Lecture 2

Microwave Remote Sensing: Theory, Algorithm and Applications

Dr. Fuzhong Weng
Center for Satellite Applications and Research
National Environmental Satellites, Data and Information Service
National Oceanic and Atmospheric Administration

2012 Update

Outline

- Basic principle of remote sensing over land
- Microwave retrieval of land emissivity
- Physical Base for MW Remote Sensing of Clouds
- Cloud Liquid Water Algorithm
- Cloud Ice Water Algorithm
- Microwave Sounding Algorithm

Principle of Microwave Land Remote Sensing

Emission-based radiative transfer equation:

$$T_b = \varepsilon T_s \exp(-\tau_s / \mu) + T_u + (1-\varepsilon) T_d \exp(-\tau_s / \mu)$$

$$\Updownarrow$$

$$T_b = T_s[1-(1-\varepsilon)\Upsilon^2] - \Delta T(1-\Upsilon)[1+(1-\varepsilon)\Upsilon]$$

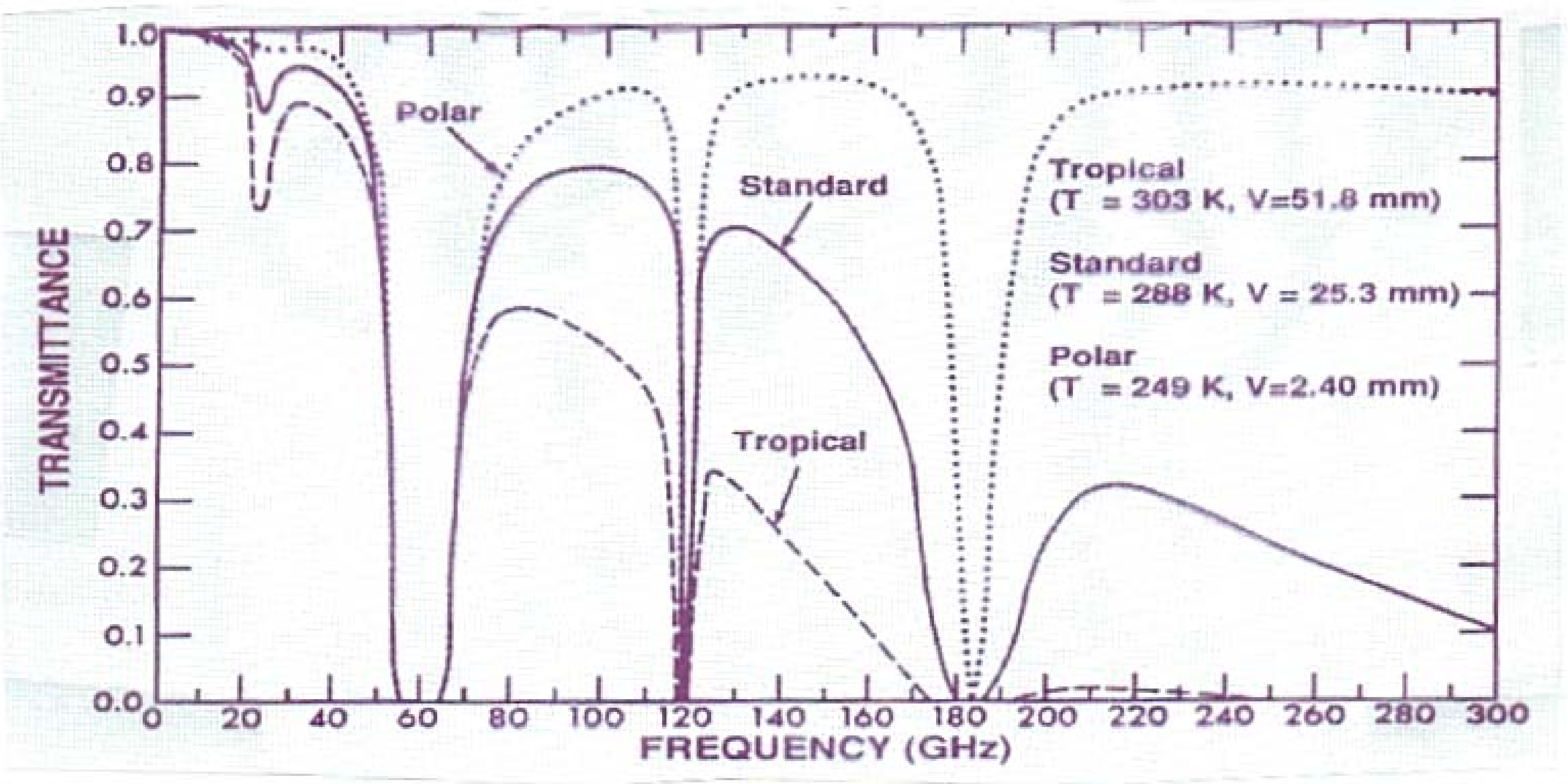
If atmosphere is transparent like a glass window, then $\Upsilon = 1$

$$T_b = \varepsilon T_s$$

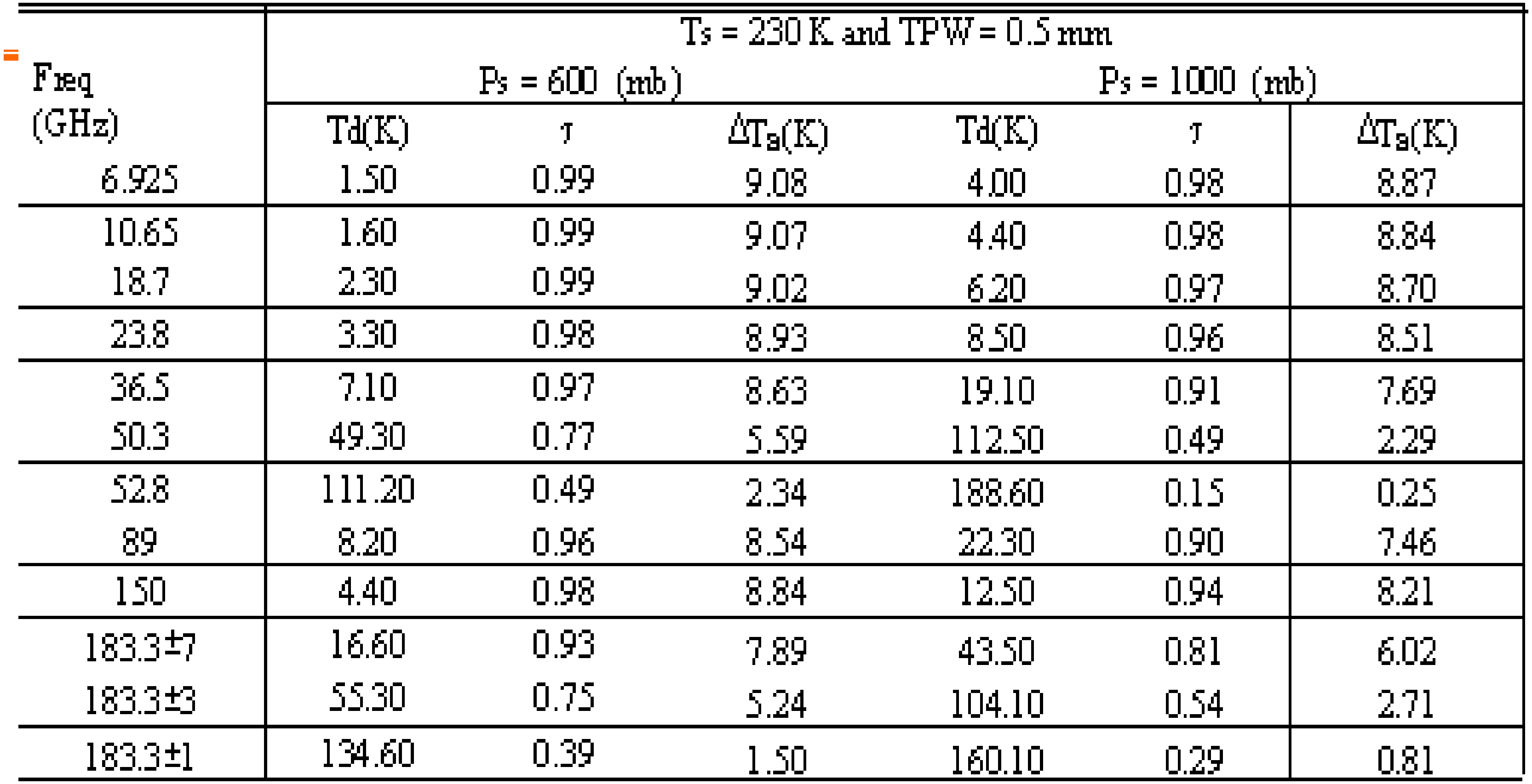
Brightness temperature is a linear function of surface emissivity!

This is a basic principle for microwave remote sensing of land surface property.

Microwave Transmissivity Spectrum



BT Sensitivity to Surface Emissivity

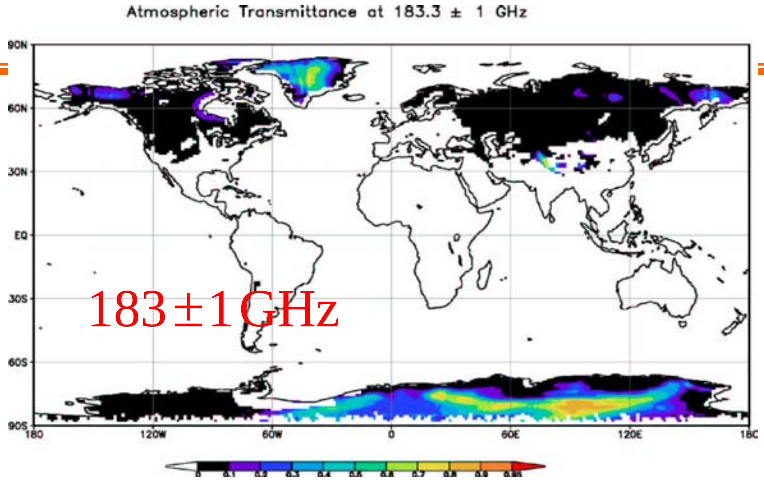


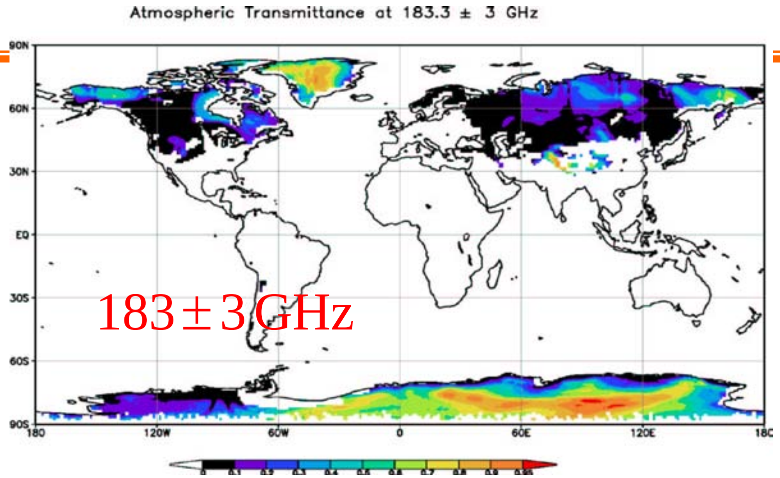
Freq (GHz)	T_s = 230 K and TPW = 0.5 mm					
	Ps = 600 (mb)			Ps = 1000 (mb)		
	T_d(K)	τ	ΔT_a(K)	T_d(K)	τ	ΔT_a(K)
6.925	1.50	0.99	9.08	4.00	0.98	8.87
10.65	1.60	0.99	9.07	4.40	0.98	8.84
18.7	2.30	0.99	9.02	6.20	0.97	8.70
23.8	3.30	0.98	8.93	8.50	0.96	8.51
36.5	7.10	0.97	8.63	19.10	0.91	7.69
50.3	49.30	0.77	5.59	112.50	0.49	2.29
52.8	111.20	0.49	2.34	188.60	0.15	0.25
89	8.20	0.96	8.54	22.30	0.90	7.46
150	4.40	0.98	8.84	12.50	0.94	8.21
183.3±7	16.60	0.93	7.89	43.50	0.81	6.02
183.3±3	55.30	0.75	5.24	104.10	0.54	2.71
183.3±1	134.60	0.39	1.50	160.10	0.29	0.81

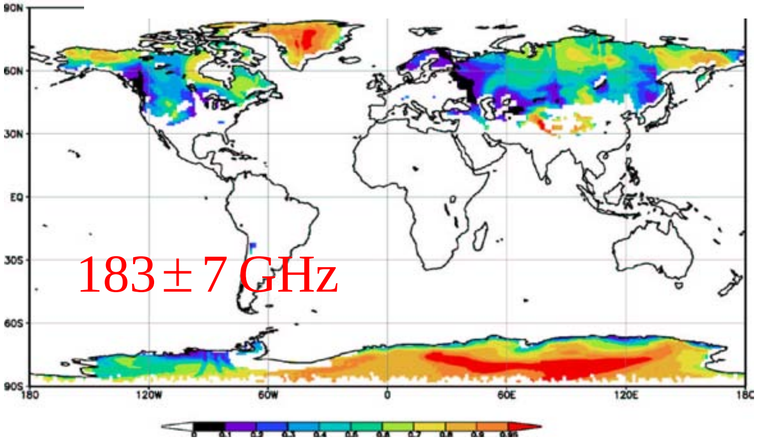
$$\Delta T_B = \tau(T_s - T_d)\Delta\varepsilon, \qquad \Delta\varepsilon = 0.04$$

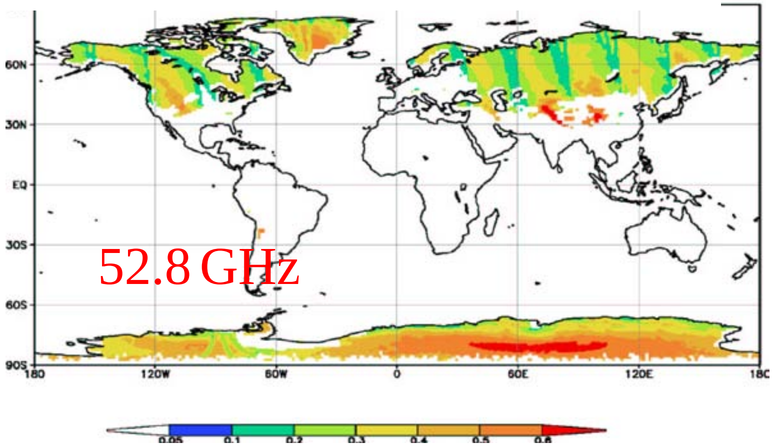
Surface emissivity uncertainty of 5-10% will produce brightness temperature uncertainty up to several degrees!

Atmospheric Transmittance (ϒ)







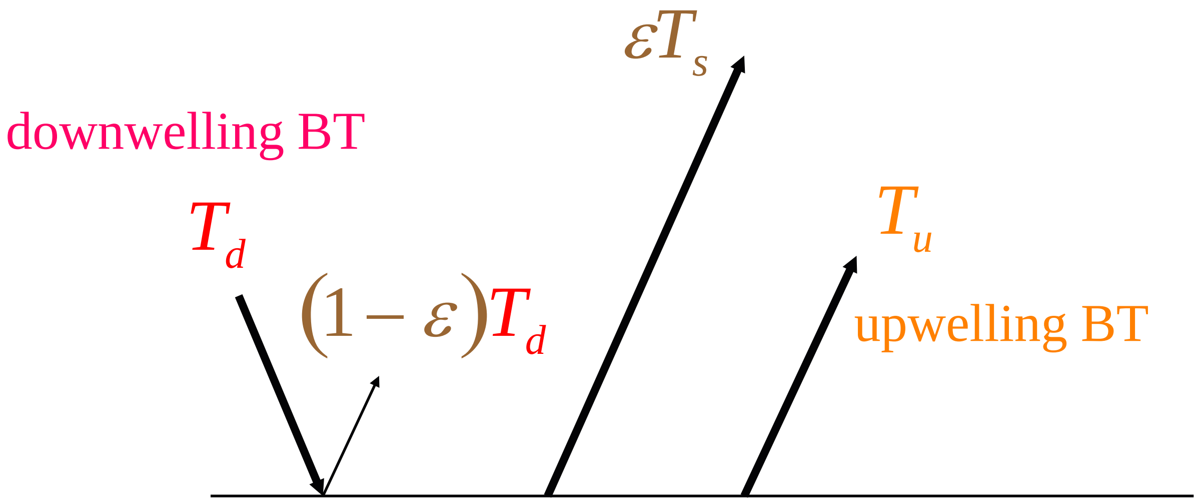


A typical channel for atmospheric profiling can become surface sensitive in certain conditions (e.g. dry moisture, high elevation).

