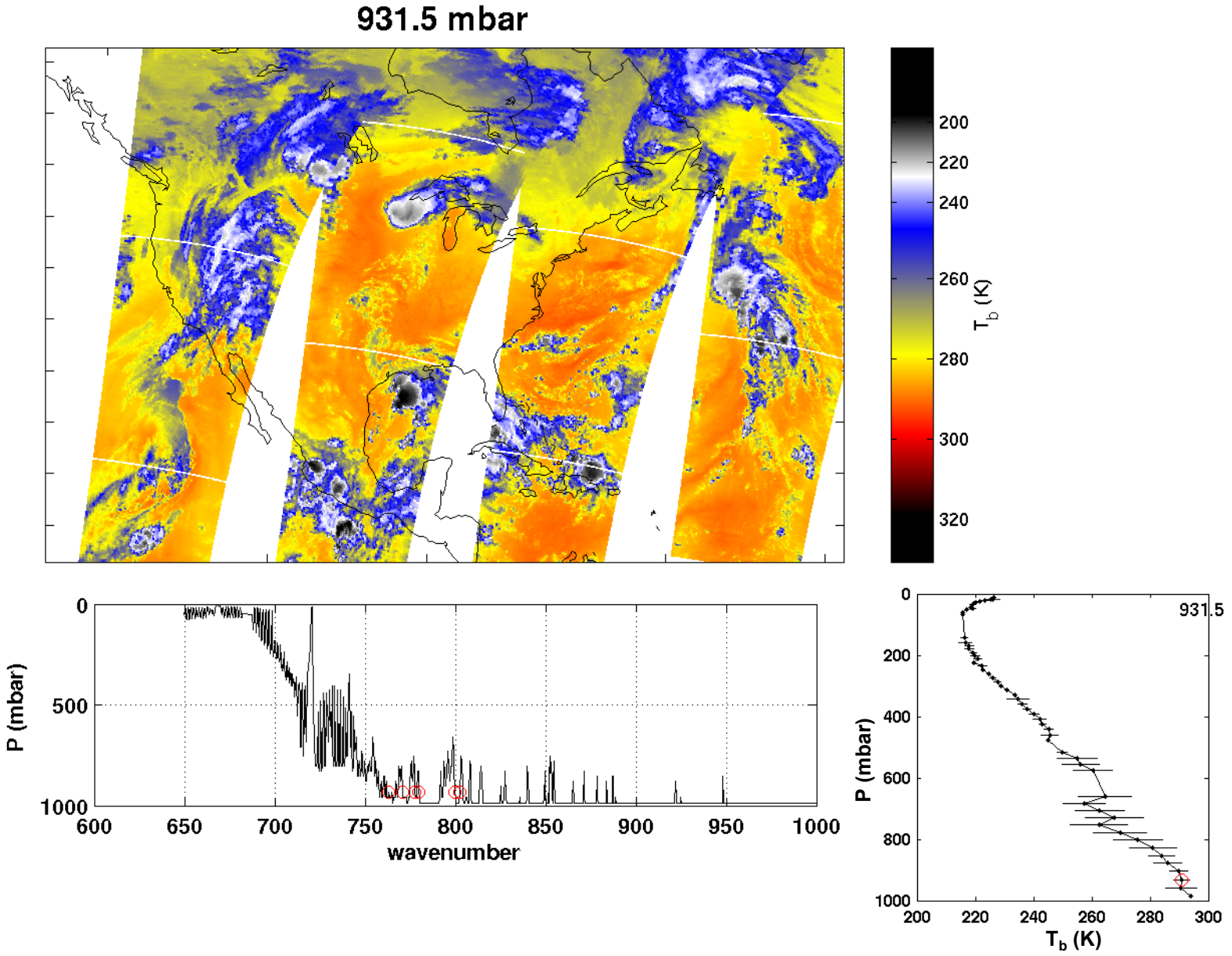
280
300
T_b (K)

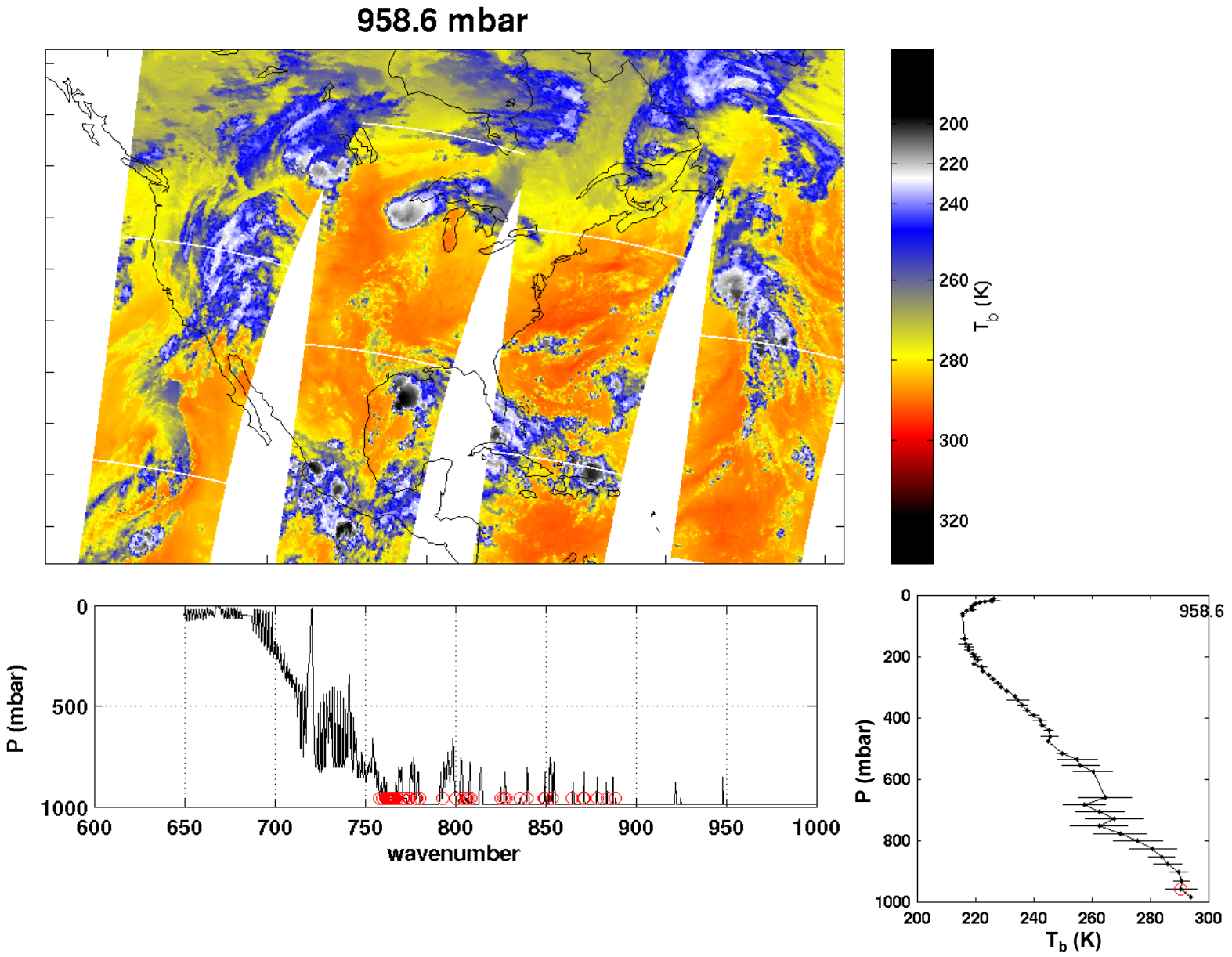

827.4 mbar
200
220
240
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
827.4
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)

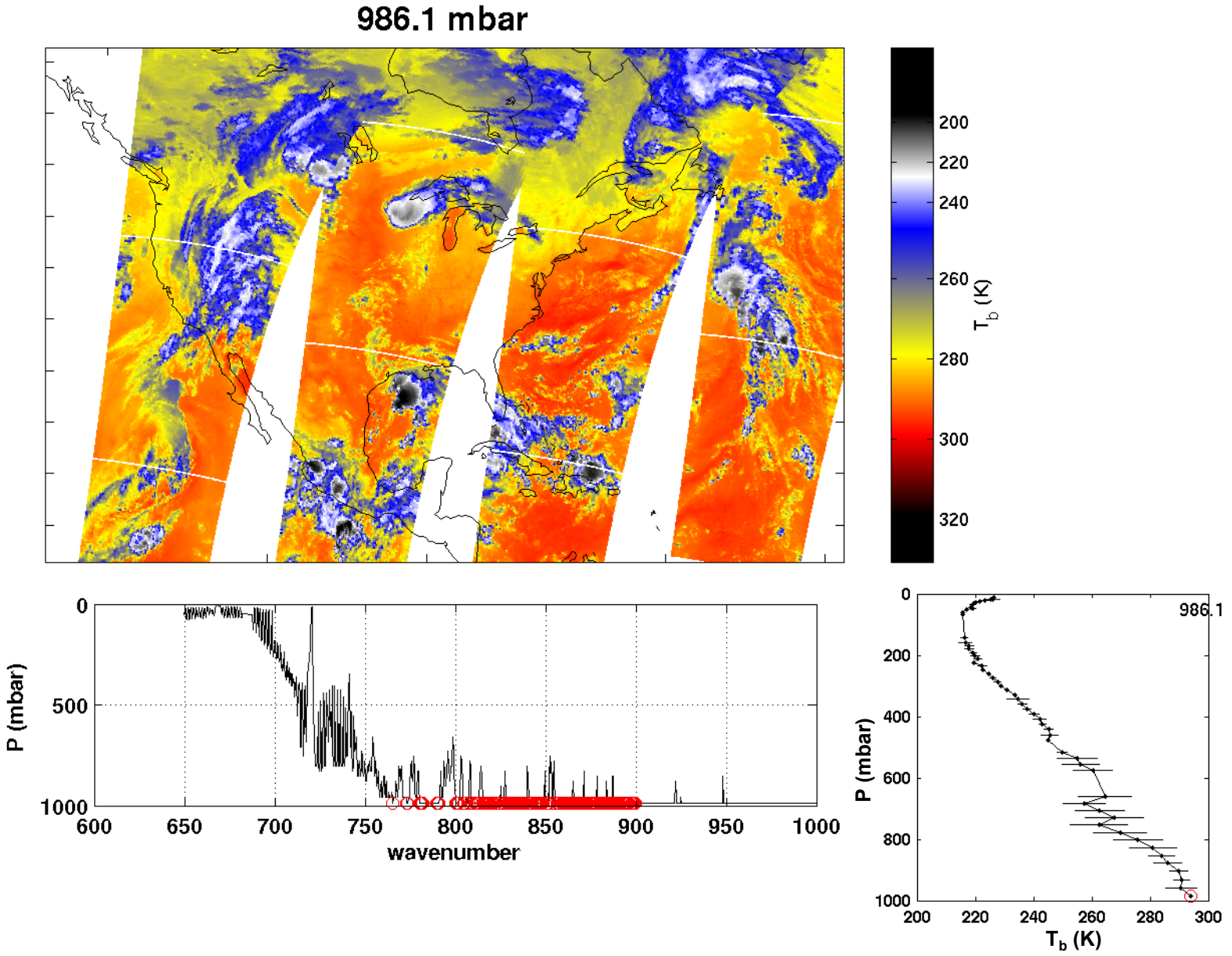

852.8 mbar
200
220
240
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
852.8
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)


878.6 mbar
200
220
240
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
878.6
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)


904.9 mbar
200
220
240
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
904.9
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)


931.5 mbar
200
220
240
260
280
300
320
T_b (K)
P (mbar)
0
500
1000
600
650
700
750
800
850
900
950
1000
wavenumber
931.5
200
400
600
800
1000
220
240
260
280
300
T_b (K)


958.6 mbar
200
220
240
260
280
300
320
T_b (K)
P (mbar)
0
500
1000
600
650
700
750
800
850
900
950
1000
wavenumber
958.6
P (mbar)
0
200
400
600
800
1000
200
220
240
260
280
300
T_b (K)

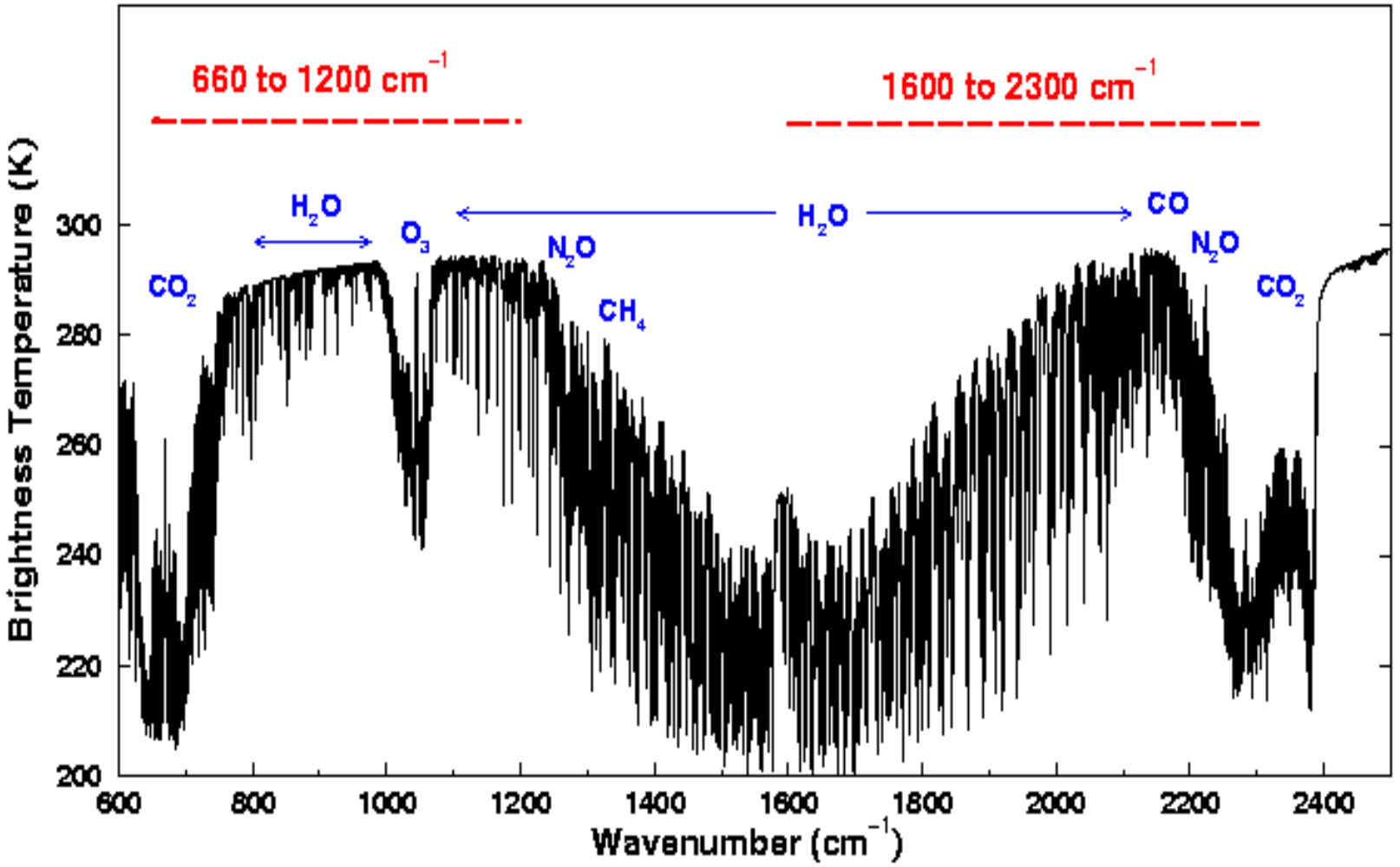

986.1 mbar
200
220
240
260
280
300
320
T_b (K)
0
500
1000
P (mbar)
600
650
700
750
800
850
900
950
1000
wavenumber
986.1
0
200
400
600
800
1000
P (mbar)
200
220
240
260
280
300
T_b (K)

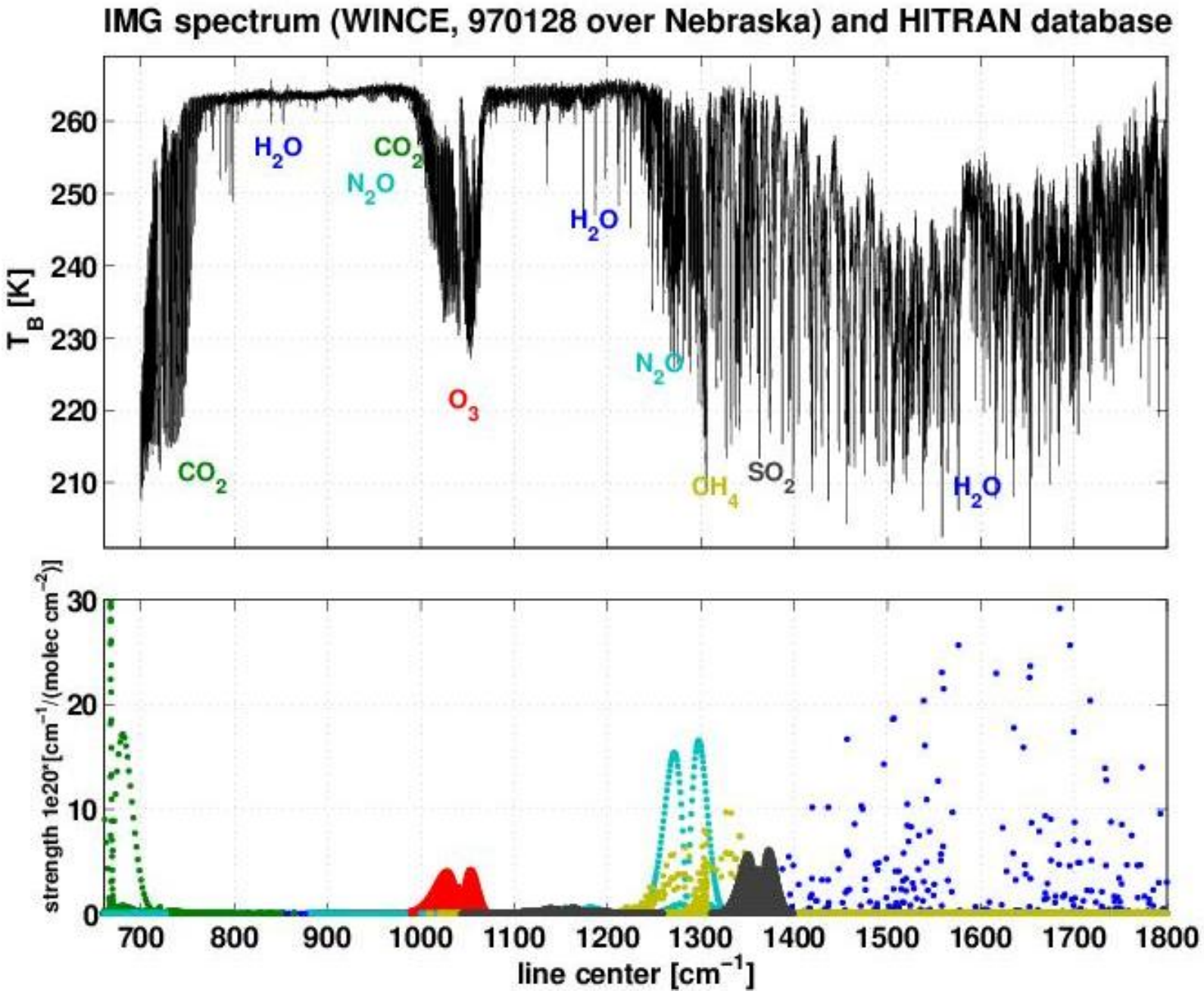
AIRS data and Level 2 Products are being processed at the GSFC DAAC and now available to the public!

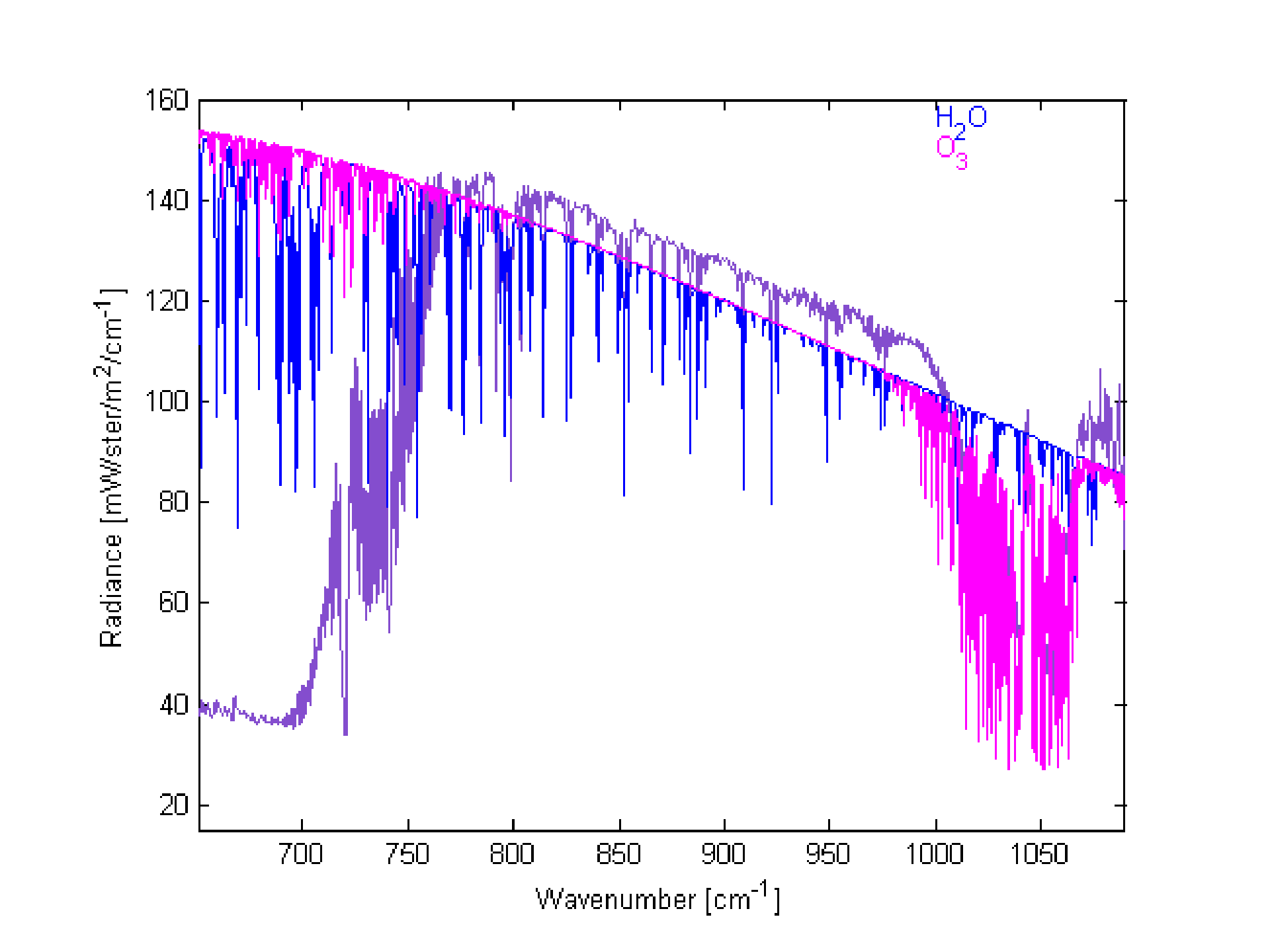
The NASA GSFC Data Active Archive Center at

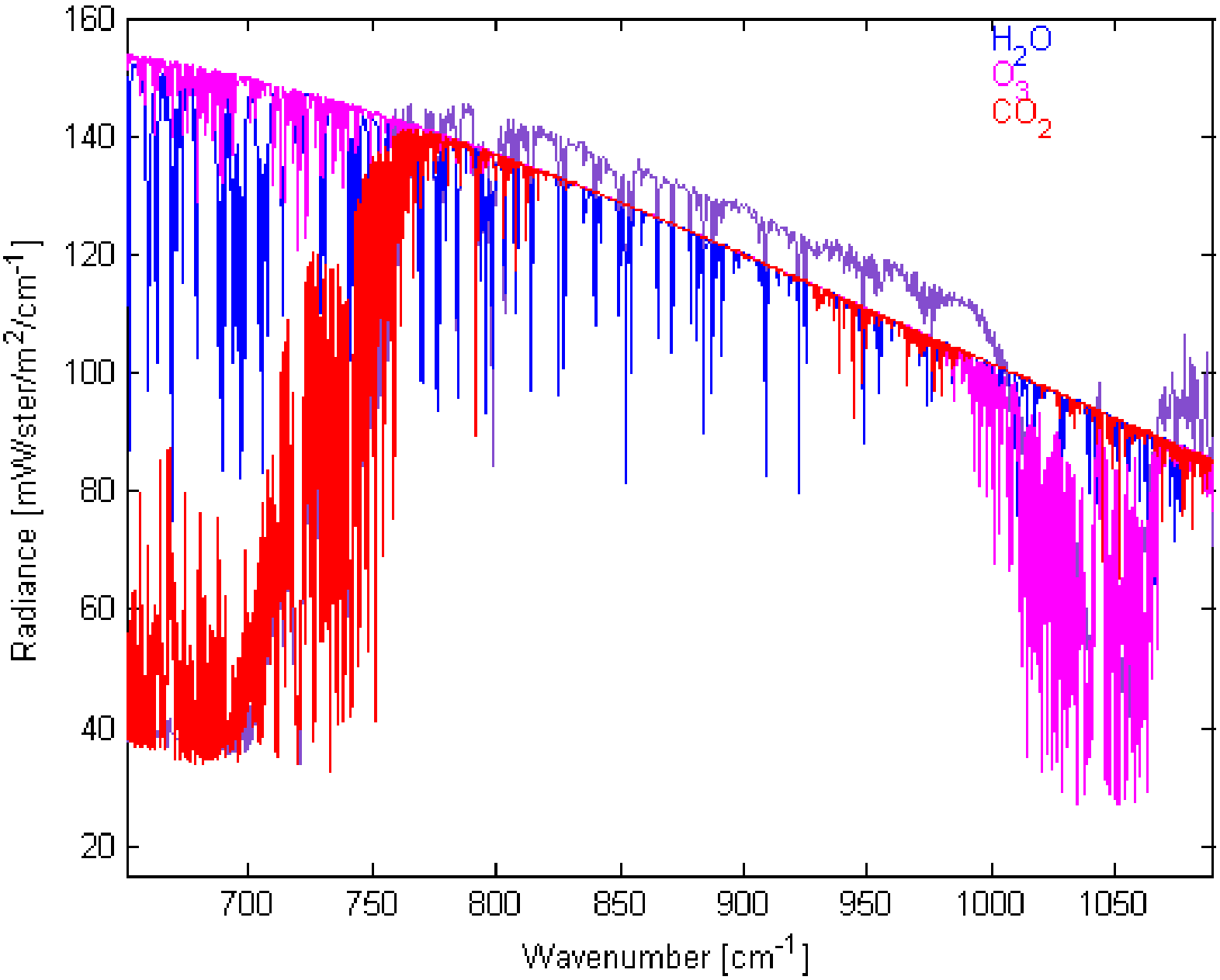
http://daac.gsfc.nasa.gov/

offers a menu driven selection of archived calibrated navigated radiances as well as derived products such as temperature and moisture soundings and total column concentrations of water vapor and ozone.


660 to 1200 cm^{-1}
1600 to 2300 cm^{-1}
H_2O
O_3
N_2O
CH_4
CO_2
H_2O
CO
N_2O
CO_2
Brightness Temperature (K)
Wavenumber (cm^{-1})
200
220
240
260
280
300
600
800
1000
1200
1400
1600
1800
2000
2200
2400


IMG spectrum (WINCE, 970128 over Nebraska) and HITRAN database
T_B [K]
260
250
240
230
220
210
H2O
CO2
N2O
H2O
N2O
O3
CO2
CH4
SO2
H2O
strength 1e20*[cm^-1/(molec cm^-2)]
30
20
10
0
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
line center [cm^-1]


160
140
120
100
80
60
40
20
700
750
800
850
900
950
1000
1050
Radiance [mW/ster/m^2/cm^{-1}]
Wavenumber [cm^{-1}]
H_2O
O_3

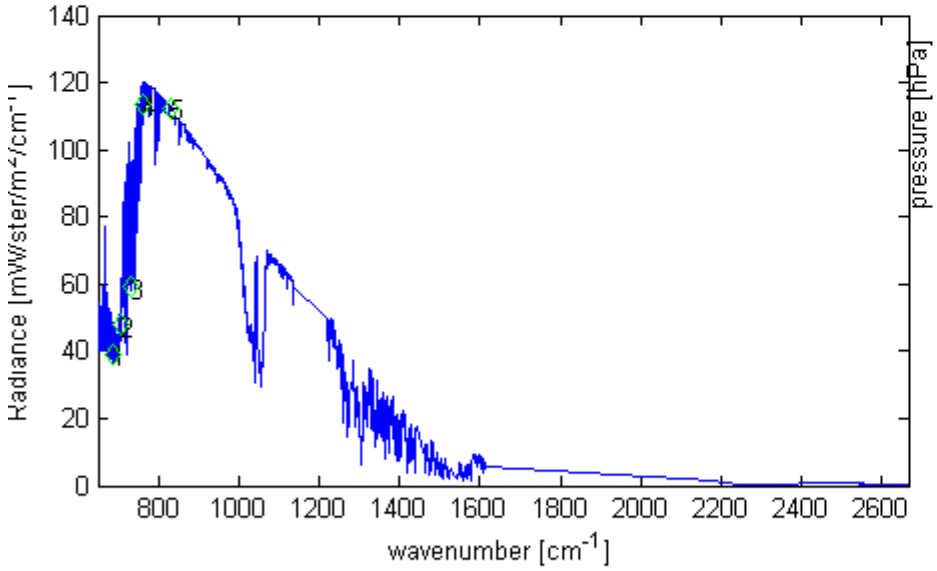

160
140
120
100
80
60
40
20
700
750
800
850
900
950
1000
1050
Radiance [mW/ster/m^2/cm^{-1}]
Wavenumber [cm^{-1}]
H_2O
O_3
CO_2

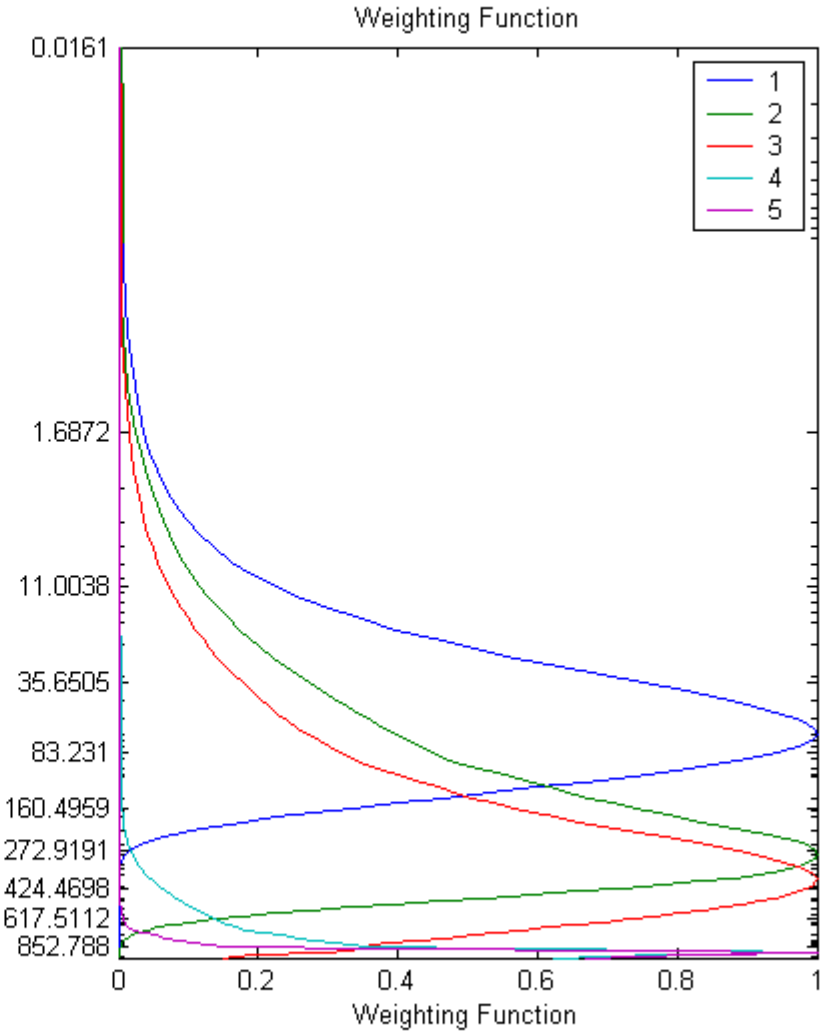
Select

5

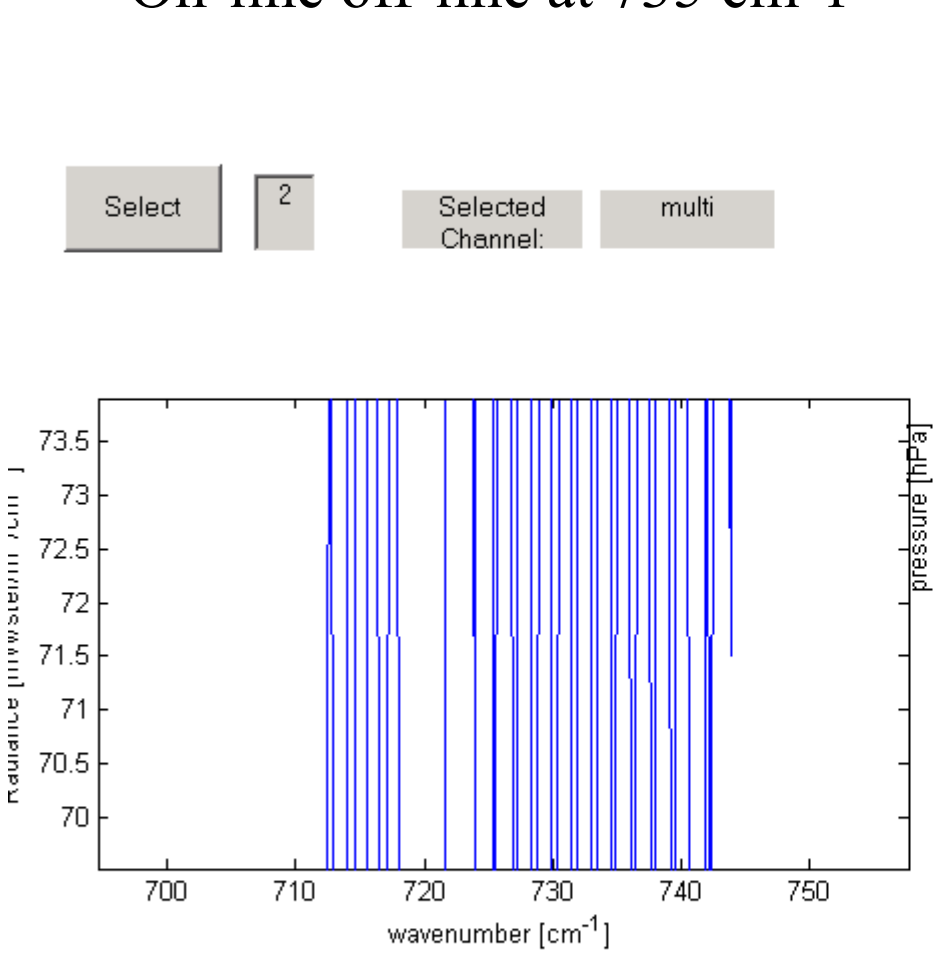
Selected Channel:

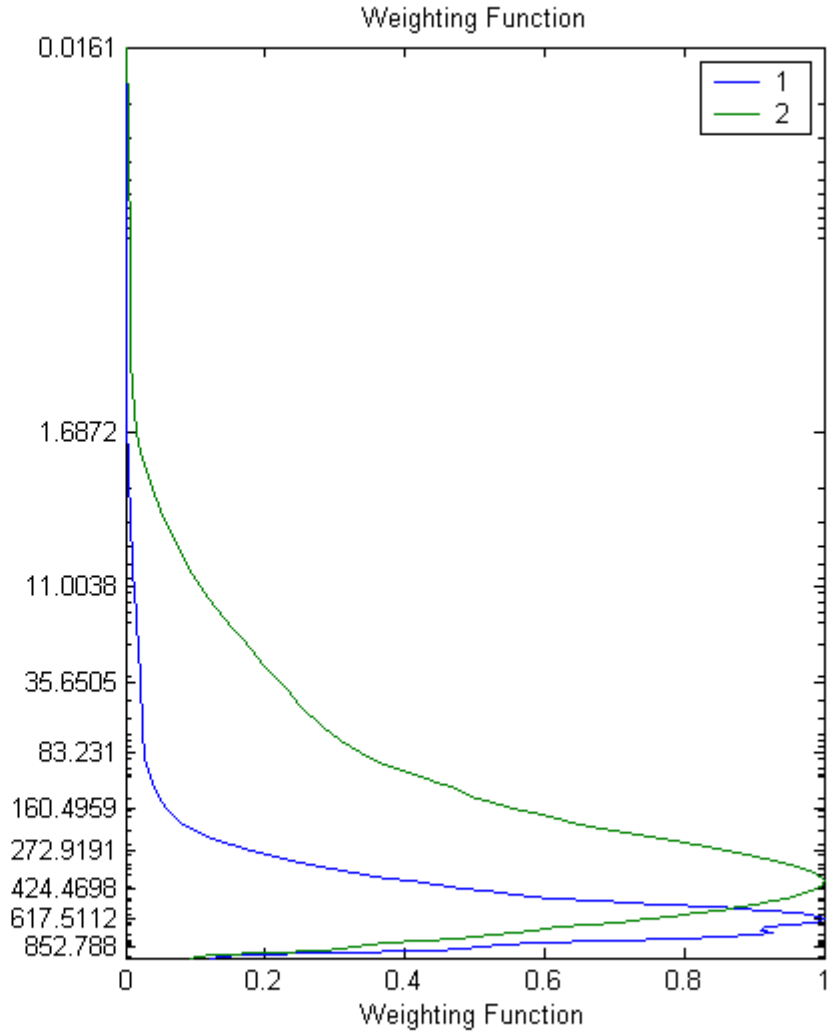
multi



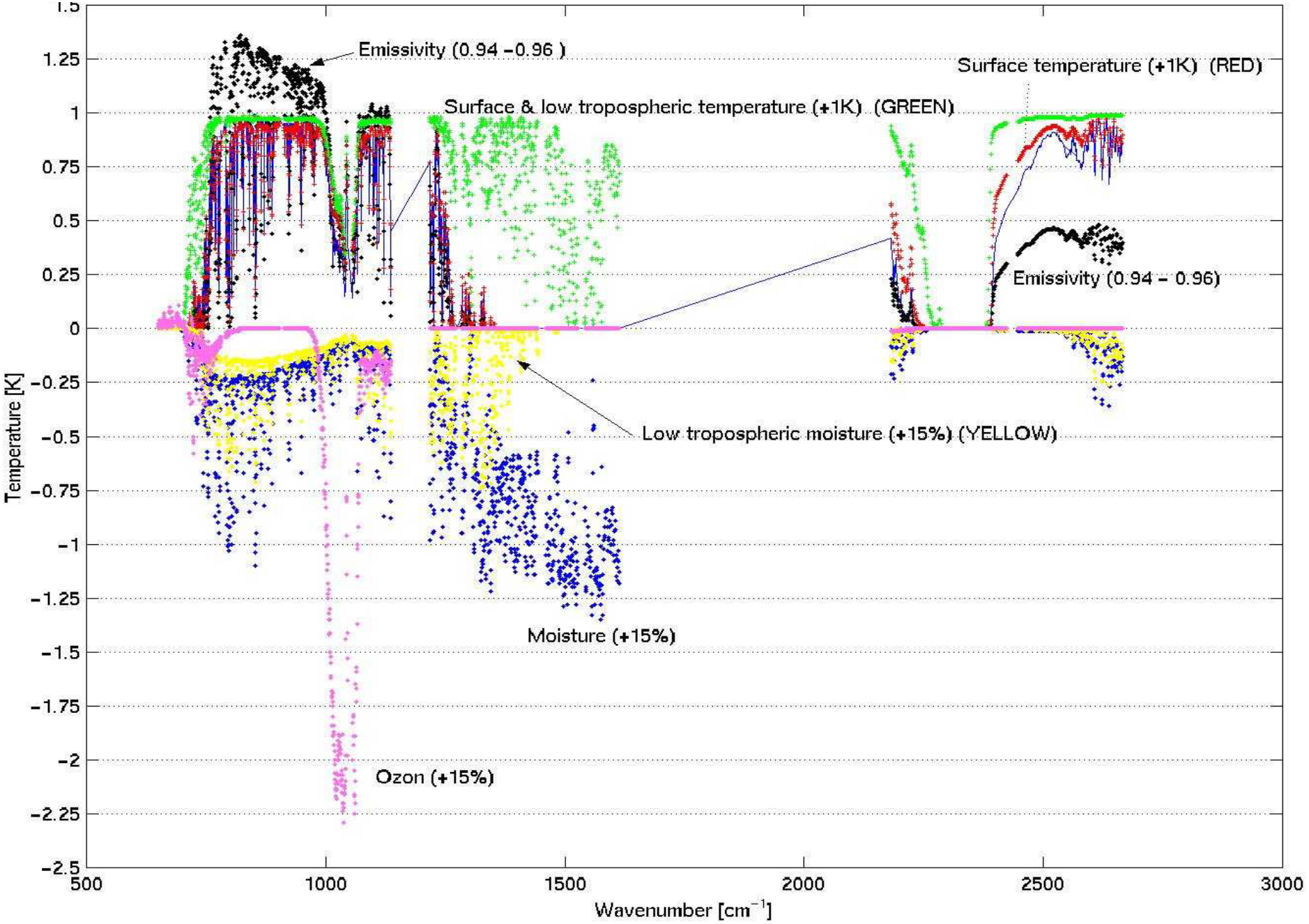


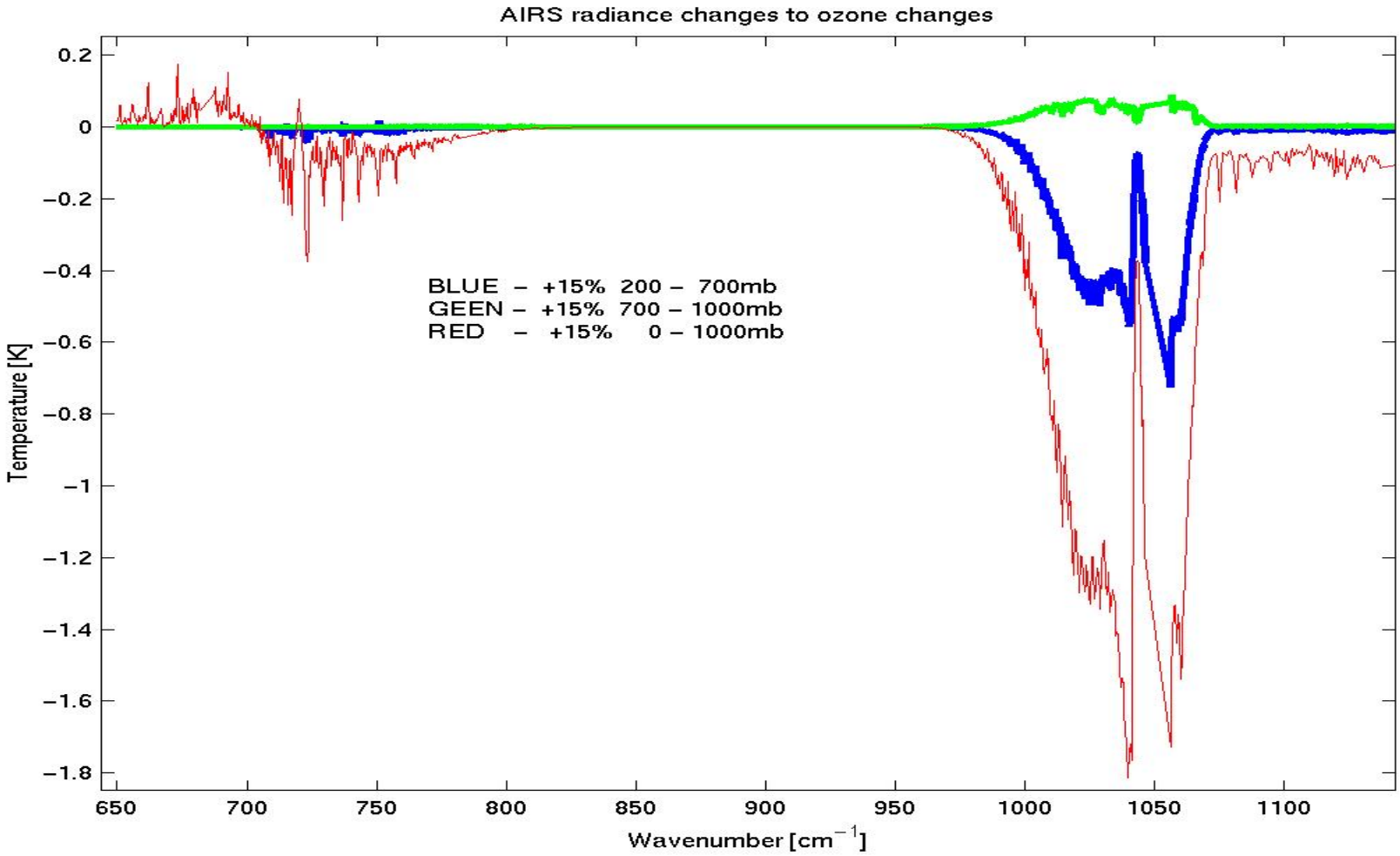
On-line off-line at 735 cm-1





AIRS radiance changes (in deg K) to atm & sfc changes





AIRS spectrum of brightness temperature changes calculated with SARTA in response to an increase in total ozone of 15% (red), an increase of boundary layer ozone of 15% between 700 – 1000 hPa (green), and an increase of tropospheric ozone of 15% between 200 – 700 hPa (blue) assuming a climatological ozone profile.