Satellite Microwave Window Channels

- SSM/I 19.35, 37, 85.5 GHz
- AMSU 31.4, 50.3, 89, 150 GHz
- TMI 10.7, 19.35, 37, 85.5 GHz
- AMSR-E 6.6, 10.7, 19.35, 37, 85.5 GHz
- SSMIS 19.35, 37, 50.3, 90, 150 GHz
- Windsat 6.6, 10.7, 19.35, 37 GHz

Retrieval of Microwave Land Emissivity



$$\boxed{\varepsilon = \frac{T_b - T_u - T_d\tau}{\tau(T_s - T_d)}}$$

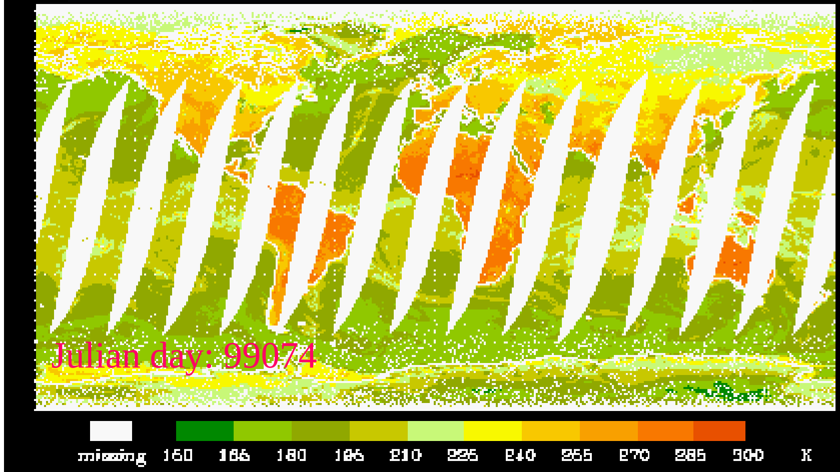
$$T_d = \int_{\tau_0}^{\tau_s} B(\tau,T)\exp(-\frac{(\tau-\tau_0)}{\mu})d\tau, \quad T_u = \int_{\tau_s}^{\tau_0} B(\tau,T)\exp(-\frac{(\tau_s-\tau)}{\mu})d\tau$$

Required Data Sets

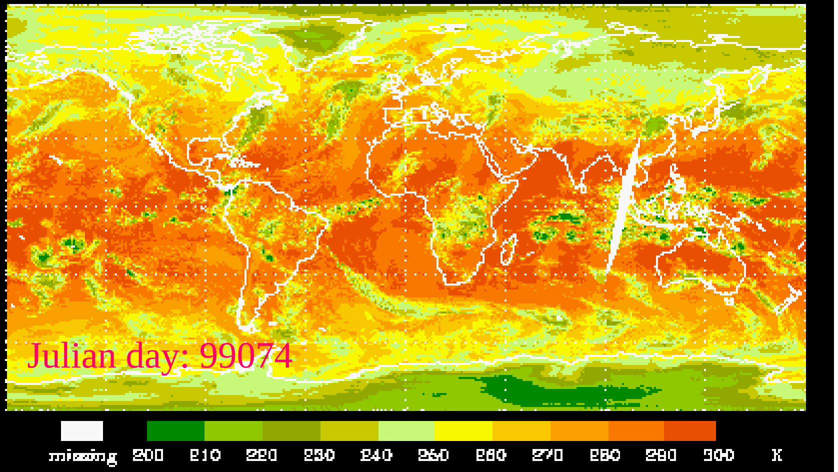
- **Satellite microwave brightness temperatures**
  (F-14 SSM/I)
- **Atmospheric temperature and moisture profiles**
  (GDAS, AMSU-A/B)
- **Land surface temperature**
  (GDAS, AVHRR)
- **Precipitation screening**
  (AVHRR, Scattering Index)

Multi-Sensor and NWP Data Sets

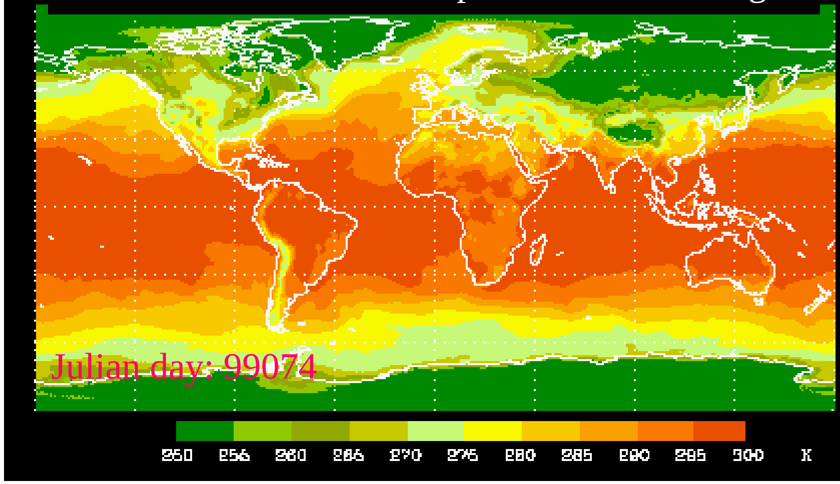
SSM/I Antenna Temperature at 19:36 GHz



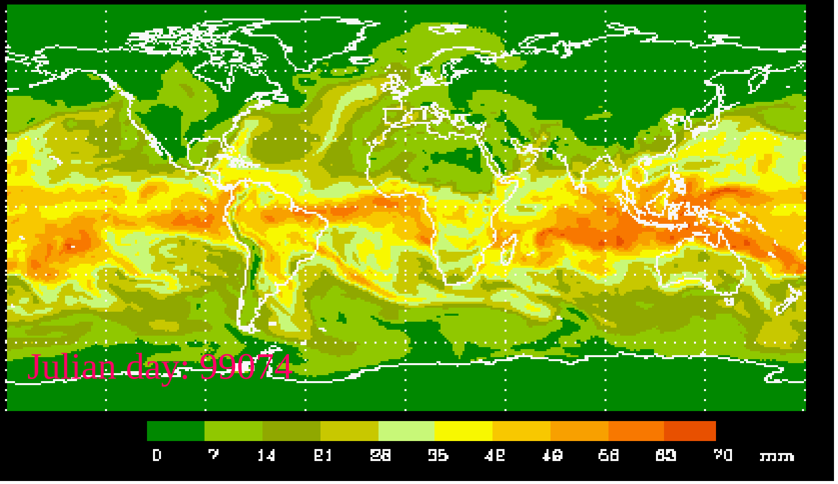
AVHRR Infrared 11 μm



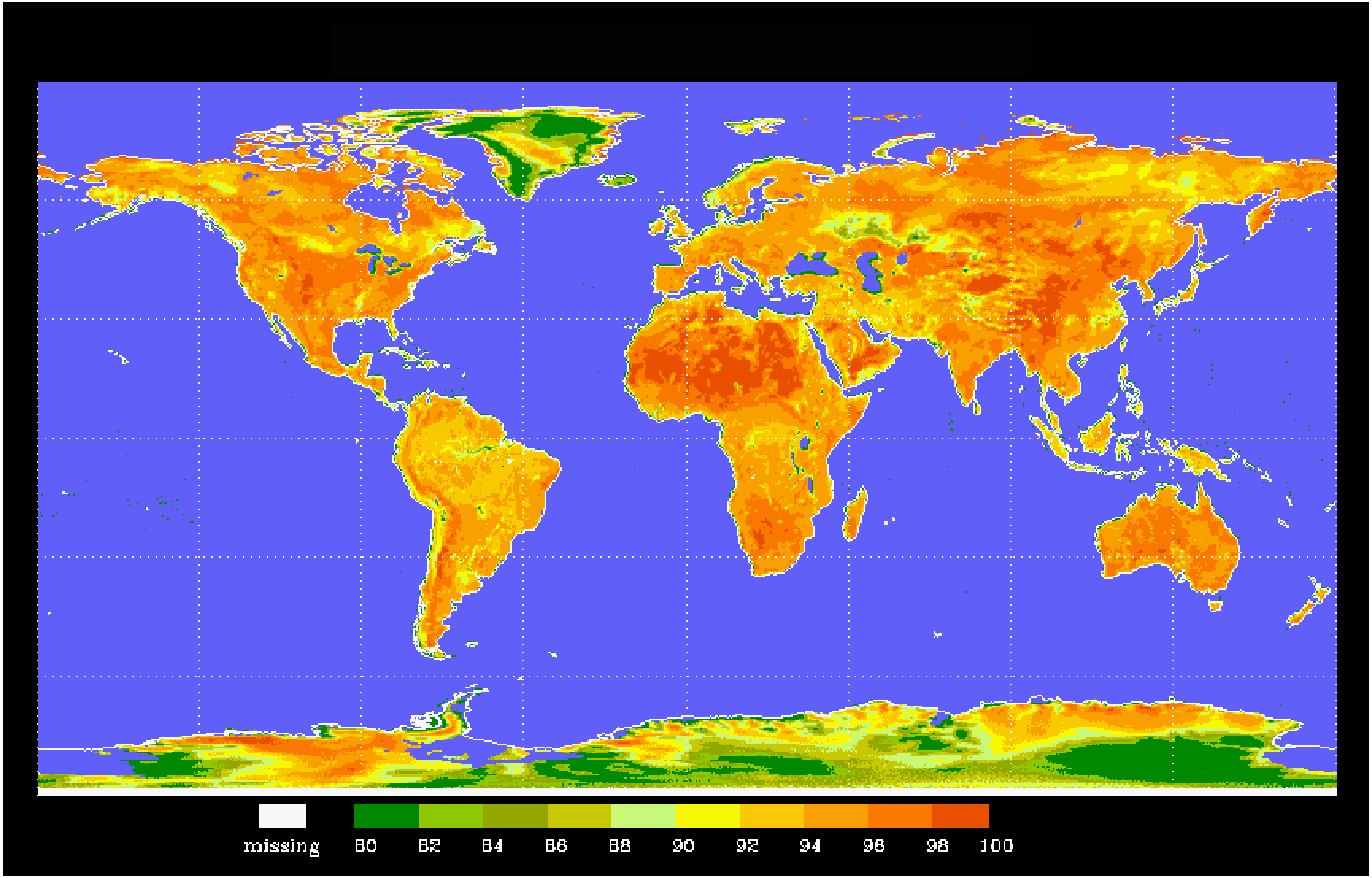
GDAS Land Surface Temperature at 2-m Height