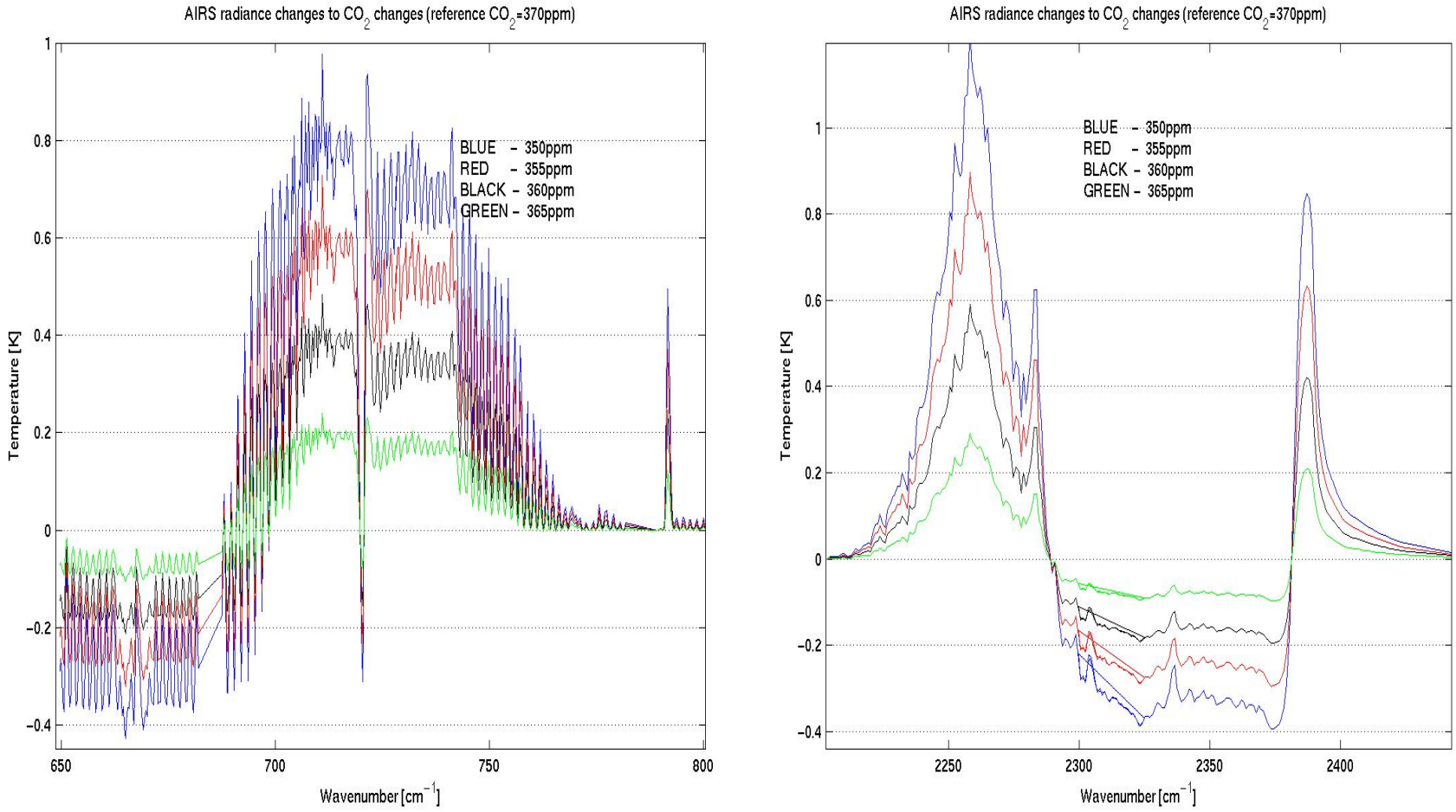
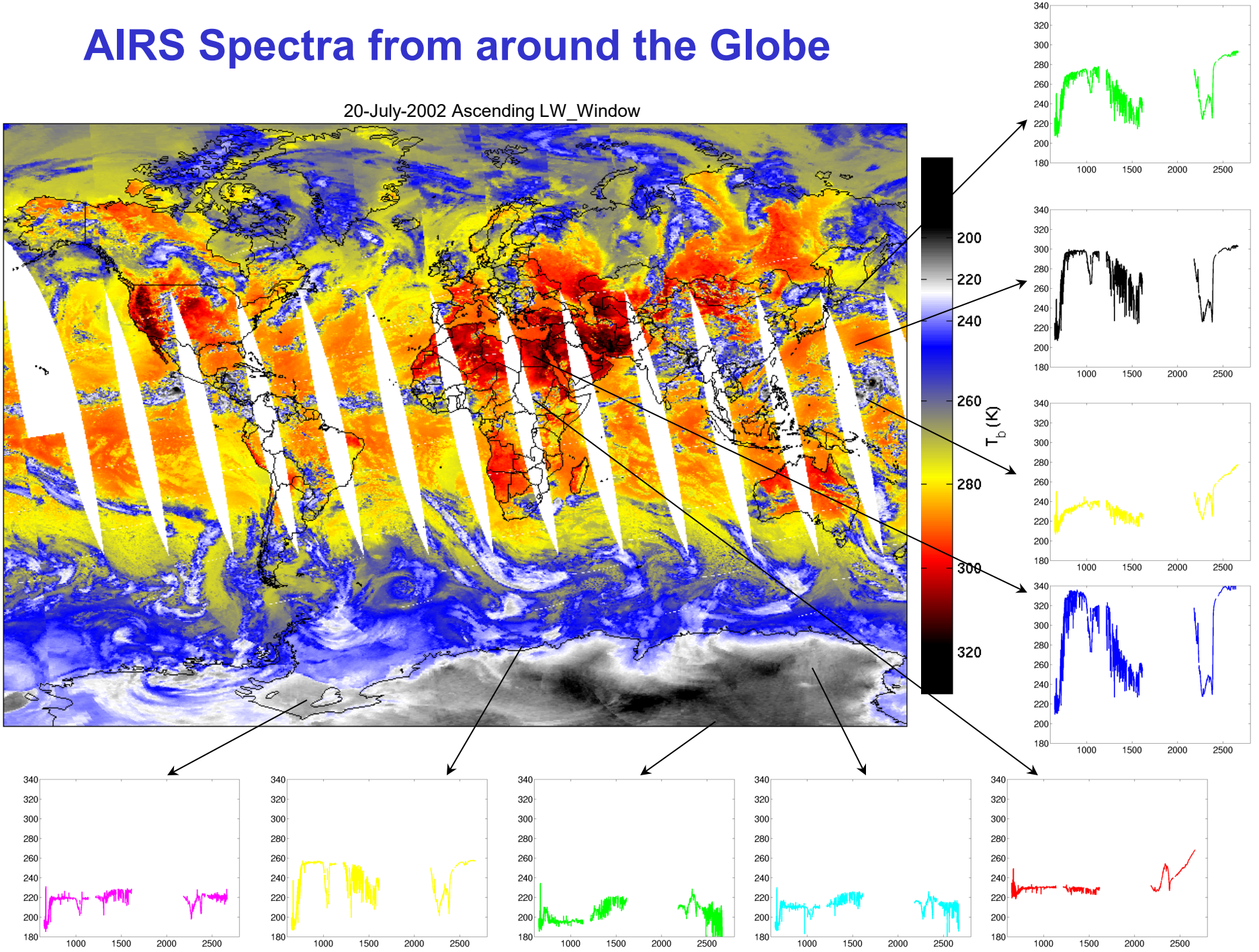
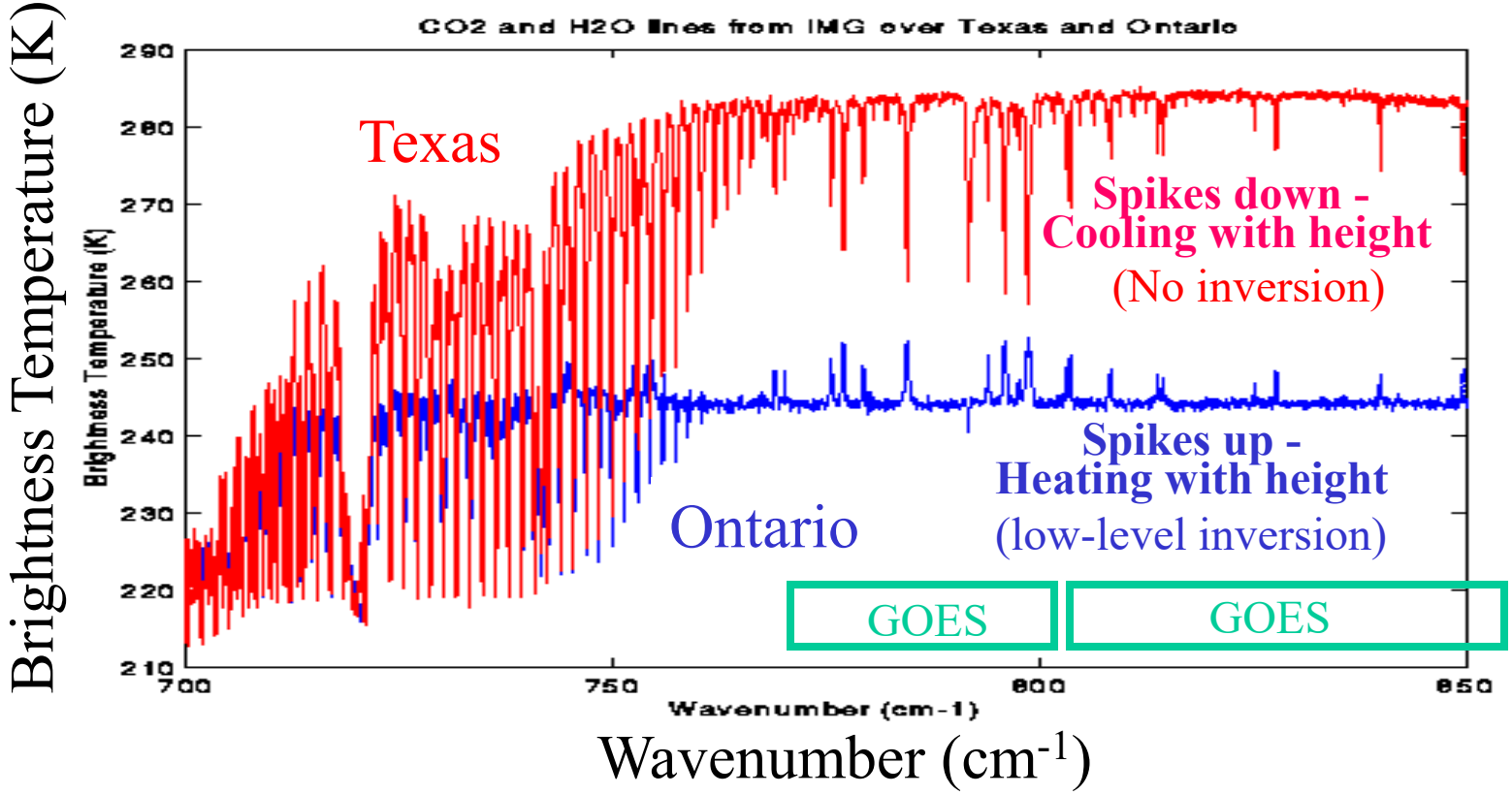


Figure YP2: The AIRS spectrum (650 to 800 cm-1 on the left and 2200 to 2500 cm-1 on the right) of brightness temperature changes calculated with SARTA in response to an decrease in total CO2 from 370 ppm to 350 ppm (blue), to 355 ppm (red), to 360 ppm (black), and to 365 ppm (green). The linearity of the response is evident.

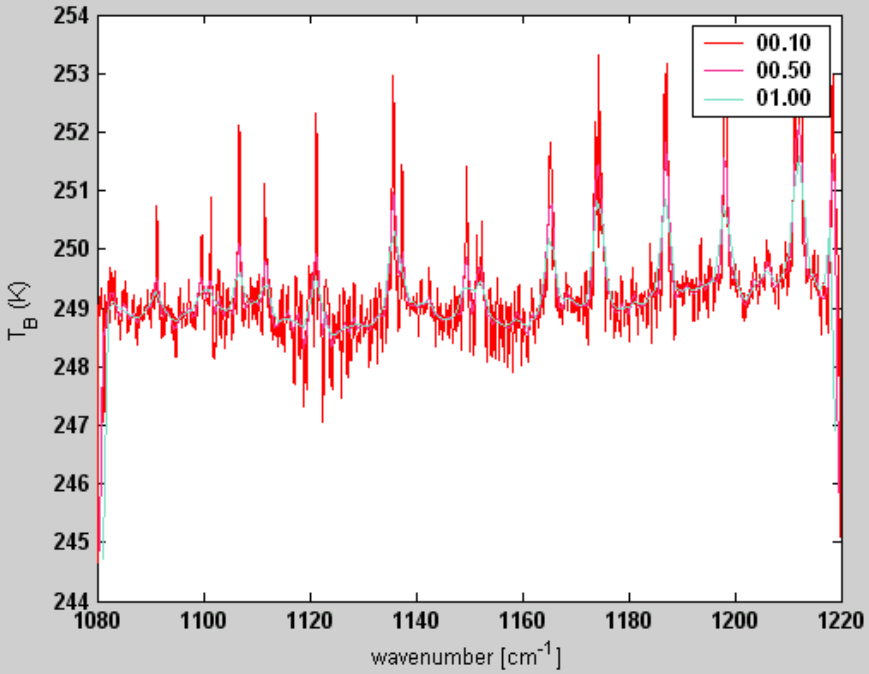
AIRS Spectra from around the Globe

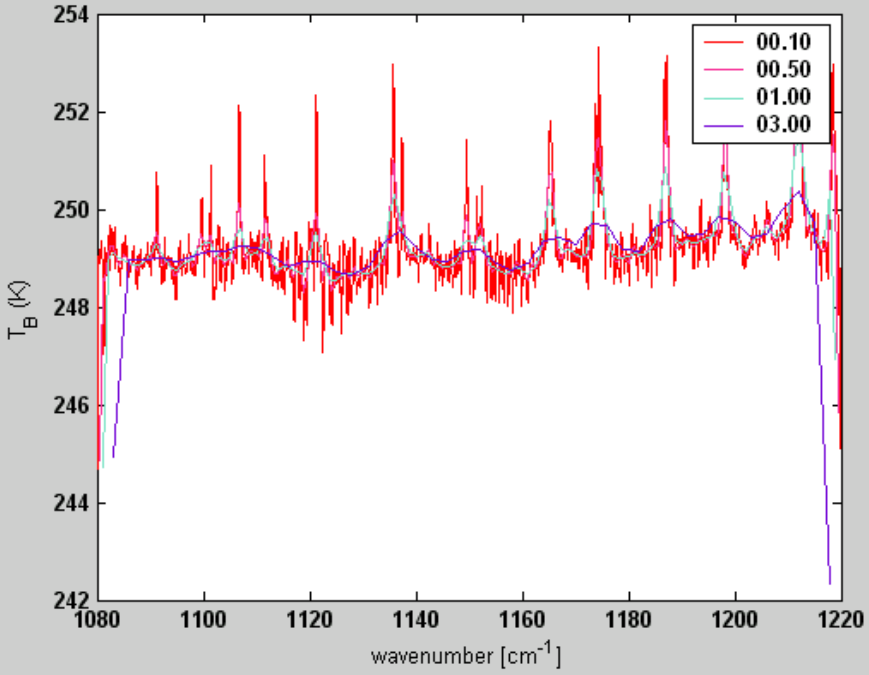


Resolving absorption features in atmospheric windows enables detection of temperature inversions



Detection of inversions is critical for severe weather forecasting. Combined with improved low-level moisture depiction, key ingredients for night-time severe storm development can be monitored.

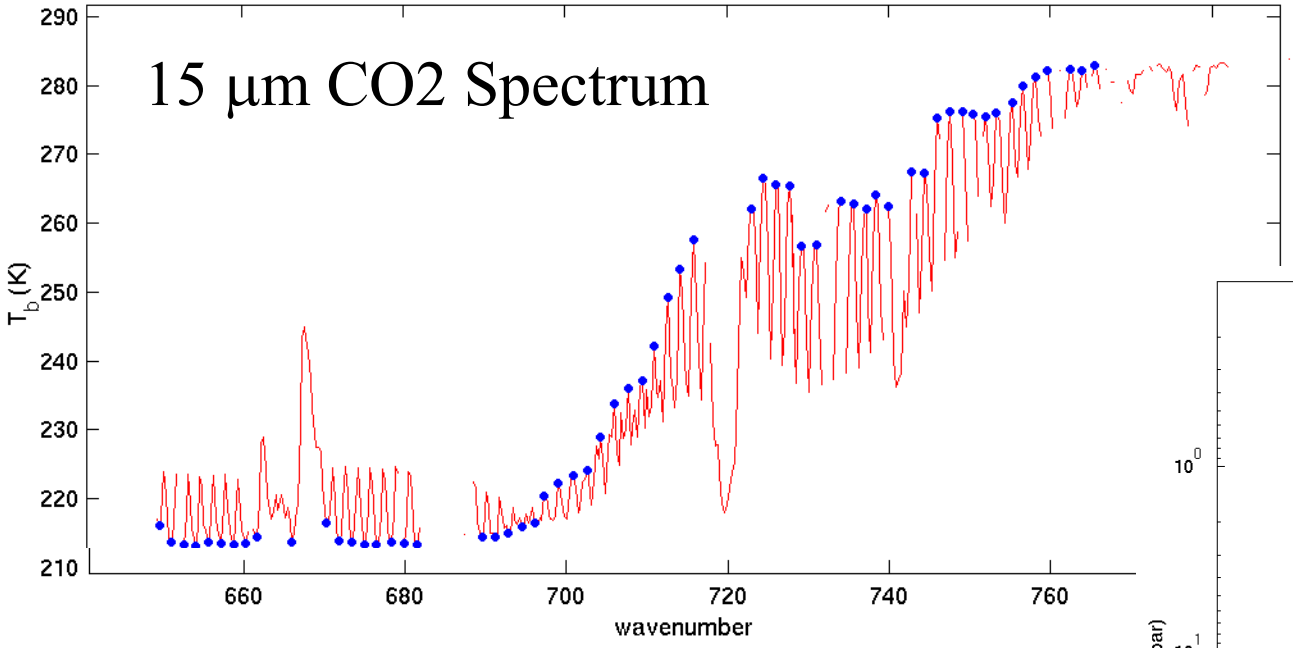


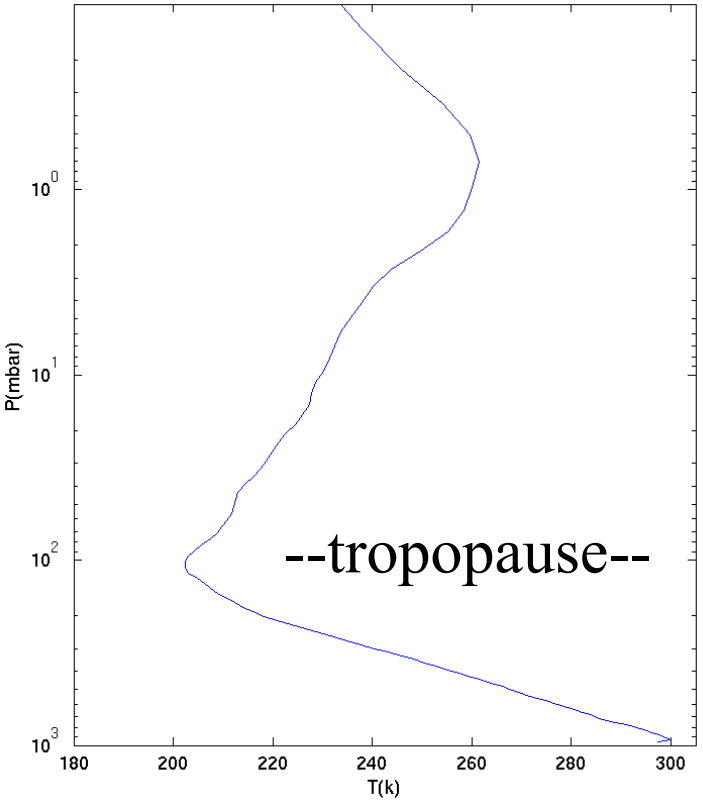


Ability to detect inversions disappears with broadband observations (> 3 cm-1)

Twisted Ribbon formed by CO_2 spectrum:

Tropopause inversion causes On-line & off-line patterns to cross

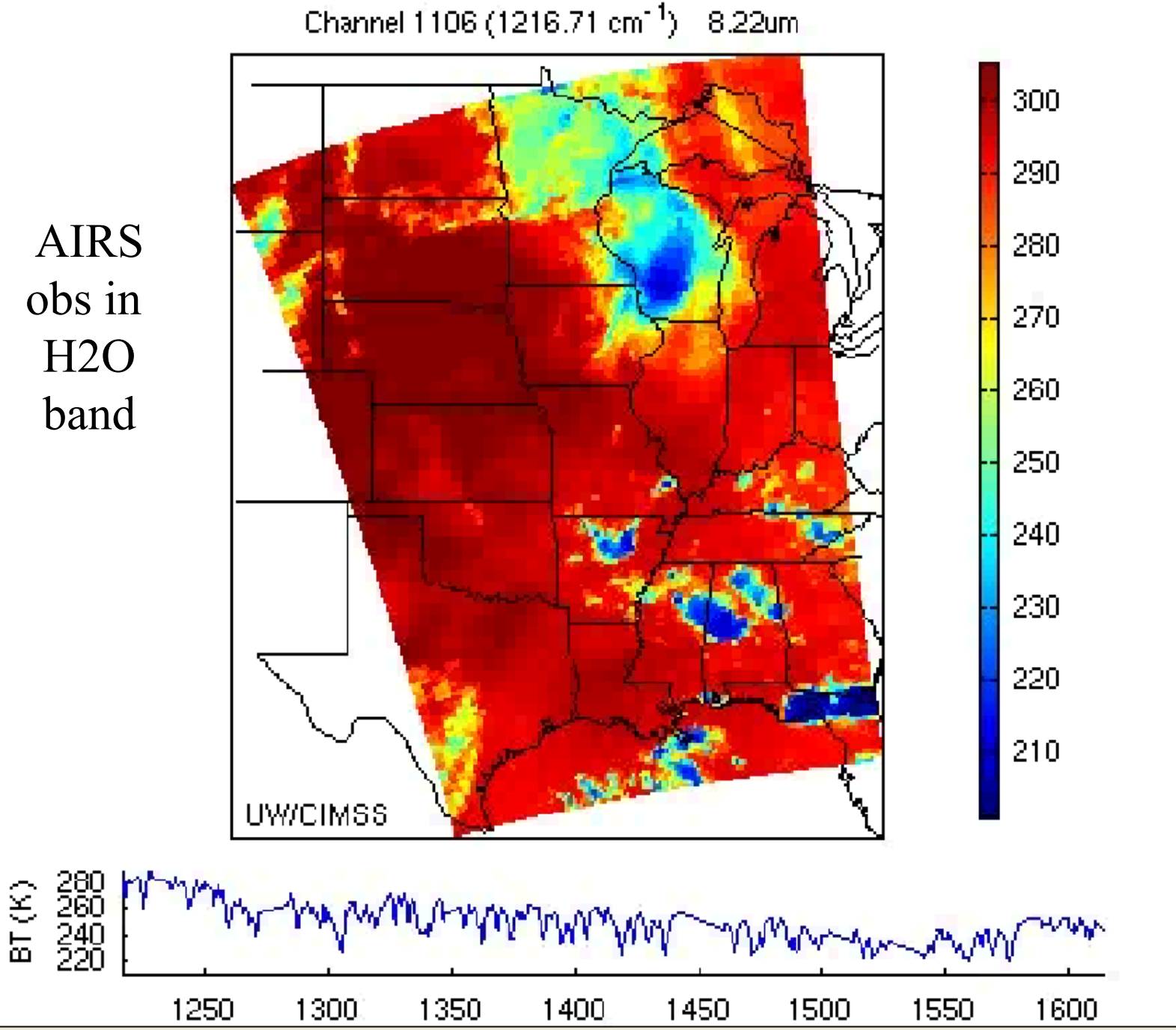




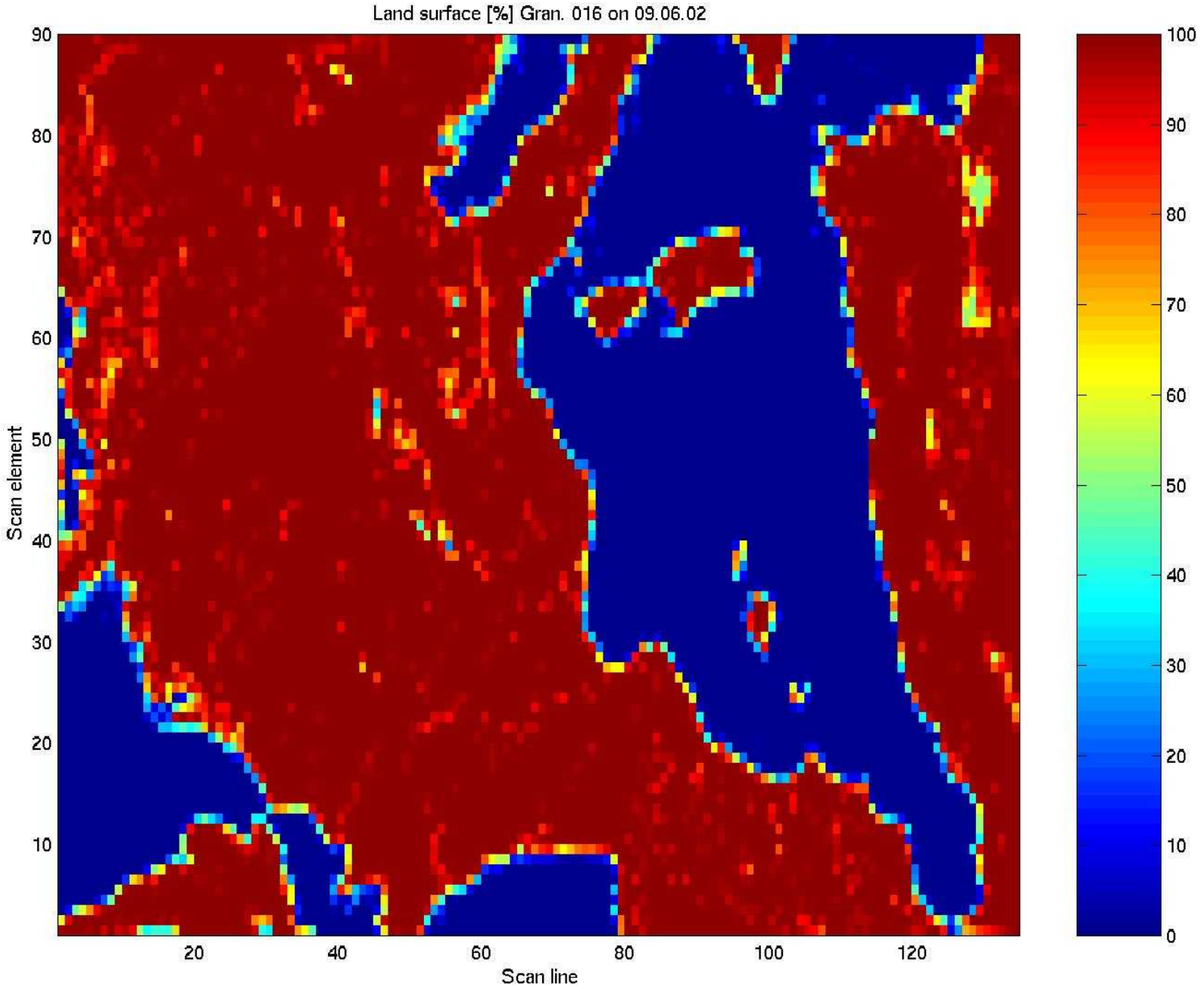
Blue between-line T_b
warmer for tropospheric channels,
colder for stratospheric channels

Signature not available at low resolution

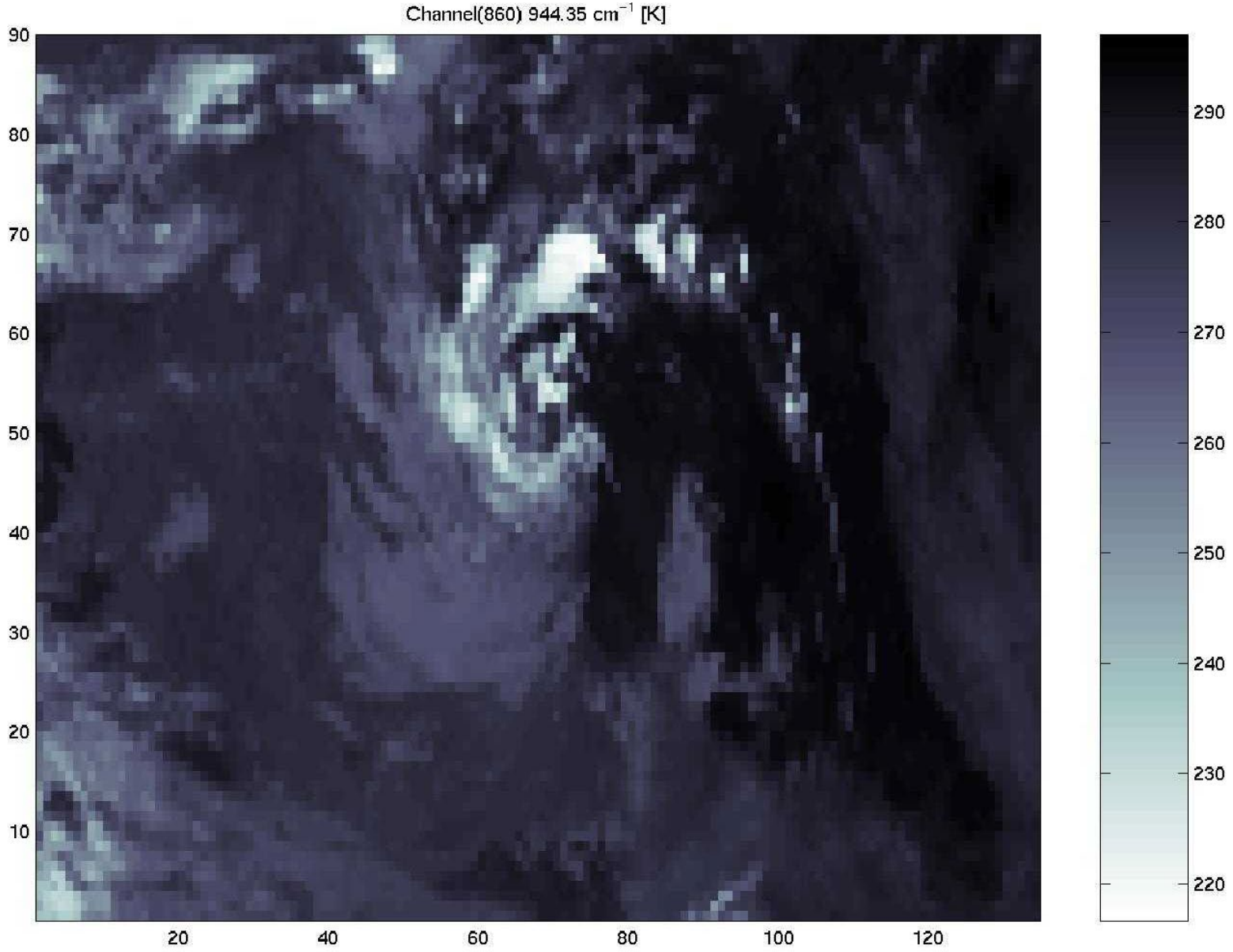
AIRS obs in H2O band



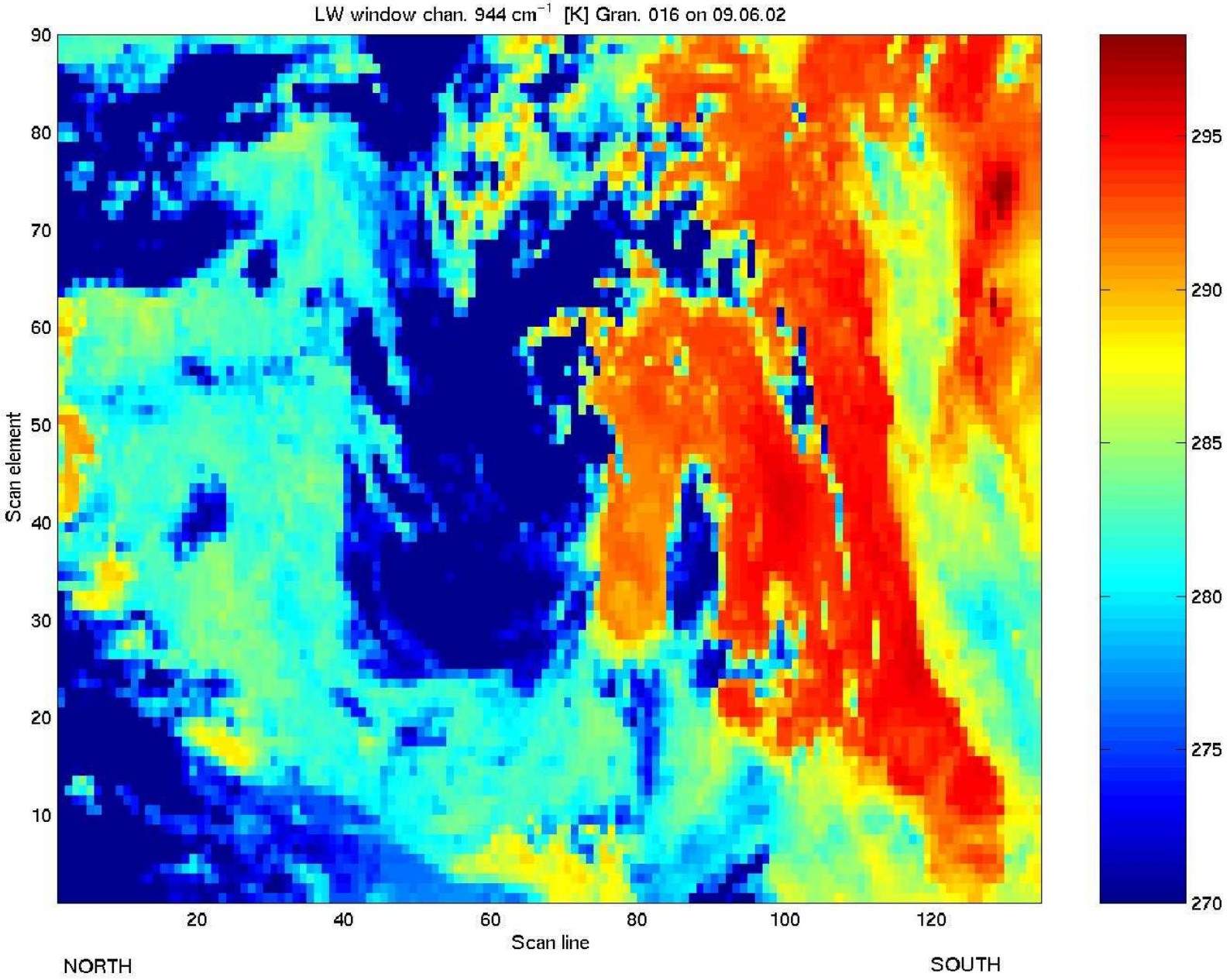
AIRS over Europe on 6 Sep 02



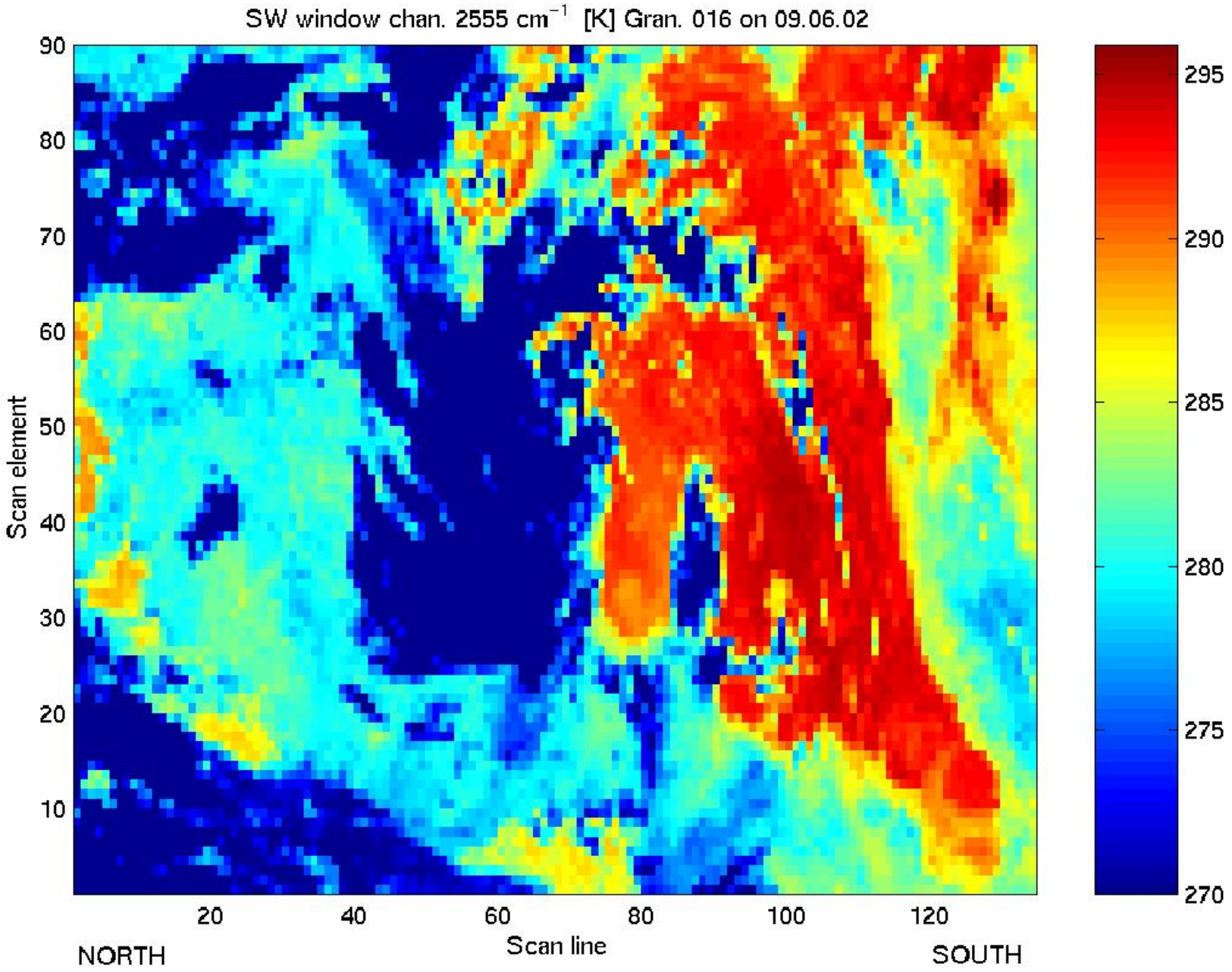
Spatial distribution of 944.1 [1/cm] measurements [K]

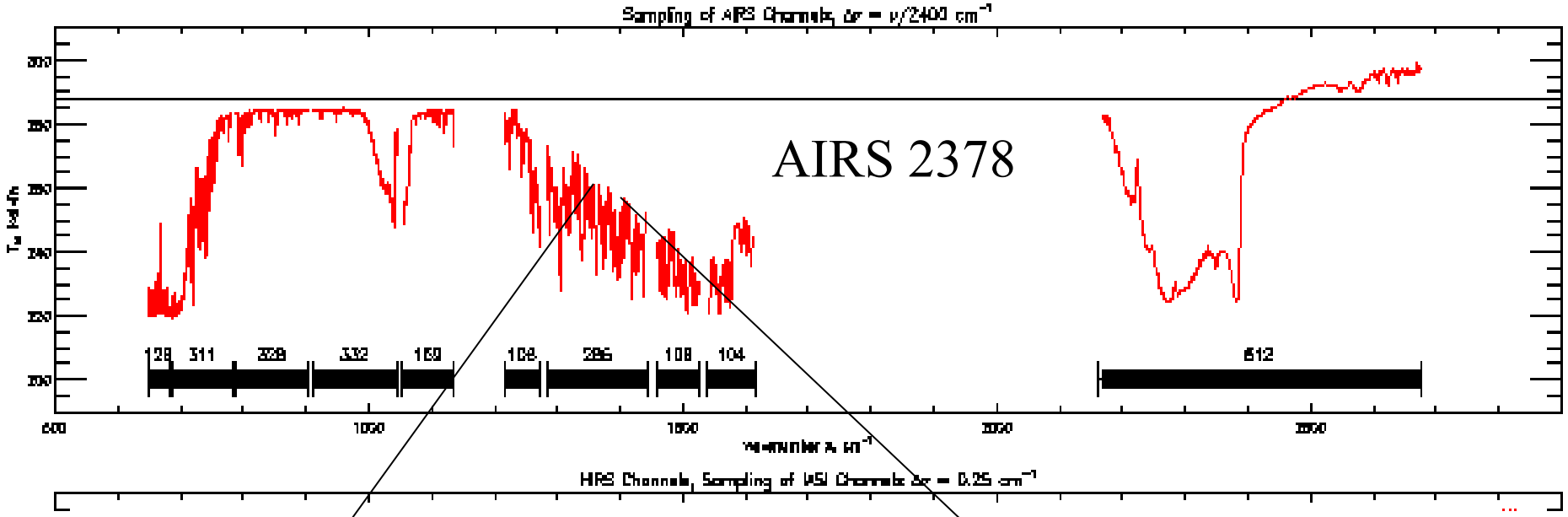


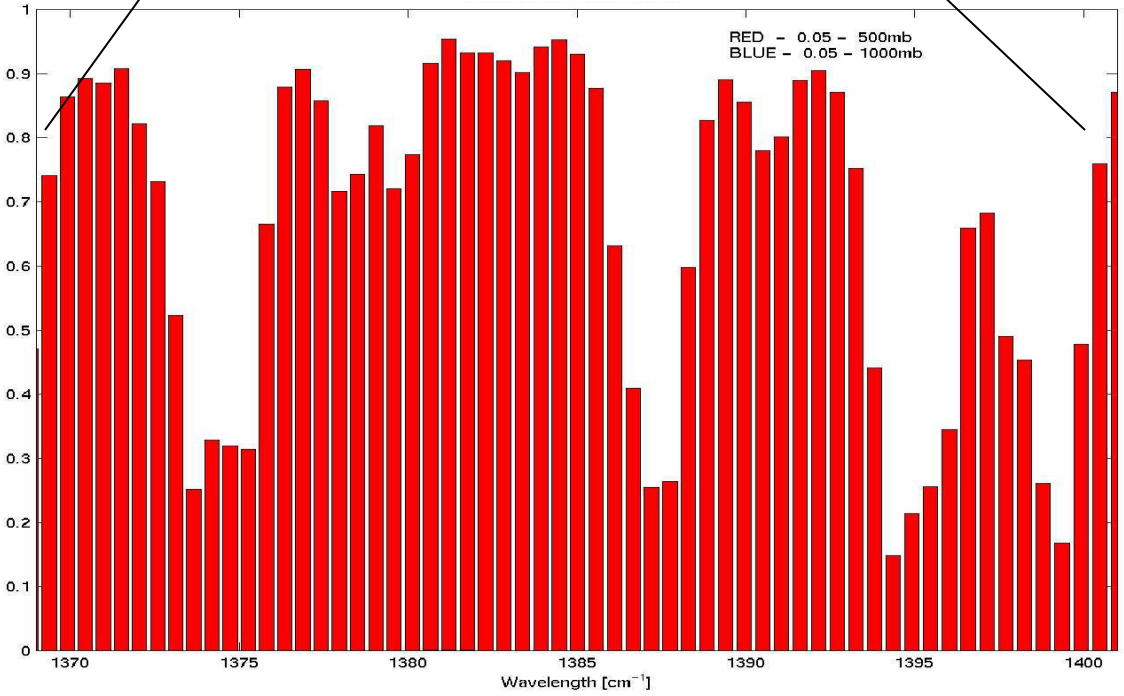
Spatial distribution of 944.1 [1/cm] measurements [K]



Spatial distribution of 2555 [1/cm] measurements [K]

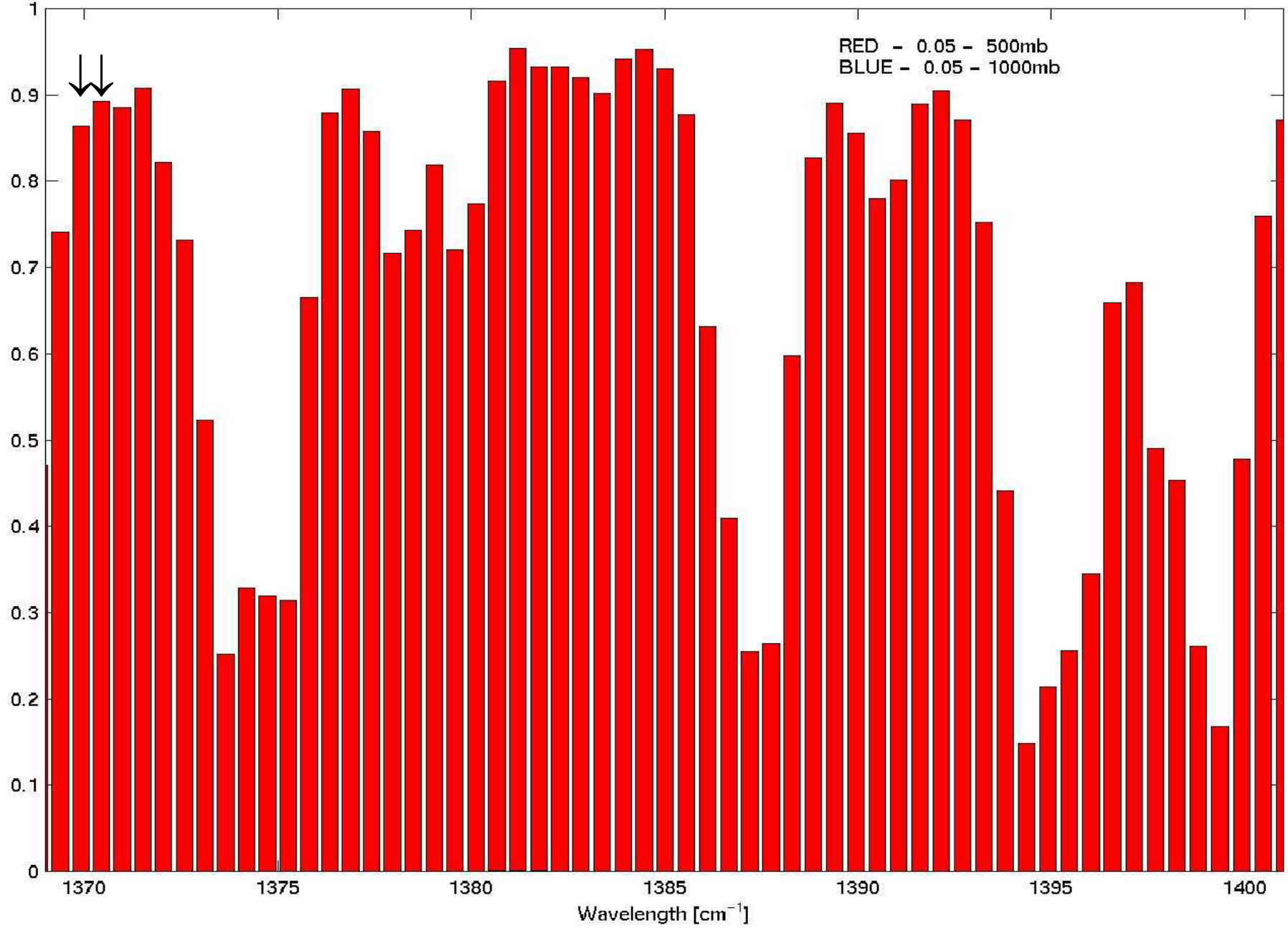




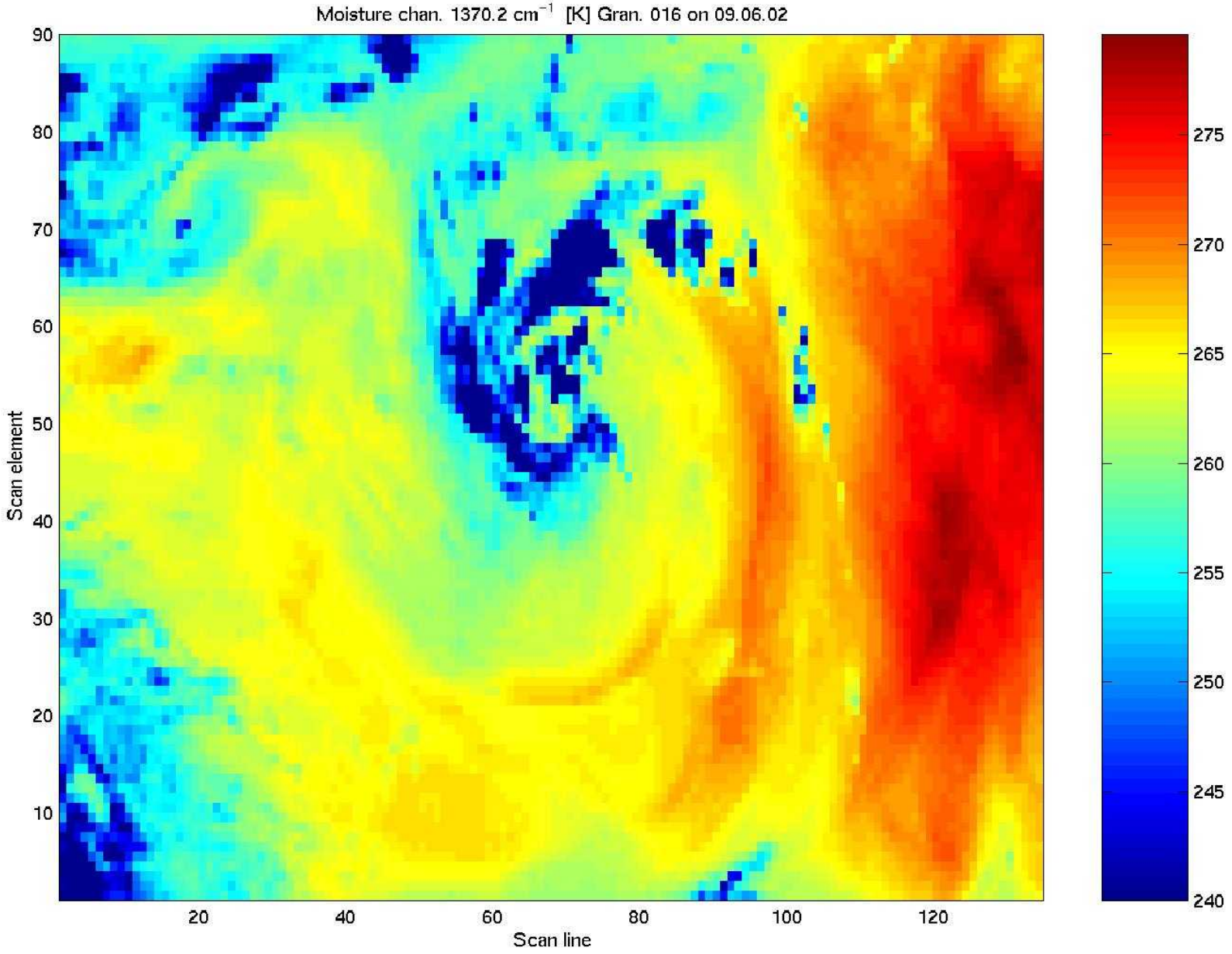


Transmittance within H20 absorption band

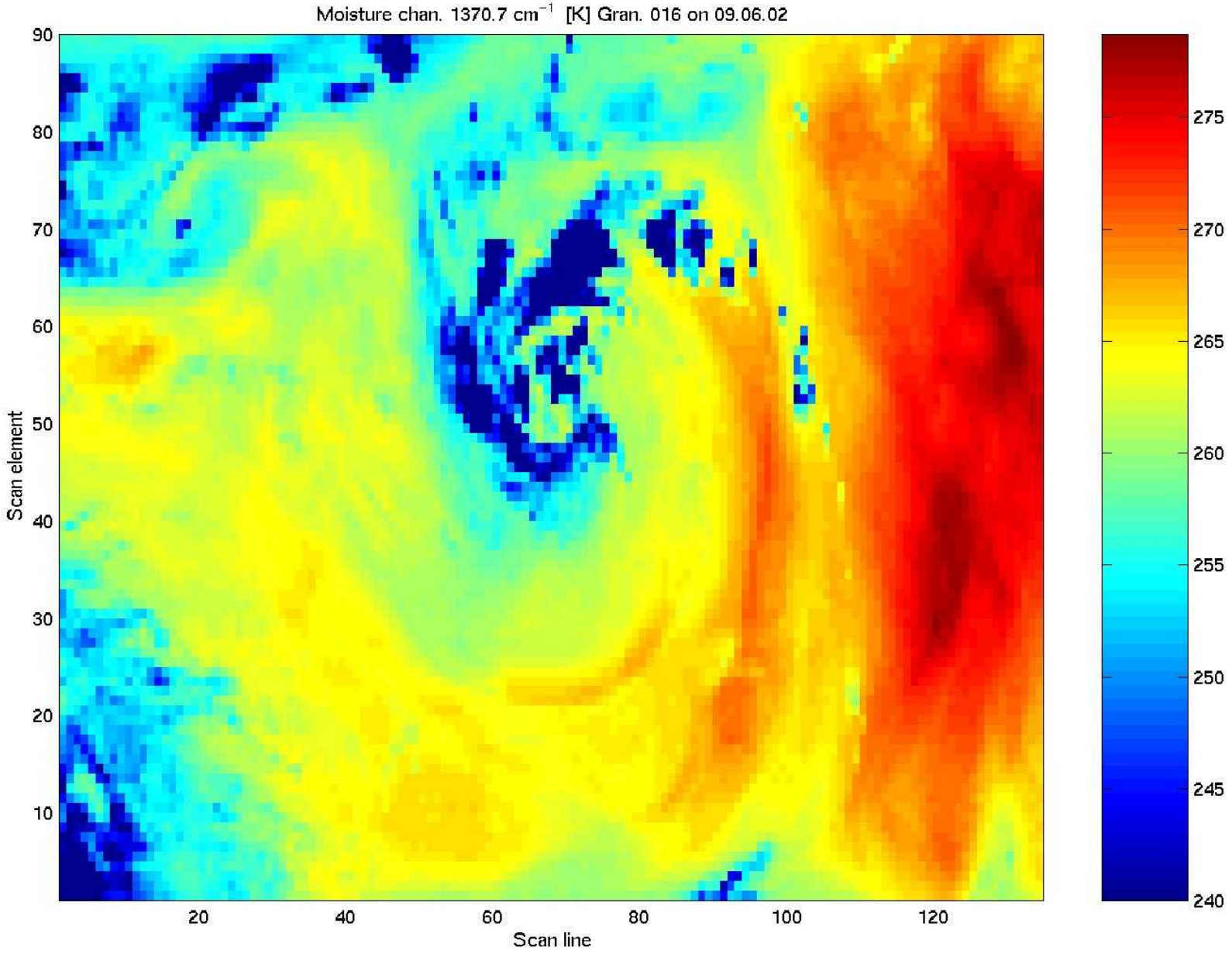
Atmospheric transmittance in H2O sensitive region of spectrum



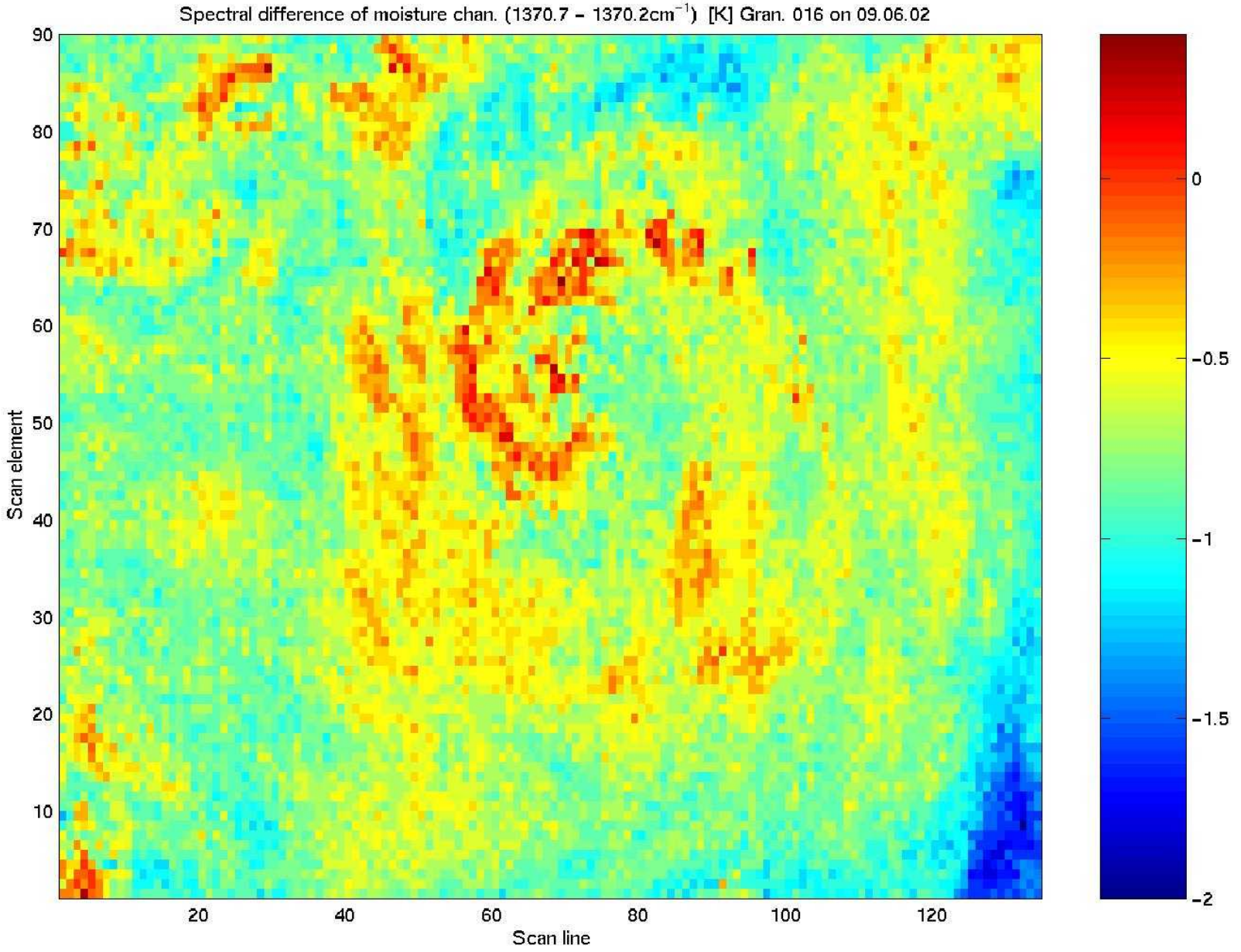
Spatial distribution of 1370.2 [1/cm] measurements [K]



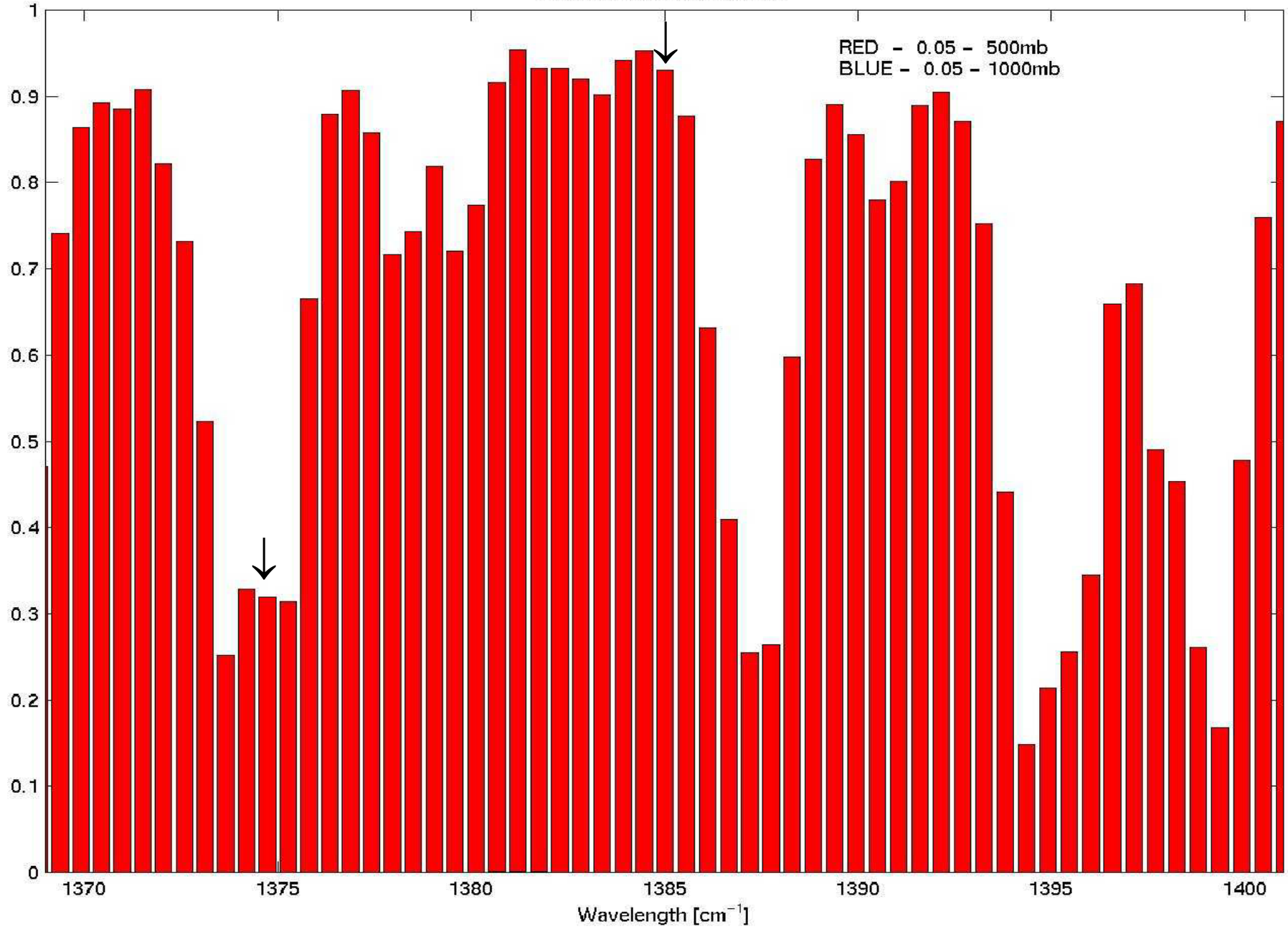
Spatial distribution of 1370.7 [1/cm] measurements [K]



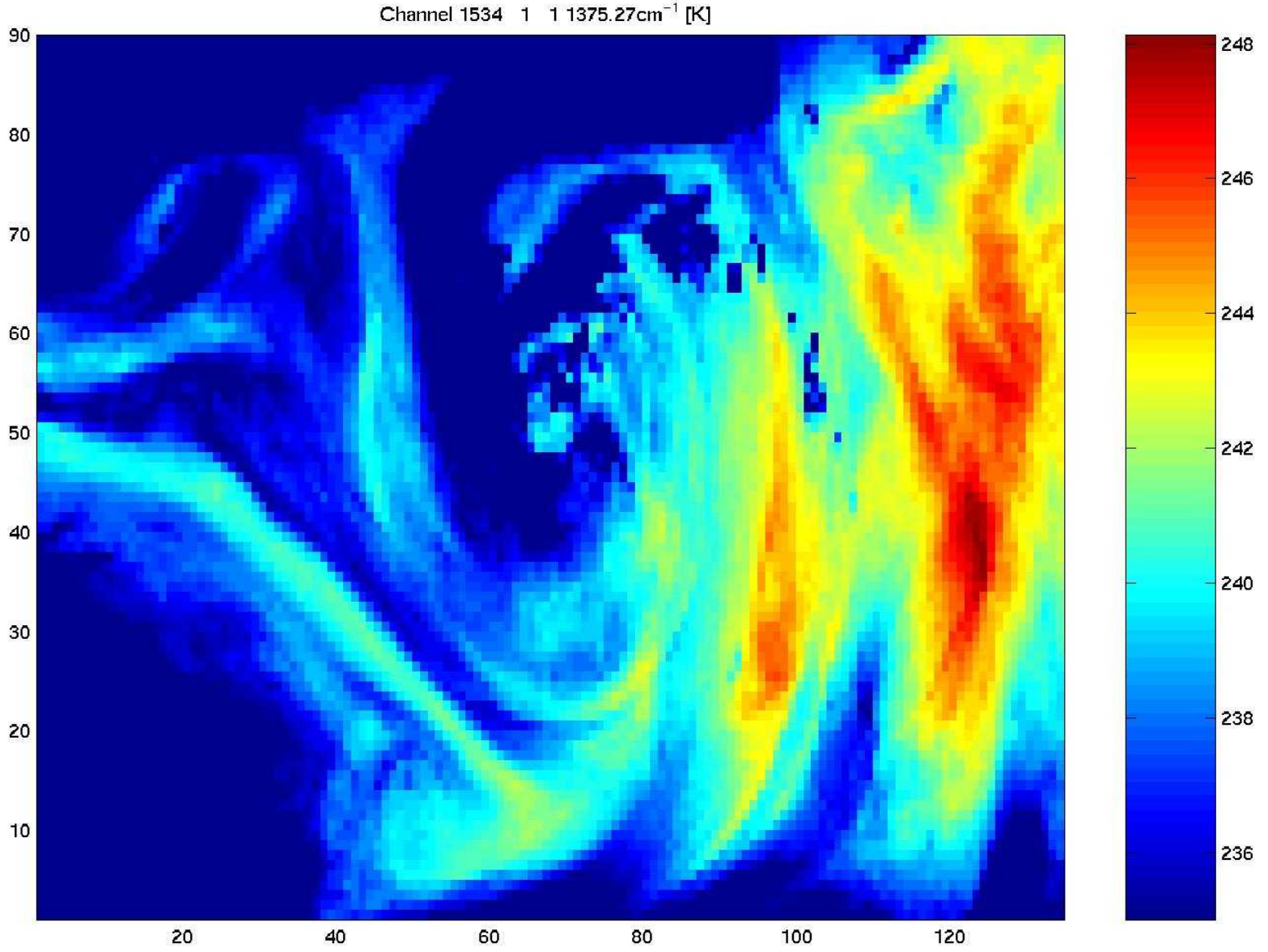
Spatial distribution of 1370.2 – 1370.7 [1/cm] measurements [K]



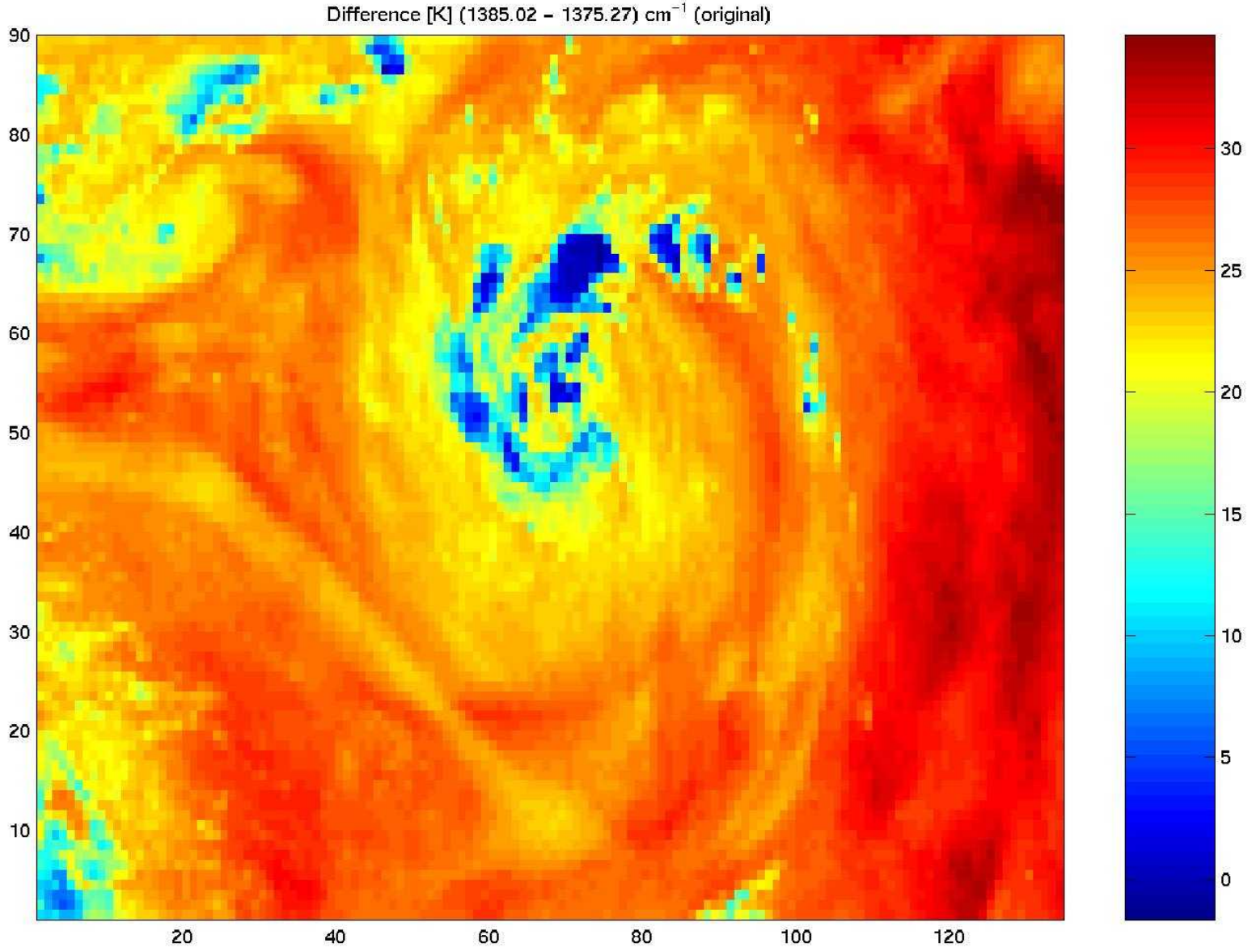
Atmospheric transmittance in H2O sensitive region of spectrum



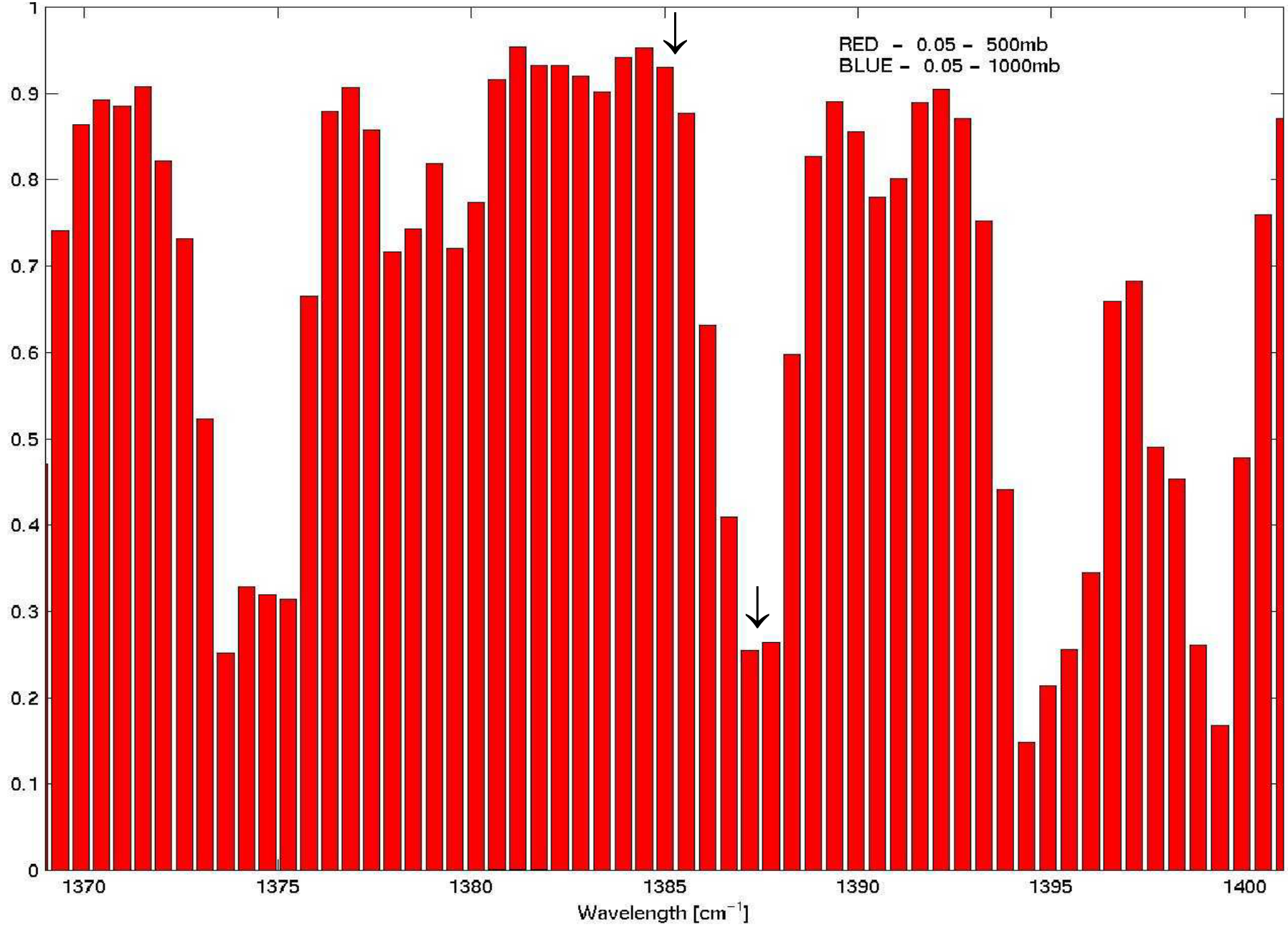
Spatial distribution of Ch 1534 at 1375.27 [1/cm] measurements [K]



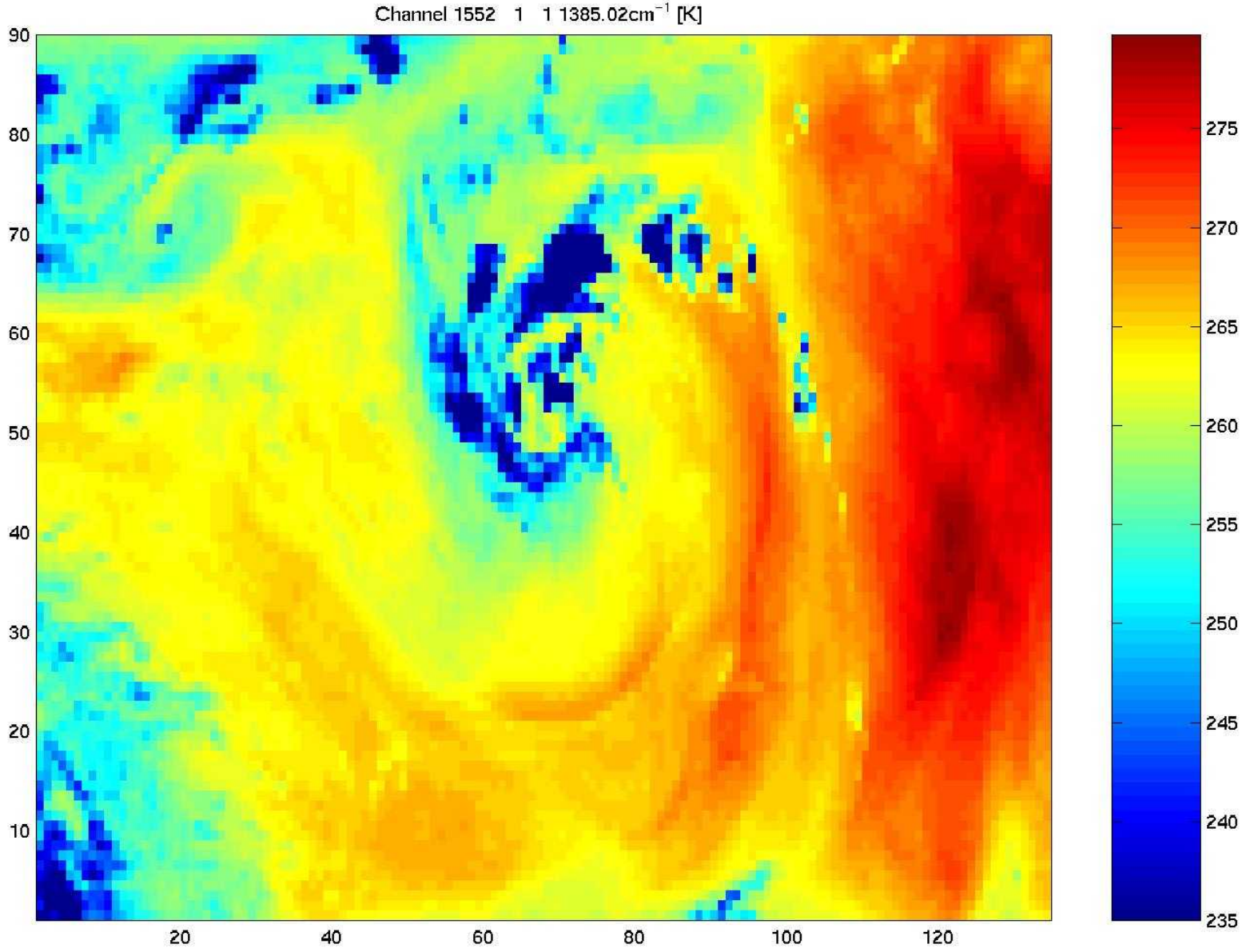
Spatial distribution of 1385.02 – 1375.27 [1/cm] measurements [K]



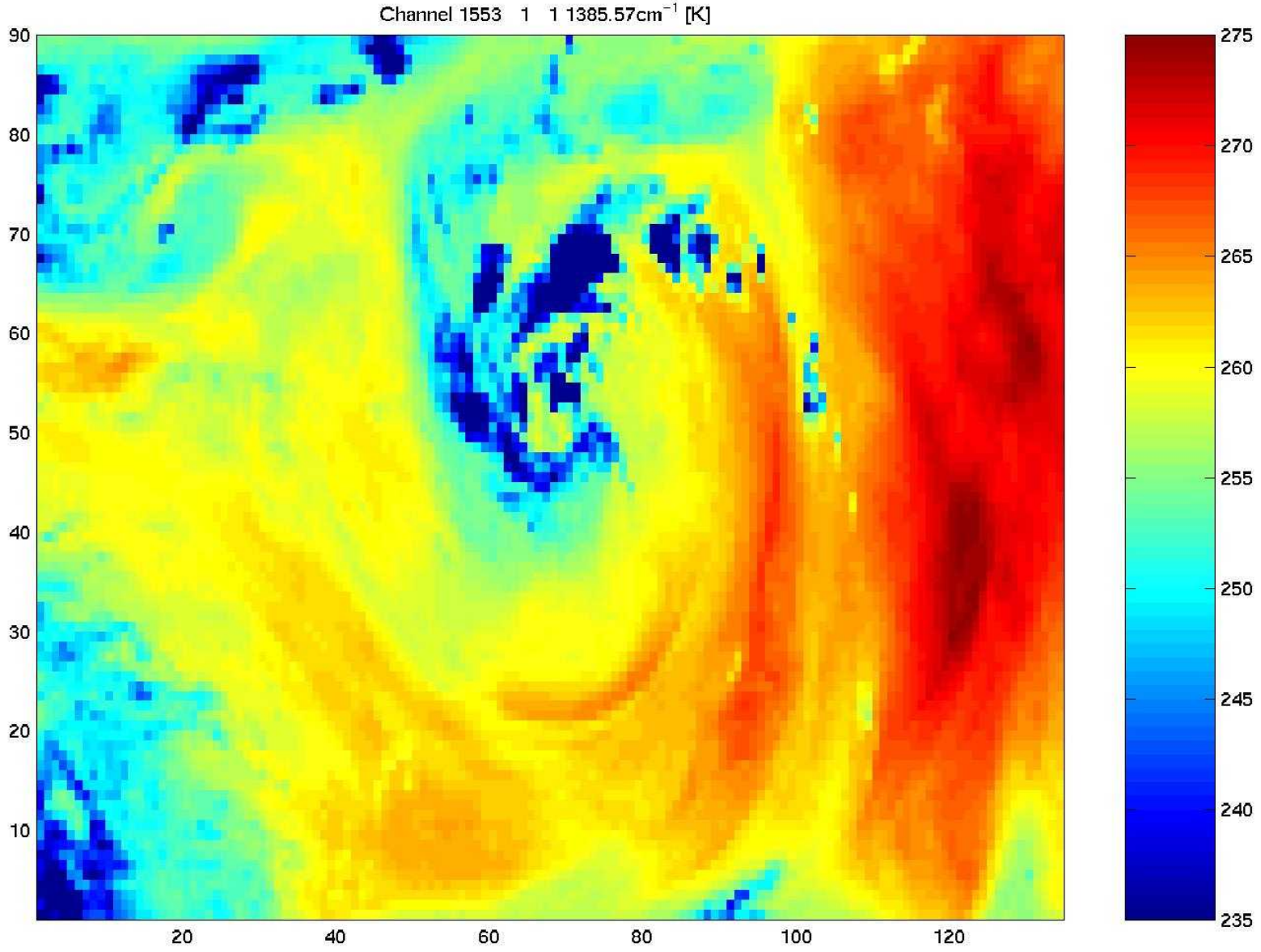
Atmospheric transmittance in H2O sensitive region of spectrum



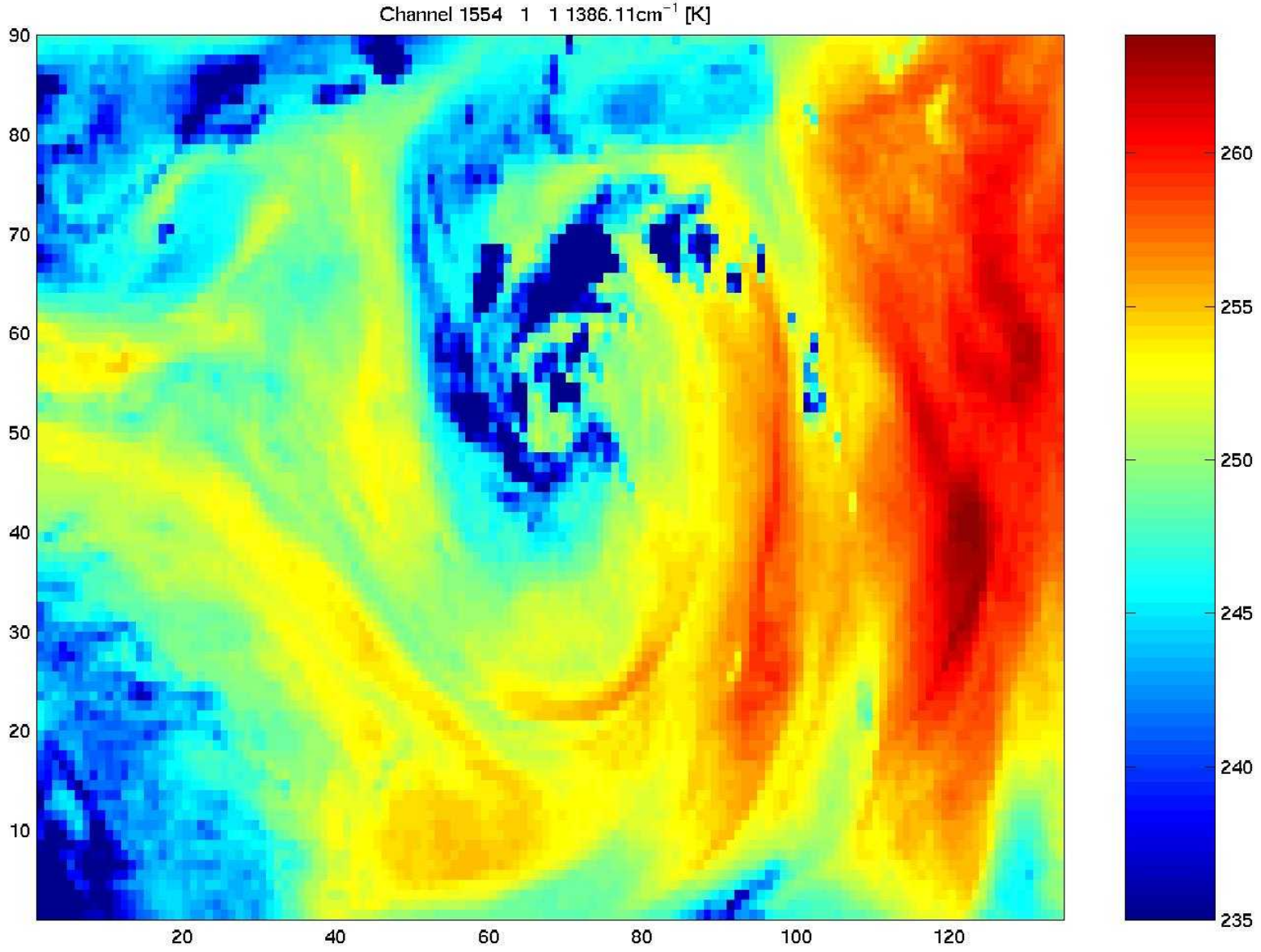
Spatial distribution of Ch 1552 at 1385.02 [1/cm] measurements [K]