GDAS Atmospheric Total Precipitable Water

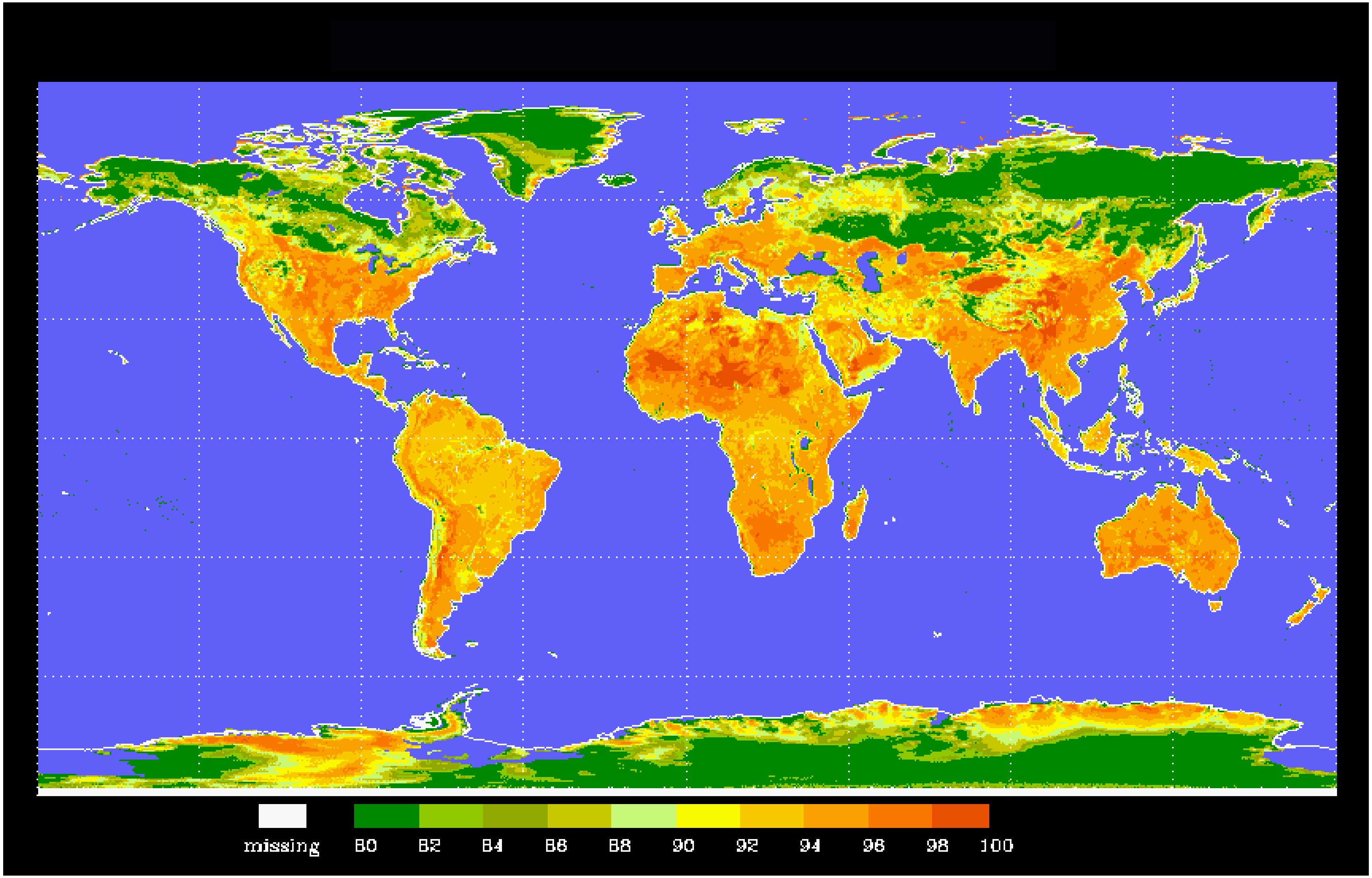


SSM/I Land Surface Emissivity (v-pol) at 19.35 GHz
March 1999

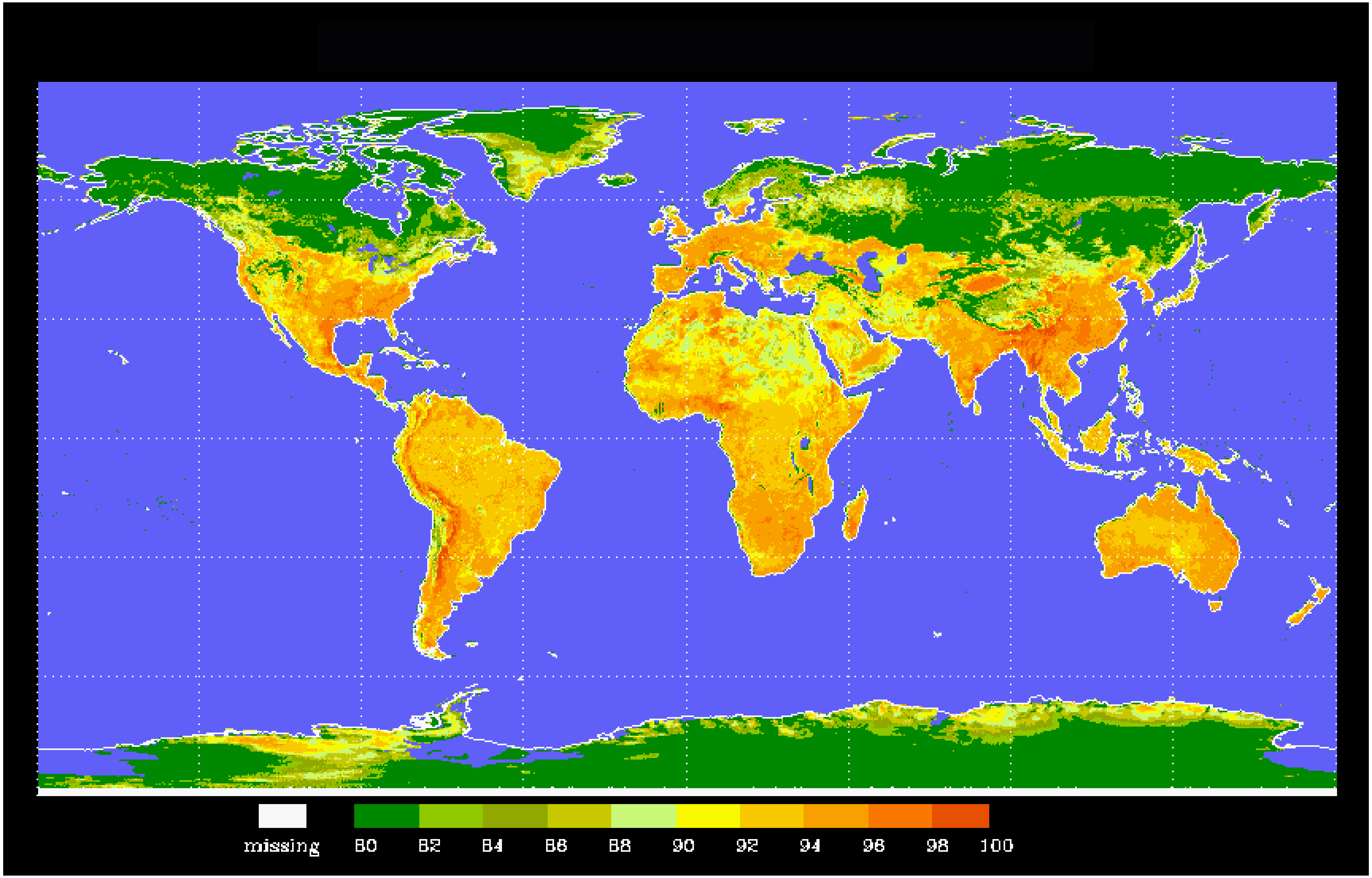


SSM/I Land Surface Emissivity (v-pol) at 37.00 GHz

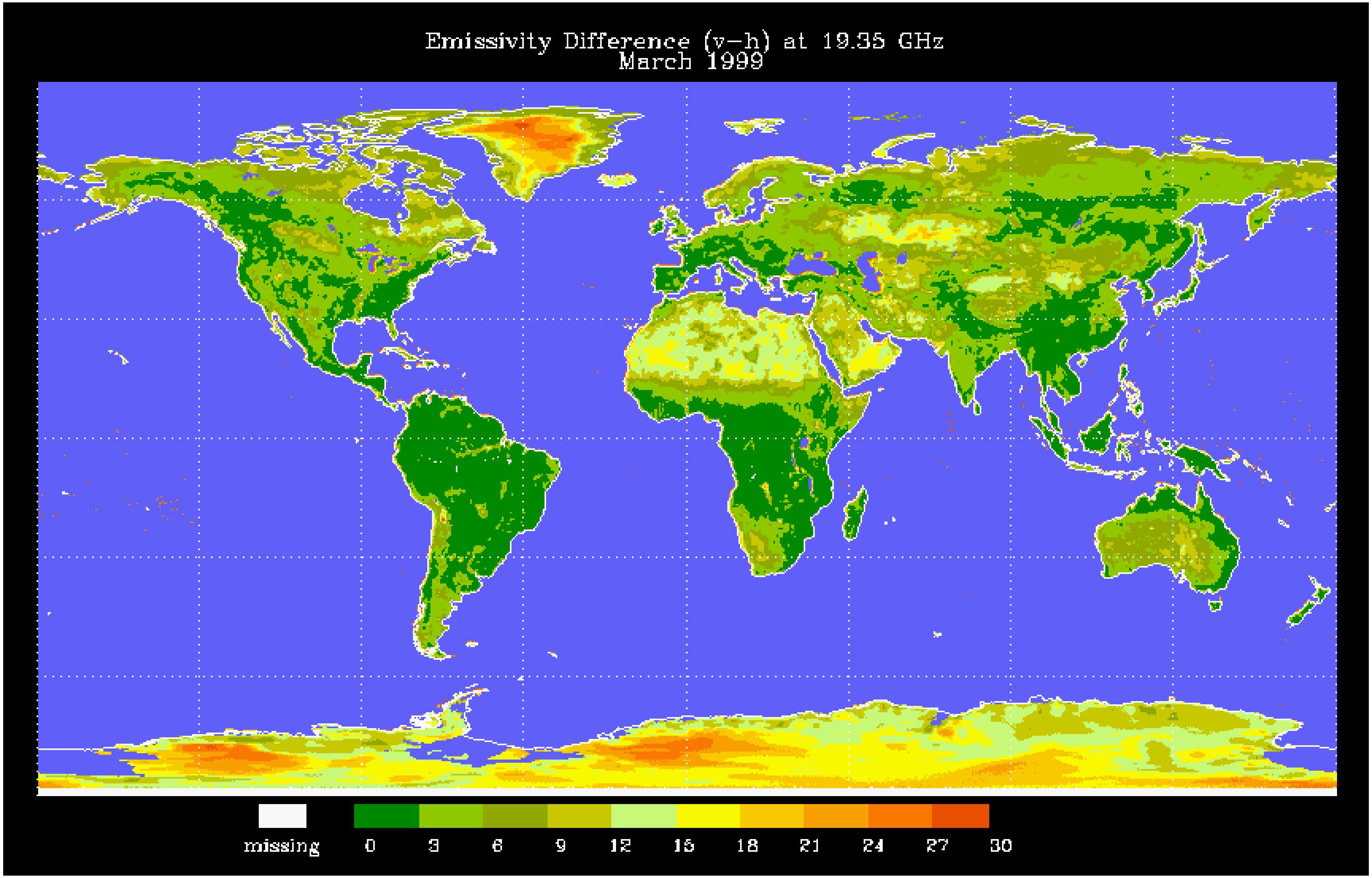
March 1999



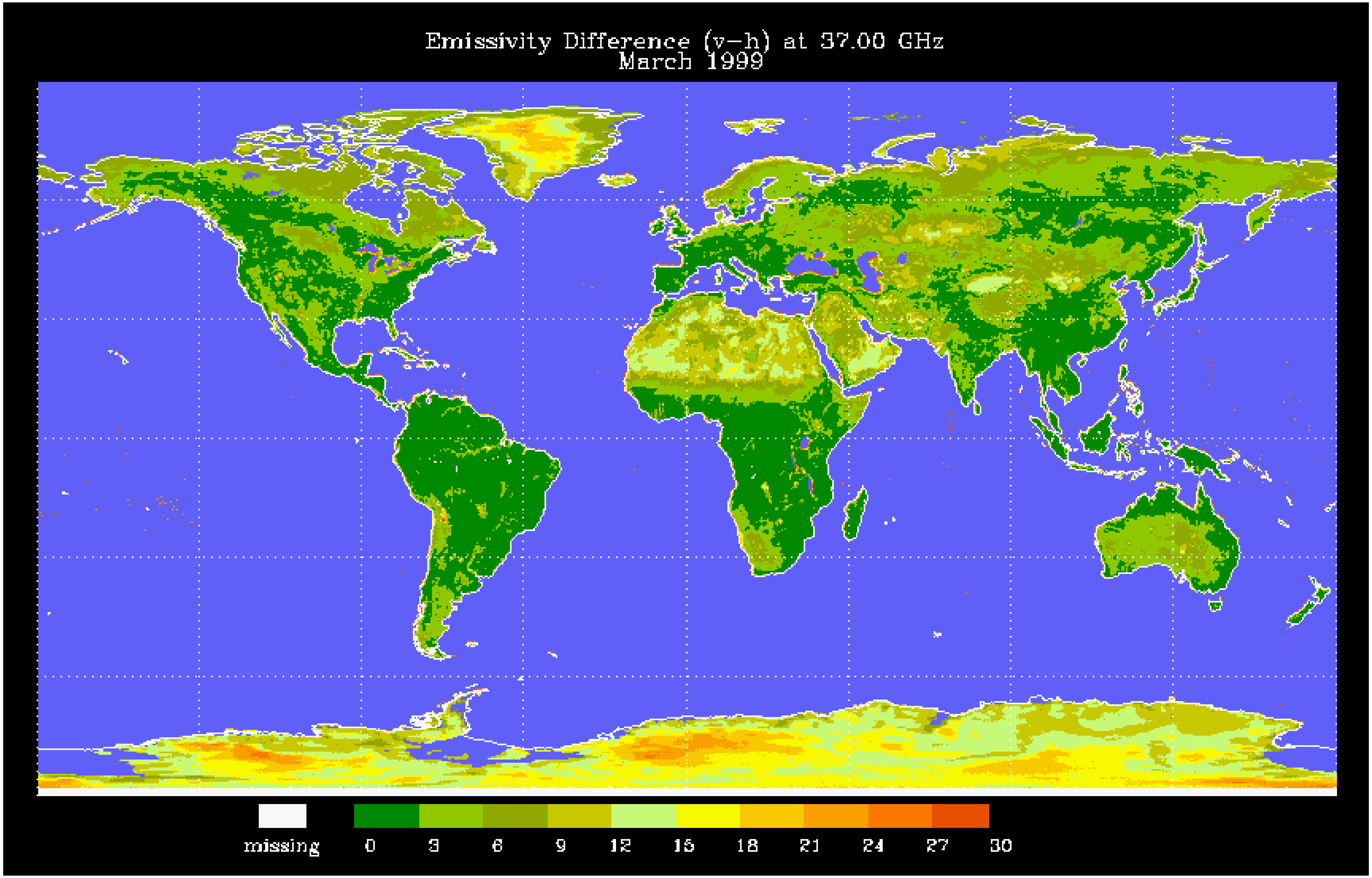
SSM/I Land Surface Emissivity (v-pol) at 85.50 GHz March 1999



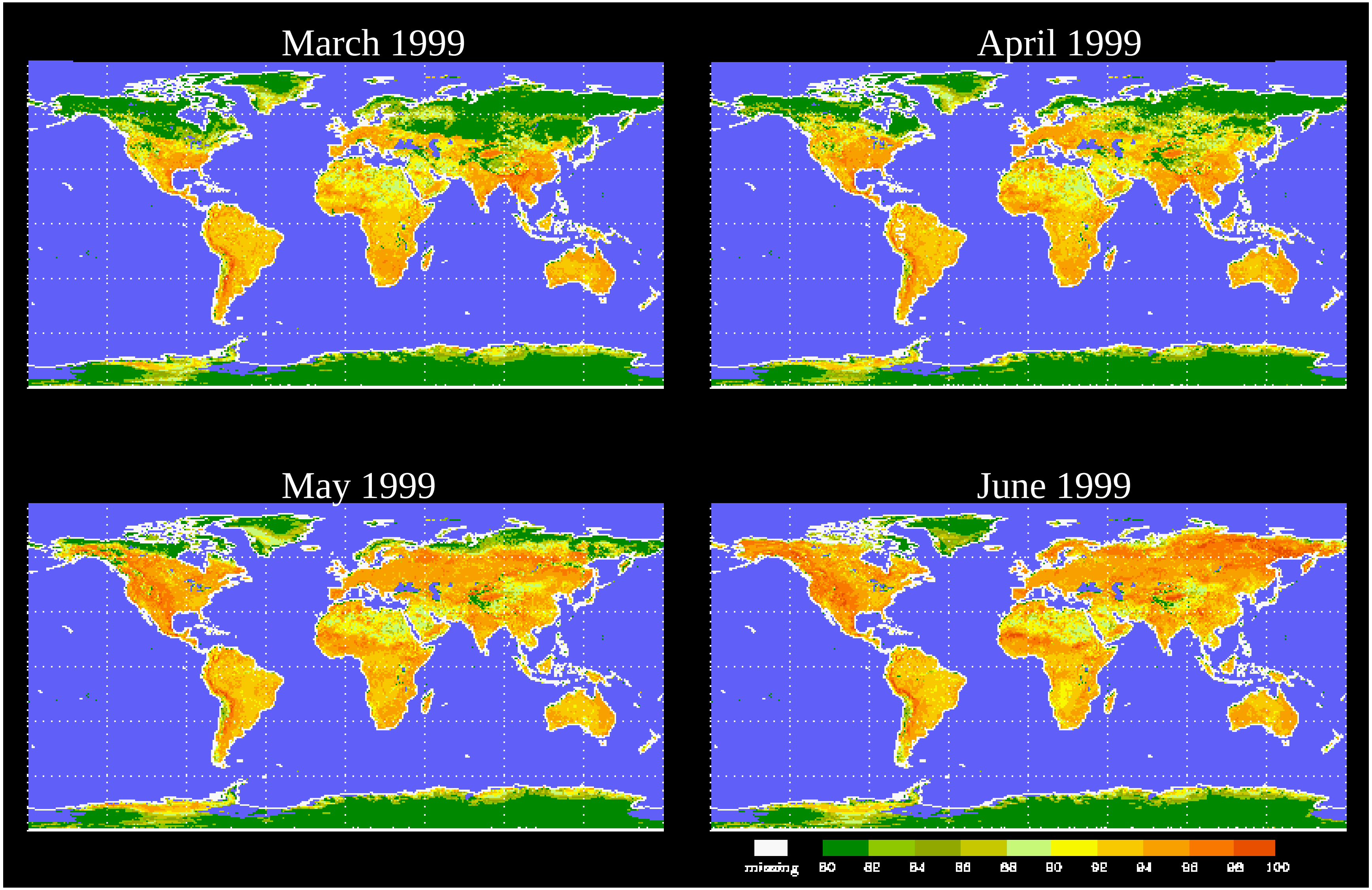
Polarization Difference (19 GHz)



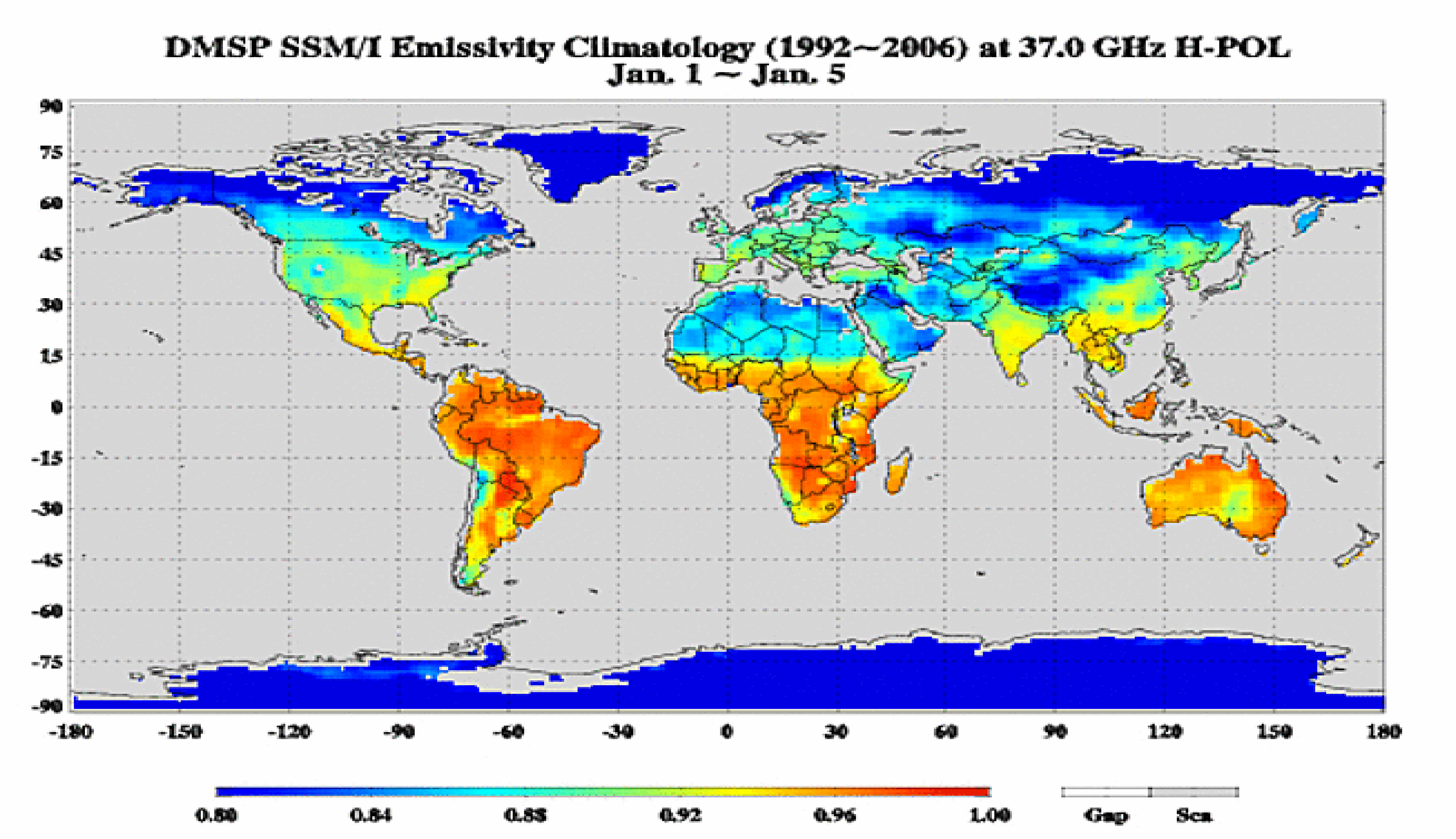
Polarization Difference (37 GHz)



Land Surface Emissivity at 85 GHz Derived from SSM/I



DMSP SSM/I Emissivity Climatology (1992-2006) at 37.0 GHz H-Pol



Global Land Emissivity Characterization
SSM/I Fifteen Year Time Series

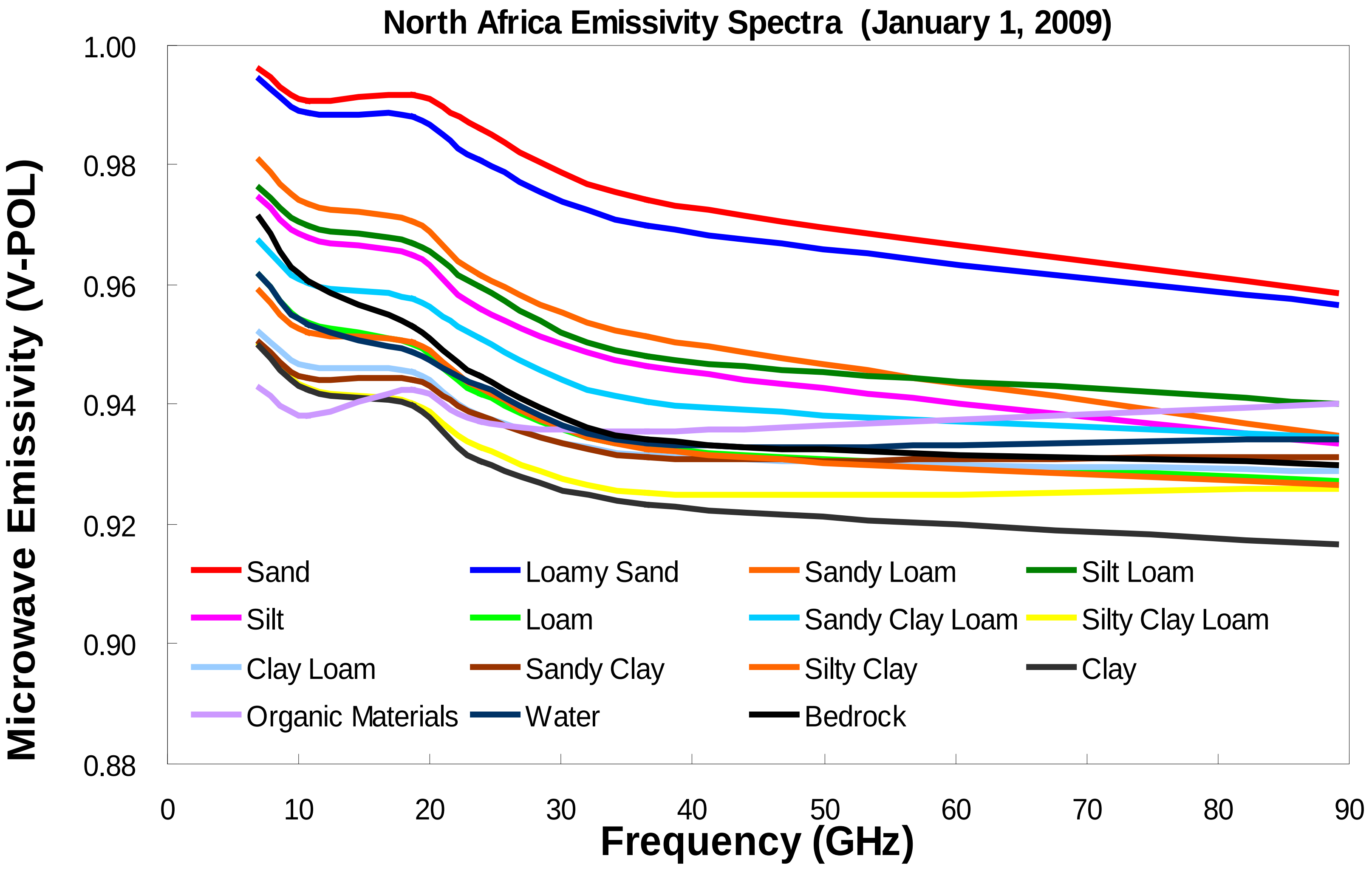
Findings:

- Large seasonal change at higher frequencies
- Large polarization difference for several surfaces such as desert, snow, flooding
- Deserts appear as a scattering medium

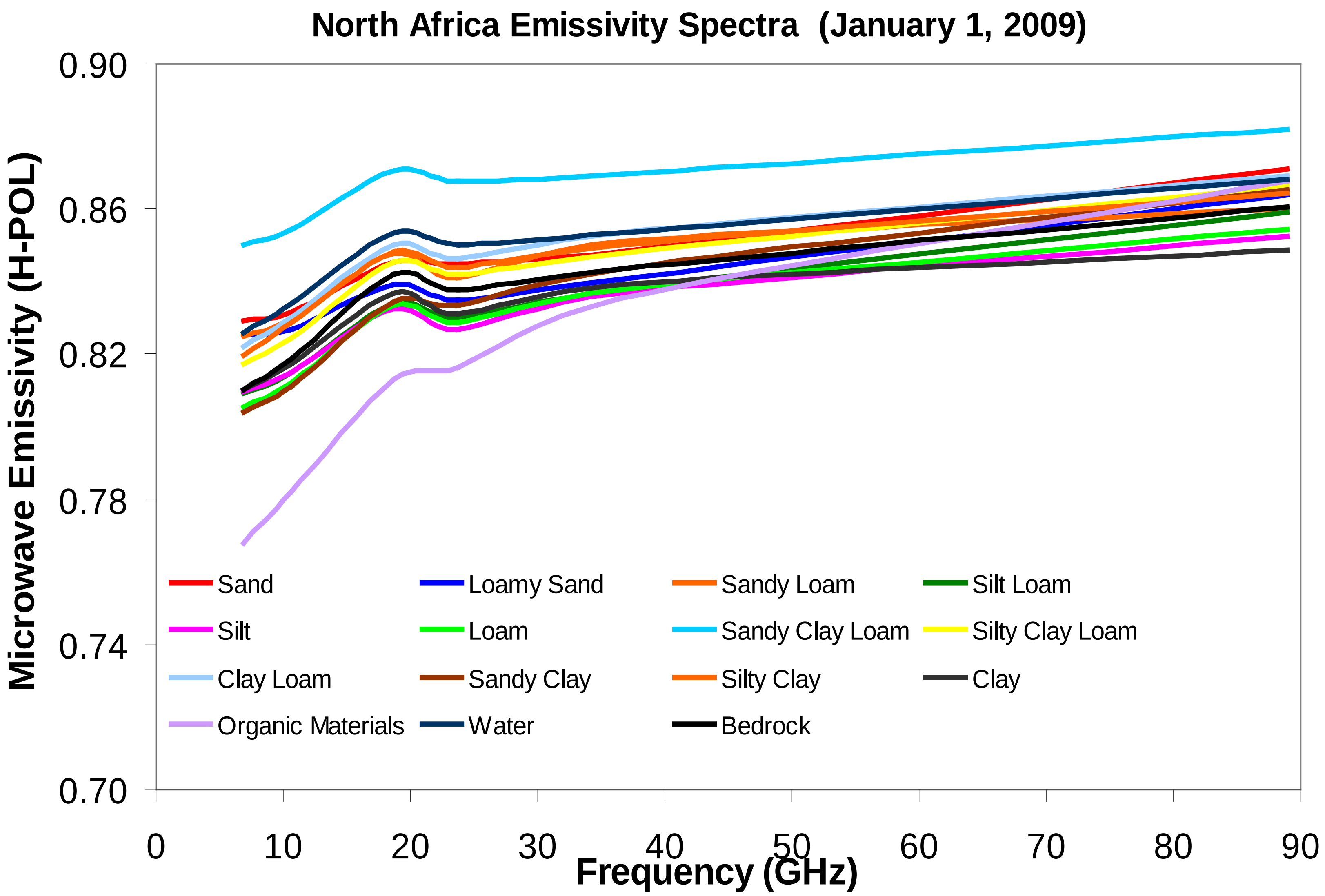
SSM/I surface emissivity climatological data set is developed at various time scales (e.g. pentad, weekly and monthly, anomaly). SSM/I sensors from F10 to 15 satellites are intercalibrated to a reference satellite (F13).

Mean Emissivity Spectra over North Africa

V-POL

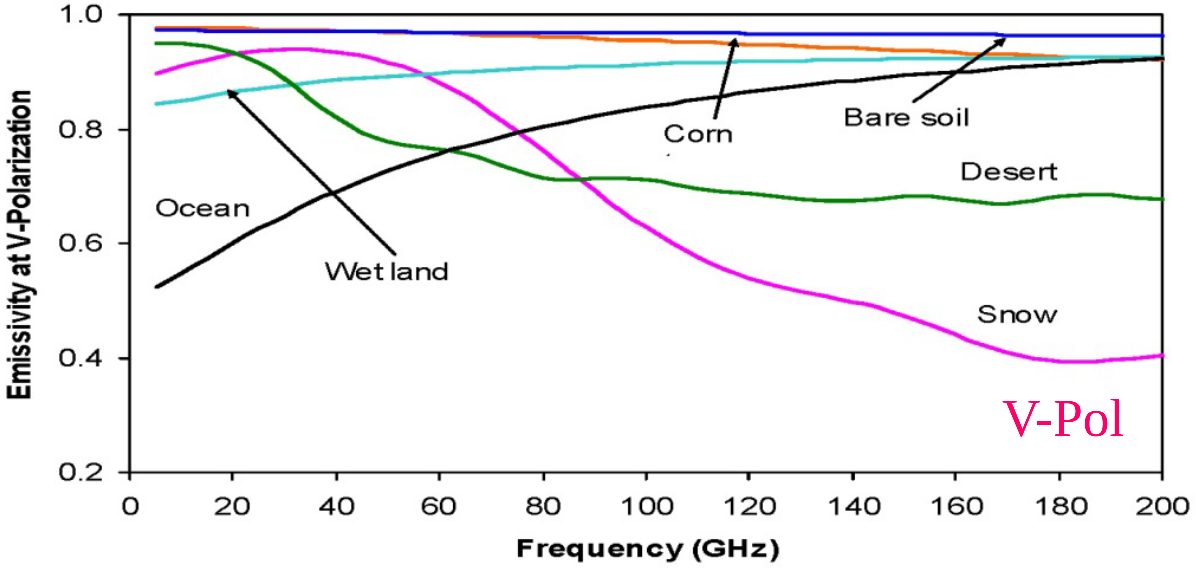


Mean Emissivity Spectra over North Africa
H-POL

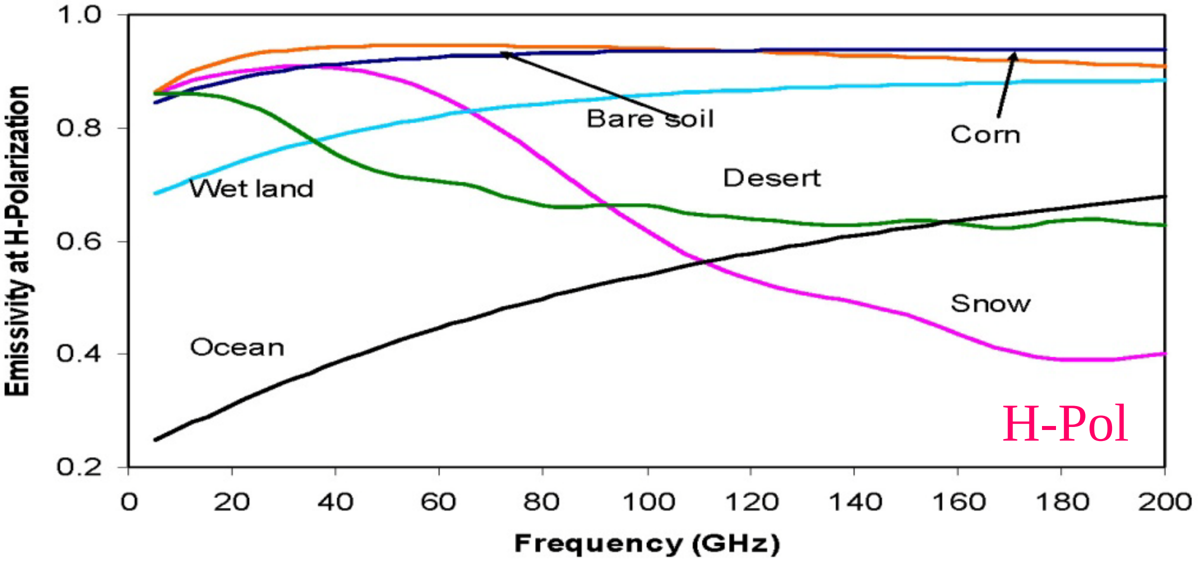


Microwave Emissivity Spectra over Various Surface Conditions

Surface emissivity spectra at a viewing angle of 53 degree



Surface emissivity spectra at a viewing angle of 53 degree



Microwave Emissivity Spectra over Various Surface Conditions (cont.)

By considering

- **Open water** – two-scale roughness theory
- **Canopy** –Geometric optical scattering
- **Bare soil** – Coherent reflection and surface roughness
- **Snow/desert** – Dense medium scattering

We obtained the following conclusions:

Model-simulated microwave emissivity spectra is qualitatively consistent with satellite and ground-based retrievals. Deserts is treated as scattering in order to produce observed characteristics from satellite.

Land Emissivity Summary

✓ Land emissivity is

- highly variable over deserts and large polarization difference
- highly variable for snow conditions
- high values over vegetated land (> 0.9)

✓ The uncertainty on retrieved land emissivity is larger at channels near water vapor and oxygen absorption lines

Significance of Microwave Remote Sensing of Atmosphere

- Validation of clouds predicted from forecast models
- Useful for climate and radiation feedback studies
- Complementary to the technology from visible wavelength
- Temperature and water vapor profiles under all weather conditions

Principle of MW Remote Sensing of Clouds

Emission-Based Radiative Transfer Equation:

$$T_b = \varepsilon T_s \exp(-\tau_s / \mu) + T_u + (1-\varepsilon) T_d \exp(-\tau_s / \mu)$$

$$\Updownarrow$$

$$T_b = T_s[1-(1-\varepsilon)\Upsilon^2] - \Delta T(1-\Upsilon)[1+(1-\varepsilon)\Upsilon]$$

If atmosphere is isothermal, $\Delta T = 0$

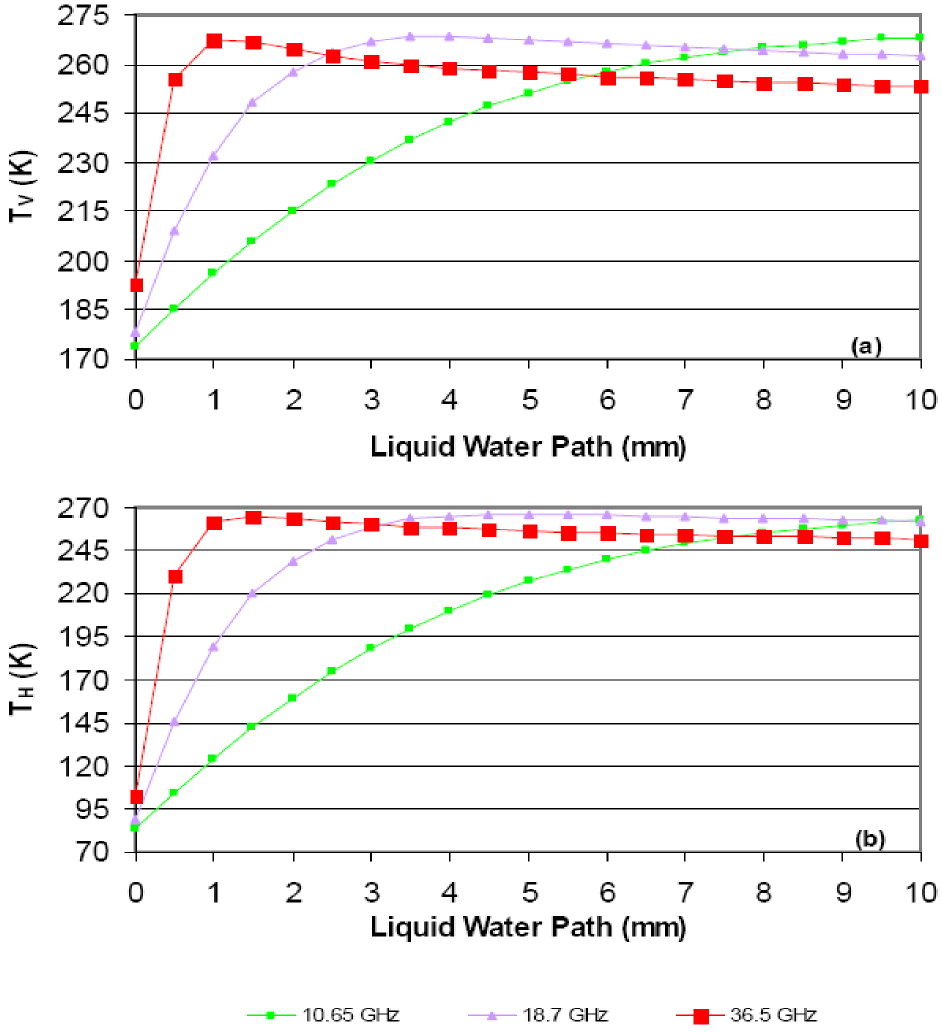
$$T_b = T_s[1-(1-\varepsilon)\Upsilon^2]$$

T_b is a quadratic function of atmospheric transmittance which is determined by cloud liquid and water vapor absorption.

This is a basic principle for microwave remote sensing of cloud properties!

Microwave Remote Sensing of Liquid Phase Clouds

- A large contrast exists between cloudy and “clear” conditions, thanks to low ocean emissivity.
- Brightness temperature increases exponentially with liquid water, thus requiring a logarithmic function for linearization
- “The linear regime” is dependent on frequency. We can meet the need of more customer (e.g. rain water...) if the measurements at each frequency are optimally utilized in the retrievals



Emission-Based RTM

$$T_b = T_s[1-(1-\varepsilon)\Upsilon^2]$$

$$\Upsilon = \exp[-(\tau_O + \tau_V + \tau_L)/\mu)]$$

$$\tau_V = \kappa_V V = \int_0^\infty \kappa^{H_2O} \rho_V dz$$

$$\tau_L = \kappa_L L = \int_{\Delta Z} \kappa^{Ray} LWCdz$$

$$\kappa^{Ray} = \frac{6\pi}{\lambda \rho_w} Im\left\{\frac{m^2-1}{m^2+2}\right\}$$

Emission-Based RTM (cont.)

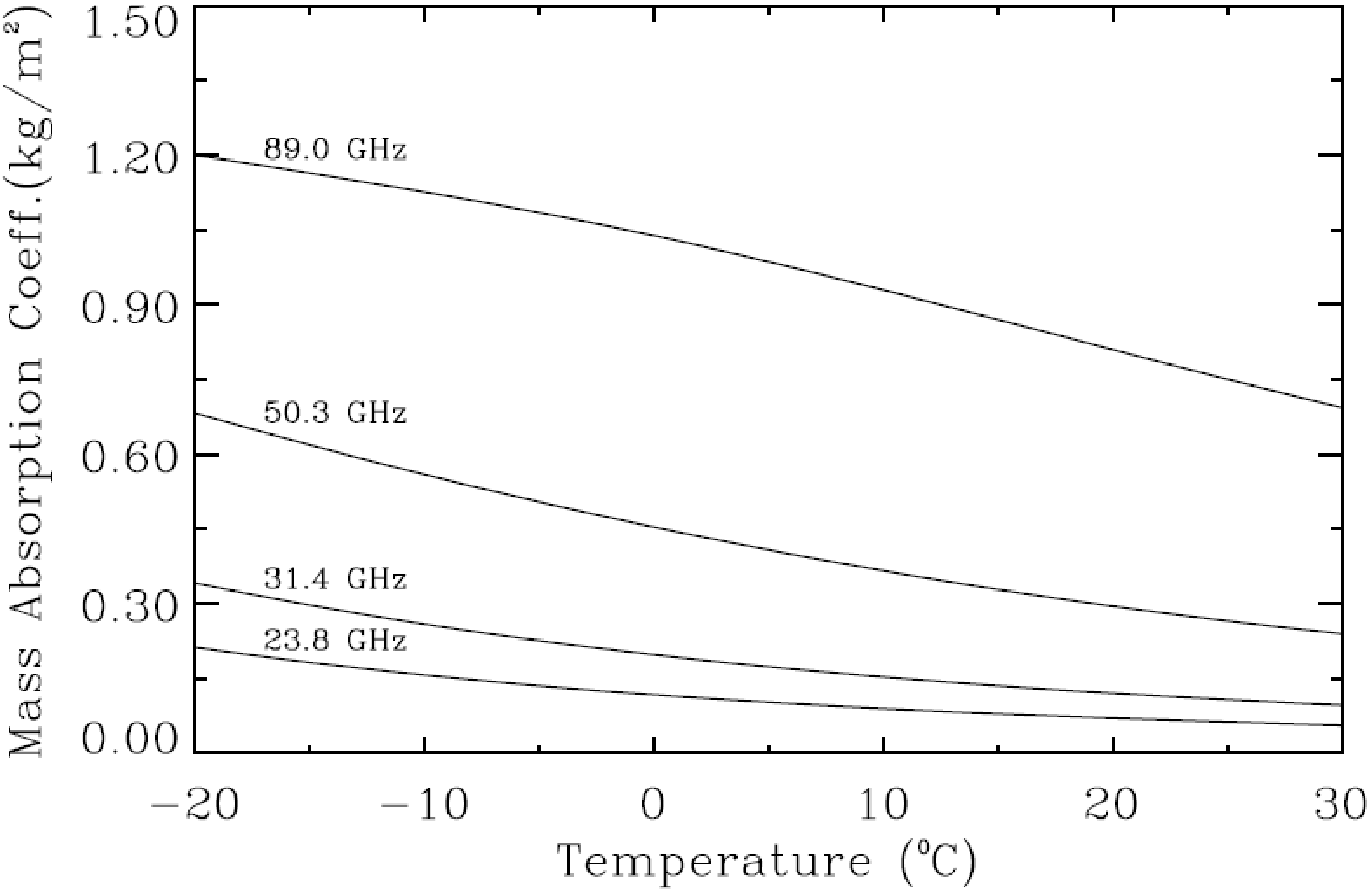
$$\Upsilon = \exp[-(\tau_O + \kappa_V V + \kappa_L L)/\mu)$$

$$\kappa_V V + \kappa_L L = -\frac{\mu}{2}\left\{\ln(T_s - T_b) - \ln[T_s(1-\varepsilon)] + \frac{2\tau_{O_2}}{\mu}\right\}$$

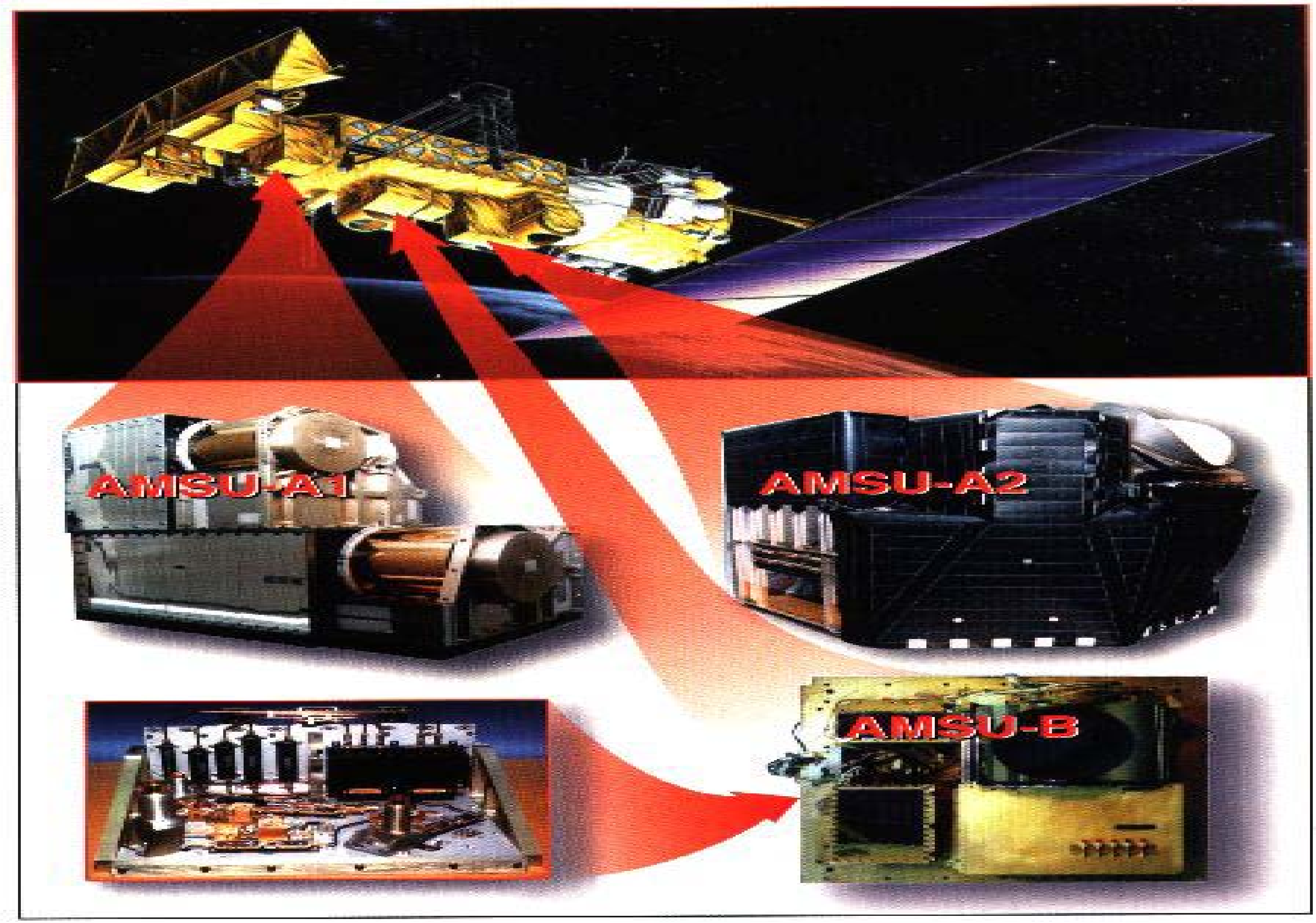
$$L = a_0\mu[\ln(T_s - T_{b,1}) - a_1\ln(T_s - T_{b,2}) - a_2]$$

$$V = b_0\mu[\ln(T_s - T_{b,1}) - b_1\ln(T_s - T_{b,2}) - b_2]$$

Cloud Absorption in Relation to Temperature



AMSU on Board NOAA POES Since 1998



AMSU on Board NOAA POES Since 1998 (cont.)