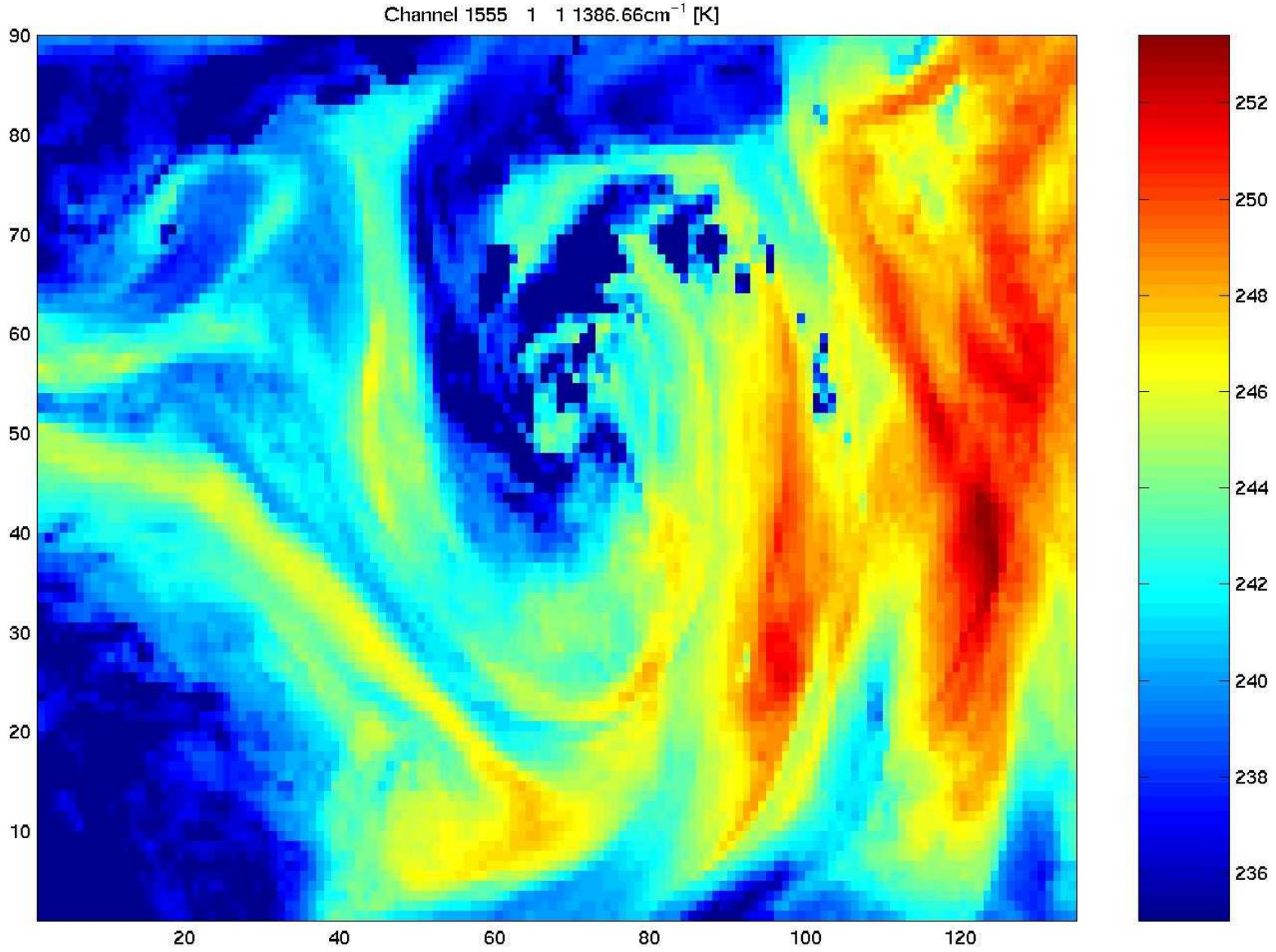
Spatial distribution of Ch 1553 at 1385.57 [1/cm] measurements [K]



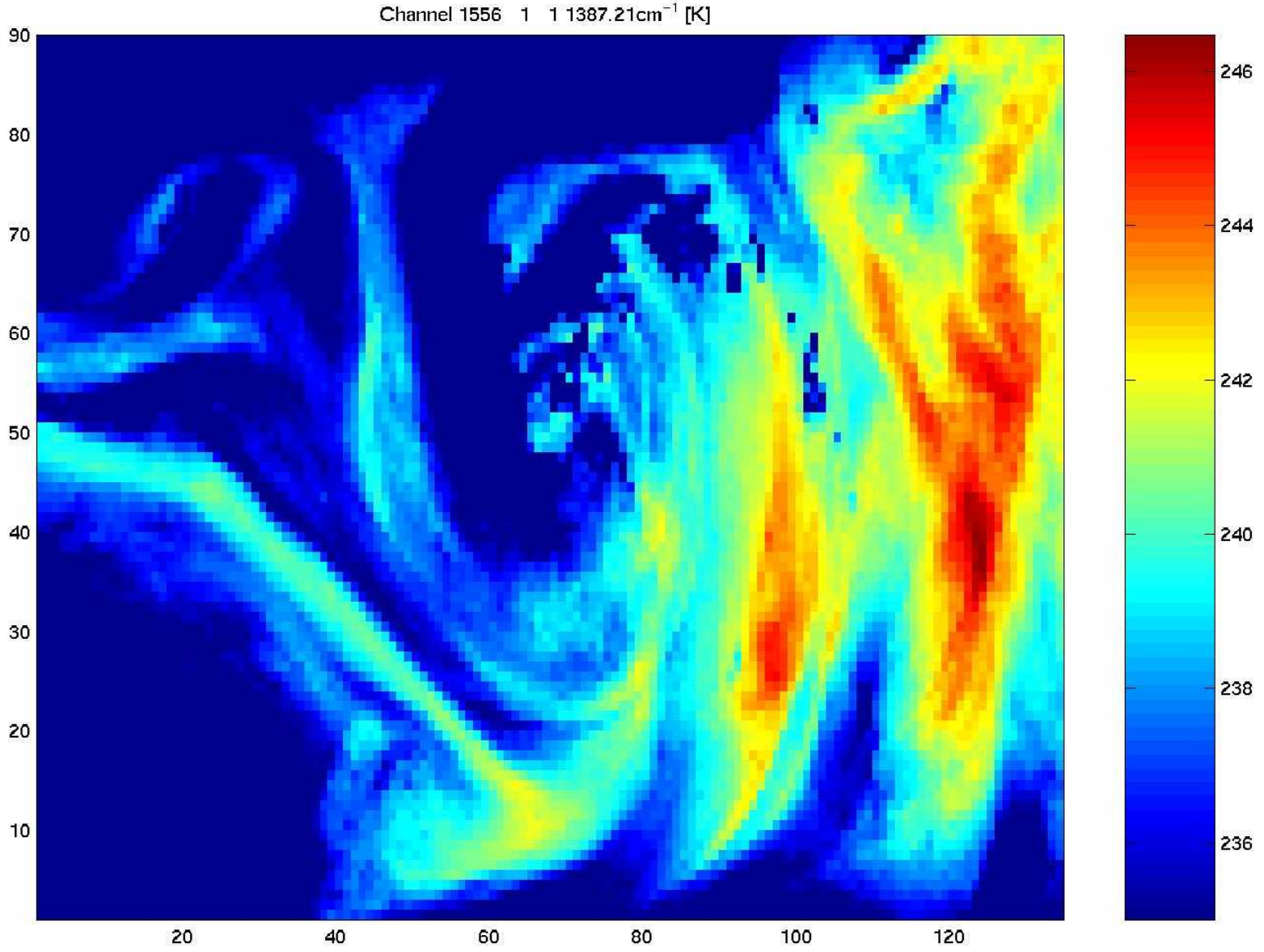
Spatial distribution of Ch 1554 at 1386.11 [1/cm] measurements [K]



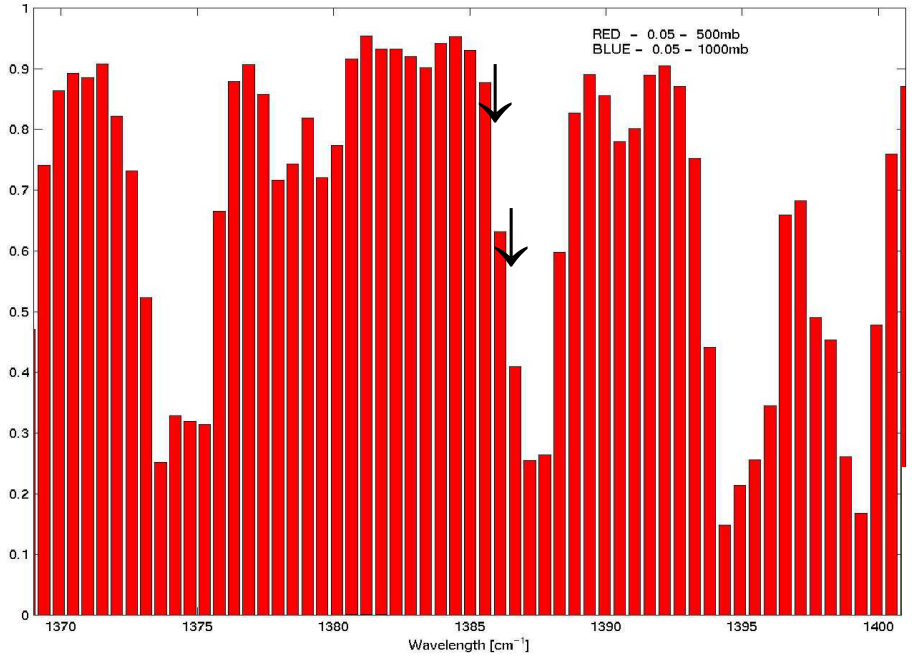
Spatial distribution of Ch 1555 at 1386.66 [1/cm] measurements [K]



Spatial distribution of Ch 1556 at 1387.21 [1/cm] measurements [K]

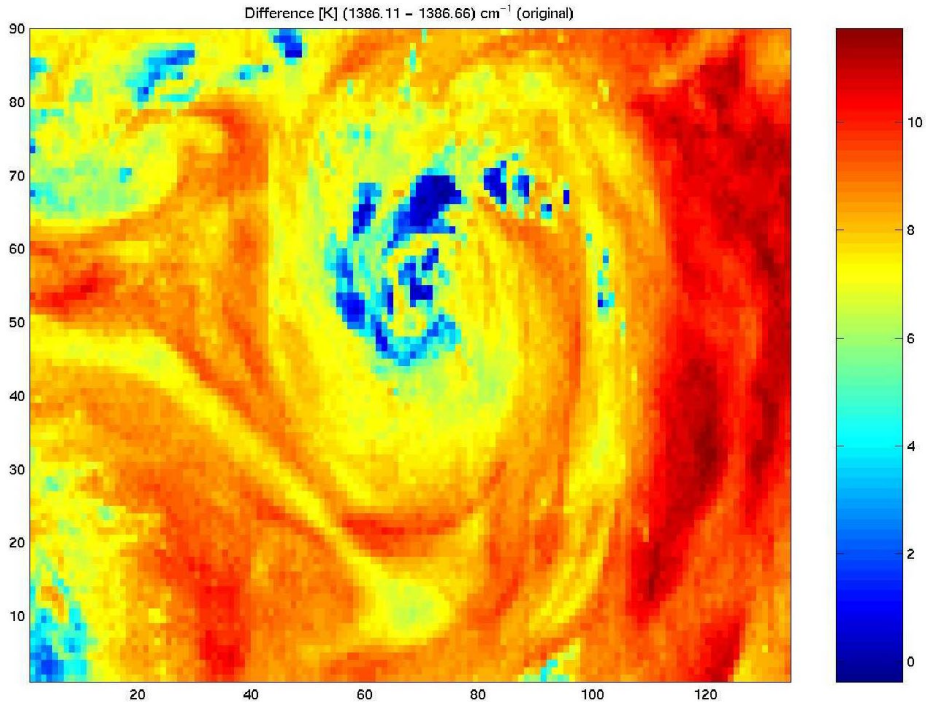


Atmospheric transmittance in H2O sensitive region of spectrum

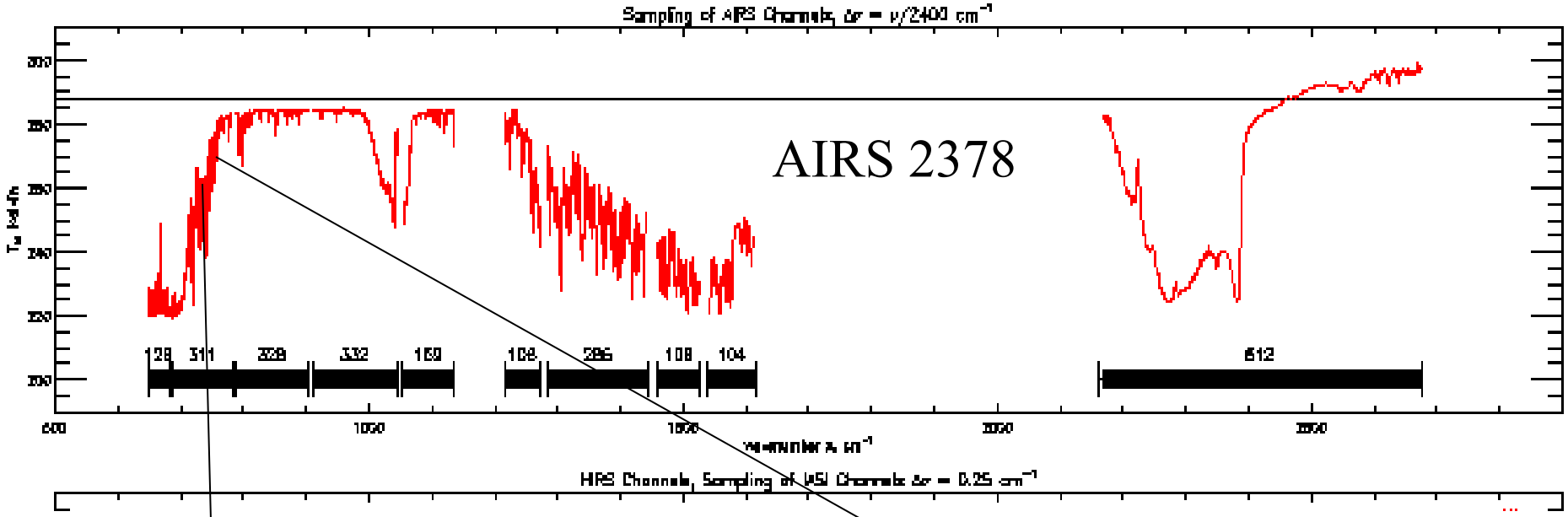


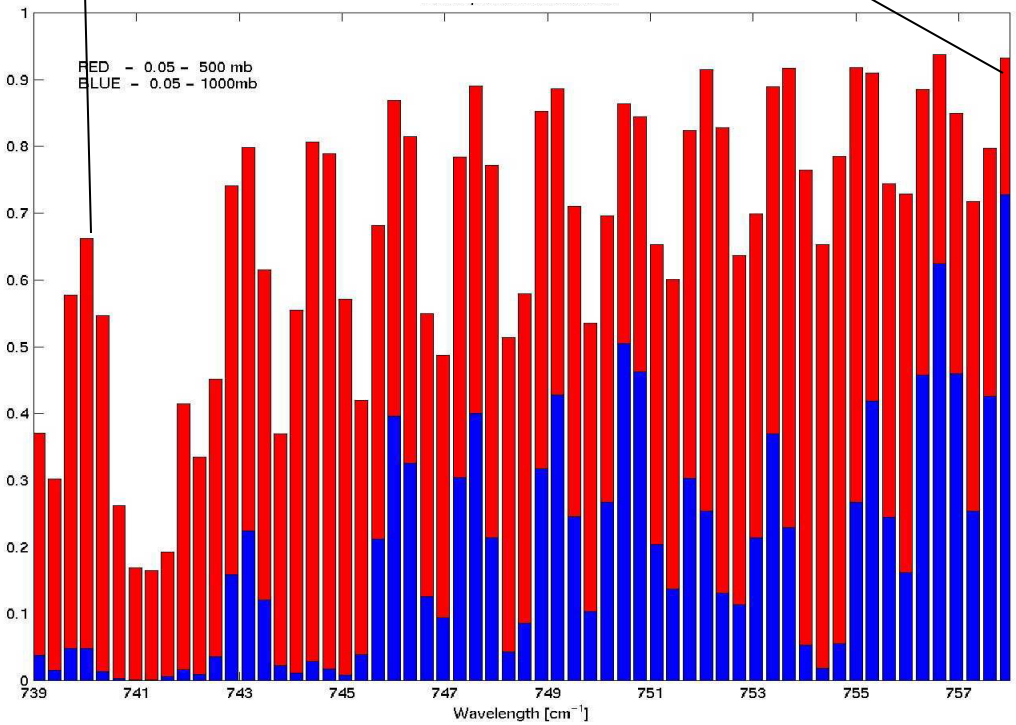
Studying spectral sensitivity with AIRS Data

AIRS BT[1386.11] – BT[1386.66]



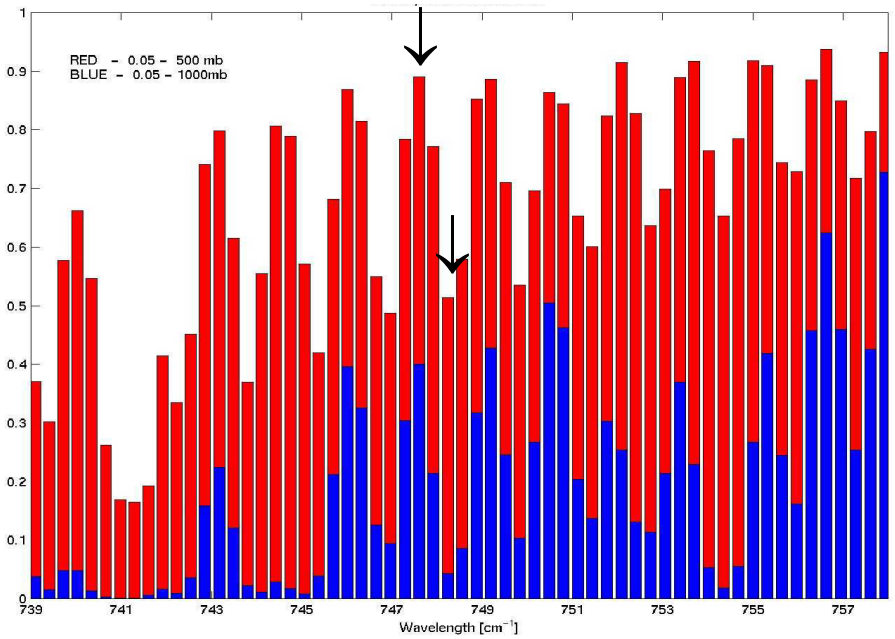
Spectral change of 0.5 cm-1 causes BT changes > 10 C





Transmittance within CO2 absorption band

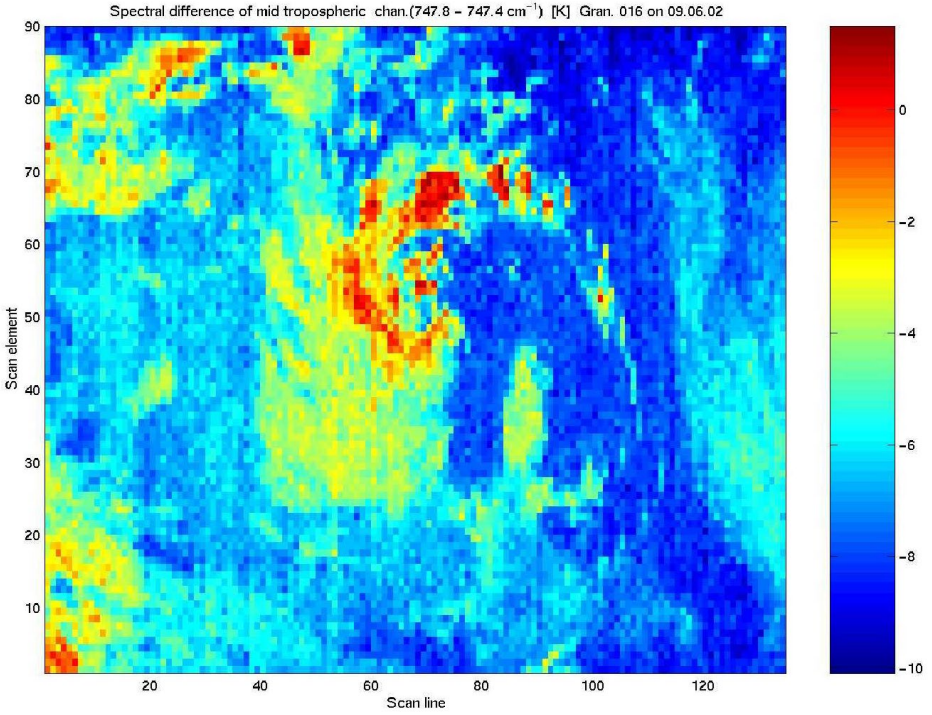
Atmospheric transmittance in CO2 sensitive region of spectrum



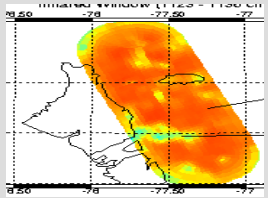
Spectral change of 0.4 cm-1 causes BT changes > 8 C

Studying spectral sensitivity with AIRS Data

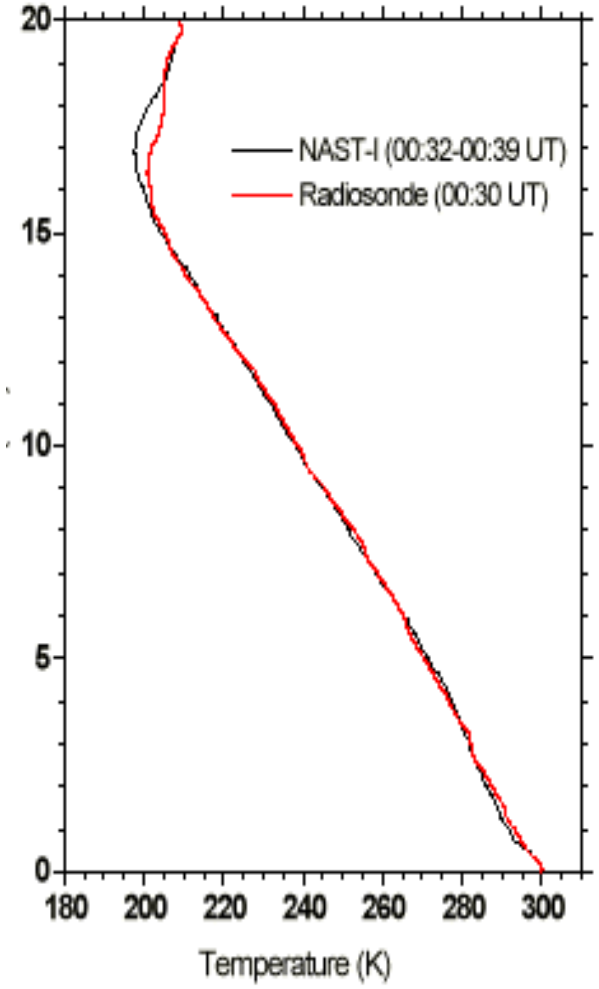
AIRS BT[747.8] – BT[747.4]

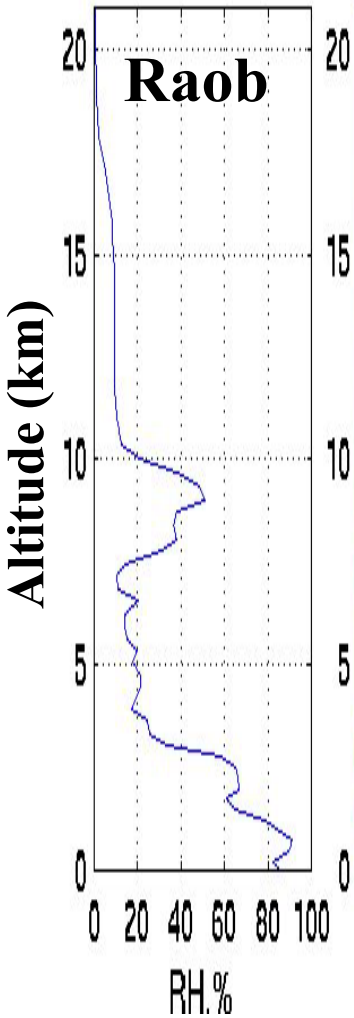


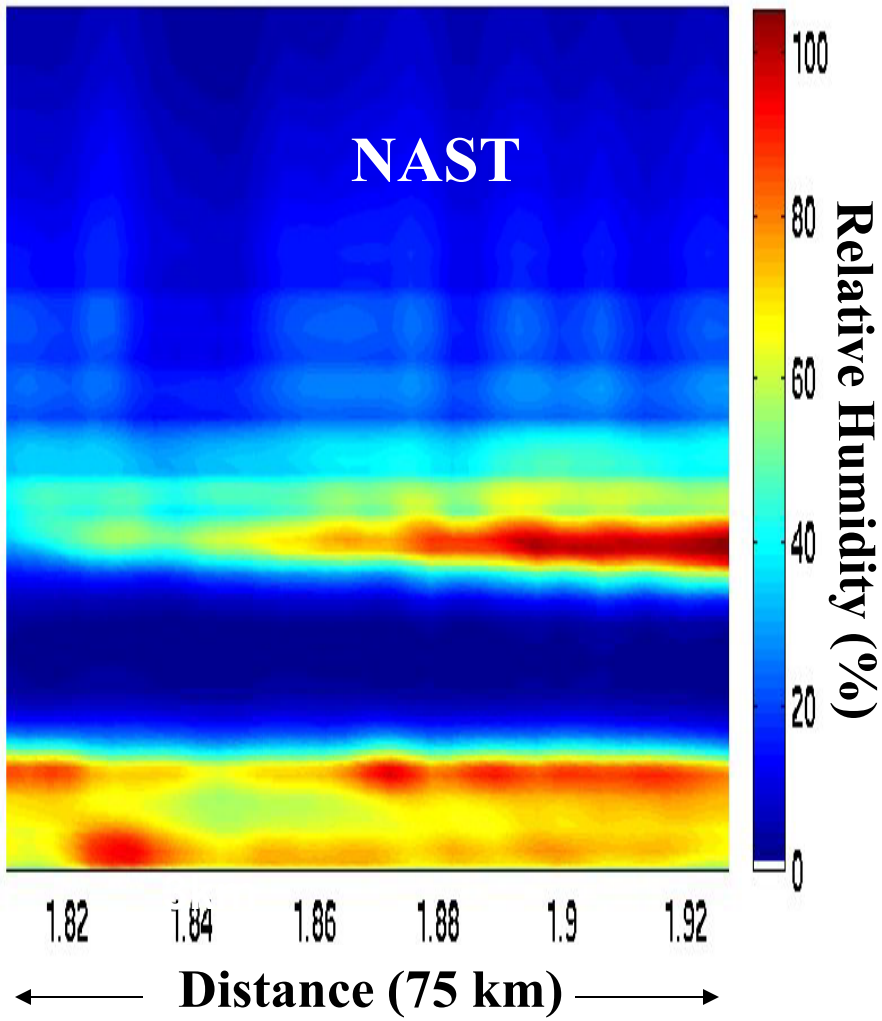
Radiosonde Validation



Andros Is. Bahamas, Sept 12, 1998

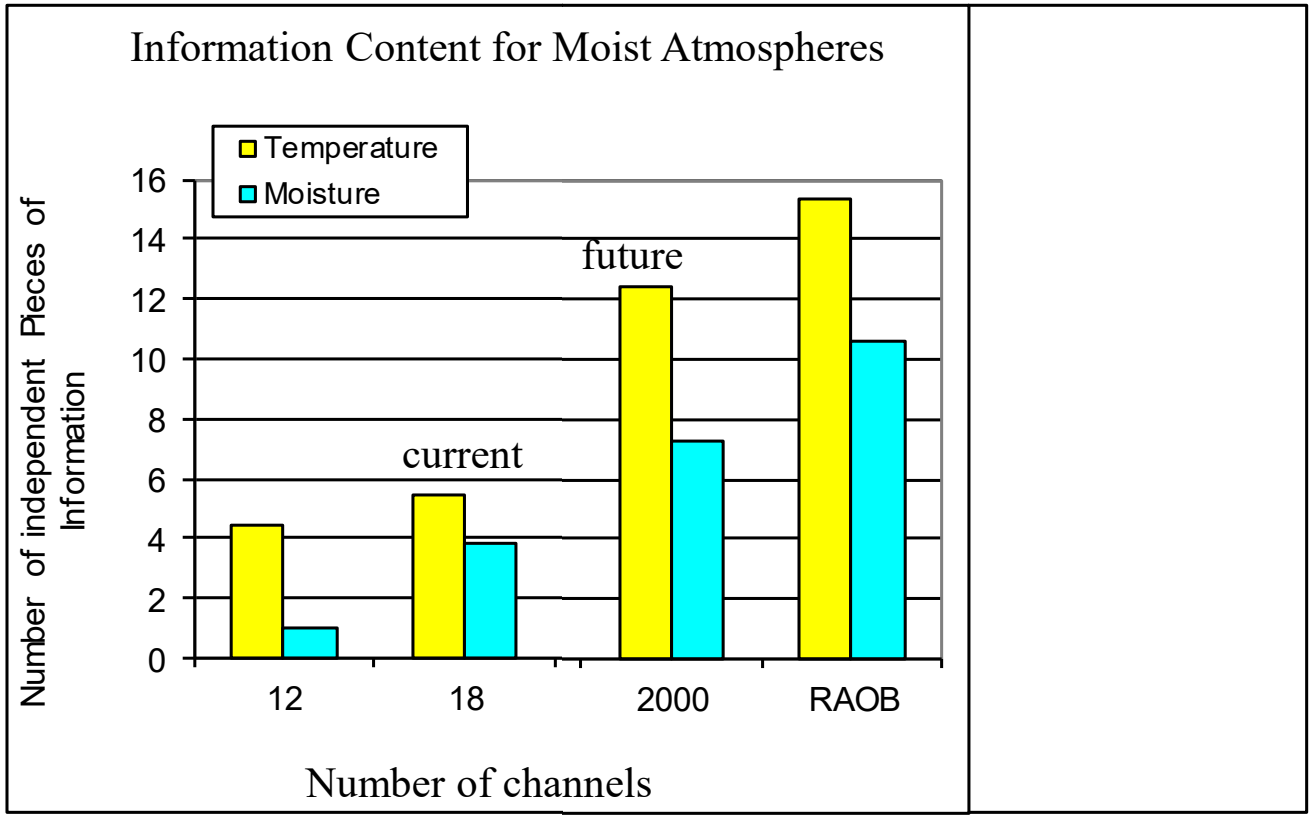






Hyperspectral IR Sounder nears Raob-like Depiction of Atmosphere

with an Order of Magnitude Increase in Spatial and Temporal Resolution



Hyperspectral IR Sounder
- land and coastal waters
- nearly instantaneous obs
- 10 km separation
- every hour

RAOB
- over land only
- 1 hour ascent
- 300 km separation
- 12 Z and 00Z only

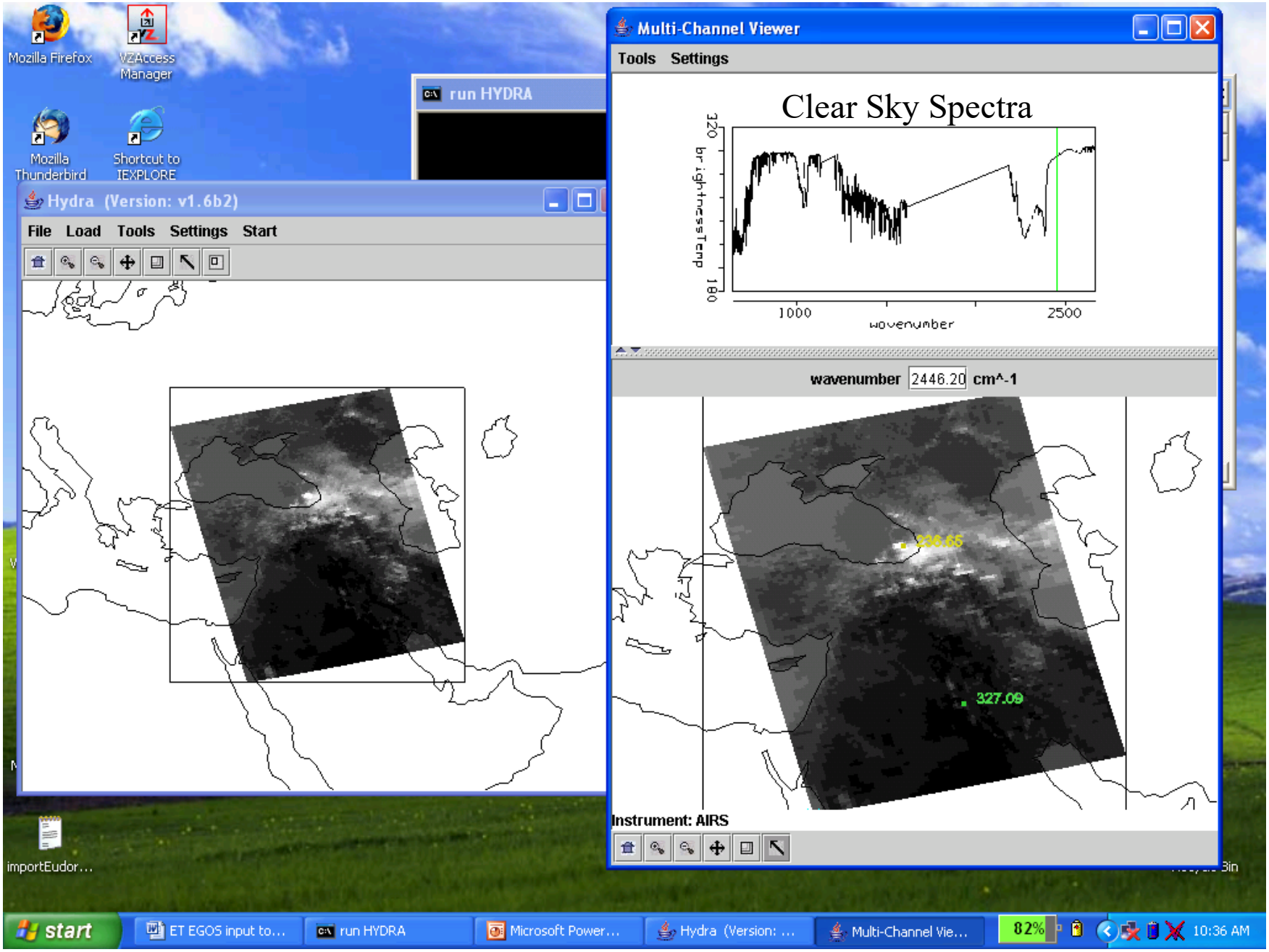
Doubles critical low-level moisture information (wrt current sounder)

Spectral Signatures seen with AIRS

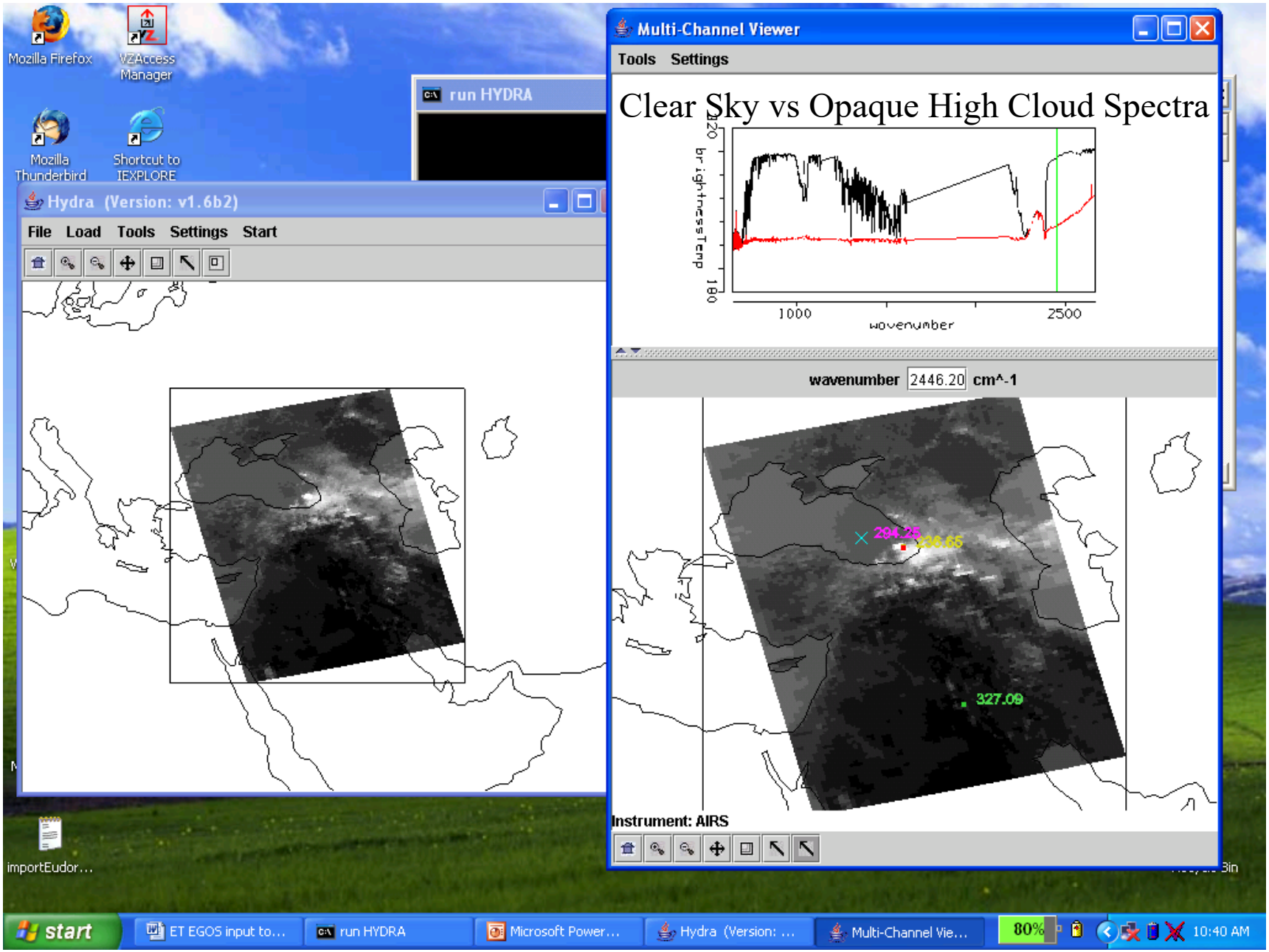
AOS 745
Lectures at UW-Madison
Jan – May 2007

Paul Menzel
UW/CIMSS/AOS

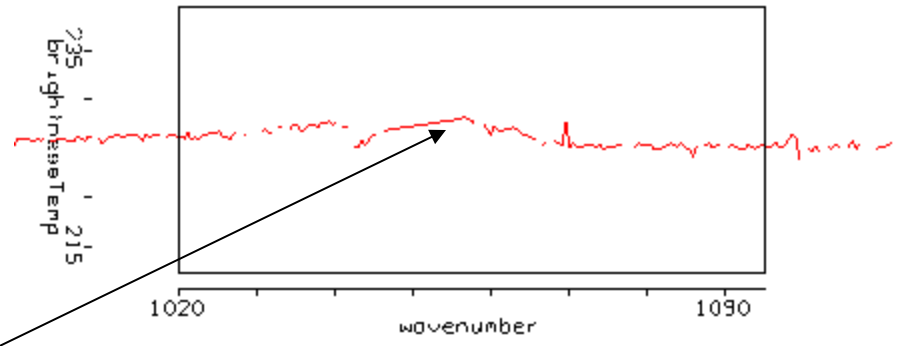
AIRS data from 28 Aug 2005

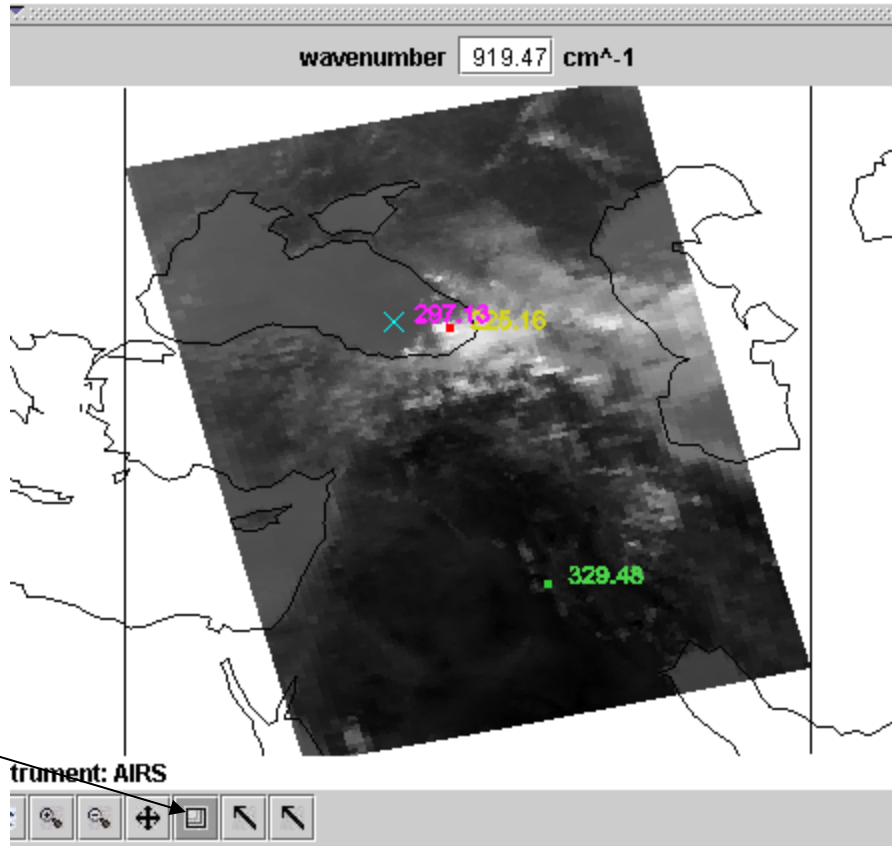


AIRS data from 28 Aug 2005



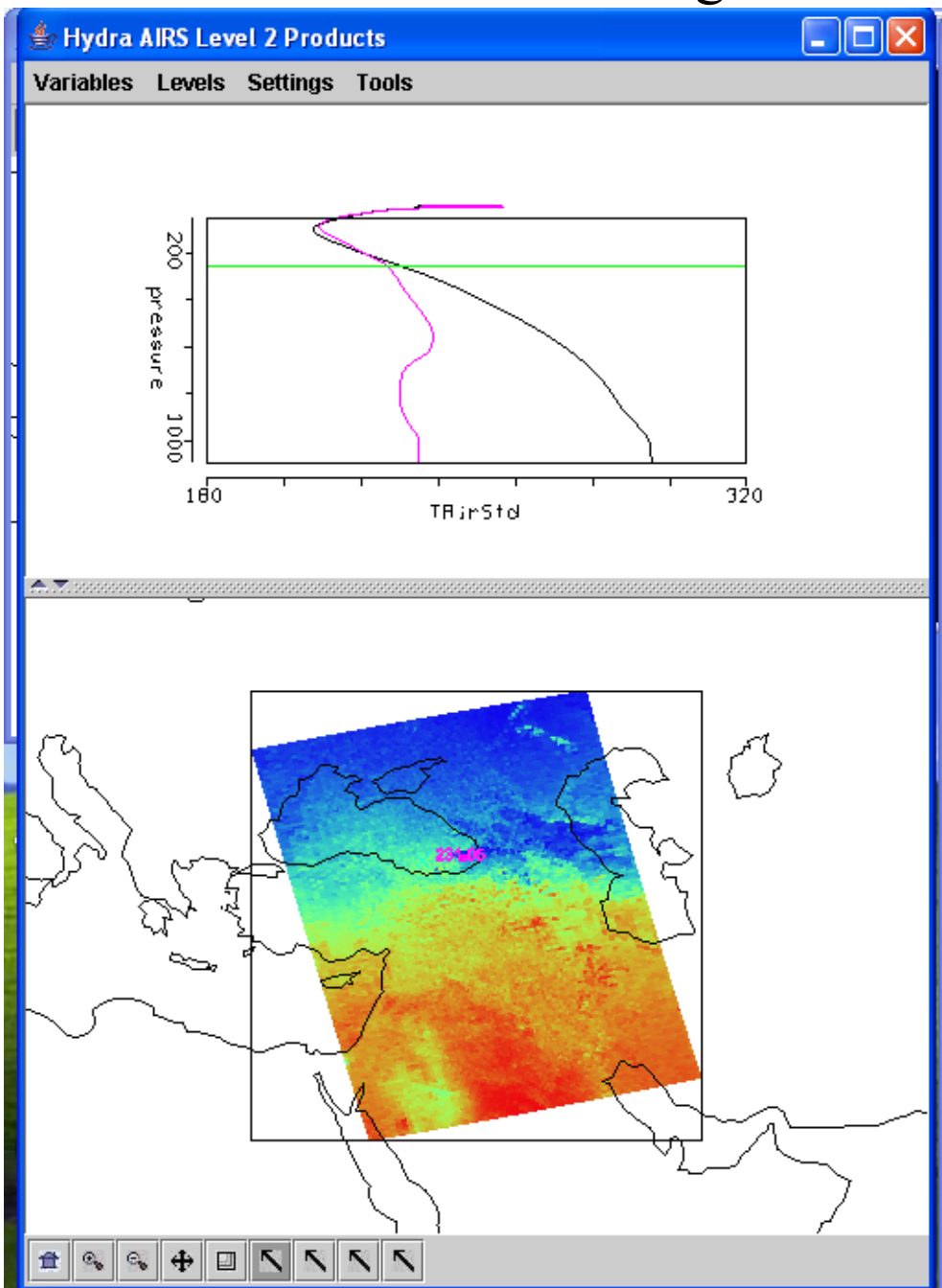
Zoom in
on spectra from cloudy fov
to see warming with height
above tropopause
in O3 absorption band