There are 20 channels divided into three sub-modules:

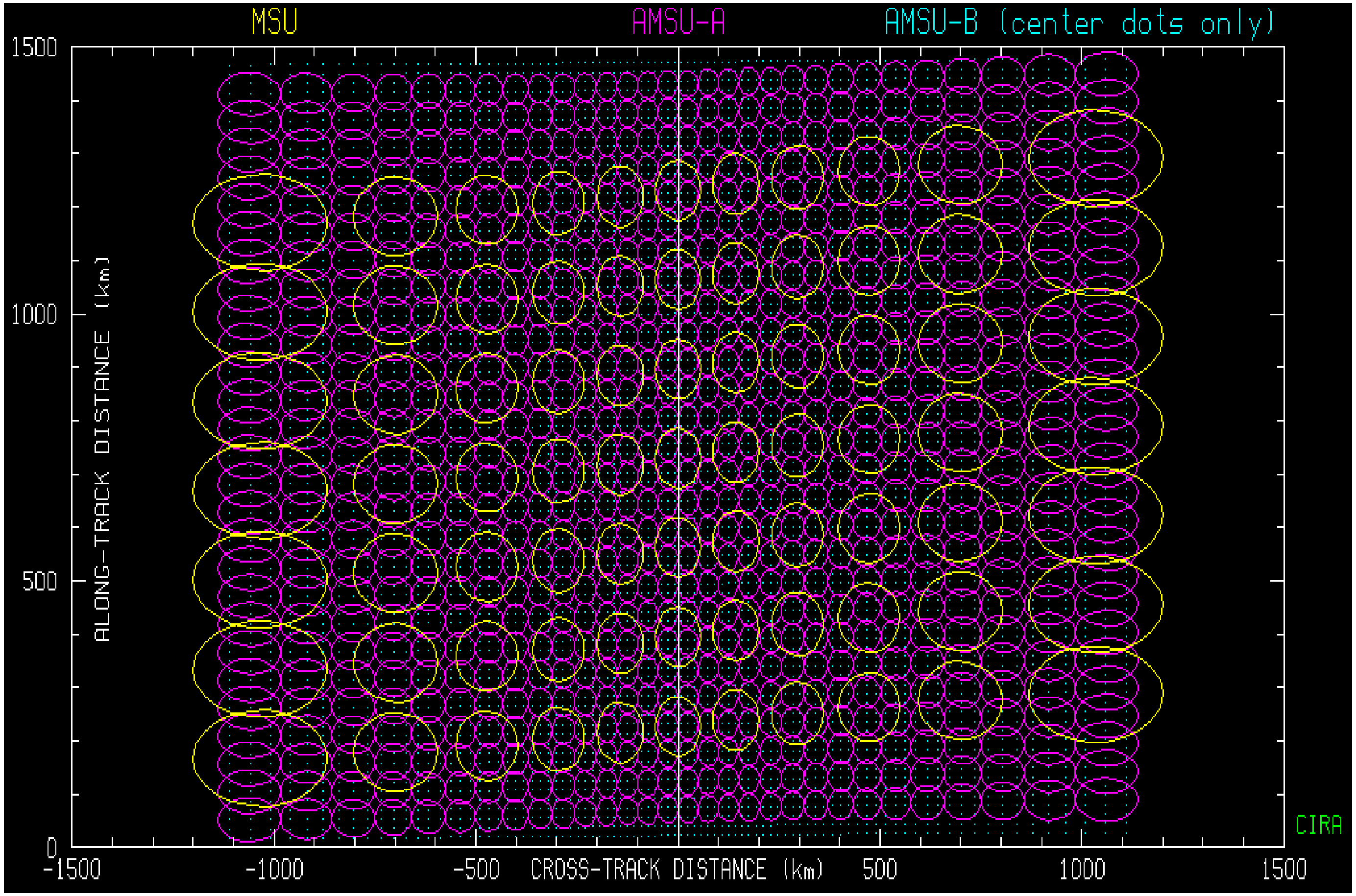
AMSU-A1 – 13 channels located near the 60 GHZ oxygen absorption band

AMSU-A2 – two window channels at 23.8 and 31.4 GHz

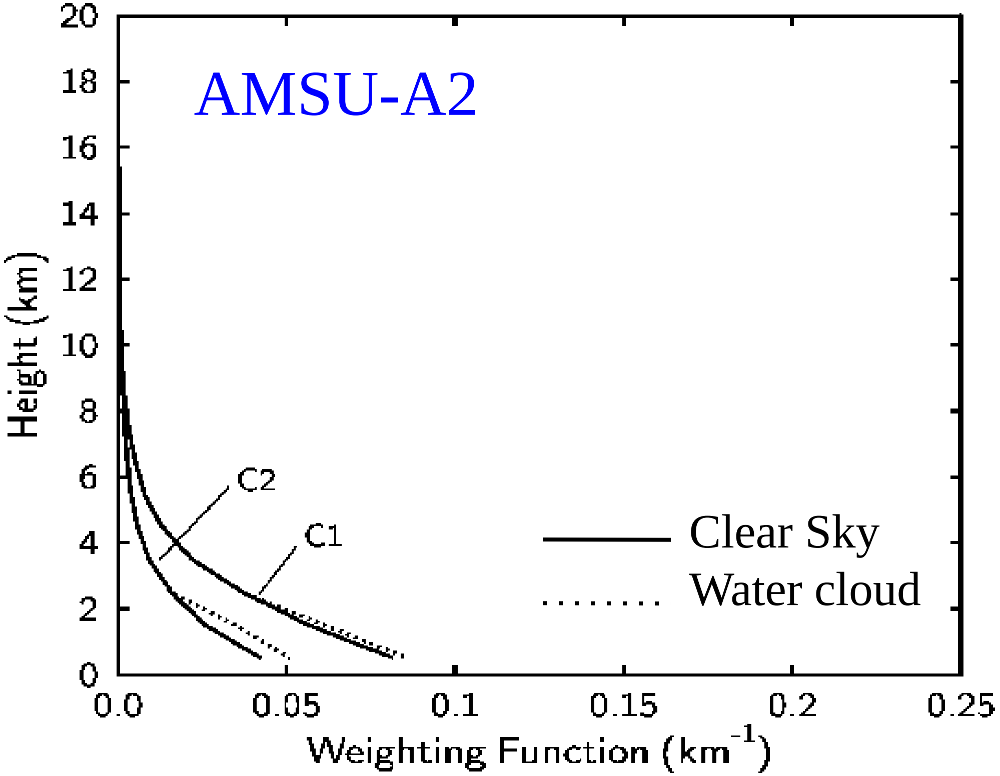
AMSU-B – two high frequency channels at 89 and 150 GHz, and three channels near 183 GHz water vapor absorption line

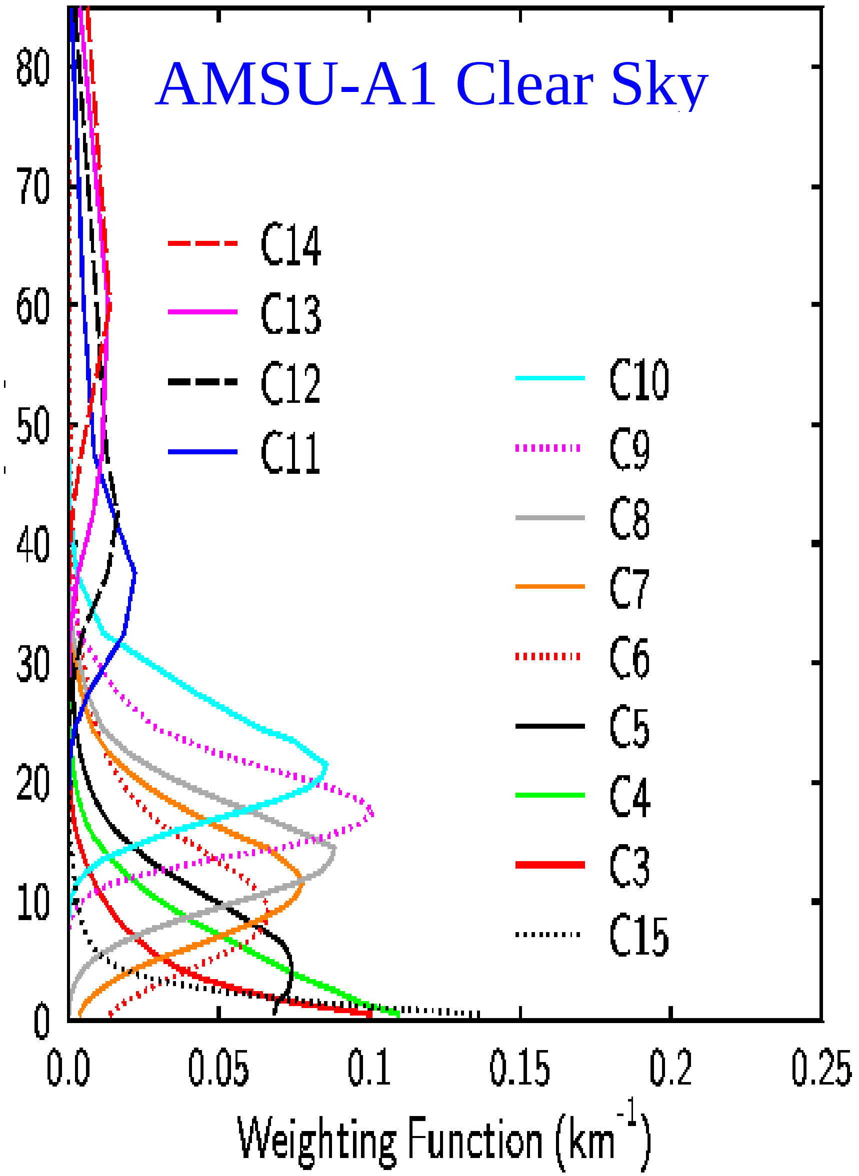
AMSU on Board NOAA POES Since 1998 (cont.)

The field-of-view size varies as the instruments scan crossing track.

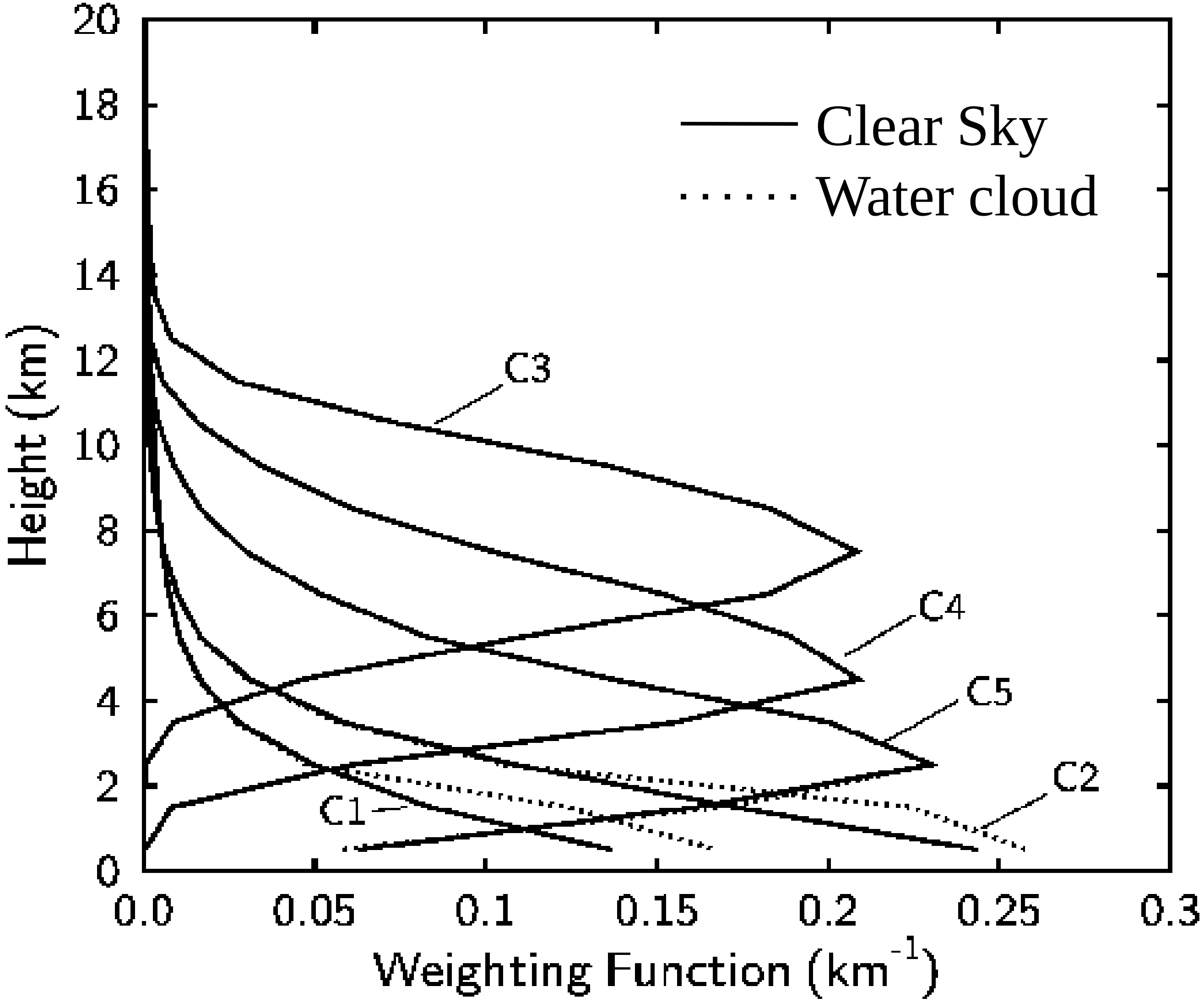


AMSU-A Weighting Functions



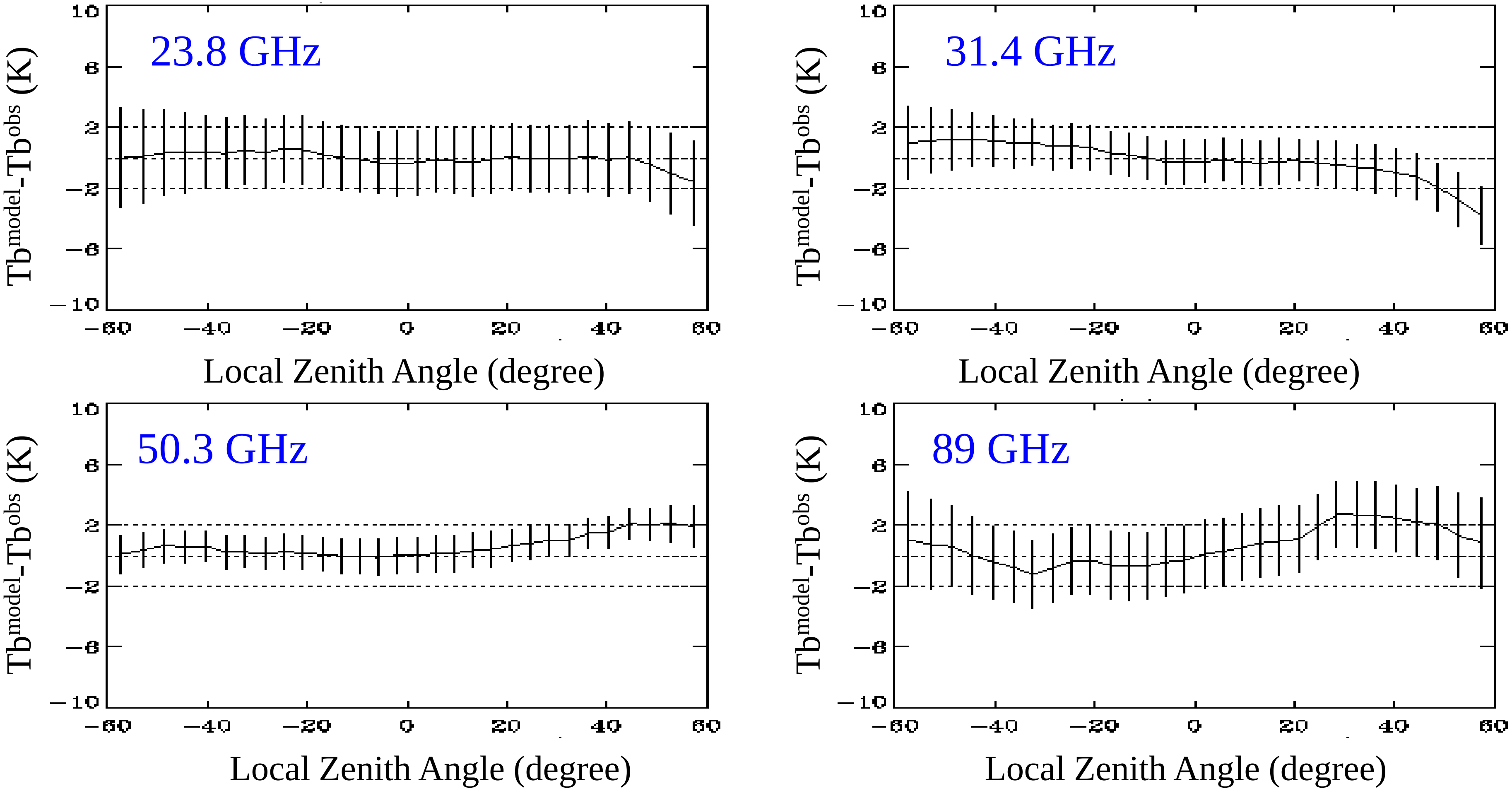


AMSU-B Weighting Functions



NOAA-16 AMSU-A Radiance Asymmetry

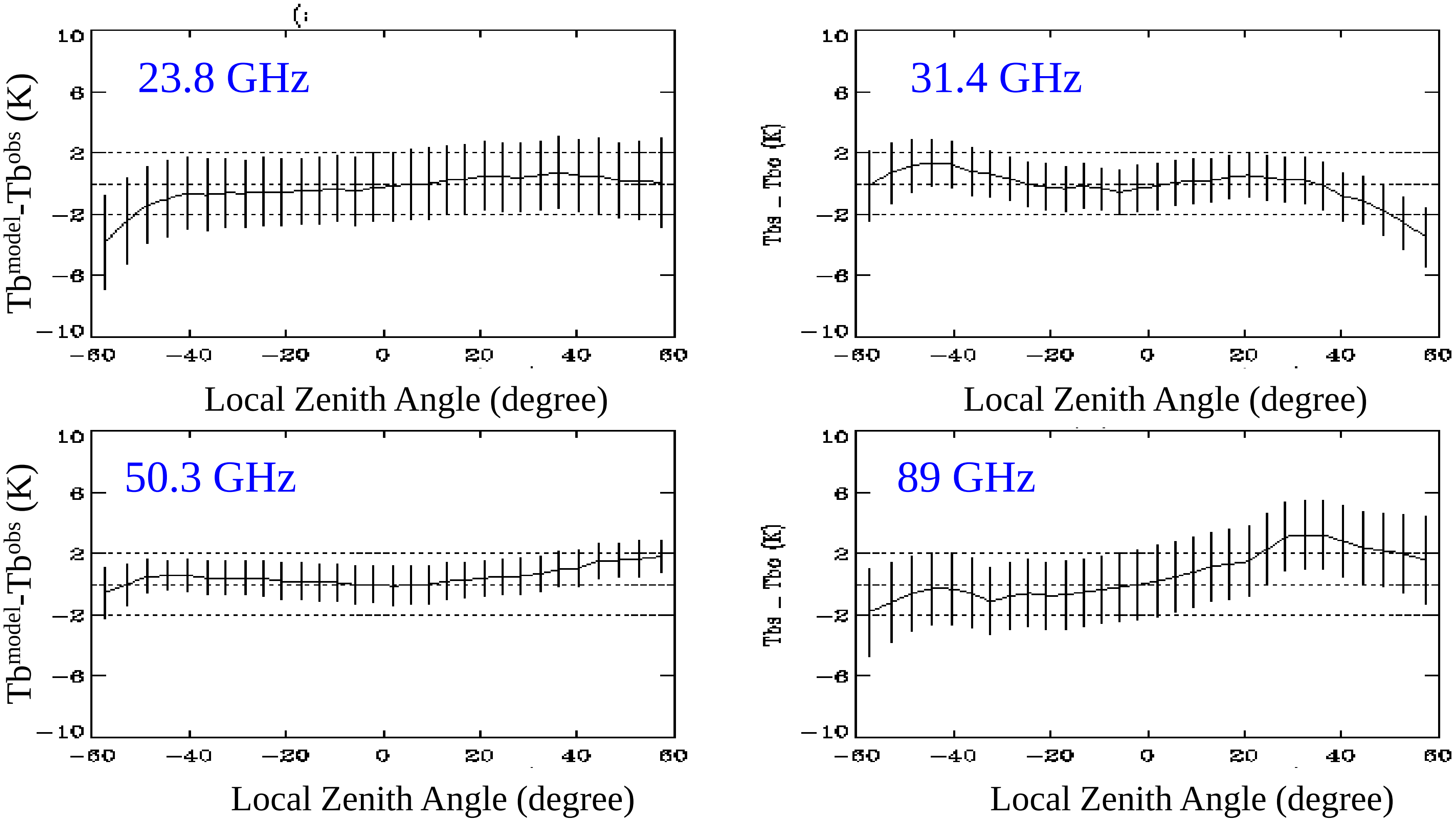
(Channels 1, 2, 3, 15)



$$\Delta T = A_0 \exp\{ -0.5[(\theta - A_1) / A_2]^2 \} + A_3 + A_4 \theta + A_5 \theta^2$$

NOAA-16 AMSU-A Radiance Asymmetry

(Channel 1,2,3,15)



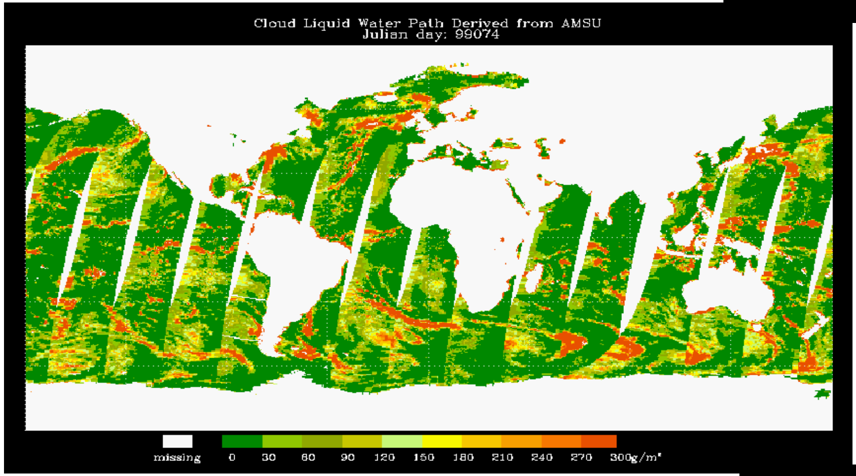
$$\Delta T = A_0 \exp\{ -0.5[(\theta - A_1)/A_2]^2 \} + A_3 + A_4\,\theta + A_5\,\theta^2$$

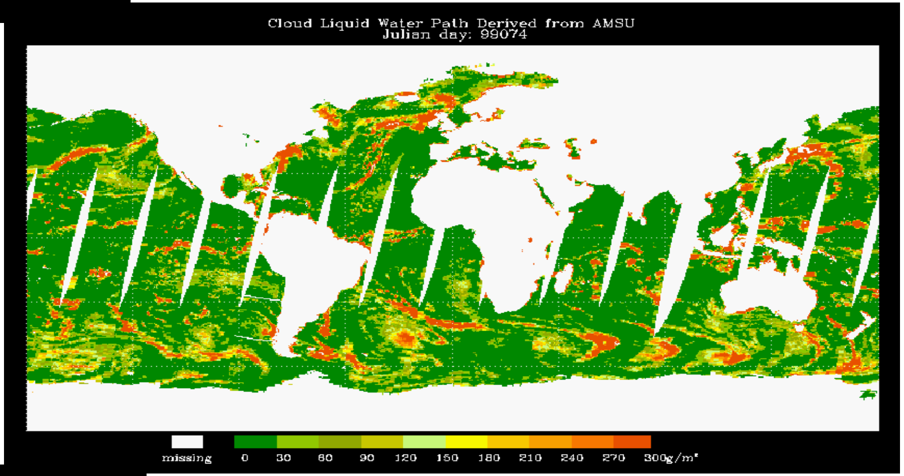
AMSU Cloud Liquid Water

Before Asymmetry Correction

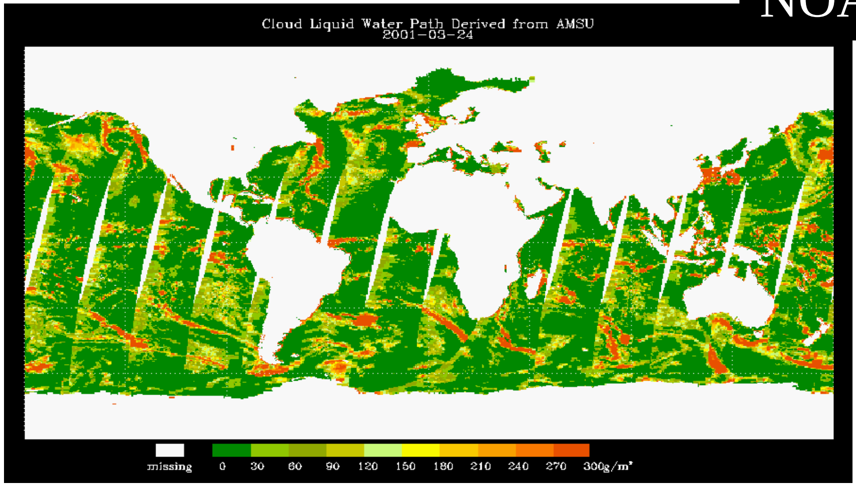
After Asymmetry Correction

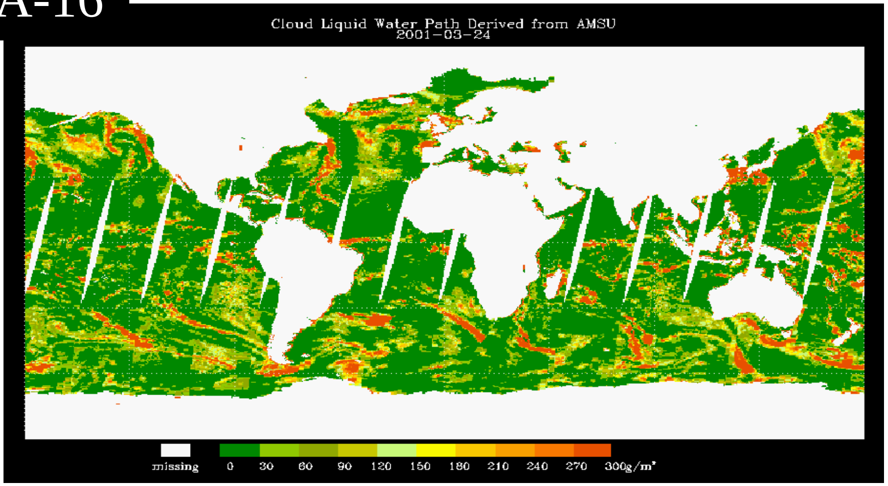
NOAA-15



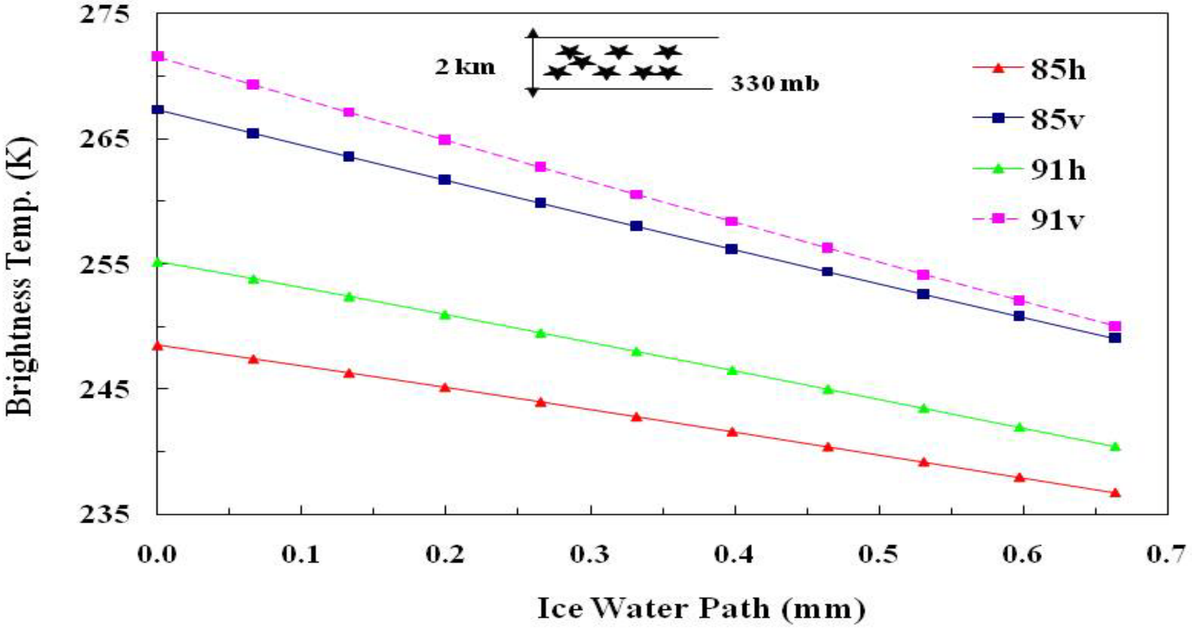


NOAA-16



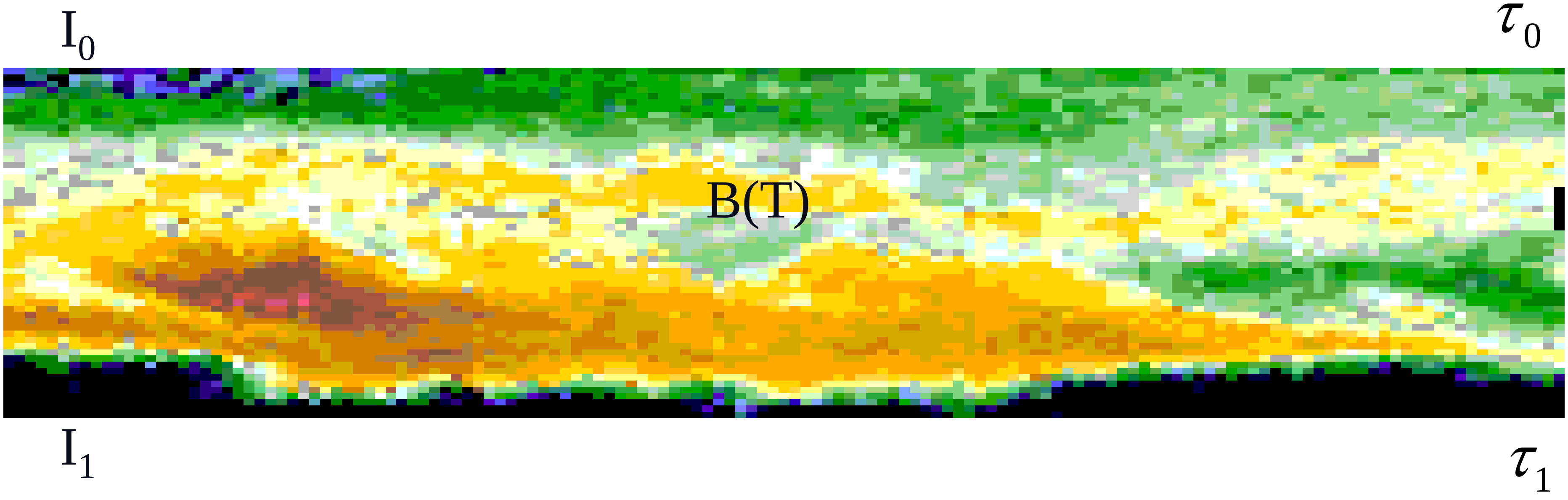


Microwave Remote Sensing of Ice Phase Clouds



Cloud Ice Water Path Algorithm

$$I(\tau,\mu)=\frac{(I_0-B)[\gamma_1 e^{-\kappa(\tau-\tau_1)}-\gamma_2 e^{\kappa(\tau-\tau_1)}]-(I_1-B)[\beta^{-1}e^{\kappa(\tau-\tau_0)}-\beta e^{-\kappa(\tau-\tau_0)}]}{\gamma_4 e^{-\kappa(\tau_1-\tau_0)}-\gamma_3 e^{\kappa(\tau_1-\tau_0)}}+B$$



Cloud Ice Water Path Algorithm

Asymptotic Limits:

1. Emission Approach

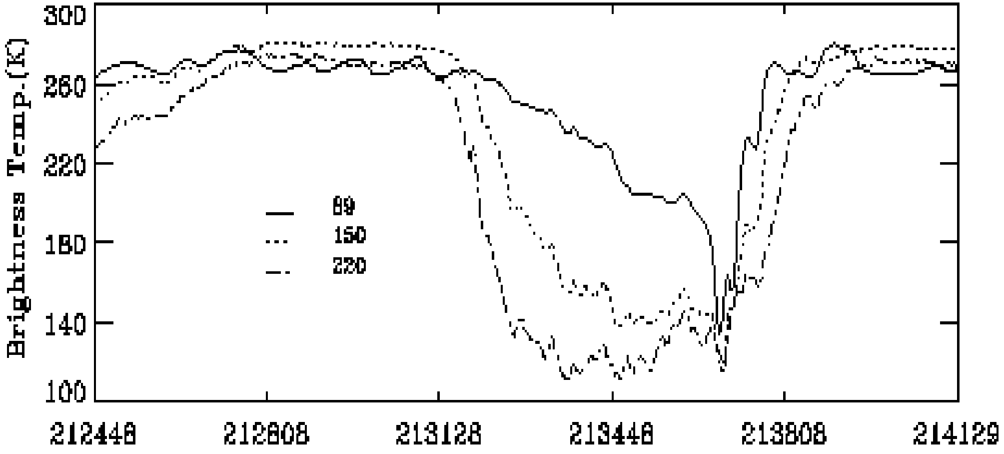
$$I(\tau_1,\mu) = B[1-(1-\varepsilon)e^{-2\tau_1/\mu}] - [B(T_s) - B(T)](1-e^{-\tau_1/\mu})[1+(1-\varepsilon)e^{-\tau_1/\mu}]$$

2. Scattering Approach:

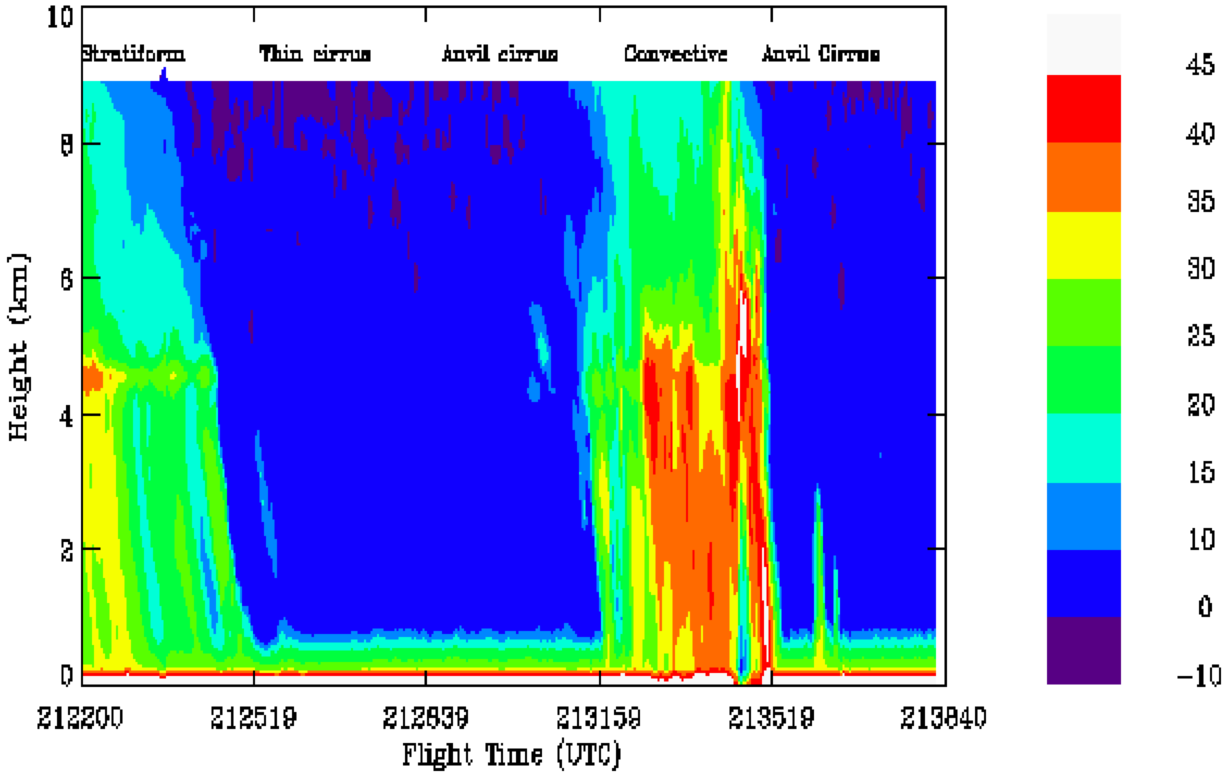
$$I(\tau_0,\mu) = \frac{I(\tau_1,\mu)}{1+\Omega(\mu)} \qquad \Omega(\mu) = \frac{IWP}{\mu\rho_i D_e}\Omega_N(x_e,m)$$

References: Weng and Grody (2000, JAS), Zhao and Weng (2002, JAM)

ER-2 MIR, DC-8 ARMAR, MODIS Simulator Measurements



(a) Millimeter-wave Imaging Radiometer (MIR)

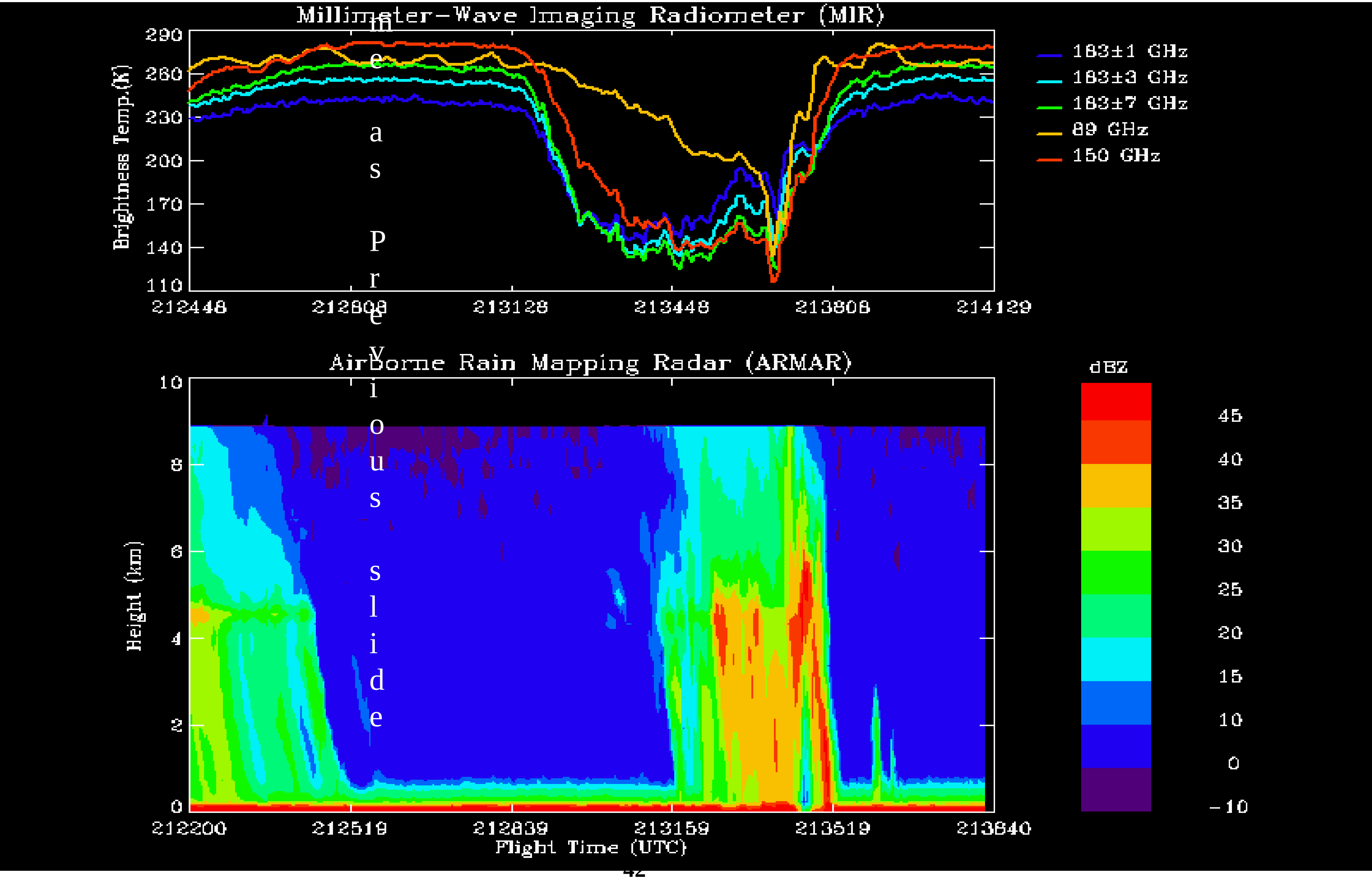


(b) Airborne Rain MApping Radar (ARMAR)

Three millimeter wavelength channels provide the overall needed sensitivity for cloud ice microphysics which can be uniquely used for precipitation mapping.