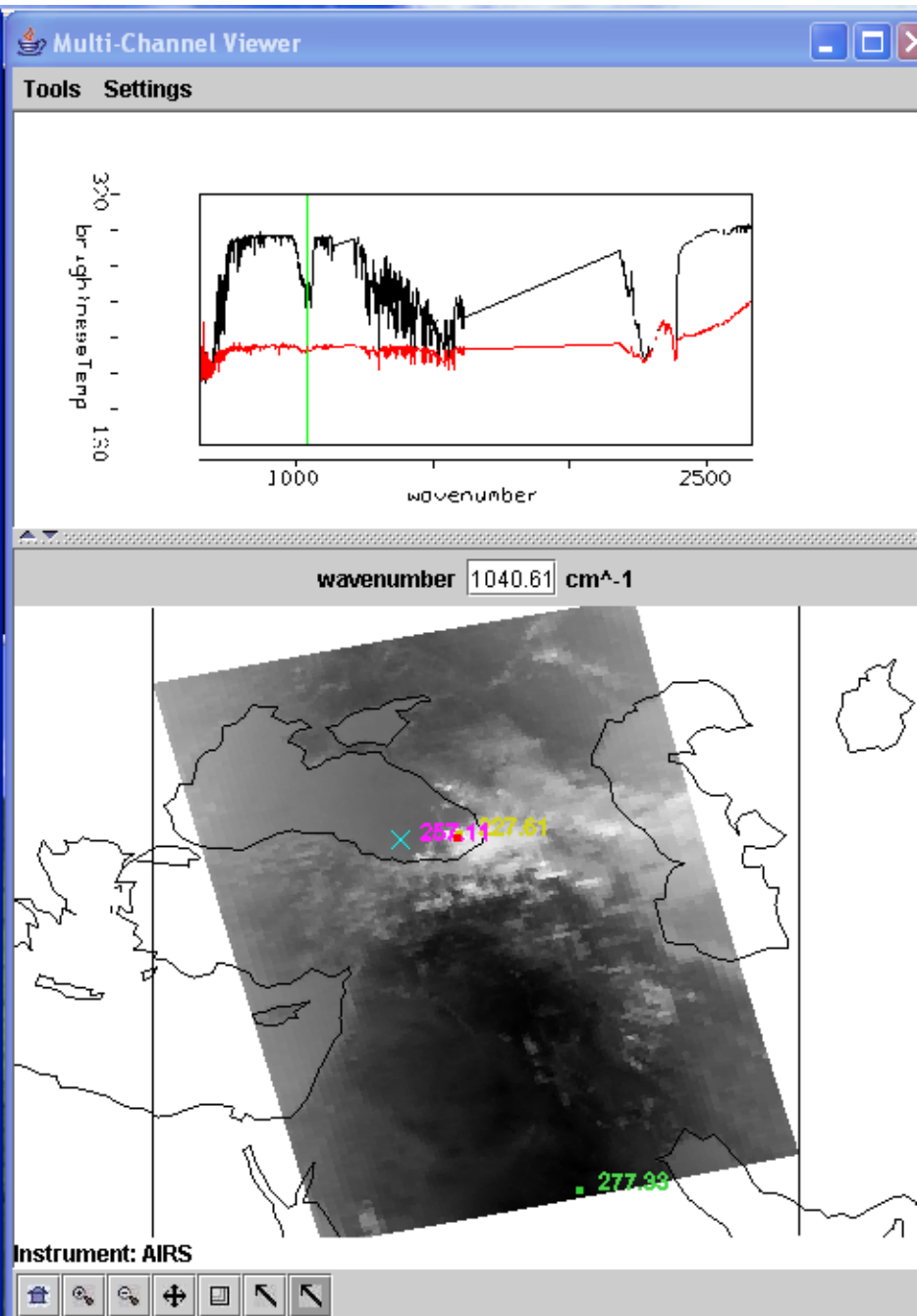




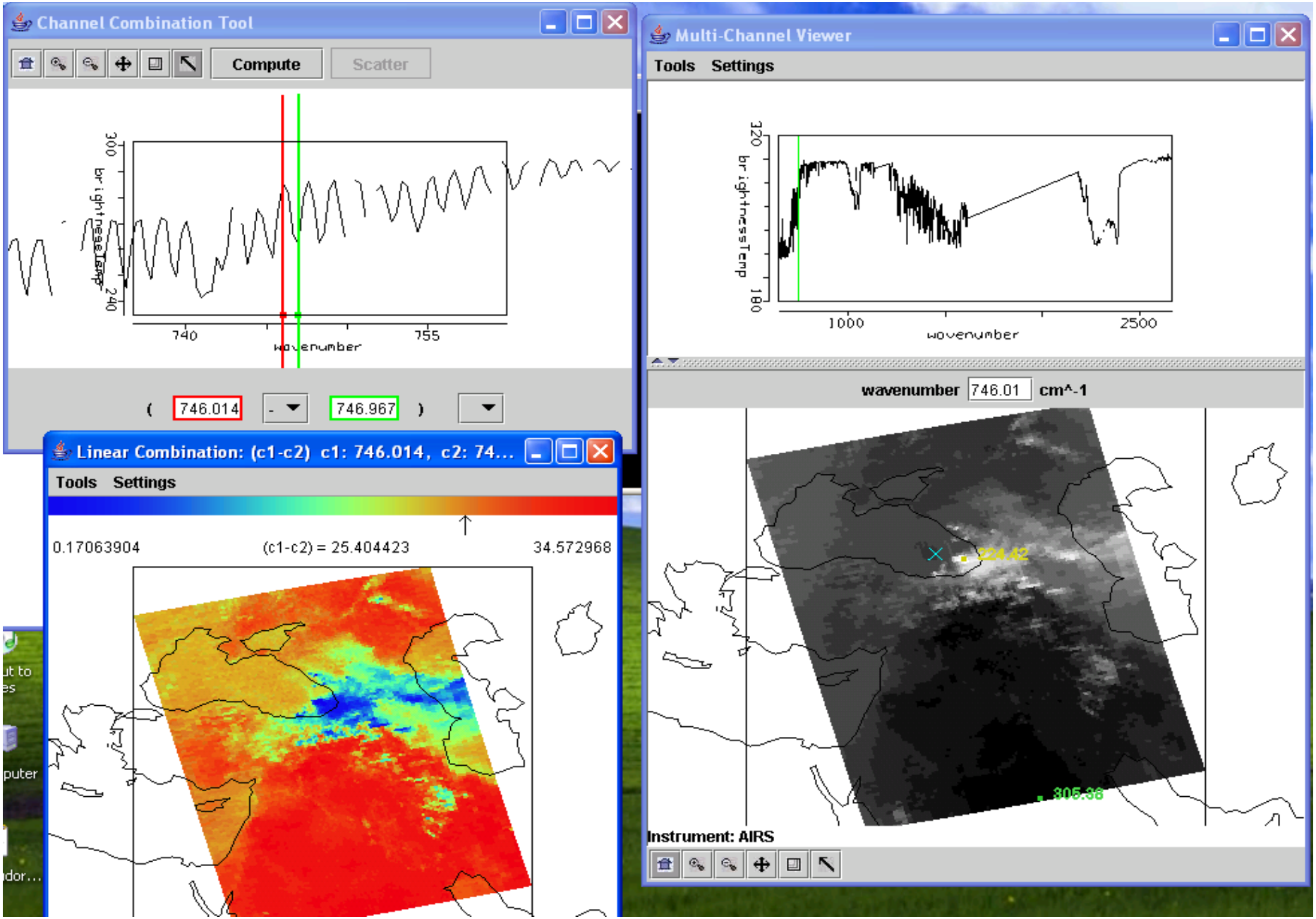
Zoom toolbar

High cloud at 250 hPa

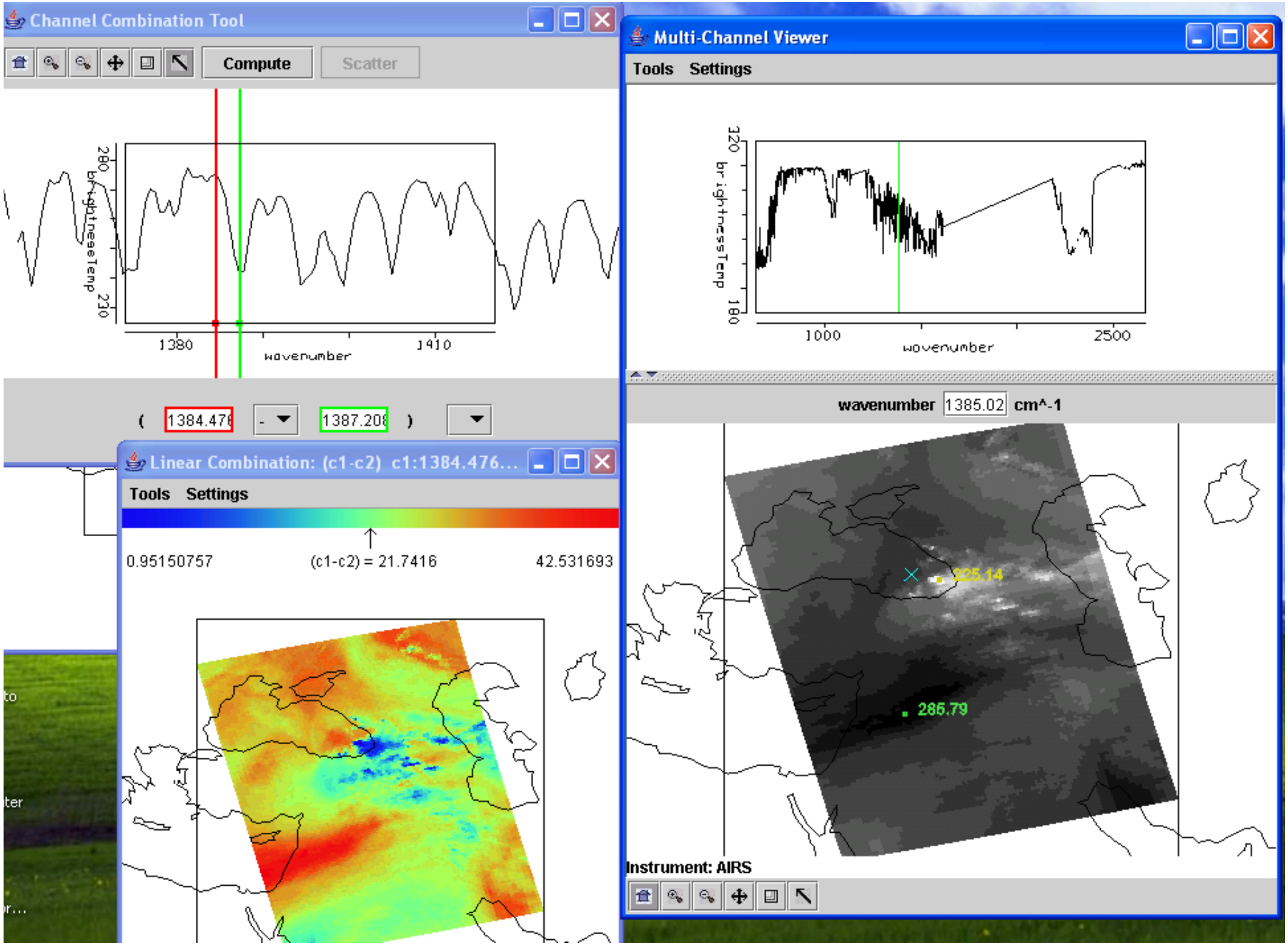




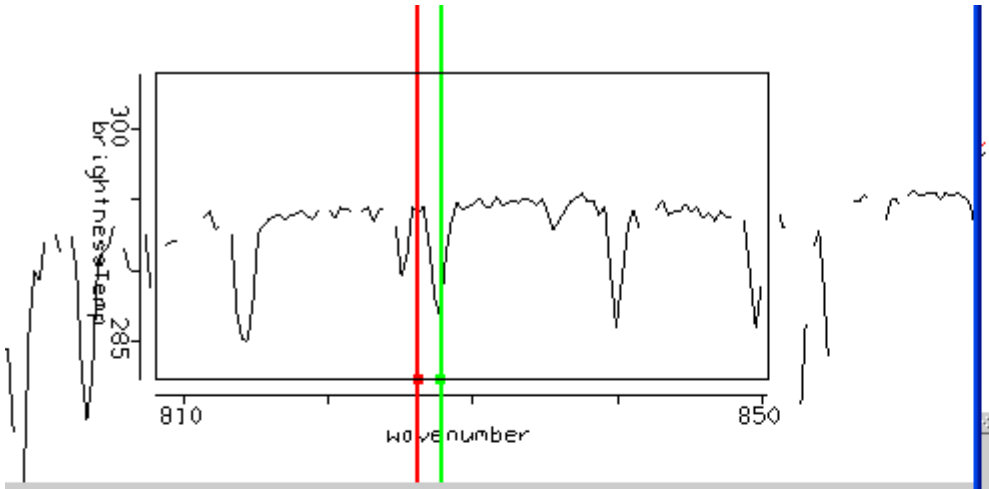
Offline-Online in LW CO2

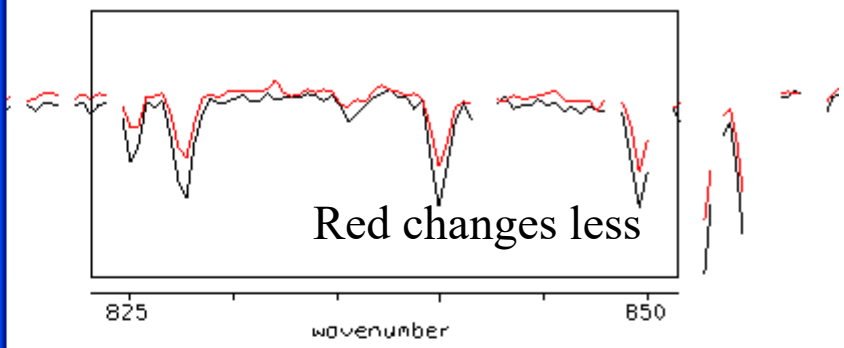


Offline-Online in H2O



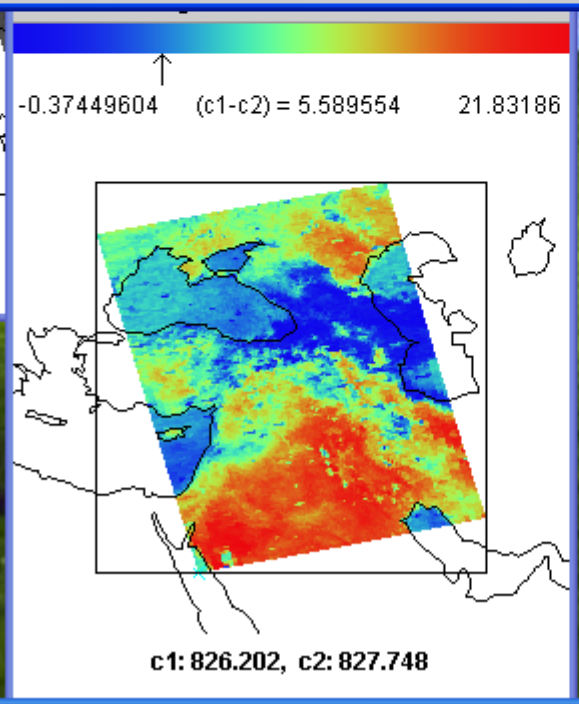
Offline-Online in LW IRW showing low level moisture

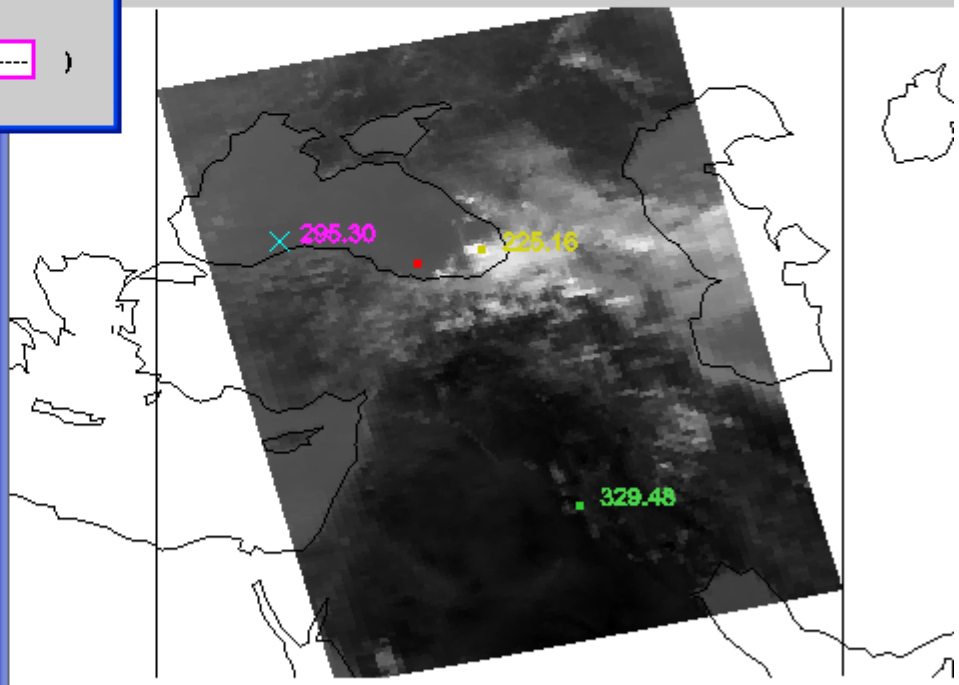




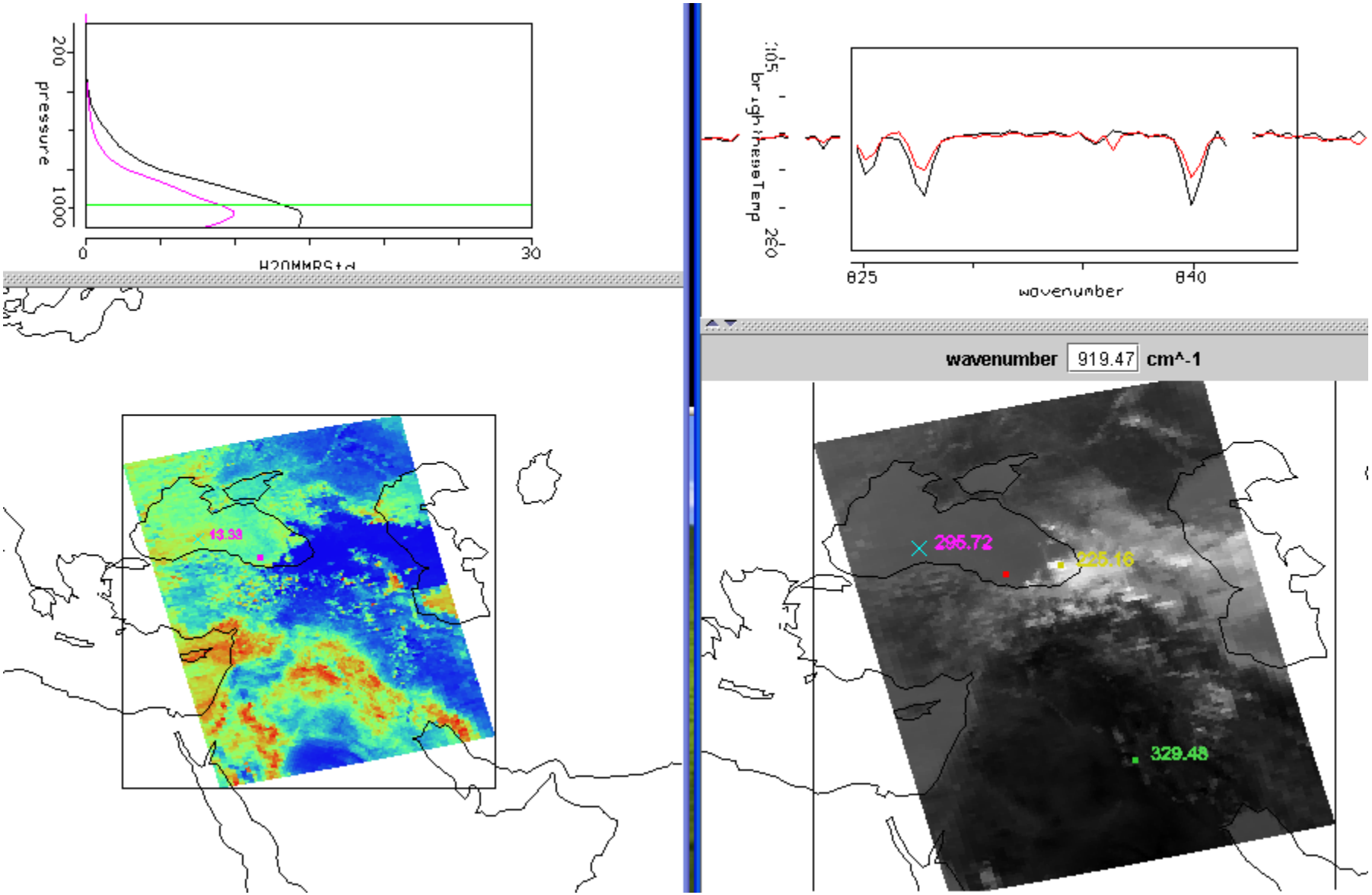
826.202 - 827.748) (------- -------)

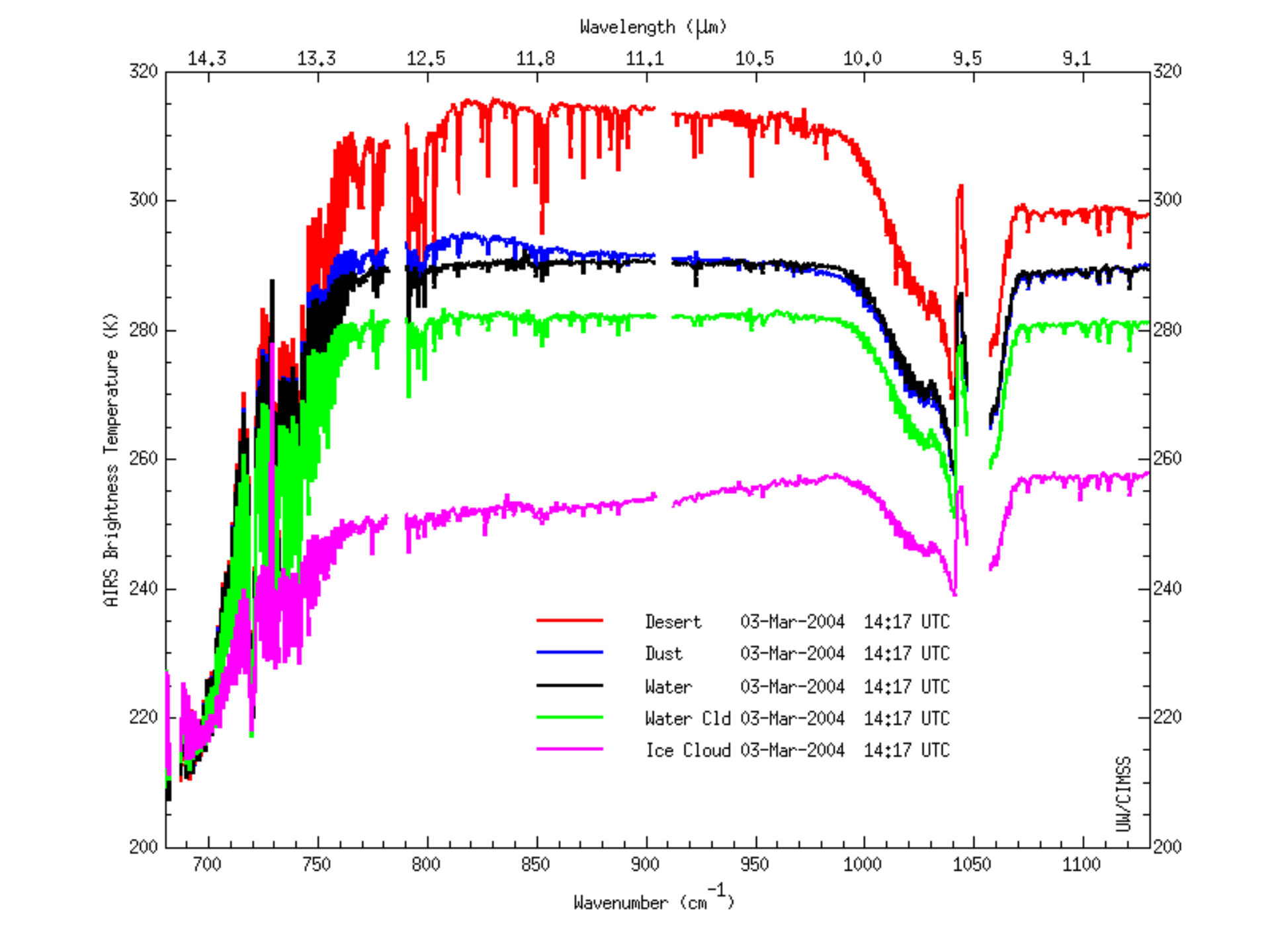
wavenumber 919.47 cm^-1





Moisture Profiles (left) confirm west Black Sea (black) is more moist

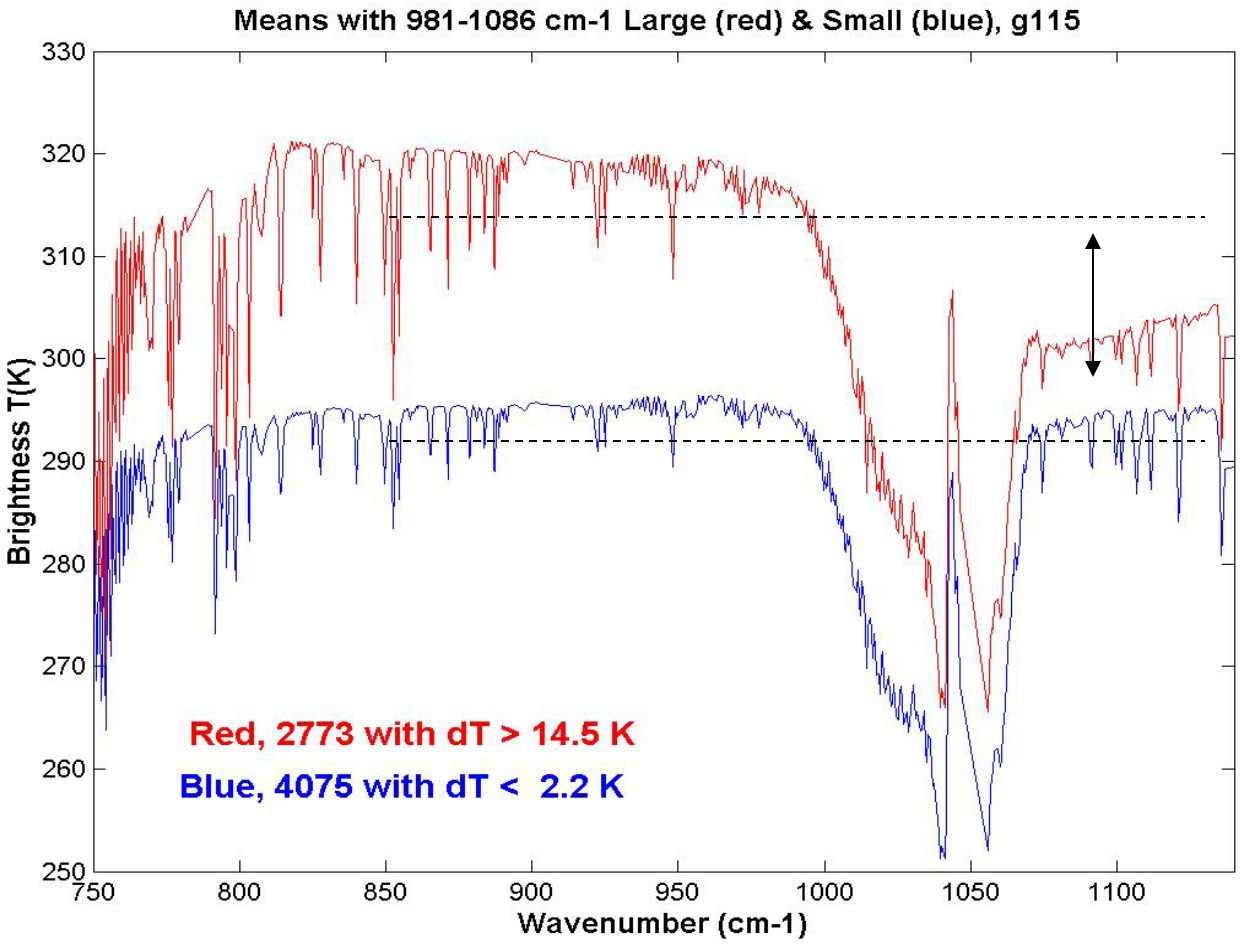



Wavelength (μm)
14.3
13.3
12.5
11.8
11.1
10.5
10.0
9.5
9.1
AIRS Brightness Temperature (K)
320
300
280
260
240
220
200
700
750
800
850
900
950
1000
1050
1100
Wavenumber (cm-1)
Desert 03-Mar-2004 14:17 UTC
Dust 03-Mar-2004 14:17 UTC
Water 03-Mar-2004 14:17 UTC
Water Cld 03-Mar-2004 14:17 UTC
Ice Cloud 03-Mar-2004 14:17 UTC
UW/CIMSS

Inferring surface properties with AIRS high spectral resolution data

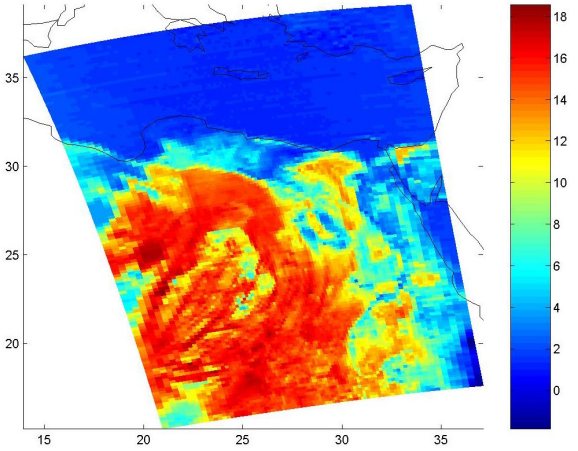
Barren region detection if T1086 < T981

Barren vs Water/Vegetated

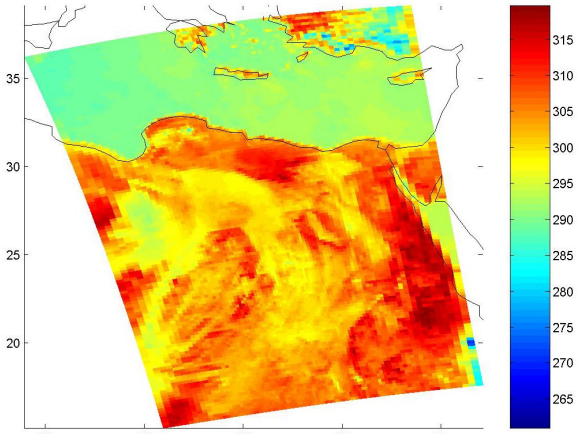


AIRS data from 14 June 2002

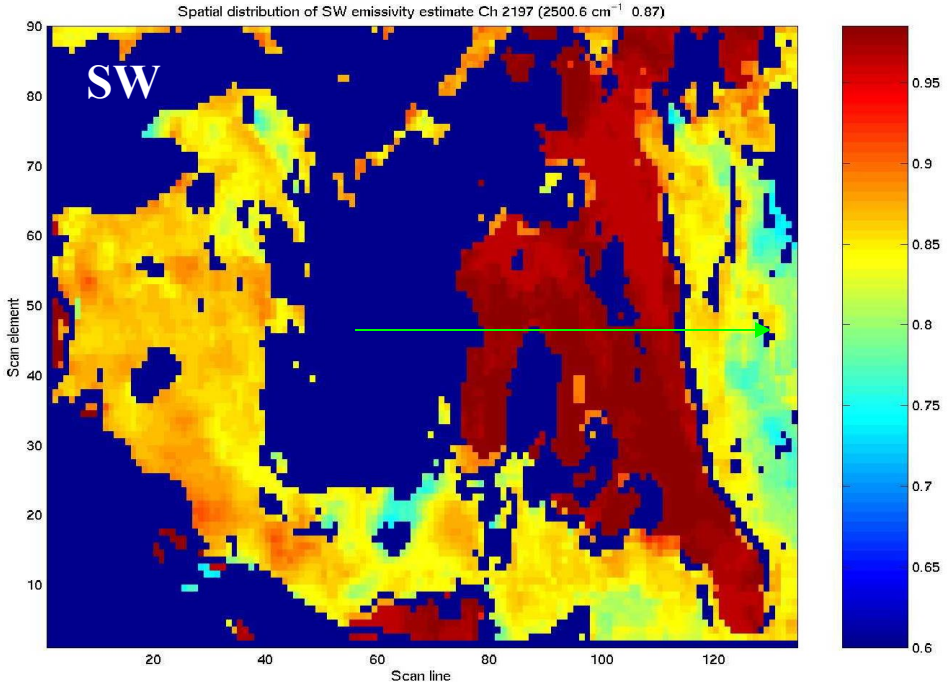
T(981 cm^{-1})-T(1086 cm^{-1})

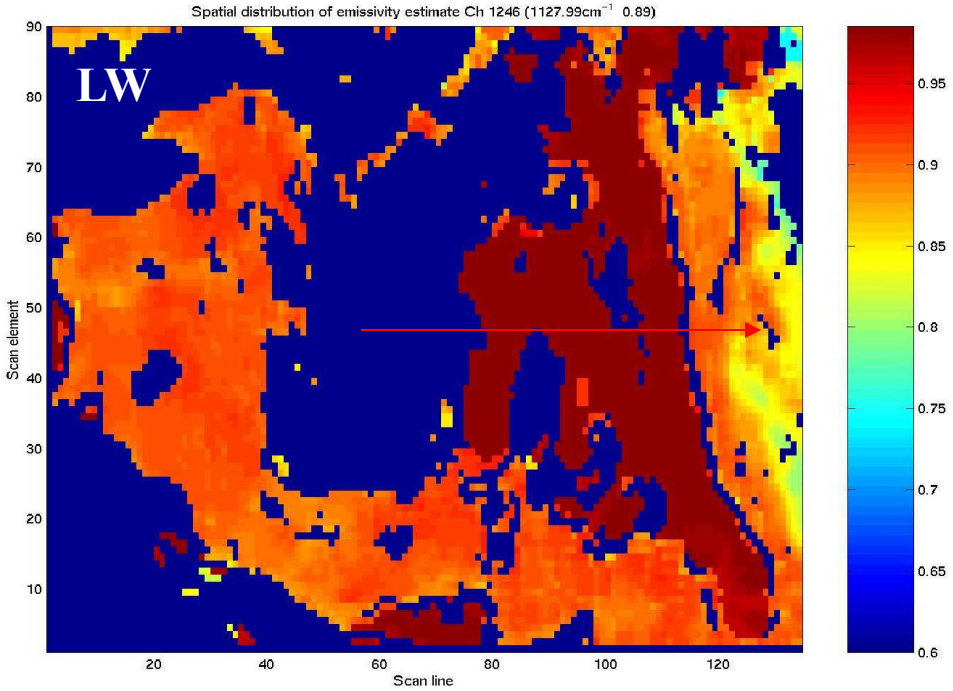


T(1086 cm^{-1})



from Tobin et al.

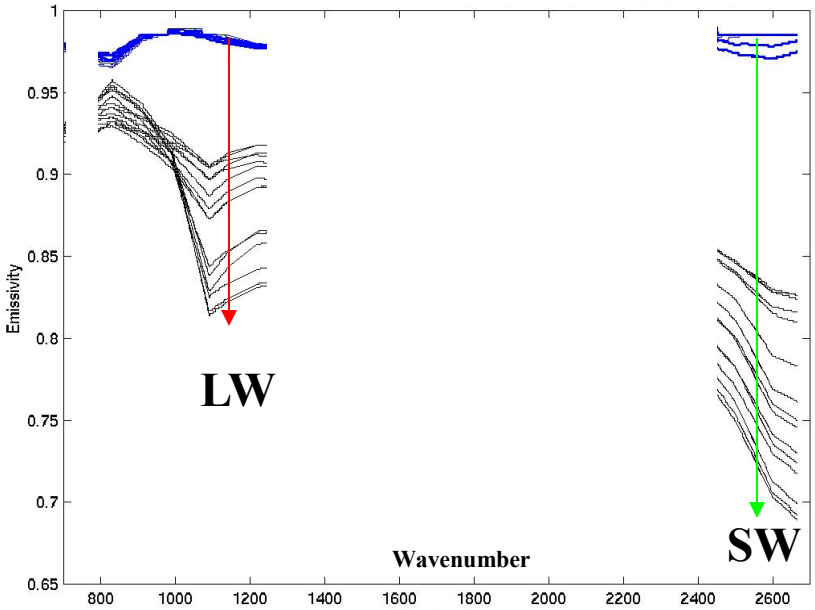




Characterizing Land and Sea Surfaces

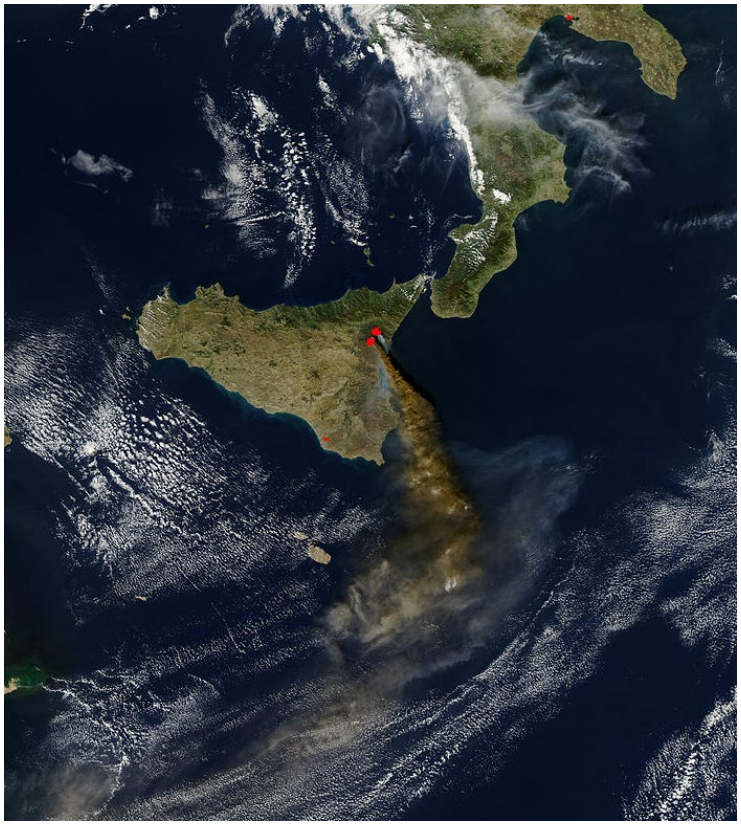
AIRS is enabling surface emissivity estimates from atmospheric window channel measurements. Example shows $\varepsilon_{sfc}(\lambda)$ over the Mediterranean Sea to Algeria to the Sahara Desert.