Weng and Grody (2000, JAS)

Same figures as those on the previous slide, but colored.



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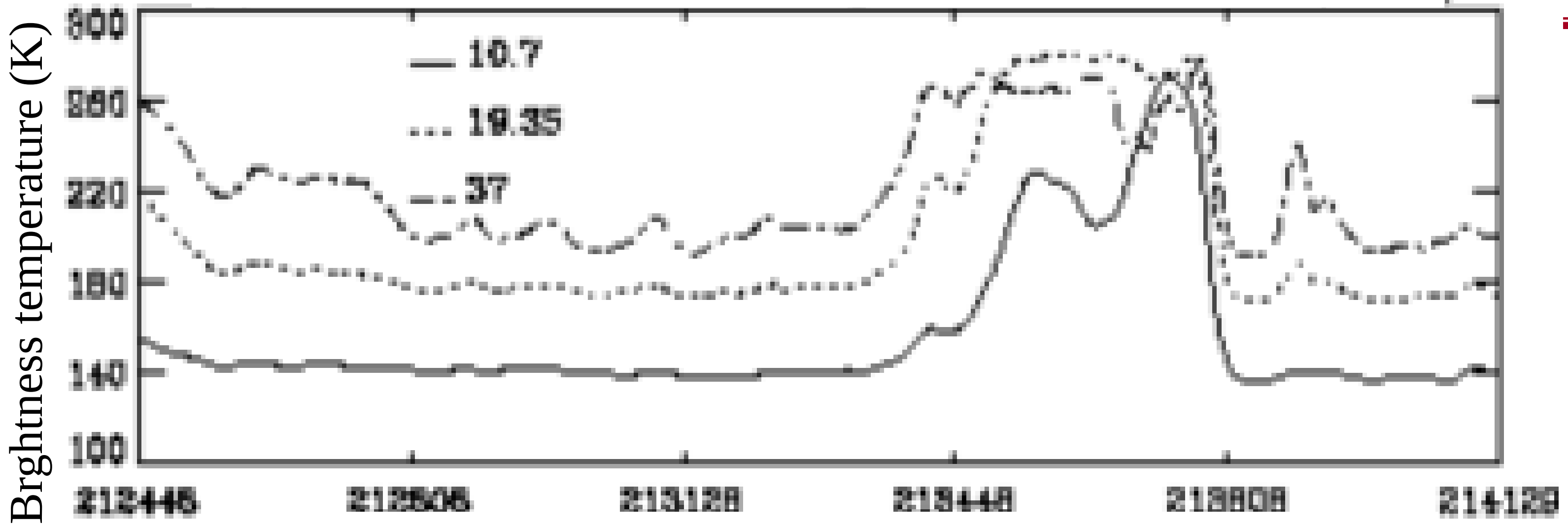
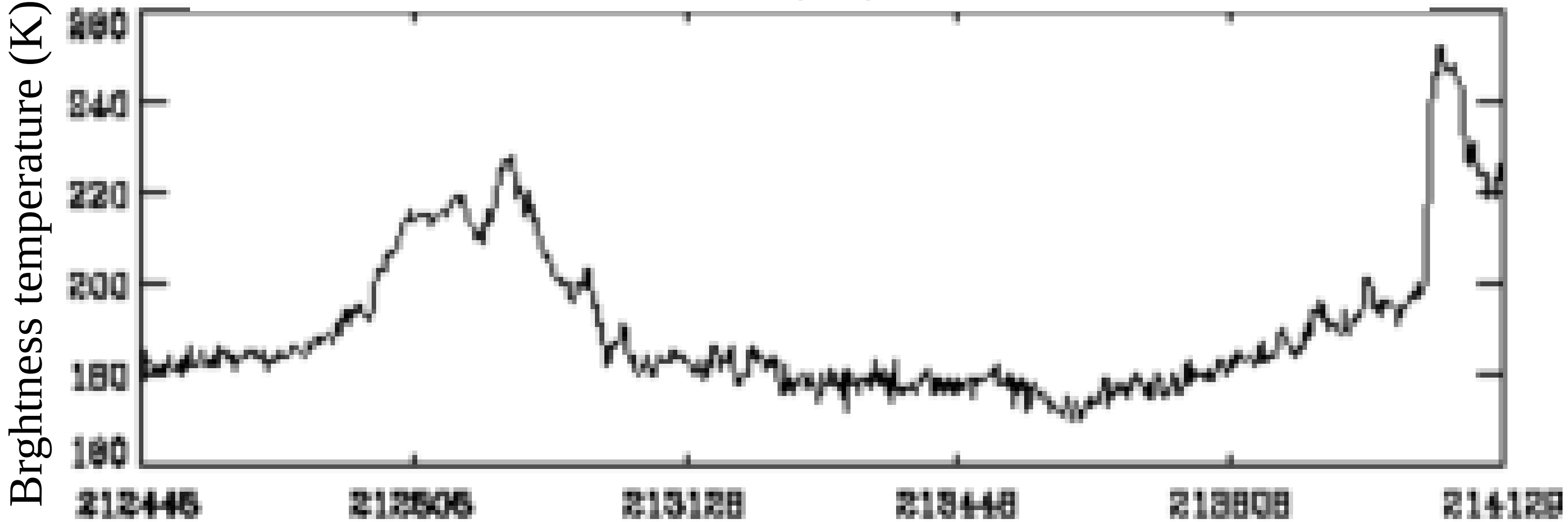
ER-2 MIR, DC-8 ARMAR, MODIS Simulator Measurements (cont.)

Advanced Microwave Precipitation Radiometer (AMPR)



Moderate-resolution Imaging Spectrometer (MODIS)



Definitions of Cloud Ice Water Path

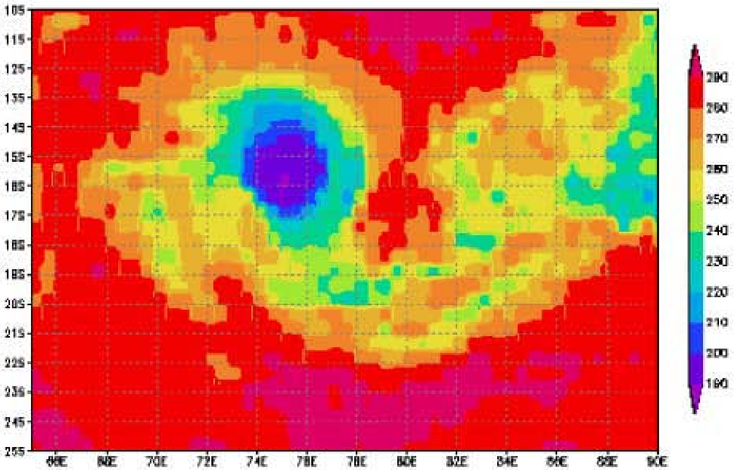
$$\tau = \int_{z_b}^{z_t} dz \int_0^{\infty} \frac{\pi}{4} D^2 \Omega_e(x,m) N(D) dD$$

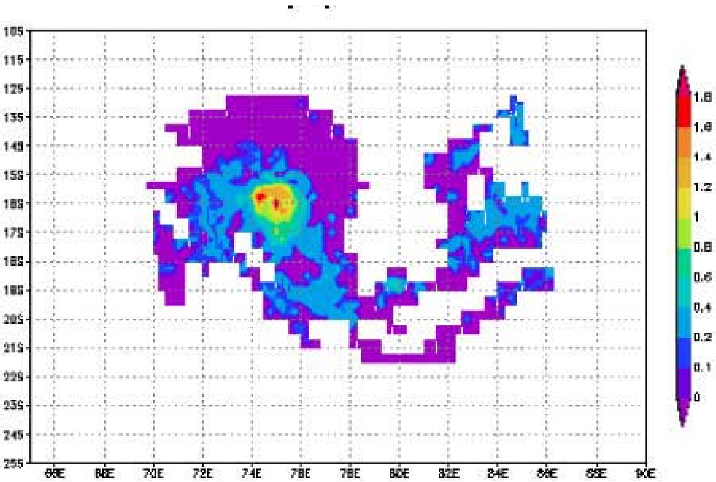
$$IWP = \int_{z_b}^{z_t} dz \int_0^{\infty} \frac{\pi}{6} D^3 N(D) dD$$

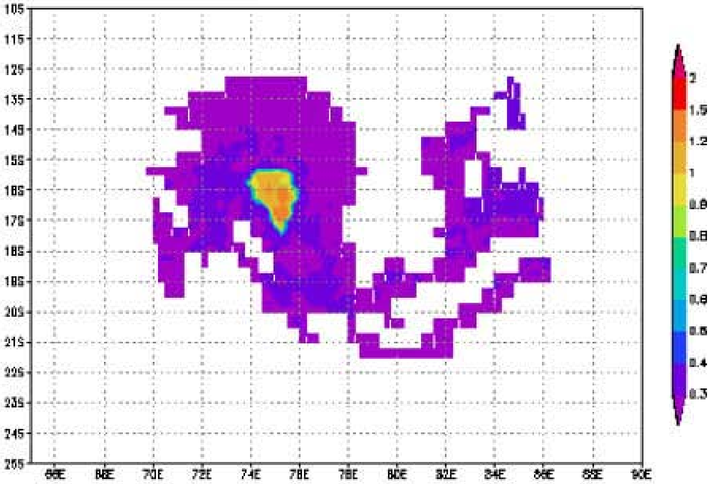
$$\Omega(\mu) = \frac{IWP}{\mu \rho_i D_e} \Omega_N(x,m)$$

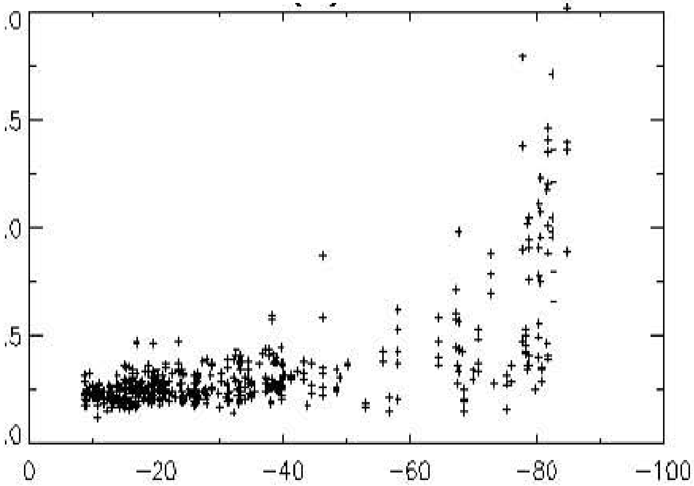
$$\Omega_N = \exp(b_0 + b_1 \ln(D_e) + b_2 (\ln D_e)^2$$

Cloud Ice Water Path

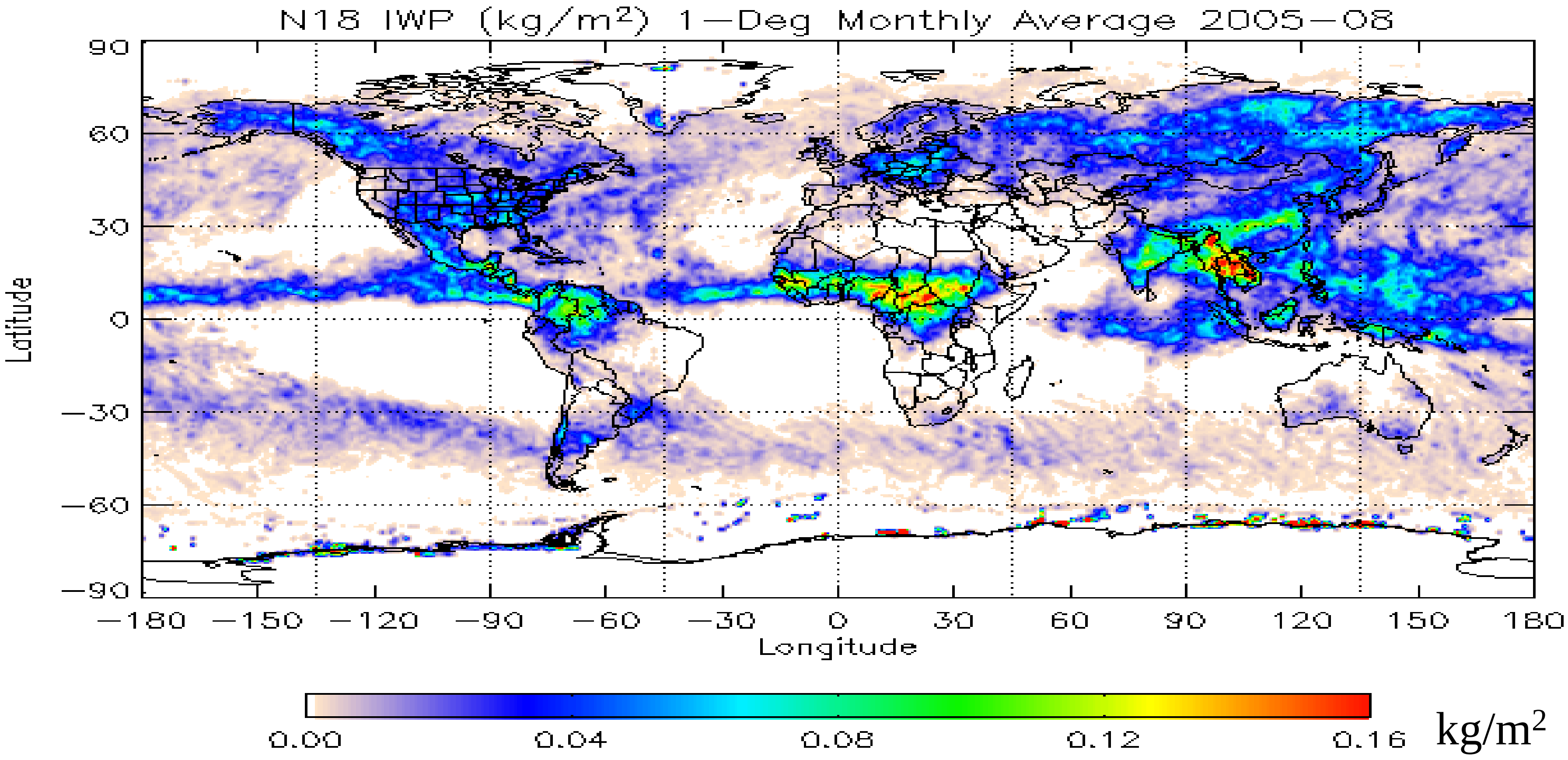








N18 IWP Monthly Average 2005-2008



kg/m^2

N18 IWP Monthly Average 2005-2008

- Brightness temperatures from AMSU-B 89 and 150 GHz are two primary channels for IWP and De
- Retrieval algorithm was published in Journal of Atmos Sci (Weng and Gody, 2000) and J. Appli. Meteor (Zhao and Weng, 2002)
- AMSU-A window channels are used for surface screening
- The algorithm works for opaque ice clouds having IWP greater than 0.05 kg/m^2

Atmospheric Sounding from MW

$$T_b = \int_{\Upsilon_s}^{1} B(T)\,d\Upsilon$$

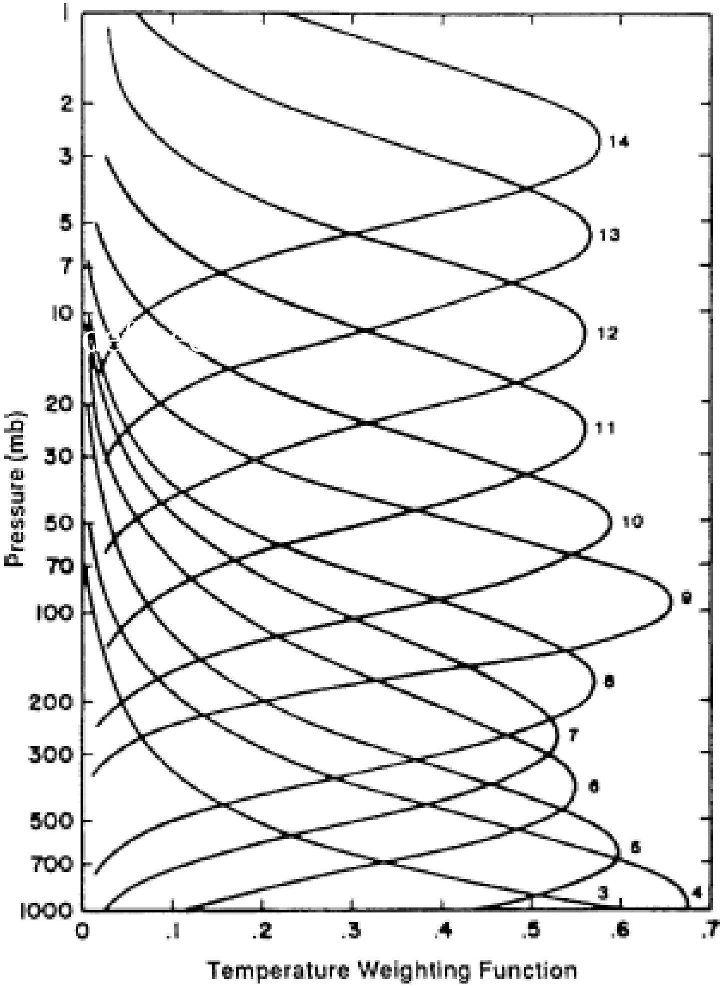
$$d\Upsilon = \exp\left(-\frac{(\tau_s - \tau)}{\mu}\right)d\tau/\mu$$