Transect from Mediterranean to Sahara

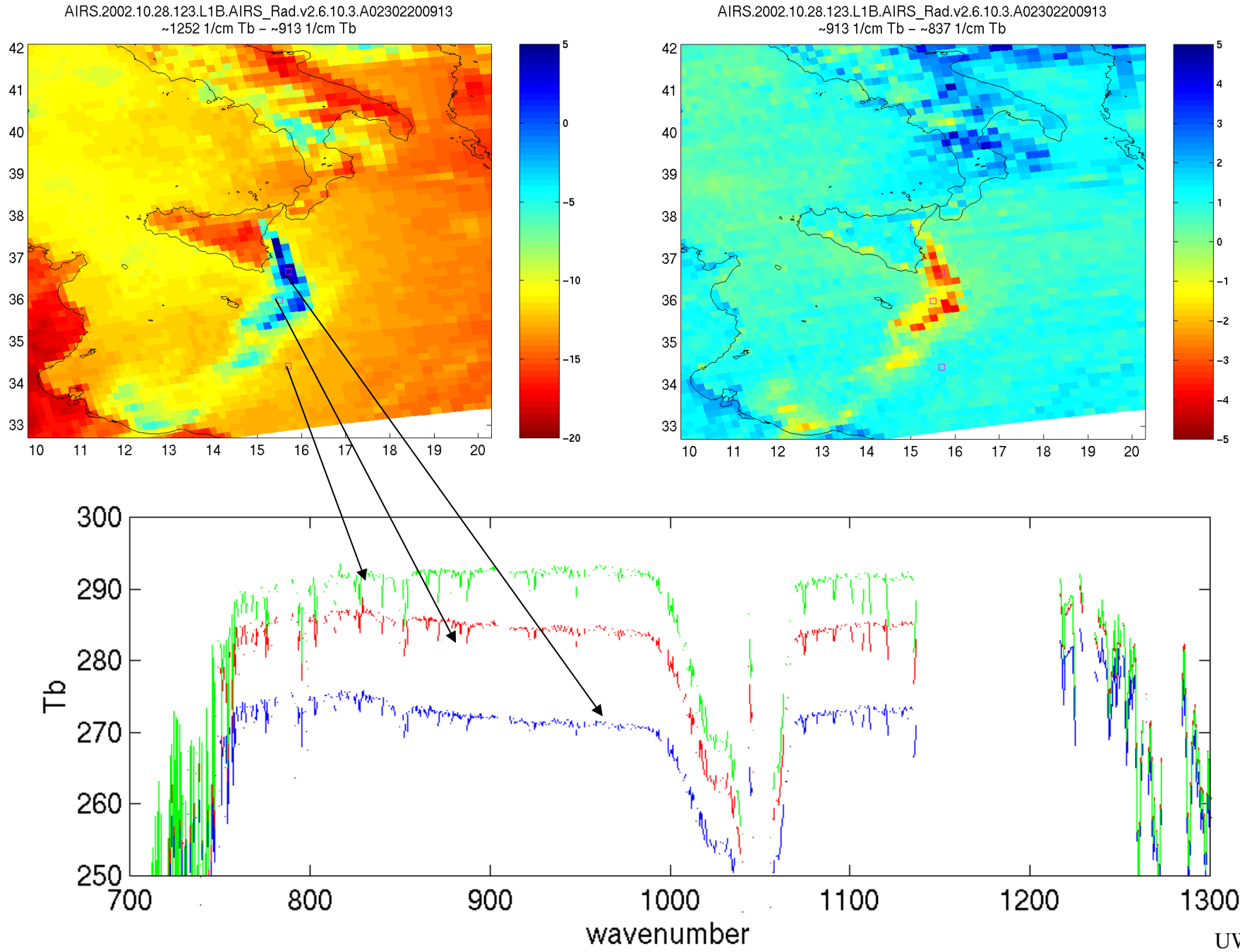


Mt Etna eruption

28 October 2002
ISS photo

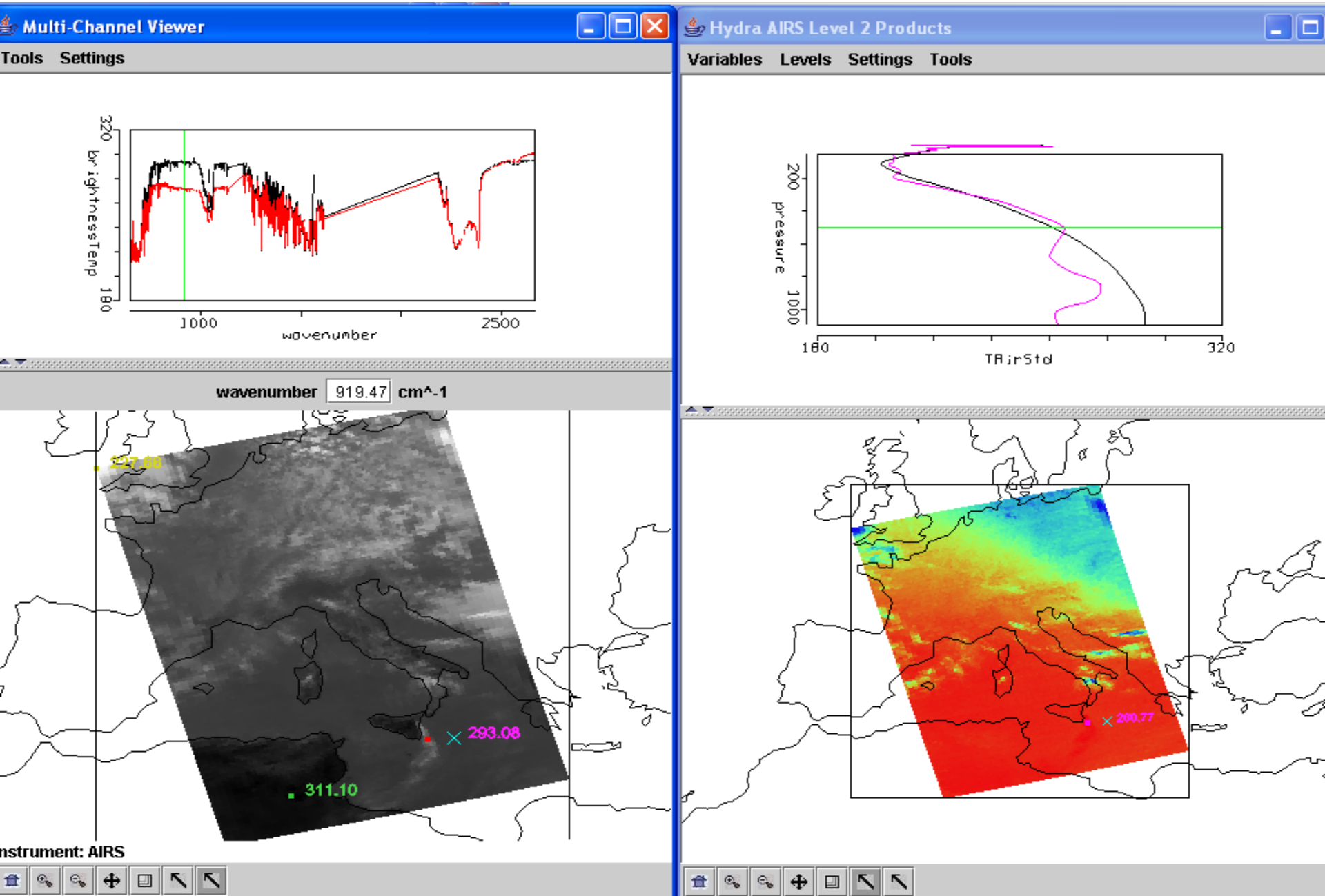


28 October 2002
MODIS Aqua

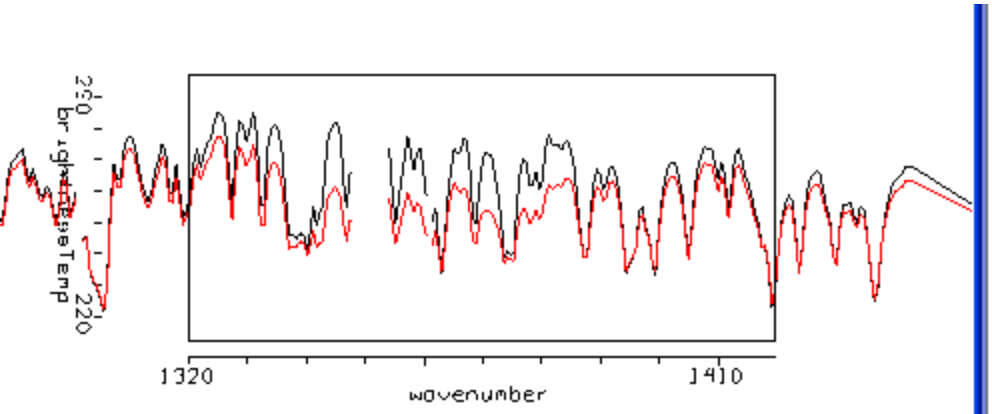

AIRS.2002.10.28.123.L1B.AIRS_Rad.v2.6.10.3.A02302200913
~1252 1/cm Tb – ~913 1/cm Tb
AIRS.2002.10.28.123.L1B.AIRS_Rad.v2.6.10.3.A02302200913
~913 1/cm Tb – ~837 1/cm Tb
Tb
wavenumber

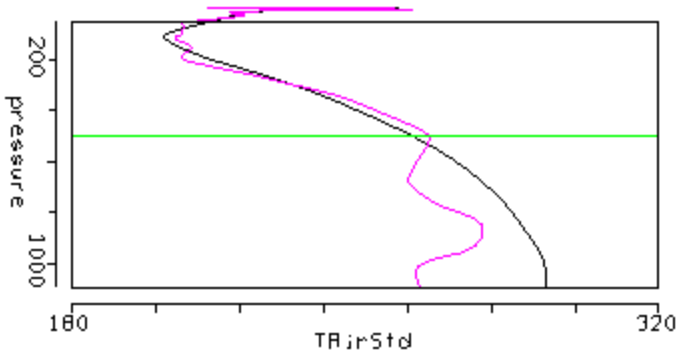
UW
CIMSS

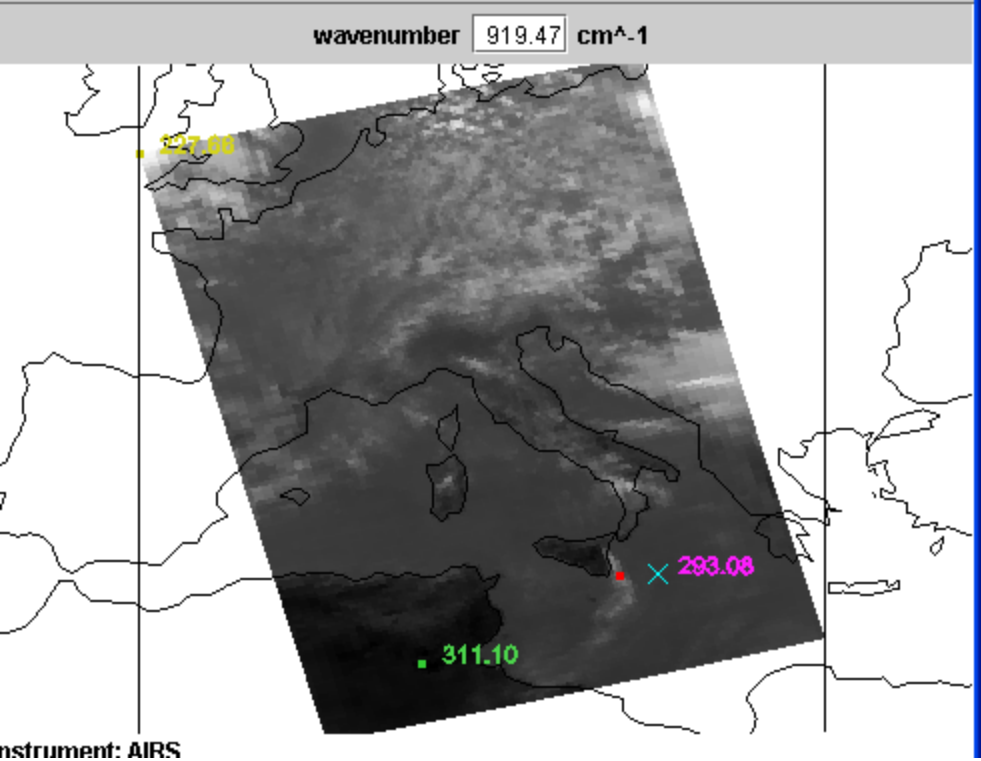
Mt Etna Ash cloud at 500 hPa

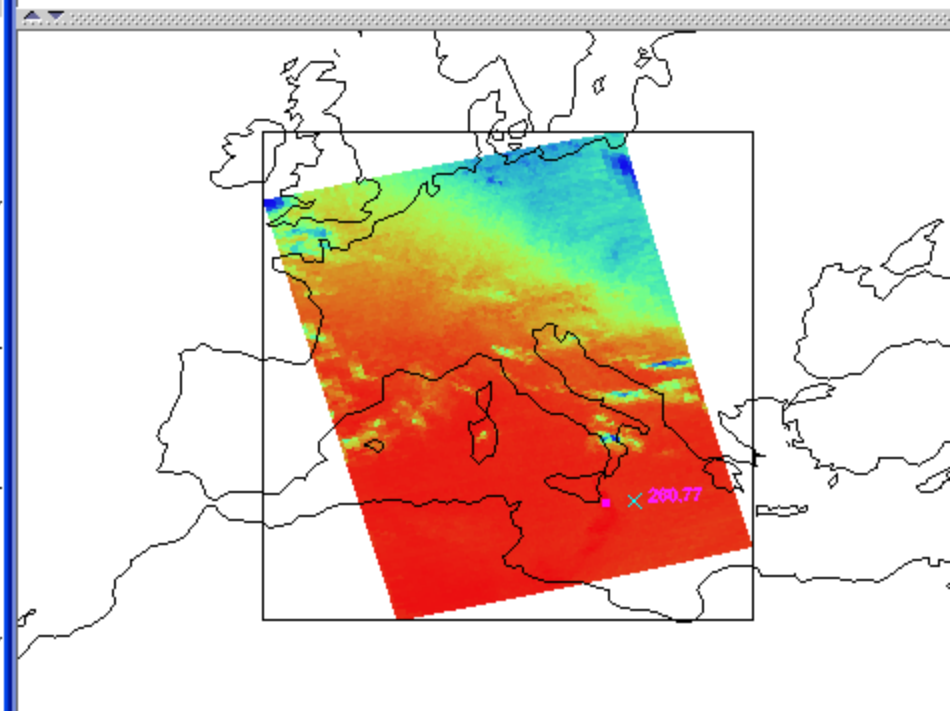


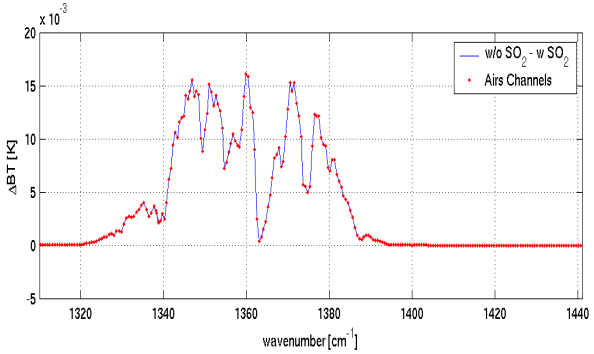
Ash cloud and clear sky spectra



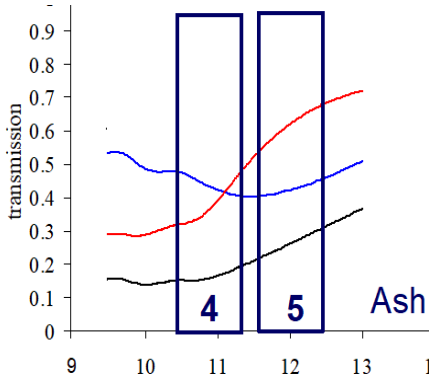


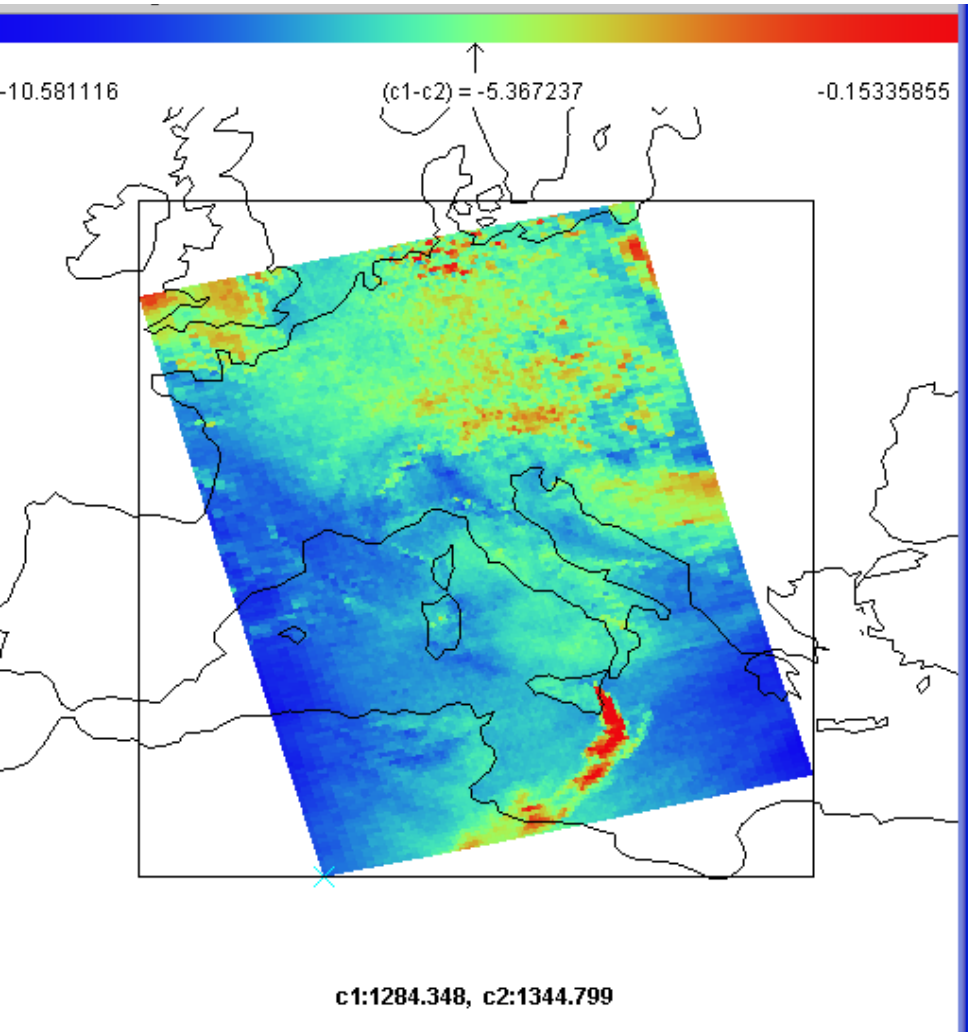


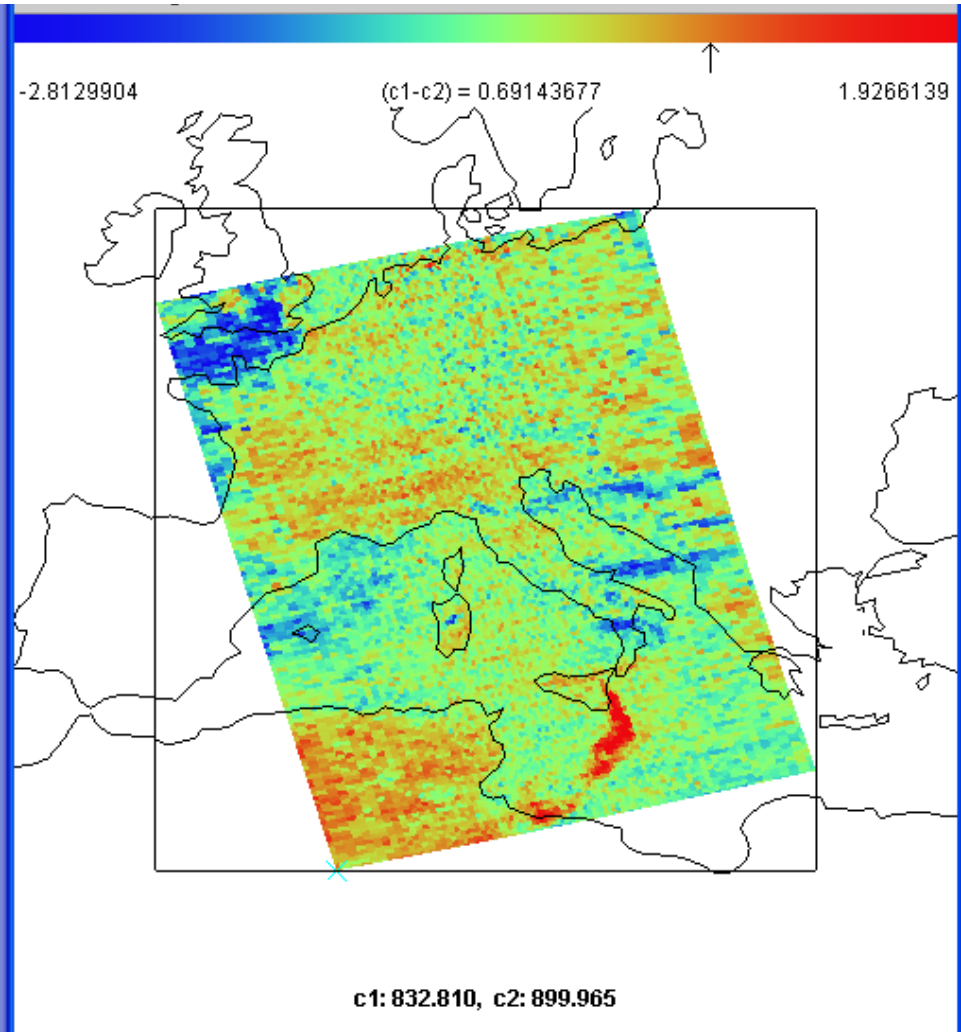


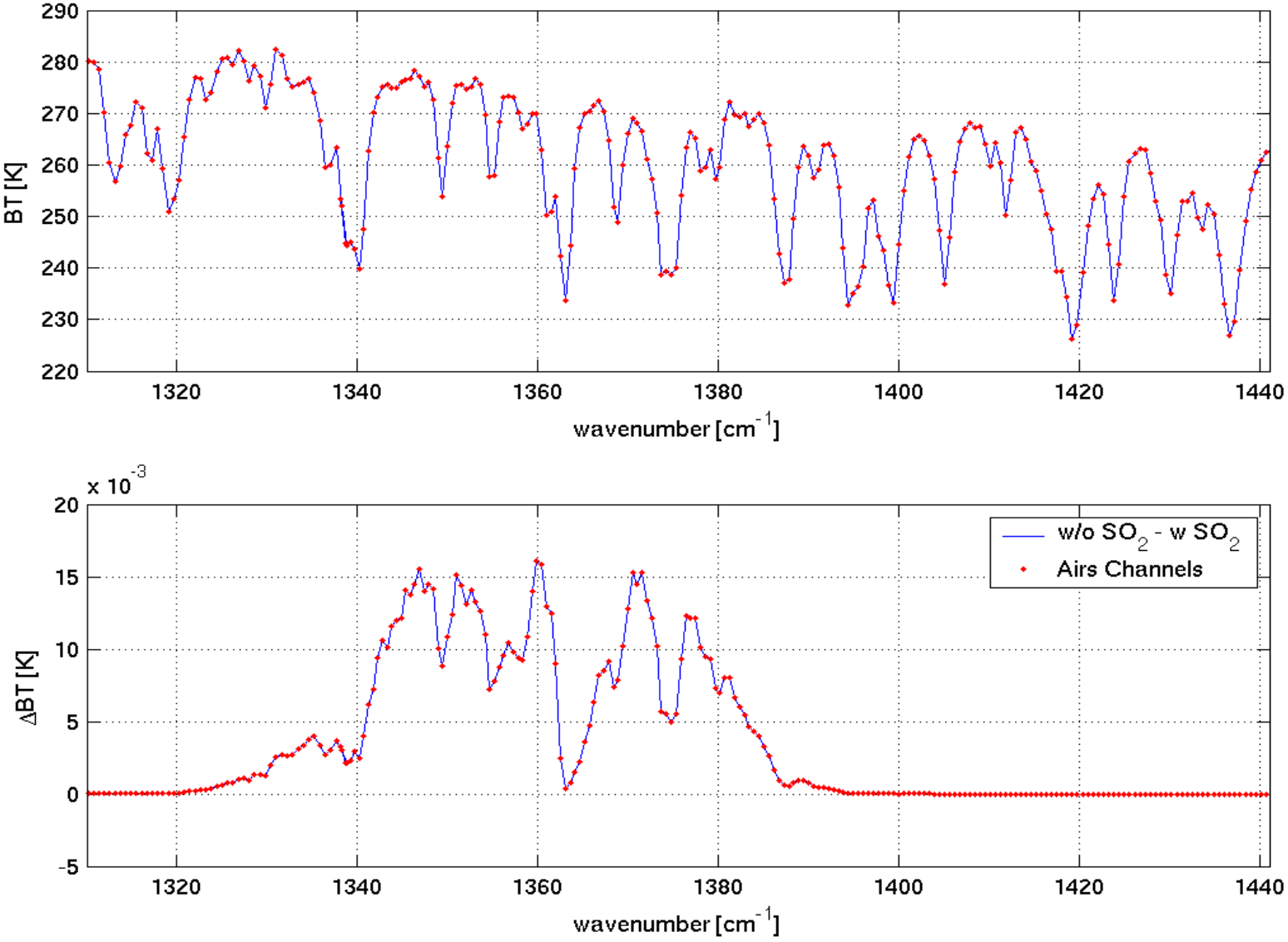


Mt Etna volcanic plume
SO2 (left) from 1284-1345
Ash (right) from 832-900



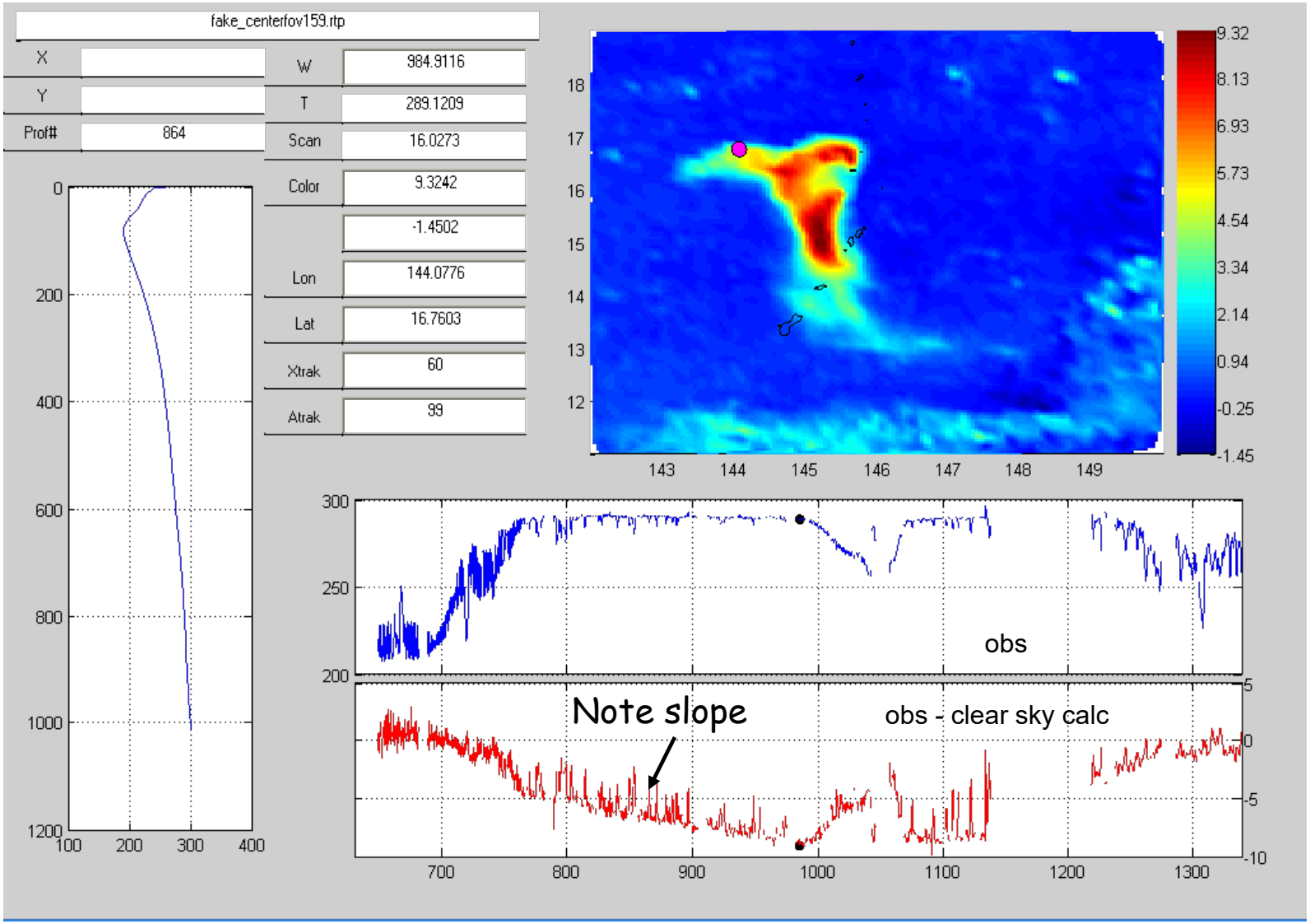




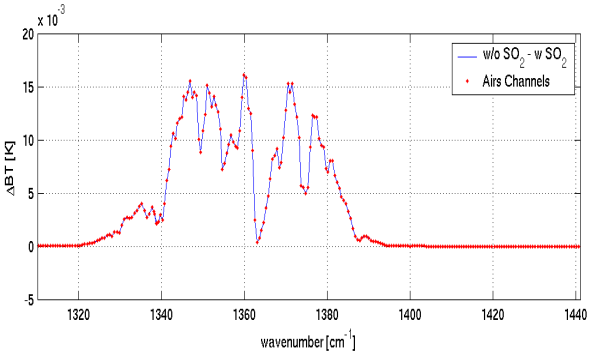

290
280
270
260
250
240
230
220
BT [K]
1320
1340
1360
1380
1400
1420
1440
wavenumber [cm-1]
x 10-3
20
15
10
5
0
-5
ΔBT [K]
w/o SO2 - w SO2
Airs Channels
1320
1340
1360
1380
1400
1420
1440
wavenumber [cm-1]

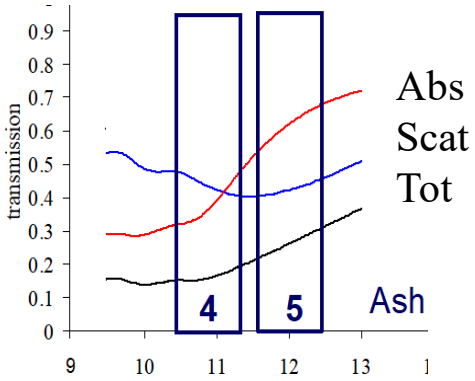
Silicate (ash cloud) signal at Anatahan, Mariana Is

Image is ECMWF bias difference of 1227 cm^{-1} – 984 cm^{-1} (double difference)



Anatahan Volcano viewed with AIRS



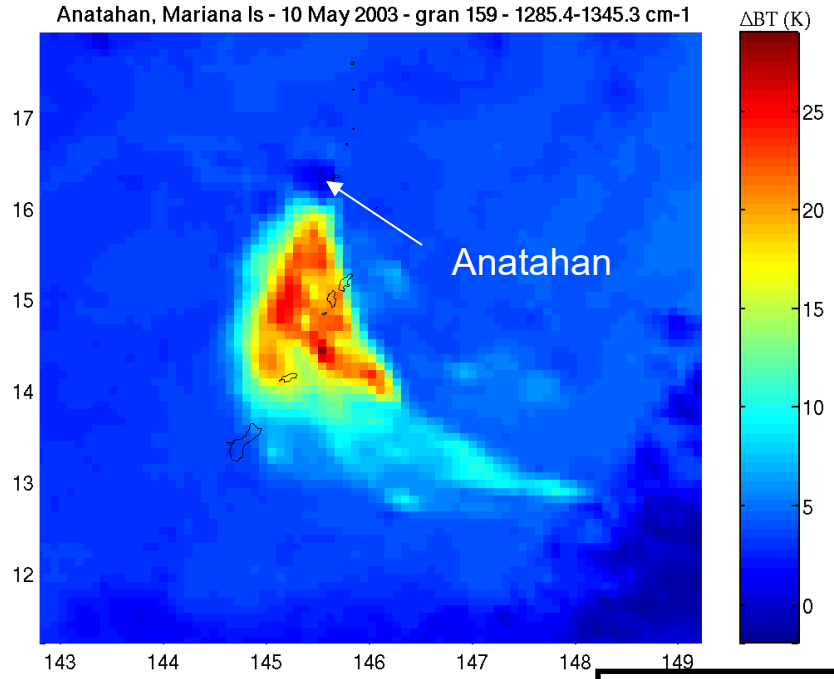


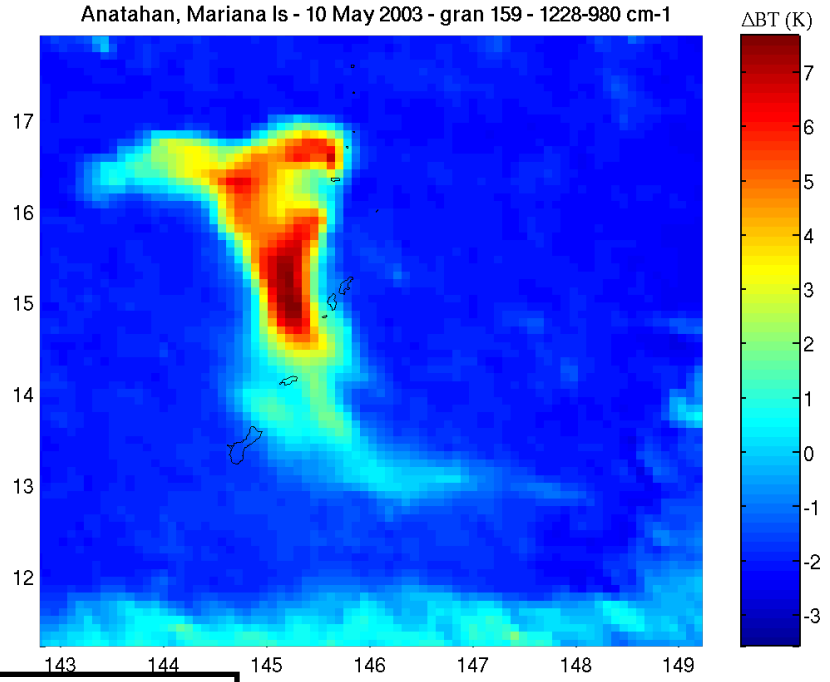
SO_2 signal

1284-1345 cm^{-1}

Ash signal

1228-995 cm^{-1}

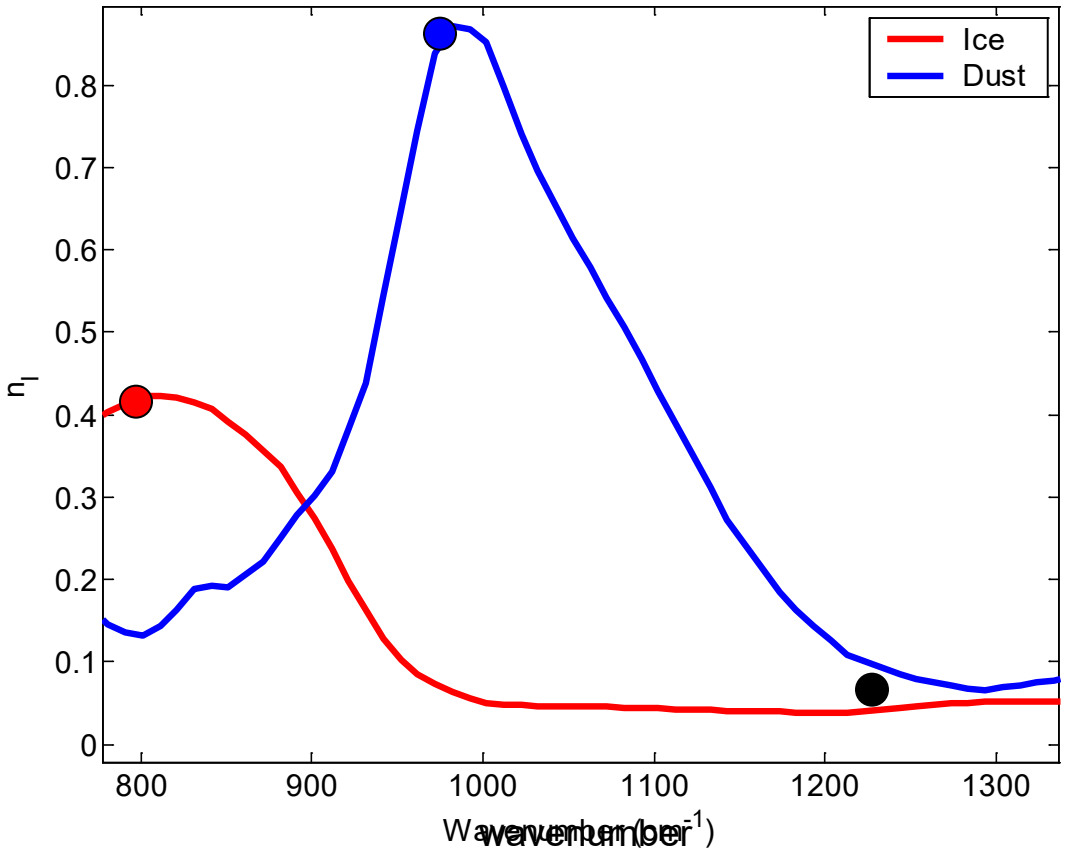




10 May 2003 (1554 UT)

Dust and Cirrus Signals

Imaginary Index of Refraction of Ice and Dust



- Both ice and silicate absorption small in 1200 cm^{-1} window
- In the 800-1000 cm^{-1} atmospheric window:

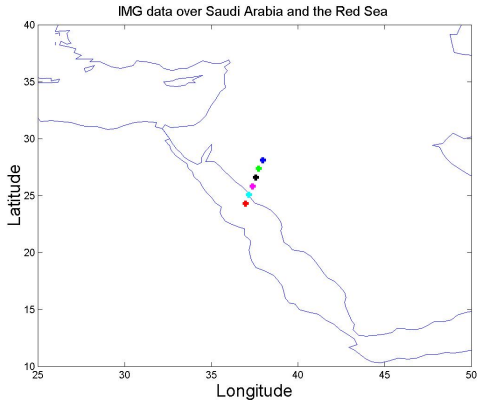
  Silicate index *increases*

  Ice index *decreases*

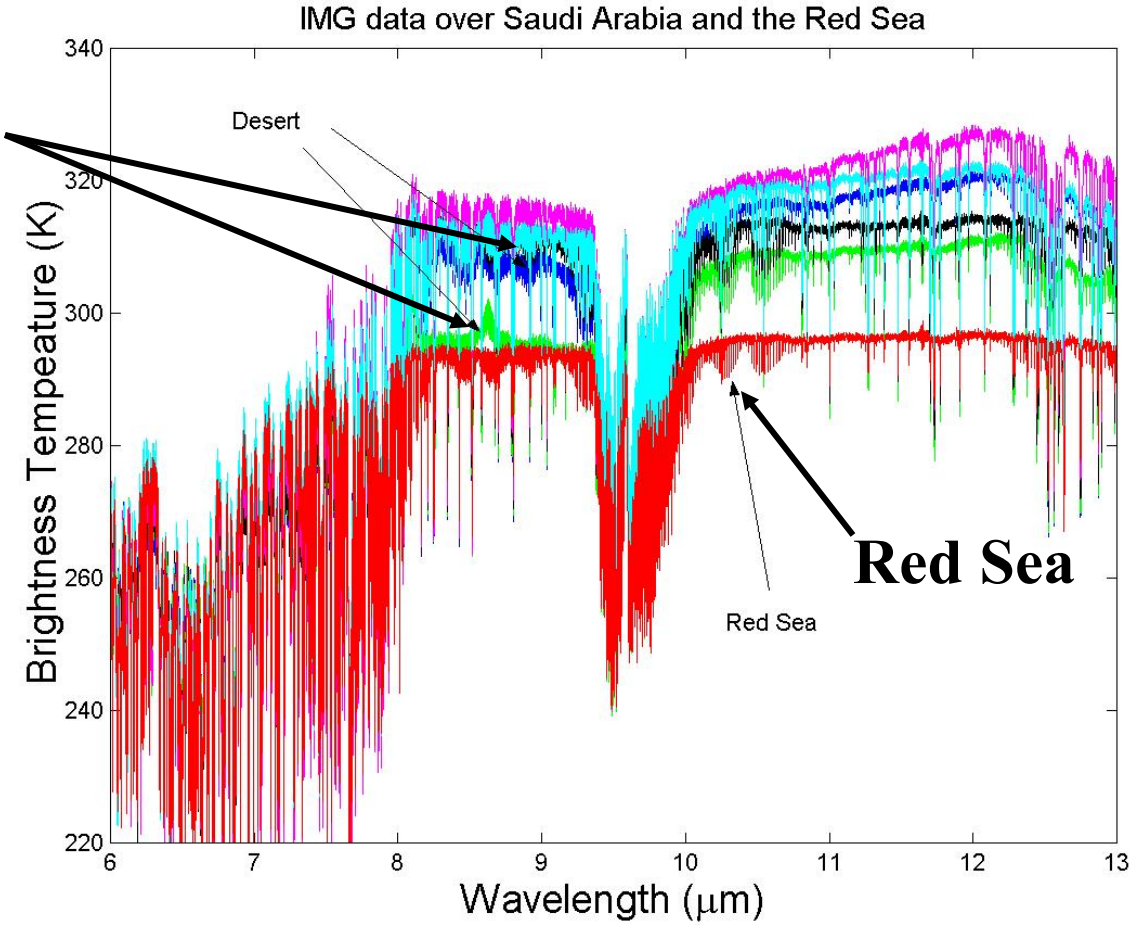
  with wavenumber

Volz, F.E. : Infrared optical constant of ammonium sulphate, Sahara Dust, volcanic pumice and flash, Appl Opt 12 564-658 (1973)