Weighting function:

$$W = \frac{\partial \Upsilon}{\partial \ln p}$$

$$T_{b,i} = \int_{P_s}^{0} B(T)W_i\,d\ln p$$

$$T_{b,i} = \sum_{j=1}^{L} c_i T_j W_{i,j},$$



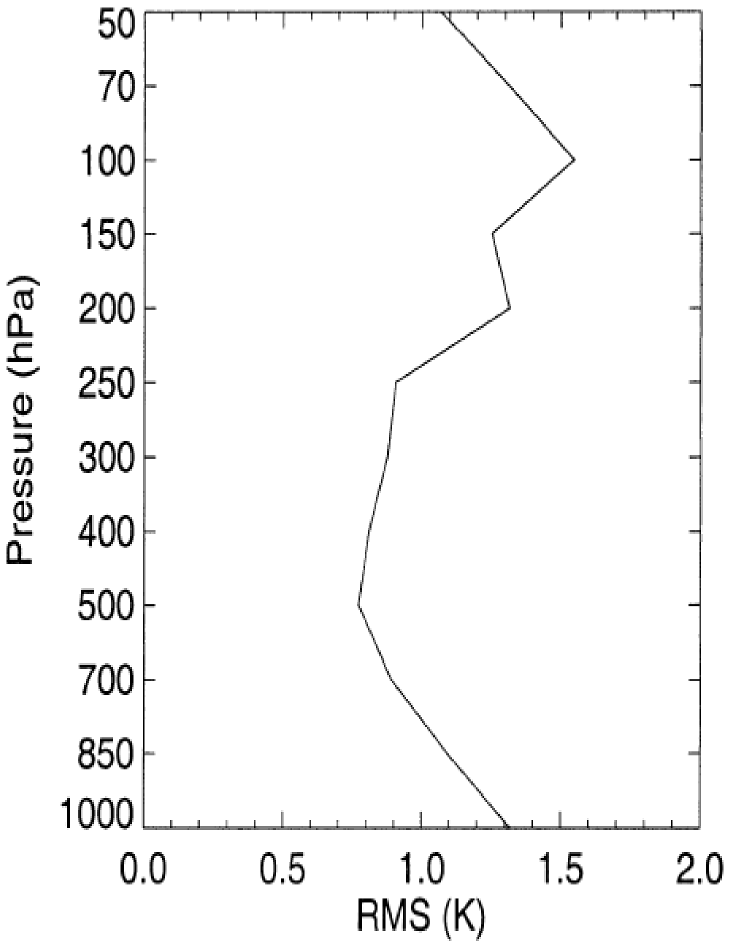
Temperature Retrieval from Linear Regression Algorithm

$$T(p) = C_0(p,\mu) + \sum_{j=1}^{L} C_j(p,\mu) T_{b,}$$

T_b is brightness temperature

μ is the cosine of local zenith angle

p: pressure



1D-VAR Retrieval

- In cloudy and precipitation conditions, the radiance become a non-linear function of temperature
- Also, we have more variables than channel measurements (an under-deterministic problem)
- A prior or background information can help to formulate an optical estimation

1D-VAR Retrieval Algorithm

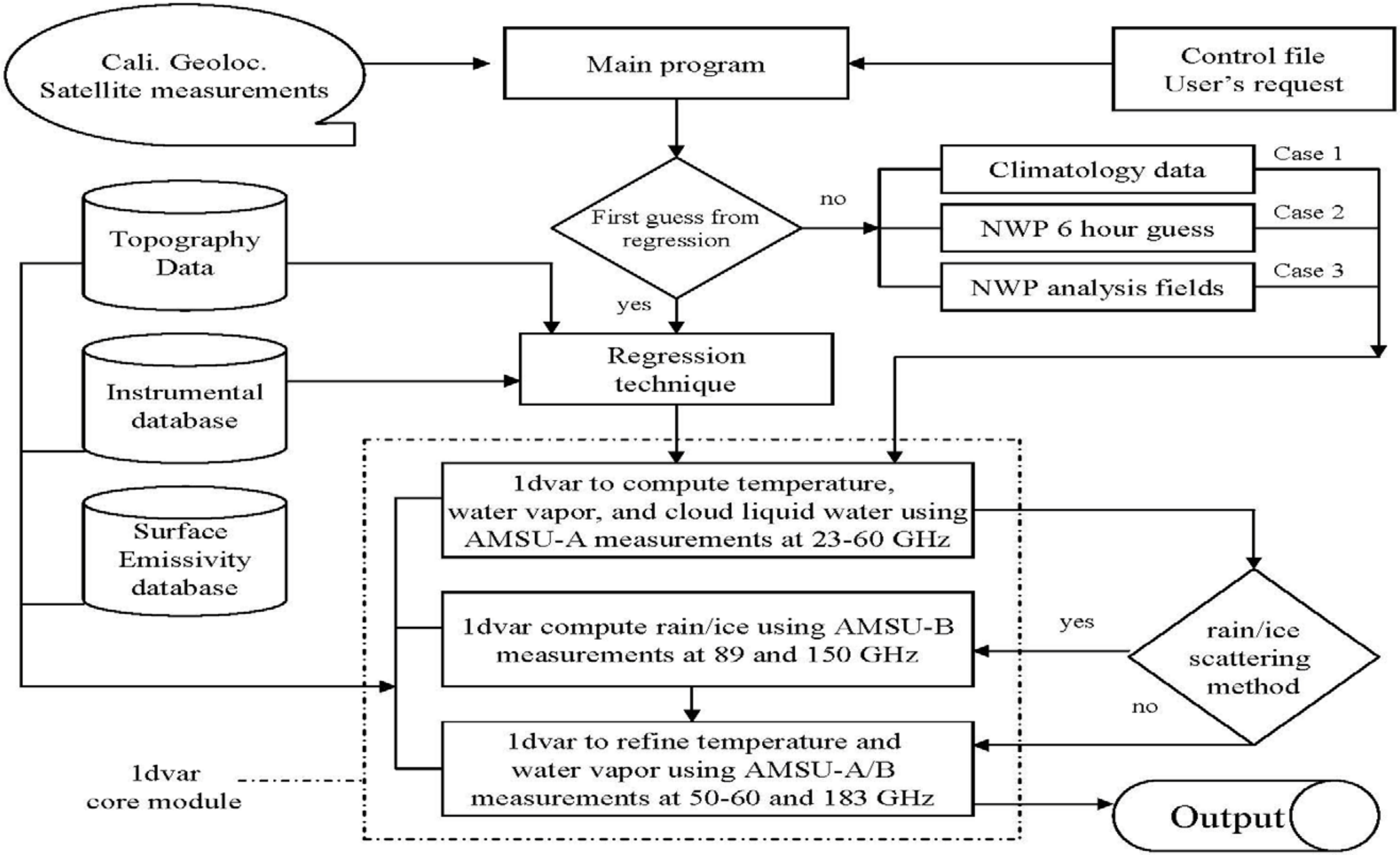
$$\mathrm{J}(\mathbf{X})=\left[\frac{1}{2}\left(\mathbf{X}\text{-}\mathbf{X}_0\right)^{\mathrm{T}}\mathbf{B}^{-1}\left(\mathbf{X}\text{-}\mathbf{X}_0\right)\right]+\left[\frac{1}{2}\left(\mathbf{Y}^{\mathrm{m}}\text{-}\mathbf{Y}(\mathbf{X})\right)^{\mathrm{T}}\mathbf{E}^{-1}\left(\mathbf{Y}^{\mathrm{m}}\text{-}\mathbf{Y}(\mathbf{X})\right)\right]$$

$$\frac{\partial \mathrm{J}(\mathbf{X})}{\partial \mathbf{X}}=\mathrm{J}'(\mathbf{X})=0$$

$$\Delta\mathbf{X}_{n+1}=\left\{\left(\mathbf{B}^{-1}+\mathbf{K}_n^T\mathbf{E}^{-1}\mathbf{K}_n\right)^{-1}\mathbf{K}_n^T\mathbf{E}^{-1}\right\}\left[\left(\mathbf{Y}^m\text{-}\mathbf{Y}(\mathbf{X}_n)\right)+\mathbf{K}_n\Delta\mathbf{X}_n\right]$$

$$\Delta\mathbf{X}_{n+1}=\left\{\mathbf{B}\mathbf{K}_n^{\mathbf{T}}\left(\mathbf{K}_n\mathbf{B}\mathbf{K}_n^{\mathbf{T}}+\mathbf{E}\right)^{-1}\right\}\left[\left(\mathbf{Y}^{\mathbf{m}}-\mathbf{Y}(\mathbf{X}_n)\right)+\mathbf{K}_n\Delta\mathbf{X}_n\right]$$

MW 1D-VAR System for Atmospheric Sounding



Cali. Geoloc.
Satellite measurements

Main program

Control file
User's request

First guess from regression

no

yes

Climatology data

NWP 6 hour guess

NWP analysis fields

Case 1

Case 2

Case 3

Topography Data

Instrumental database

Surface Emissivity database

Regression technique

1dvar to compute temperature, water vapor, and cloud liquid water using AMSU-A measurements at 23-60 GHz

1dvar compute rain/ice using AMSU-B measurements at 89 and 150 GHz

1dvar to refine temperature and water vapor using AMSU-A/B measurements at 50-60 and 183 GHz

rain/ice scattering method

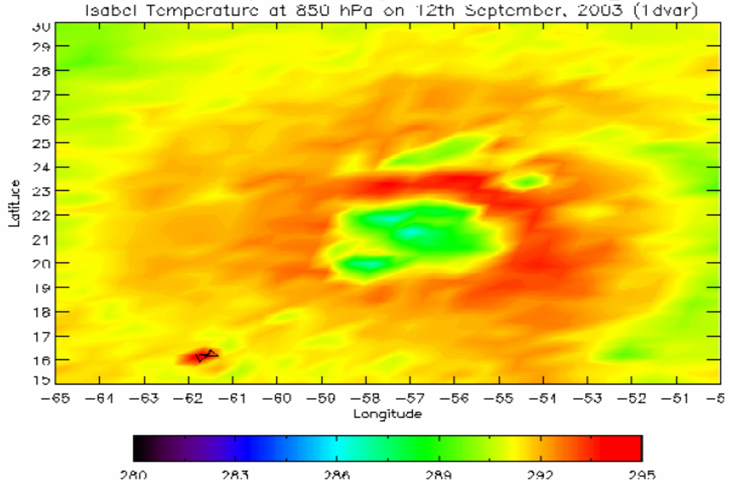
yes

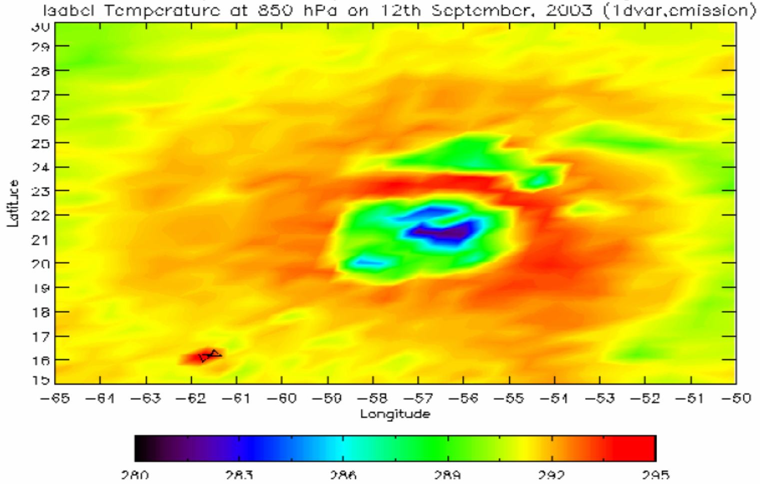
no

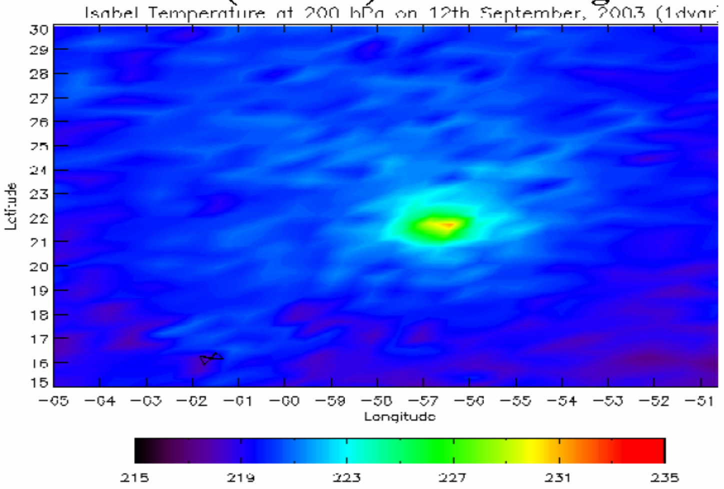
1dvar
core module

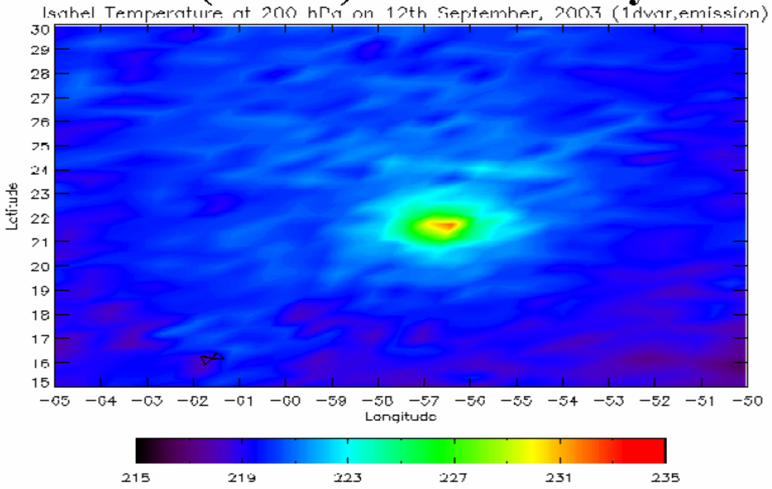
Output

Hurricane temperature Structure from Two RT models

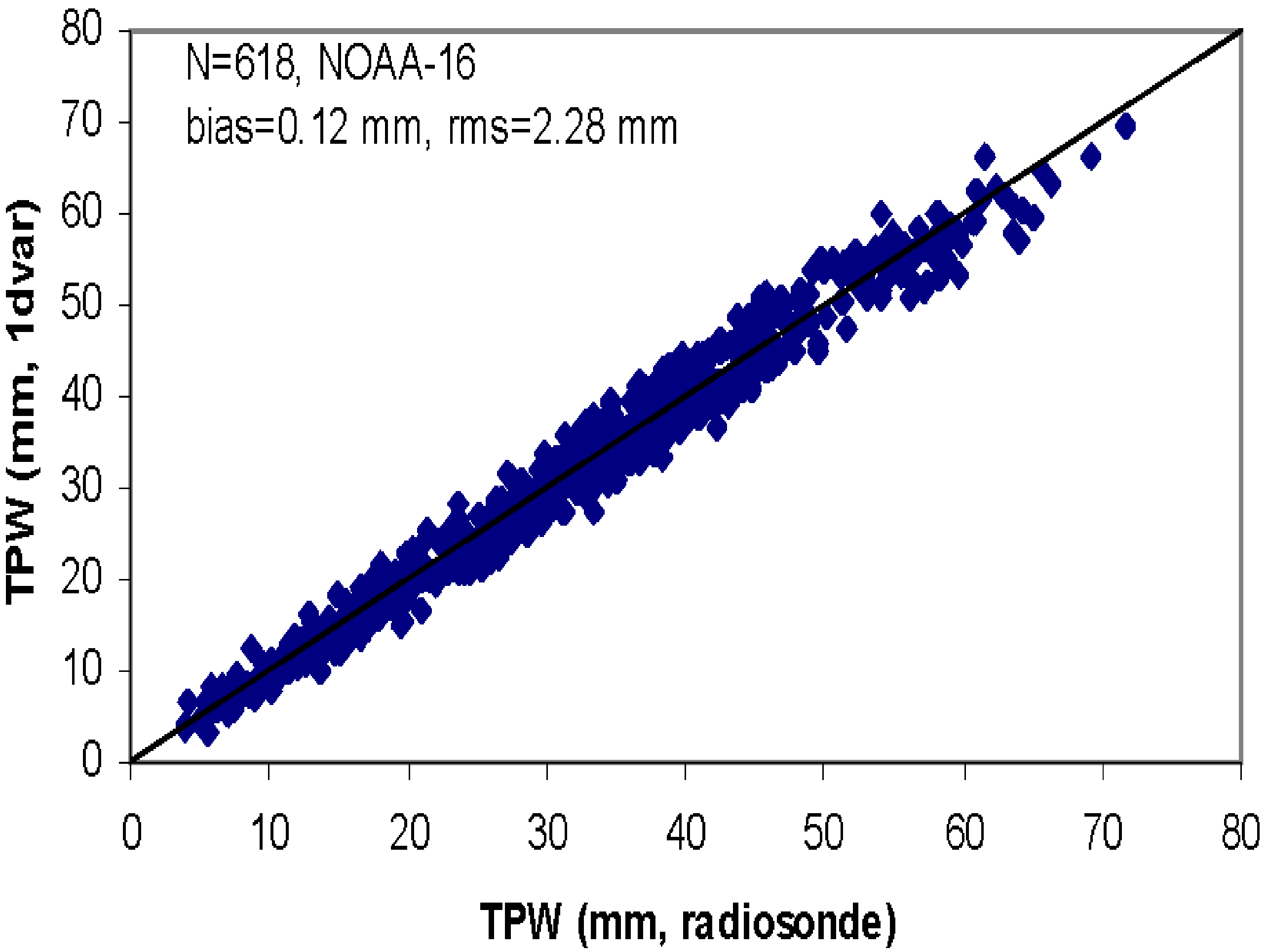

T(850hPa) – Scattering


T(850hPa) – Emission only


T(200hPa) – Scattering


T(200hPa) – Emission only

Validation of TPW Retrieval Using Radiosondes



Summary of MW Remote Sensing of Atmosphere

1. **Microwave Absorption Bands**
   - O2 (50-60 GHz, 117-120 GHz),
   - H2O (176-190 GHz)
   - Used for sounding of temperature & humidity
2. **Microwave Cloud Algorithms**
   - Emission: cloud liquid water/total precipitable water
   - Scattering: ice water path/ particle size
3. **Microwave Sounding Algorithms**:
   - simultaneous retrievals from 1dvar
   - All weather profiling requires scattering rt model
   - Accurate surface emissivity model
4. **Main Applications**:
   - NWP data assimilations
   - Hurricane monitoring

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