Hyperspectral Dust Observations



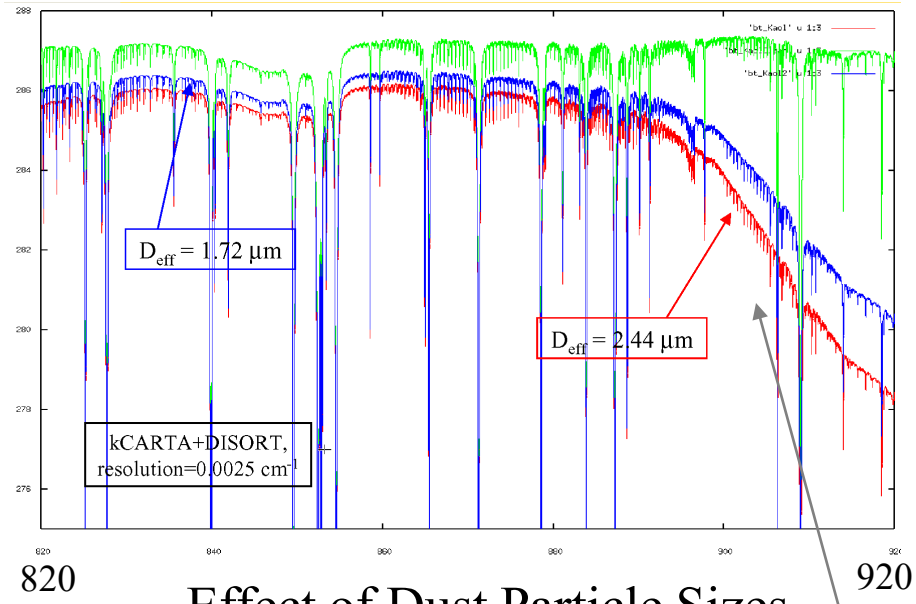
Desert



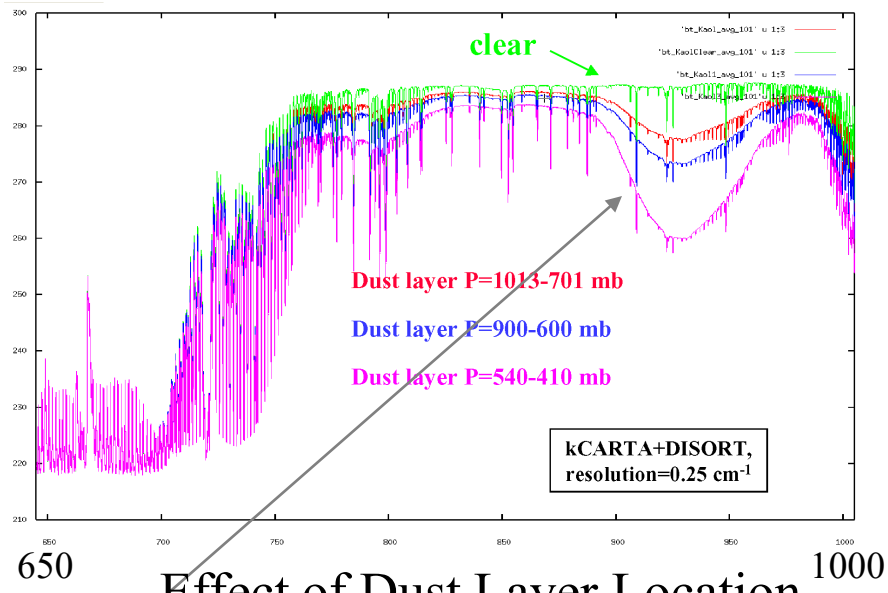
Hyperspectral Dust/Aerosol Modeling

Negative Slope 880 to 920 cm-1– The Dust Signature

Green – Clear Spectrum



Effect of Dust Particle Sizes

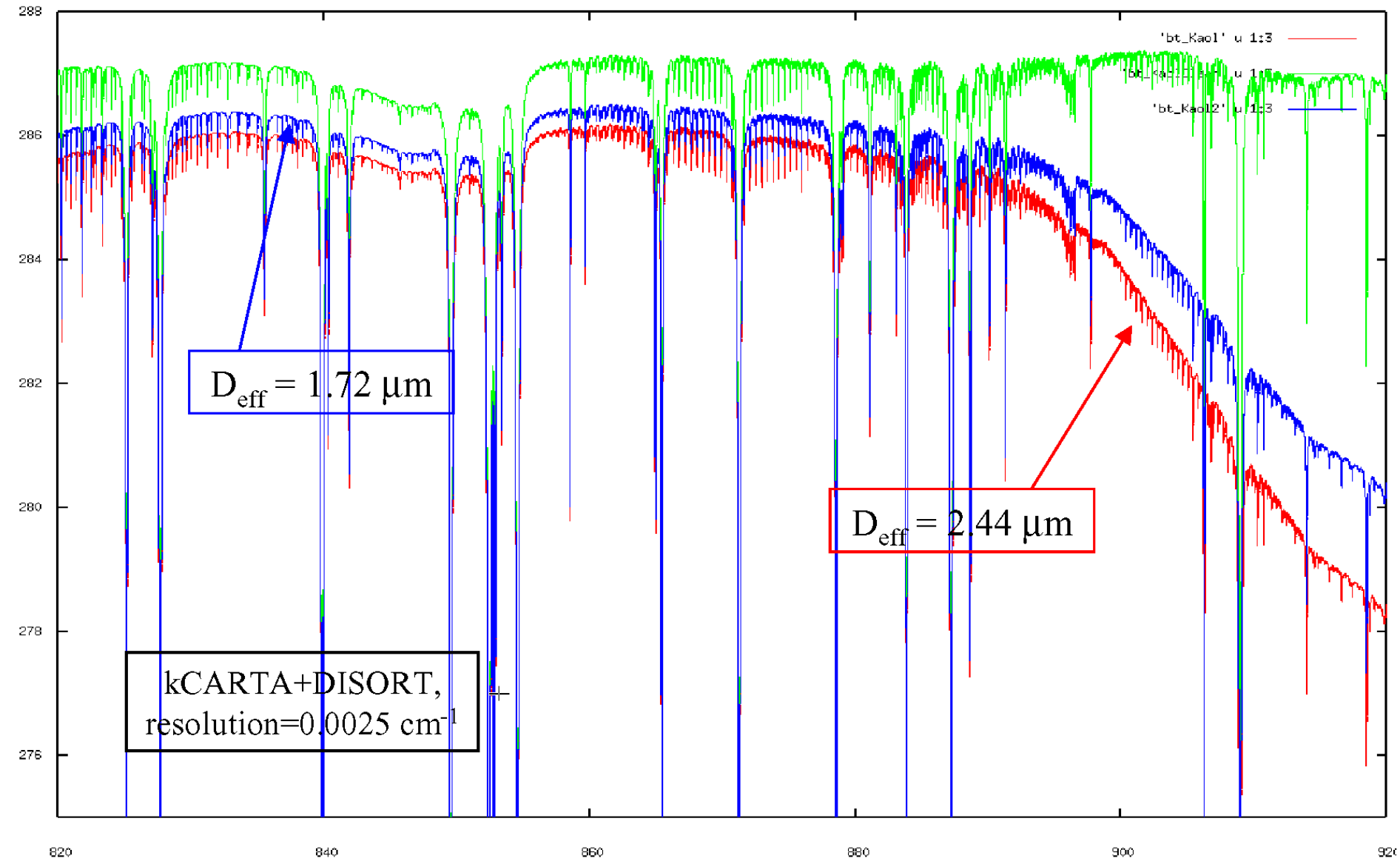


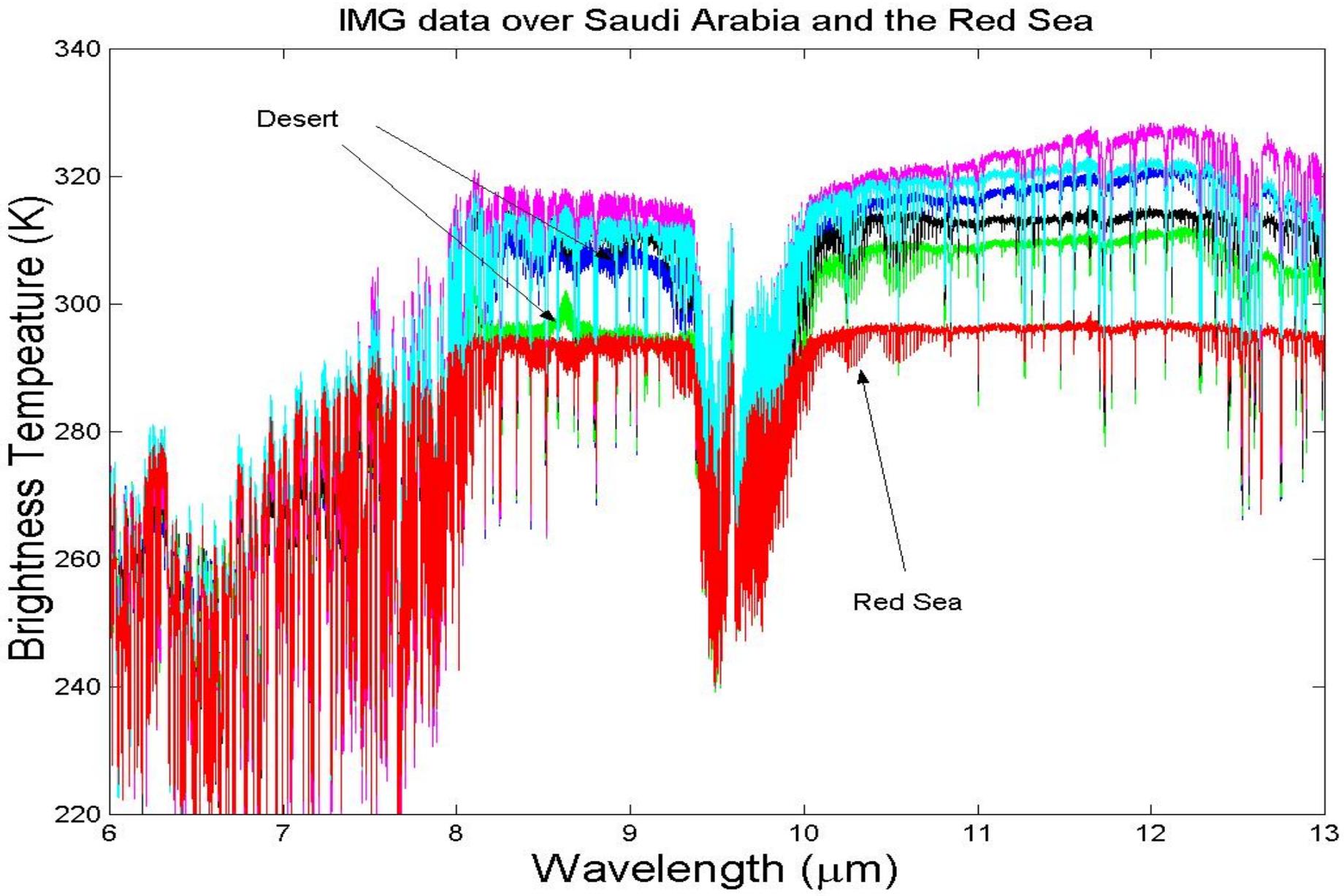
Effect of Dust Layer Location

Negative slope

kCARTA+DISORT, spectral resolution = 0.0025 cm^{-1}

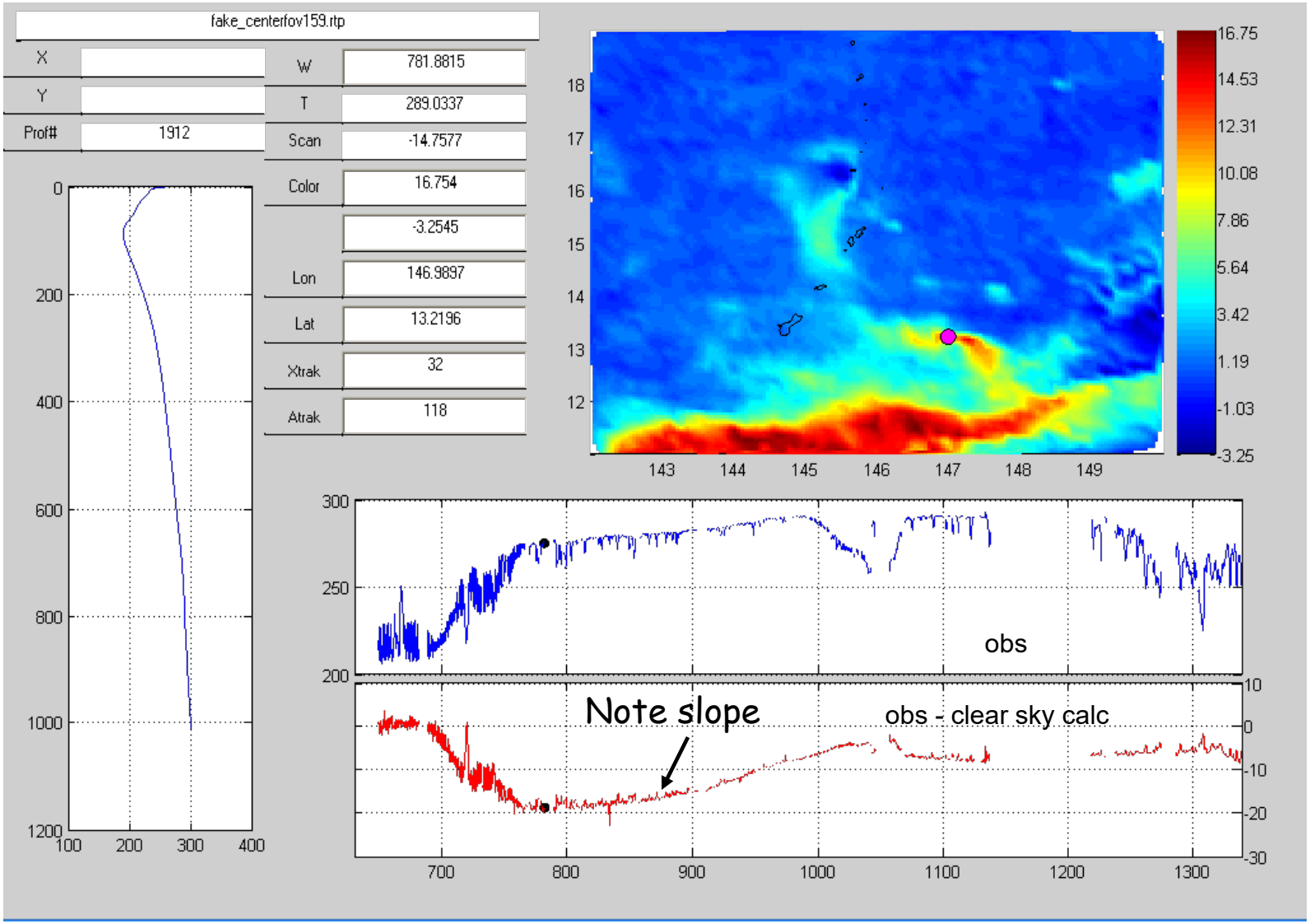
Sokolik, Univ Colo, 2002


'bt_Kao1' u 1:3
'bt_Kao12' u 1:3
288
286
284
282
280
278
276
820
840
860
880
900
920
D_{eff} = 1.72 µm
D_{eff} = 2.44 µm
kCARTA+DISORT,
resolution=0.0025 cm^{-1}


IMG data over Saudi Arabia and the Red Sea
Desert
Red Sea
Brightness Tempeature (K)
Wavelength (μm)
340
320
300
280
260
240
220
6
7
8
9
10
11
12
13

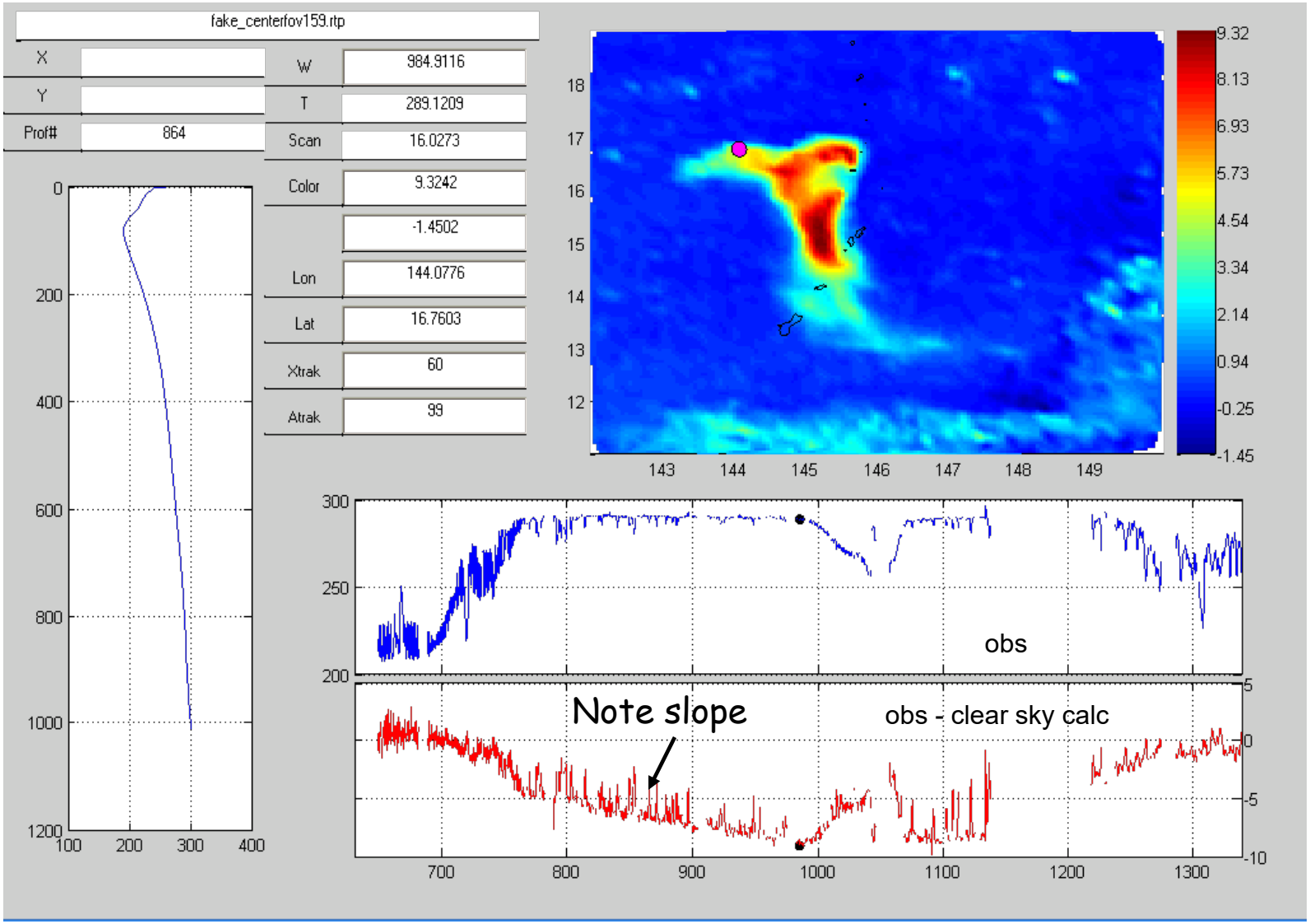
Cirrus signal at Anatahan

Image is ECMWF T_b bias difference of 1227 cm^{-1} – 781 cm^{-1} (double difference)

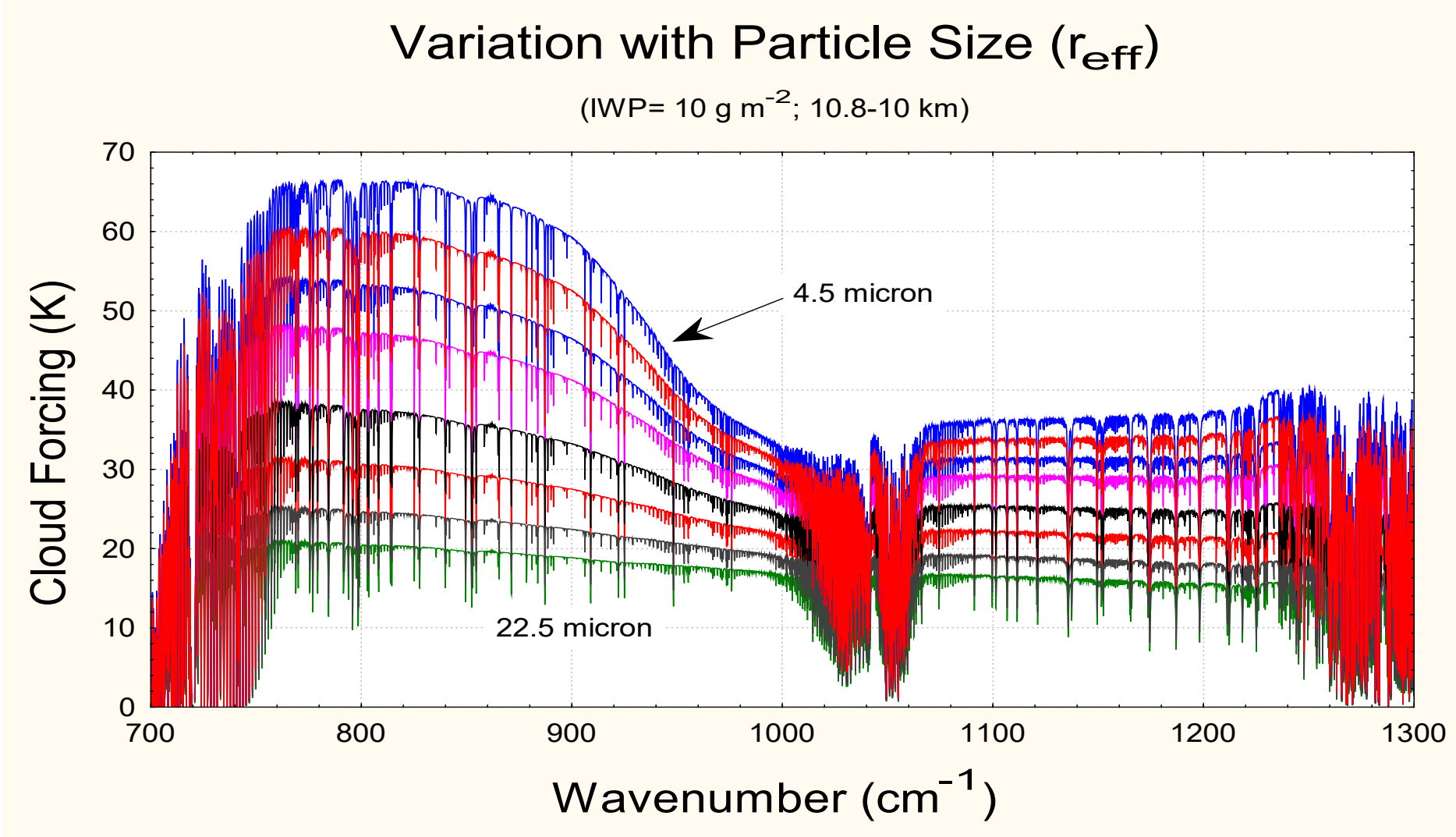


Silicate (ash cloud) signal at Anatahan, Mariana Is

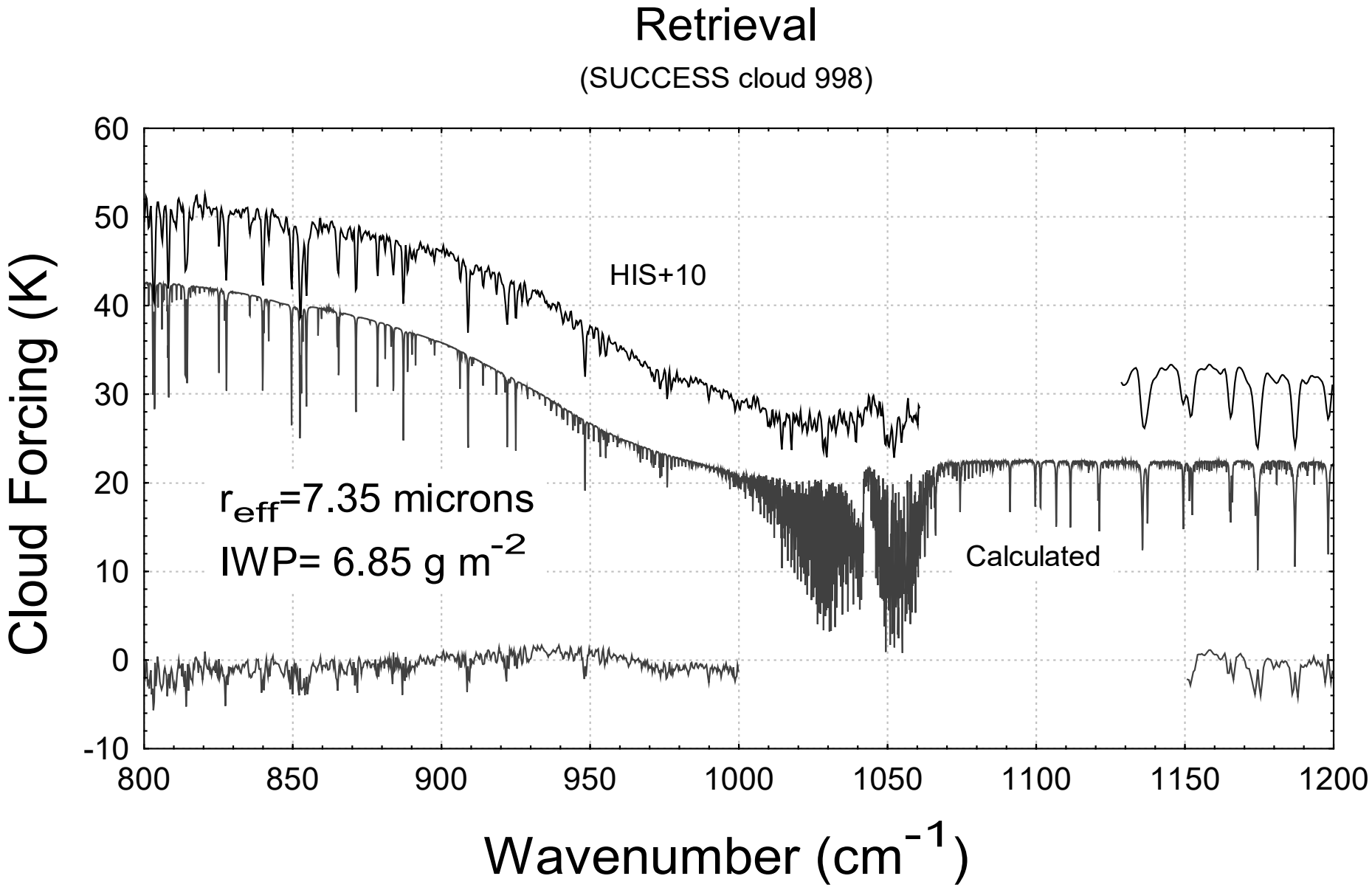
Image is ECMWF bias difference of 1227 cm^{-1} – 984 cm^{-1} (double difference)

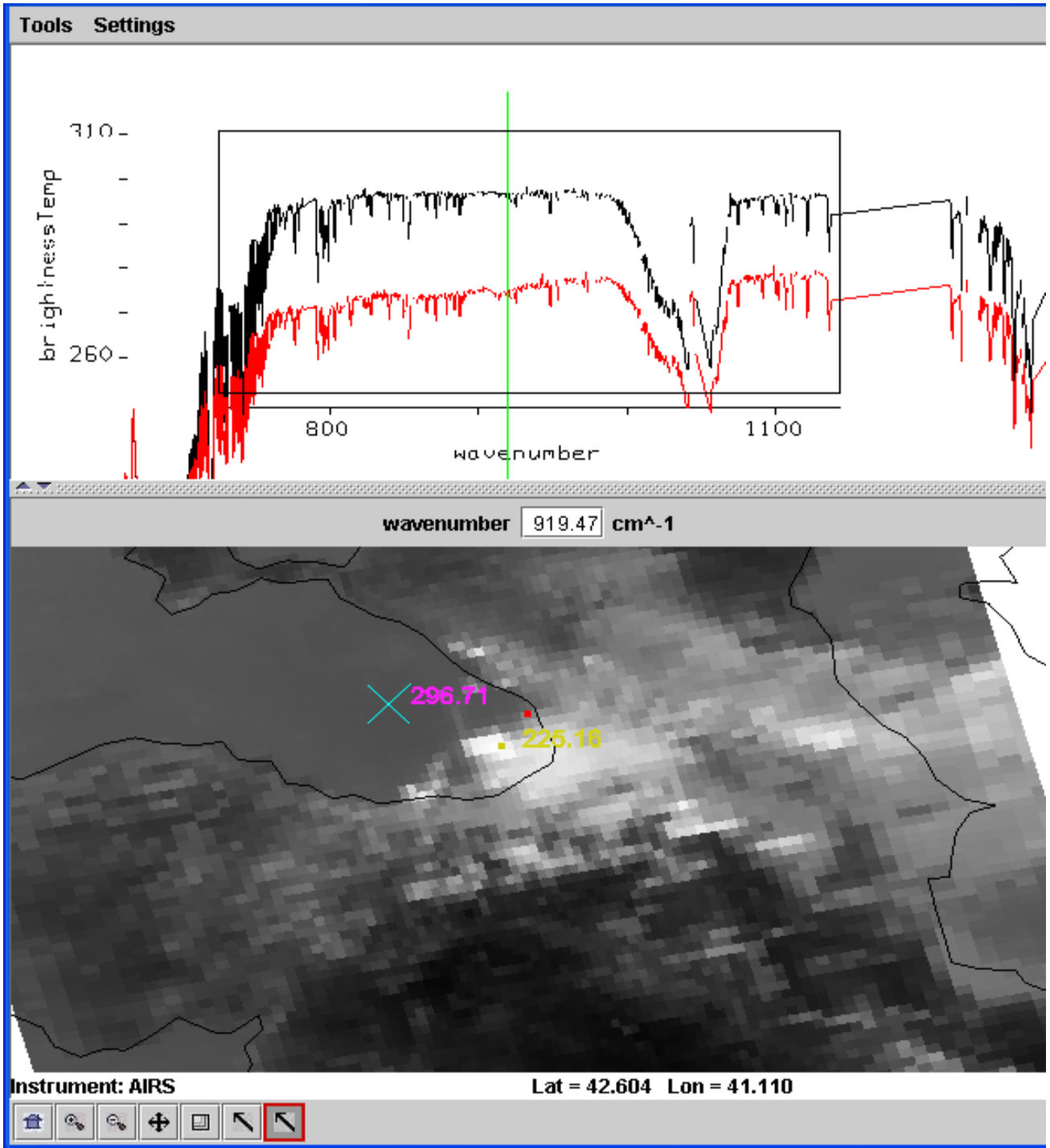


Cloud particle size emerges in high resolution IR window spectra



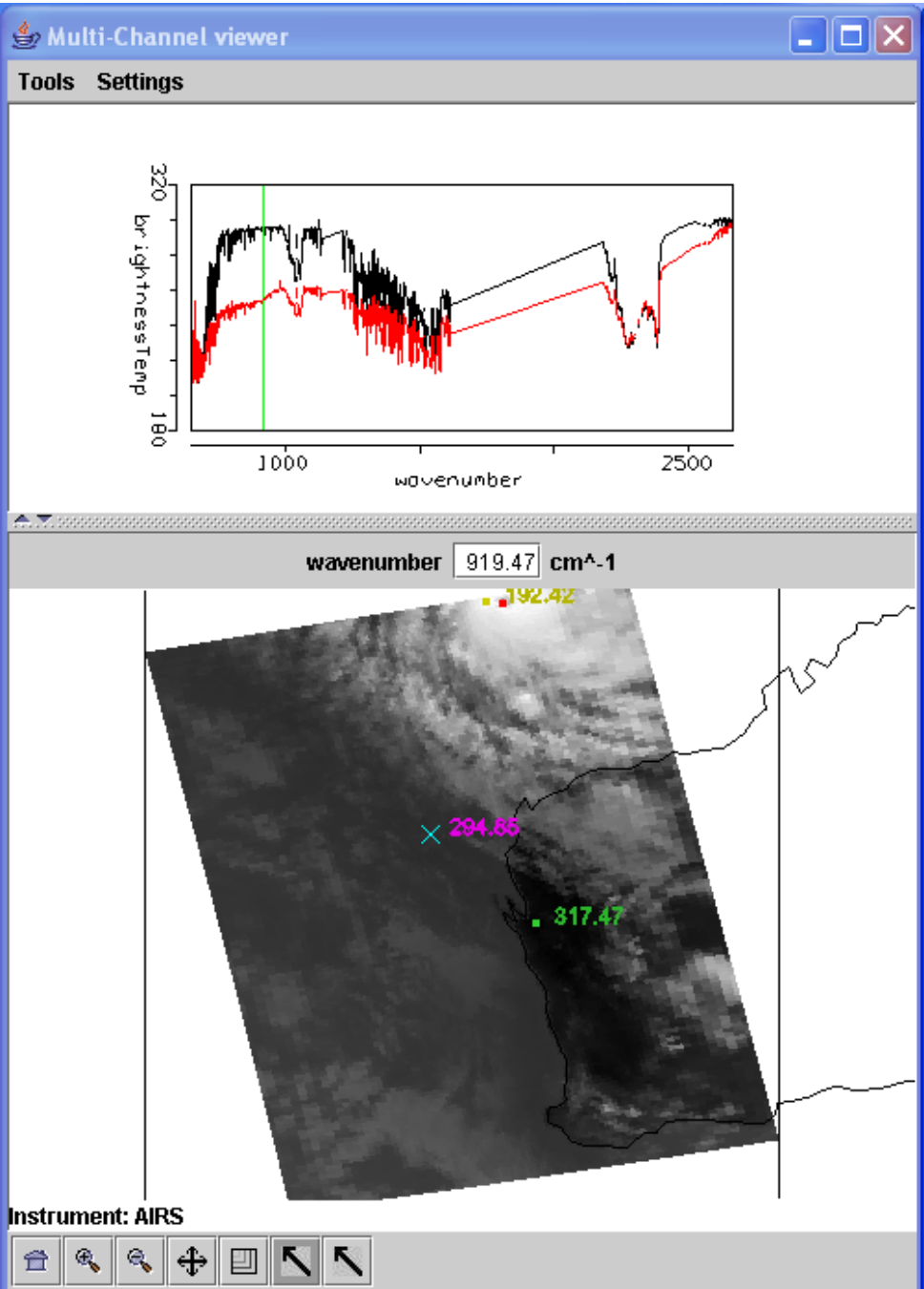
DISORT calculations agree with HIS measurements within 2 K

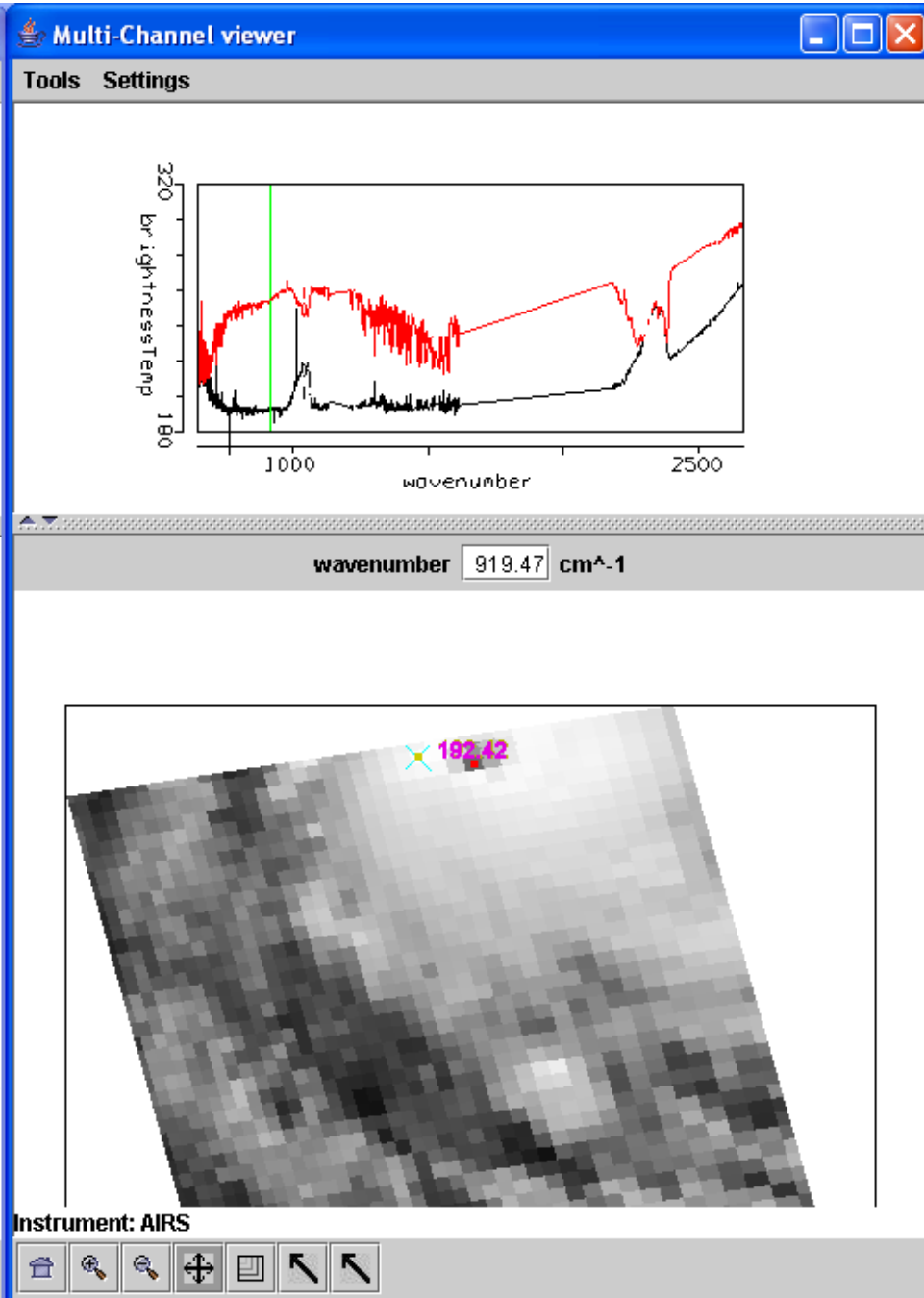




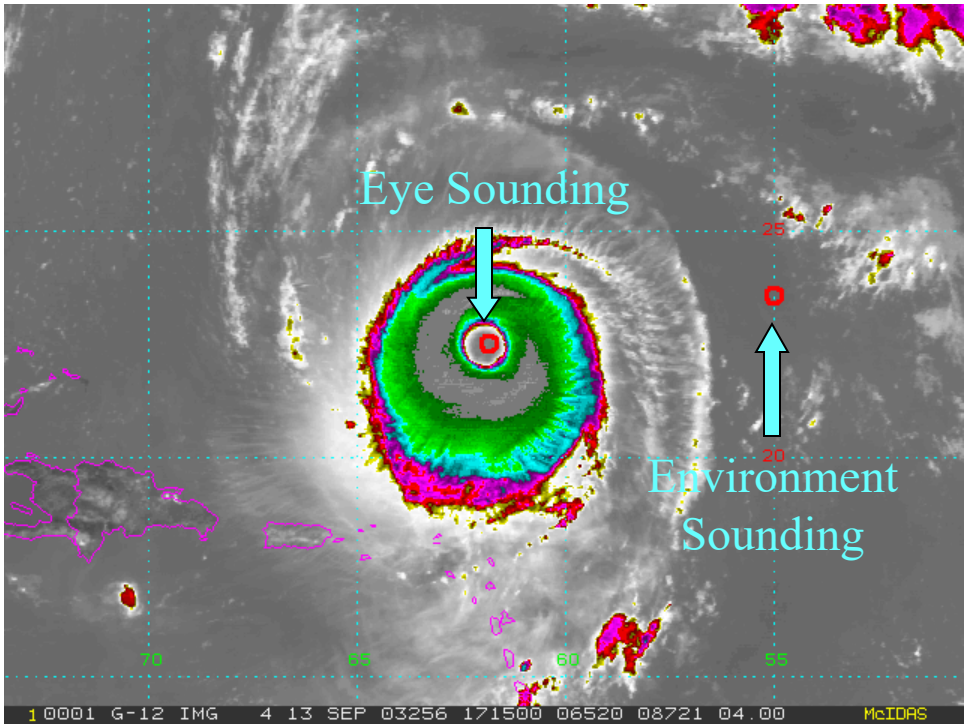
Cirrus
vs
Clear Sky
Spectra

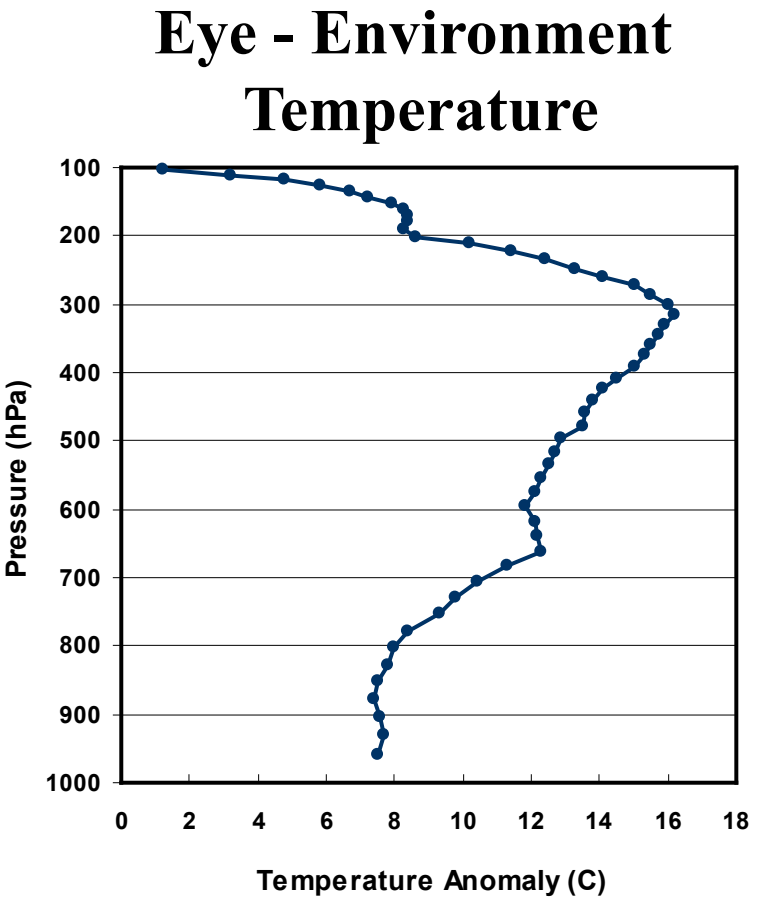
Investigating the Eye of a Tropical Cyclone with AIRS





Isabel Eye Sounding from AIRS





Integrate Hydrostatic Equation Downward from 100 hPa to Surface

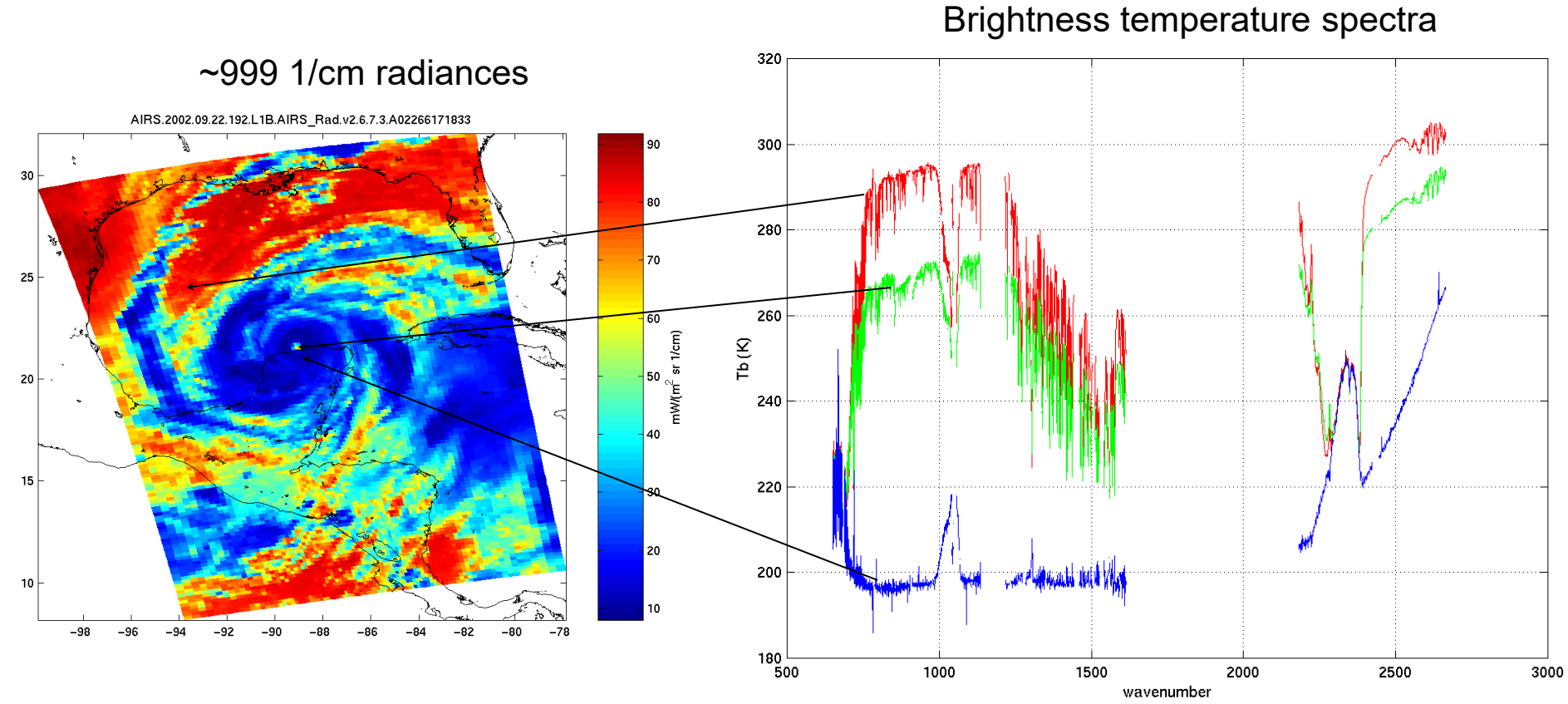
Environment Sounding: P_s = 1012 hPa

Eye Sounding: P_s = 936 hPa

Aircraft Recon: P_s = 933 hPa

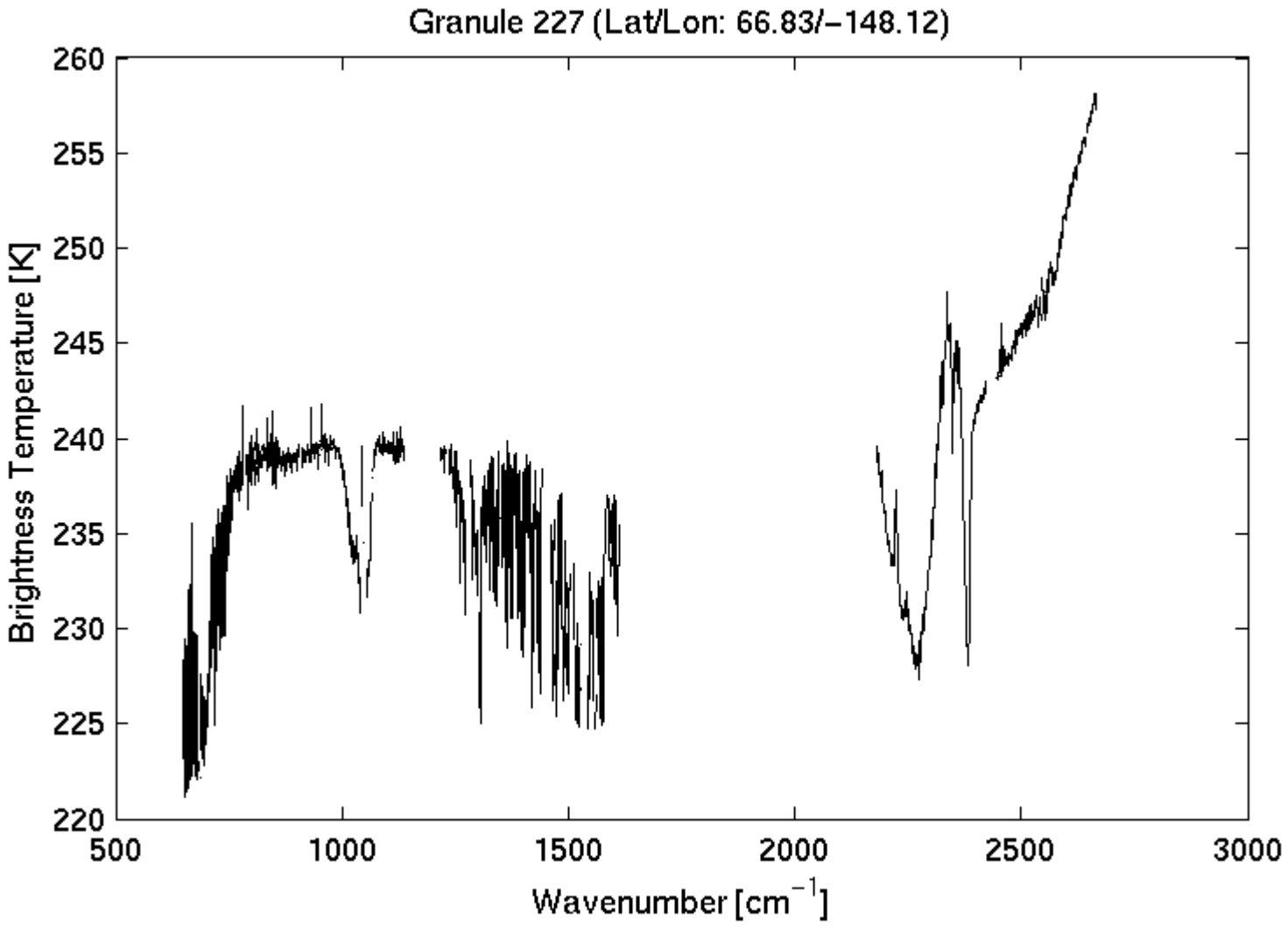
DeMaria, CIRA, 2004

Brightness Temperature Spectra reveal changes in atmosphere from eye to boundary of Tropical Cyclone

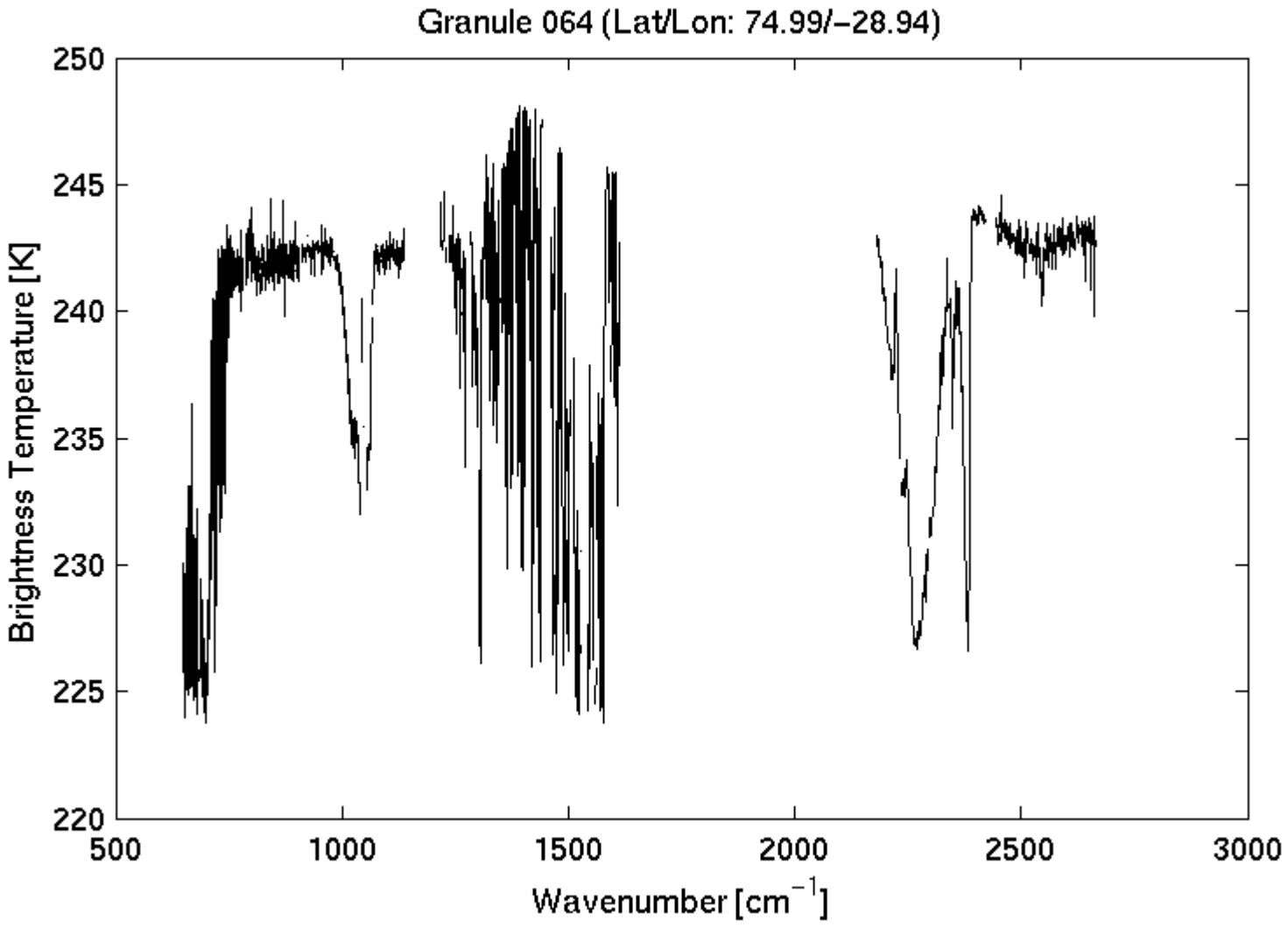


AIRS observations of tropical storm Isadore
on 22 Sept 2002 @ ~19:12-19:18 UTC

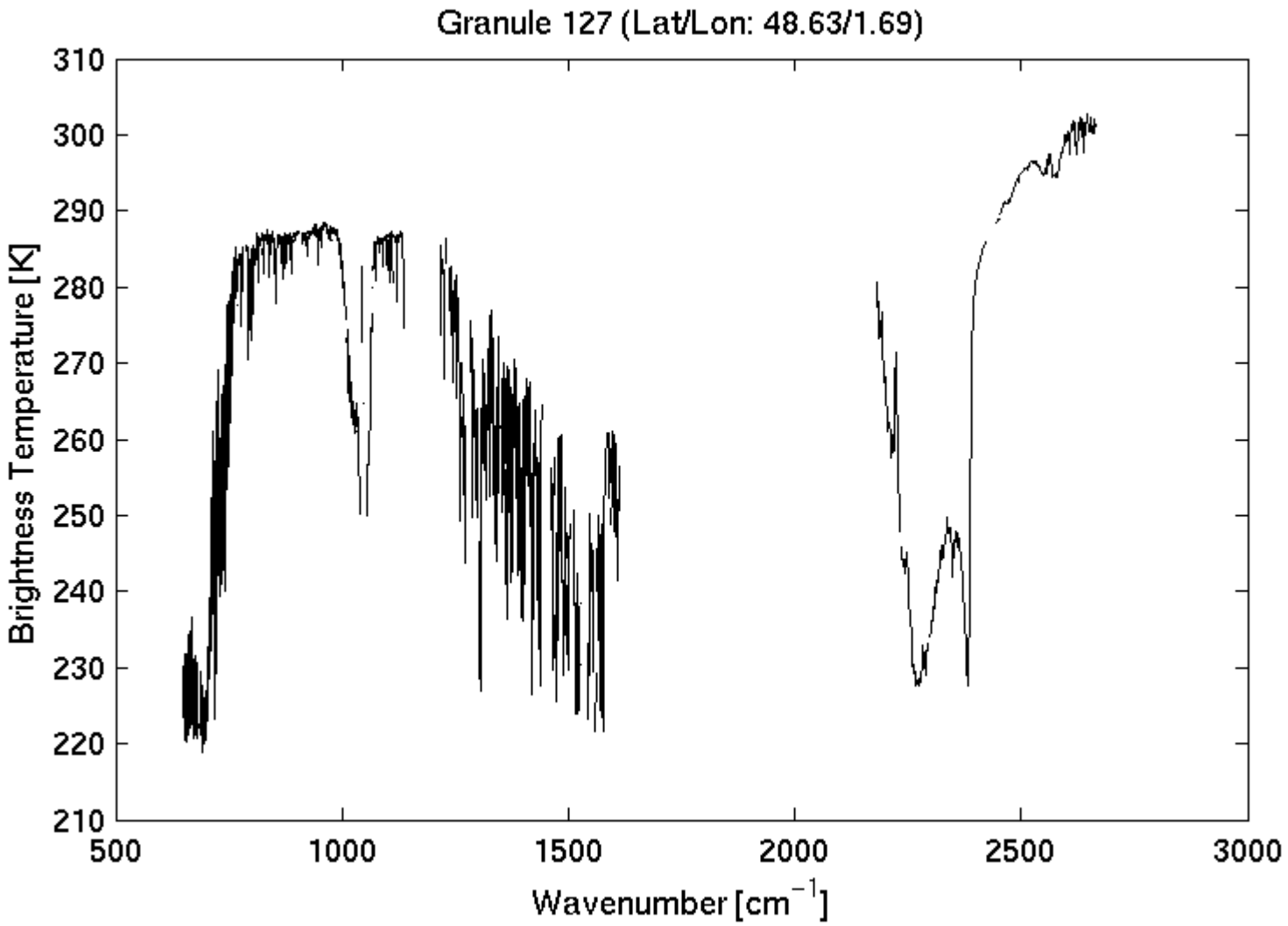
Example Spectra


Granule 227 (Lat/Lon: 66.83/−148.12)
Brightness Temperature [K]
260
255
250
245
240
235
230
225
220
500
1000
1500
2000
2500
3000
Wavenumber [cm^{-1}]

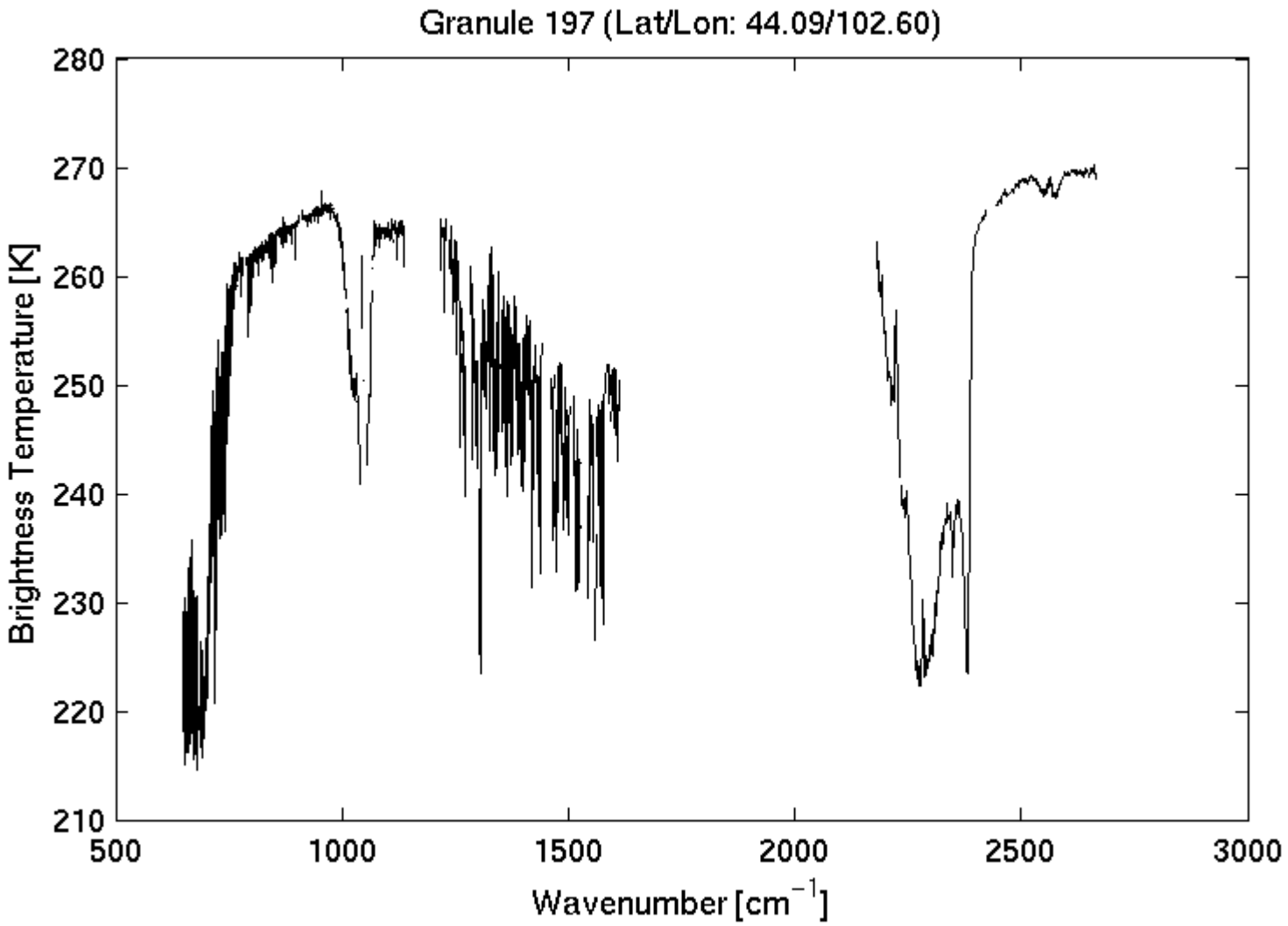
Day or night?



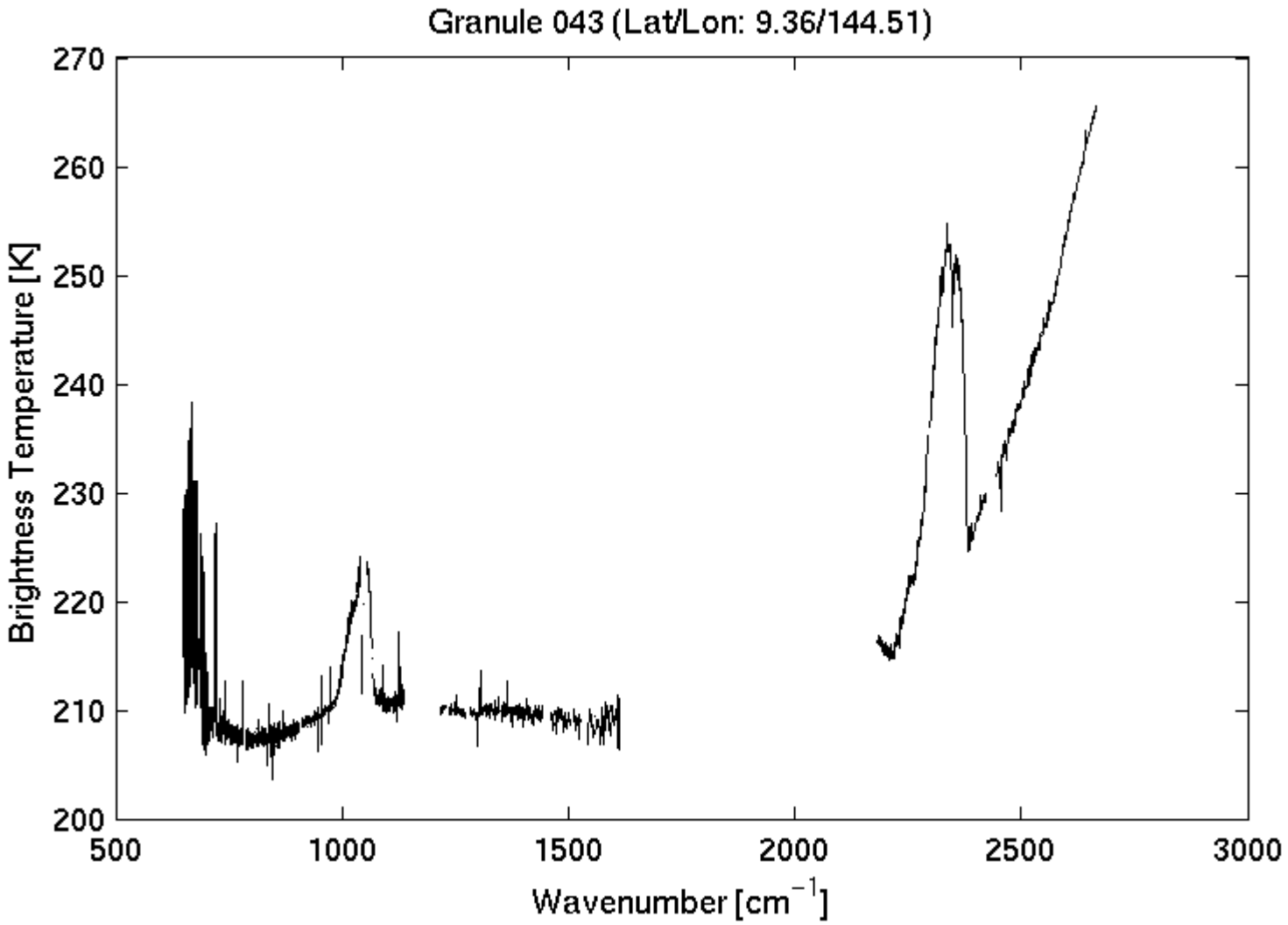
Day, night, desert, or ice/snow?


Granule 127 (Lat/Lon: 48.63/1.69)
Brightness Temperature [K]
310
300
290
280
270
260
250
240
230
220
210
500
1000
1500
2000
2500
3000
Wavenumber [cm^{-1}]

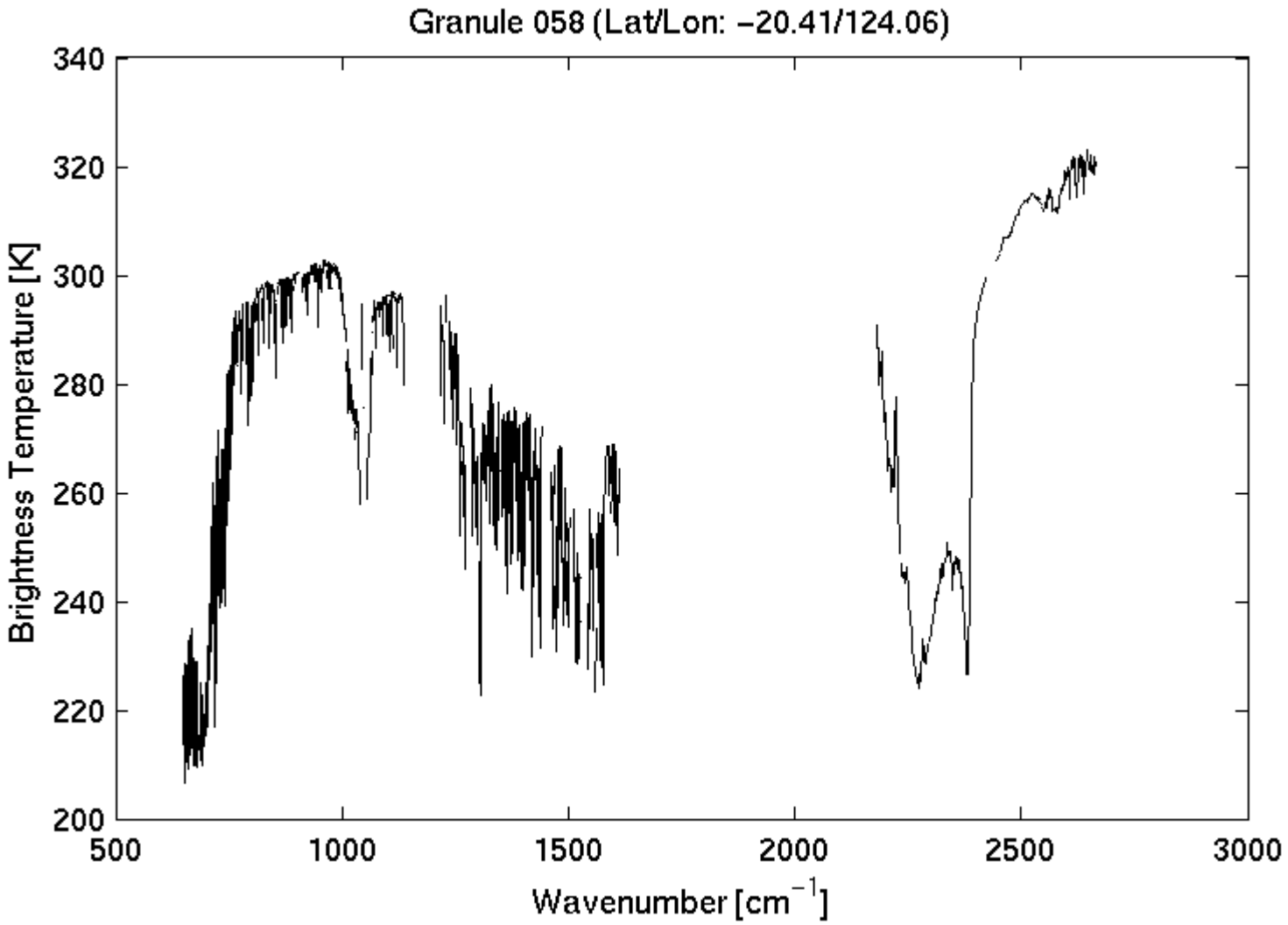
Day or night?



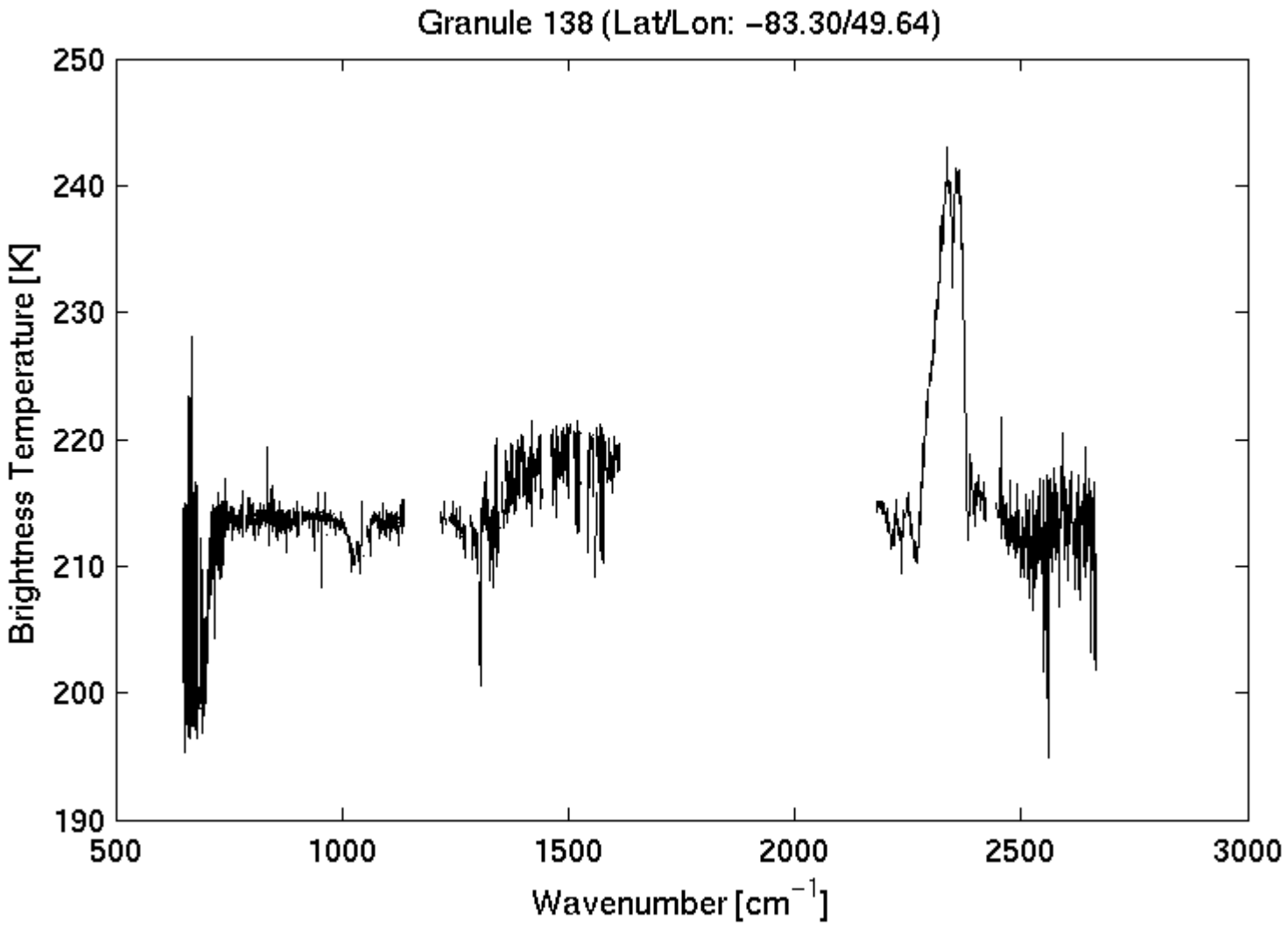
Land or ocean?



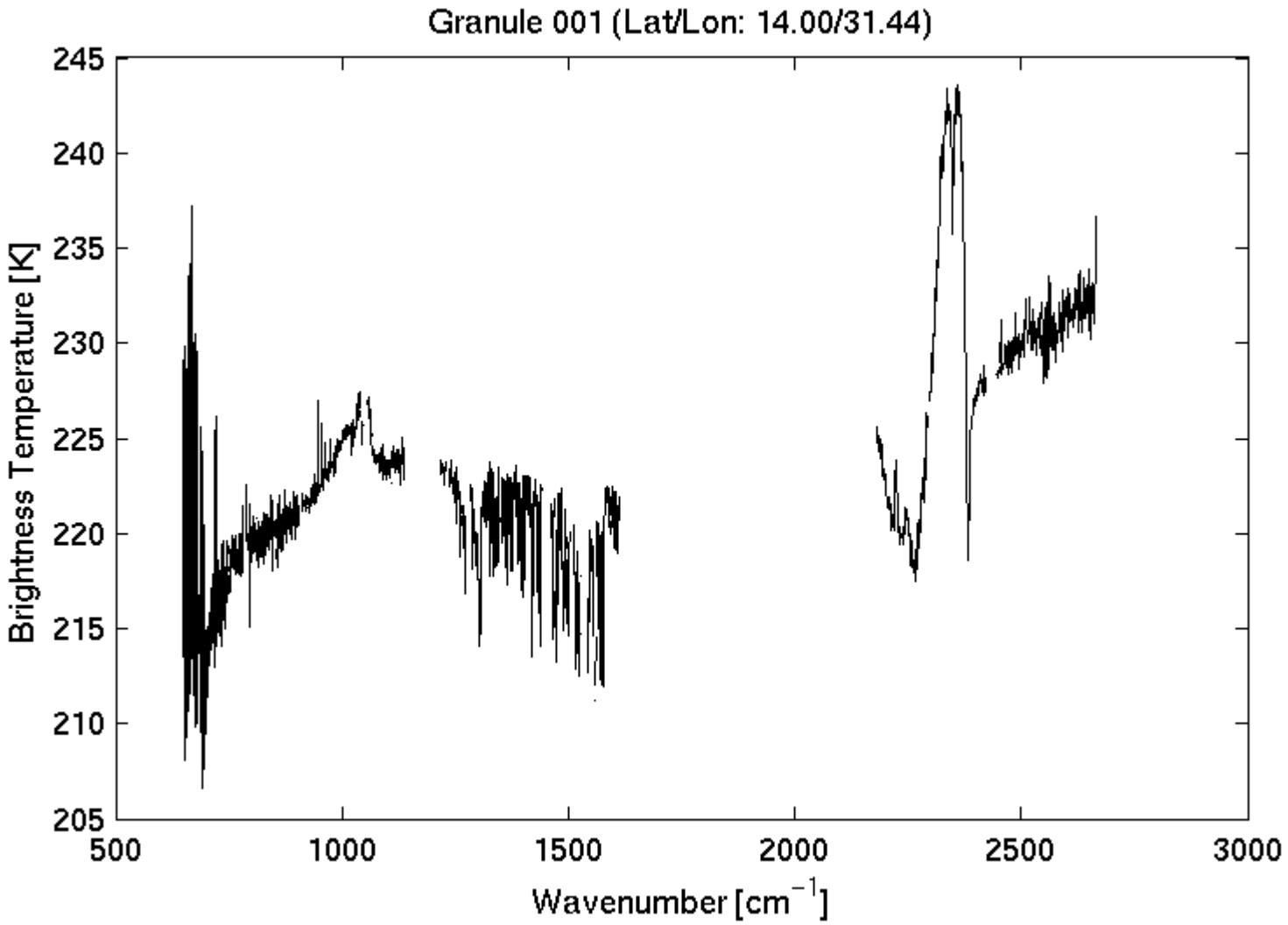
Desert, ocean, or cloudy?



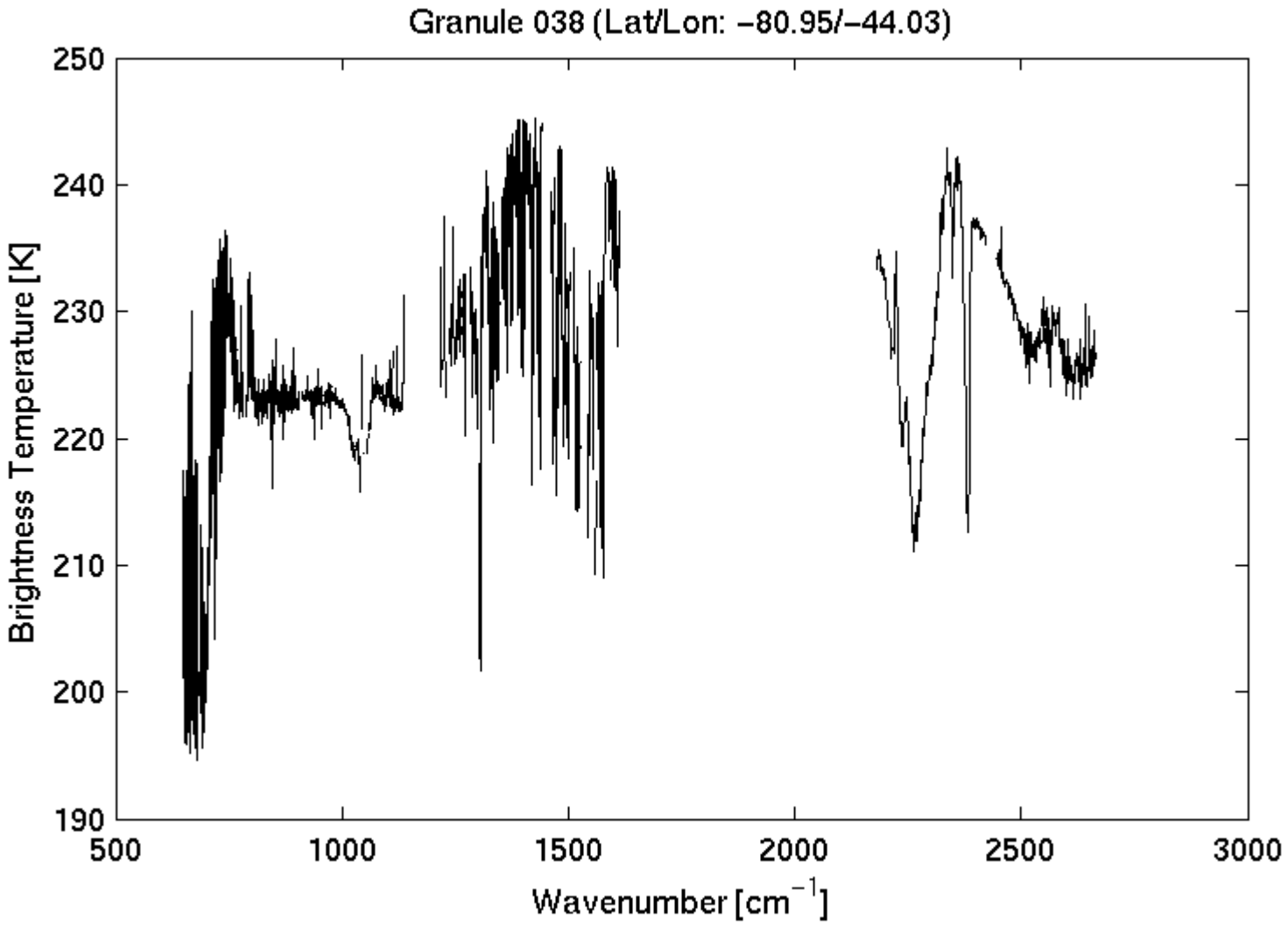
Day, night, desert, or ocean?



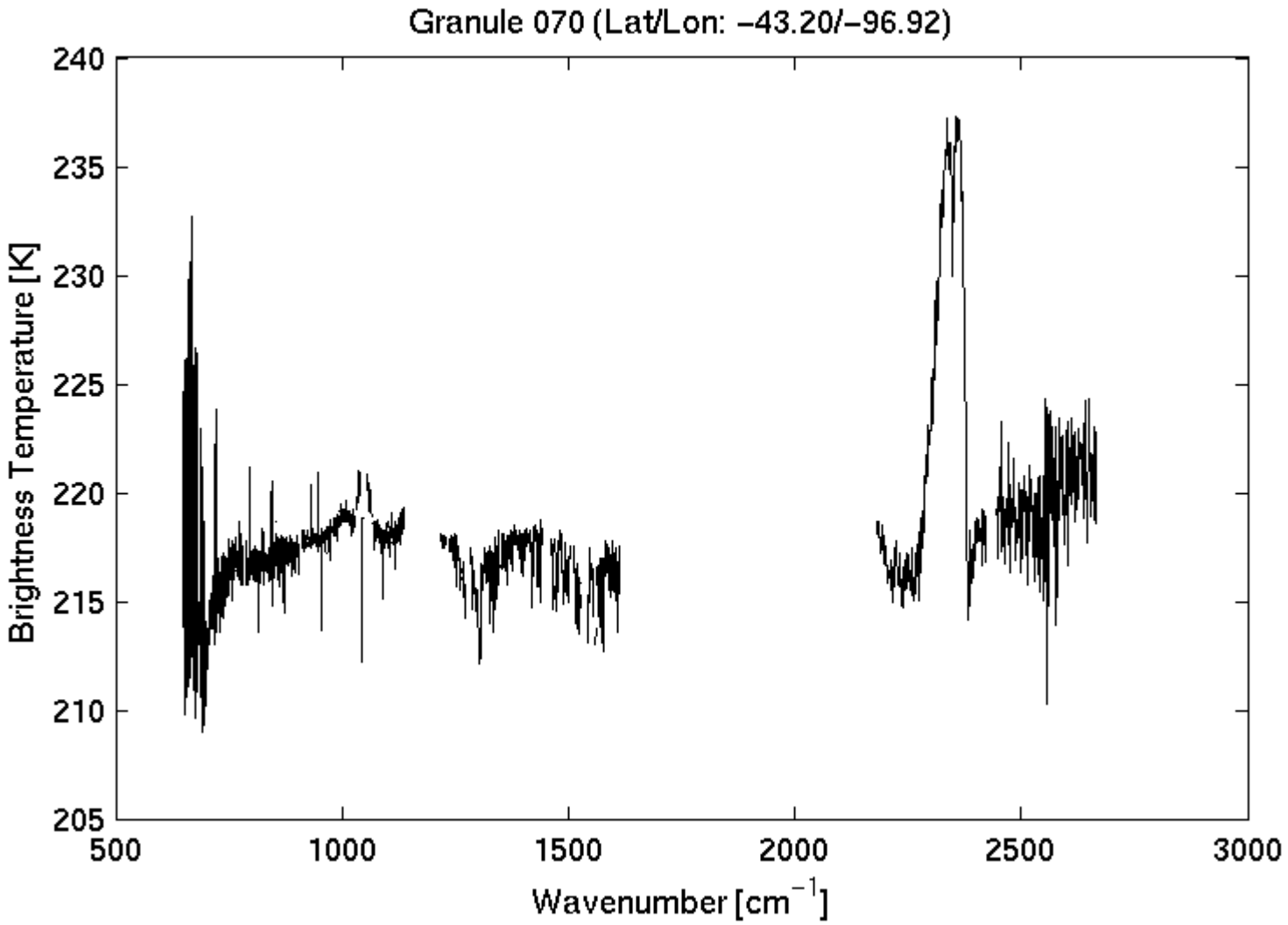
Ocean, cloudy, snow/ice, or desert?



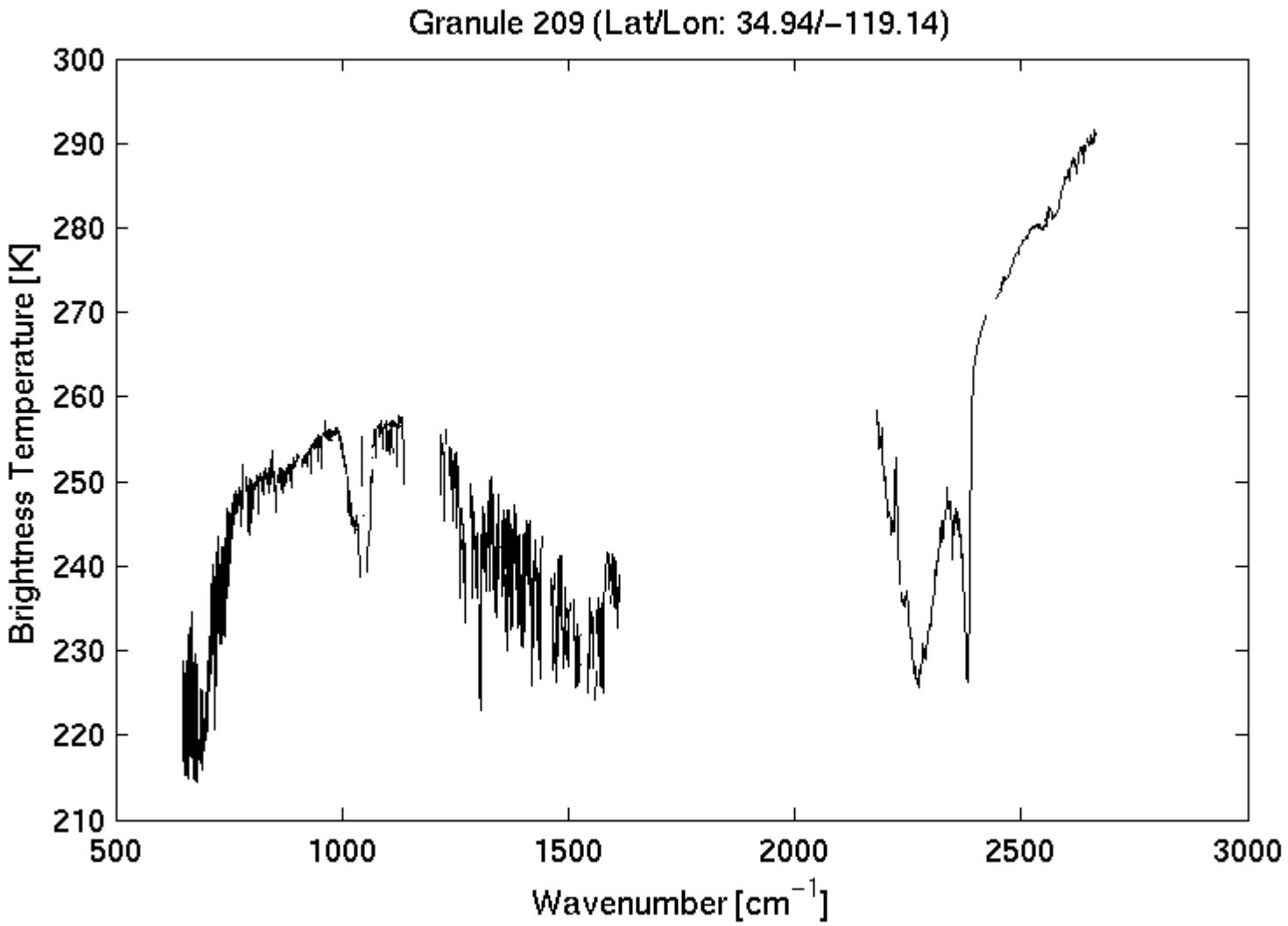
Day, night, desert, or cloudy?



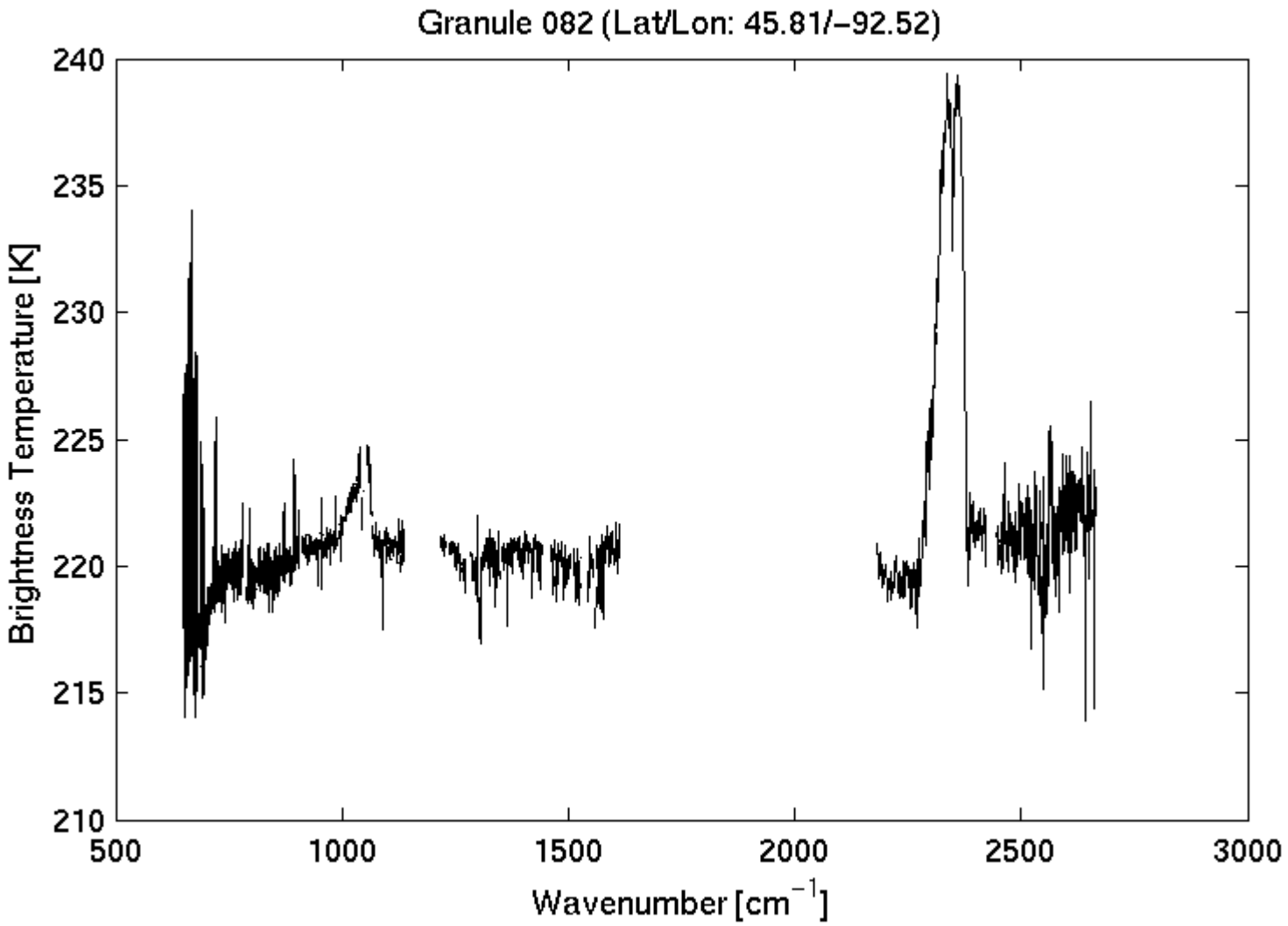
Cloudy, desert, or ocean?



Land, desert, ice/snow, or ocean?



Day, night, desert, or cloudy?



Day, night, ocean, or cloudy?