Outline of 4 Lectures

1. Sept. 17, 2008: TC best track definition and datasets, global distribution of TCs; Review of history of meteorological satellites, introducing different orbits, scanning patterns, and space-time samplings. Also introduce the differences between the satellites and the instruments.

2. Sept. 19, 2008: **Introduction of space borne instruments including visible, IR and microwave. Will briefly talk about radiative transfer theories in different channels and rainfall retrieval algorithms from IR and microwave.**

Problem set: Due on the 3rd lecture day

3. Oct. or Nov. ?: Current status of TC intensity and rainfall forecasts. Introduction of satellite-based TC intensity and rainfall prediction techniques, including DVORAK, SHIPs, and R-CLIPER.

4. Oct. or Nov. ?: Convective properties of tropical cyclones. An introduction of TRMM-base TCPF database. Climatology of tropical cyclone rainfall and its contribution to global precipitation.

Outline for Today (Sept. 19, 2008)

1. Basic Radiative Transfer

2. Image Interpretation for visible, IR, and microwave channels; Introduce microwave instruments including TRMM TMI, SSM/I, AMSR-E, AMSU-B, PR and CPR

3. Rainfall retrieval from IR

4. Rainfall retrieval from microwave

Radiative Transfer Equation

The rate of change of radiance (*I*) with distance =
Extinction + Emission + (Scattering into the beam)

$$dI = dI_{ext} + dI_{emit} + dI_{scat}$$

Extinction = Absorption by the atmosphere +
Scattering out of the beam into other directions

Extinction Term

$$dI_{ext} = -\beta_e I ds$$

where the extinction coefficient is the sum of the absorption coefficient and scattering coefficient,

$$\beta_e = \beta_a + \beta_s$$

$$\beta_e = \int N(D)\sigma_e(D)dD$$

the extinction cross section σ_e, in units of area m^2, is the sum of the absorption and scattering cross sections ($\sigma_a + \sigma_s$).

Emission Term

$$dI_{emit} = \beta_a B(T) ds$$

The intensity of radiation emitted by a blackbody with a physical temperature *T* is given by Planck's Function : $B(T)$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5 (e^{hc/k_B \lambda T} - 1)}$$

Scattering Source Term

The source due to the radiation from any direction θ' scattered into the beam in the direction of interest θ Is:

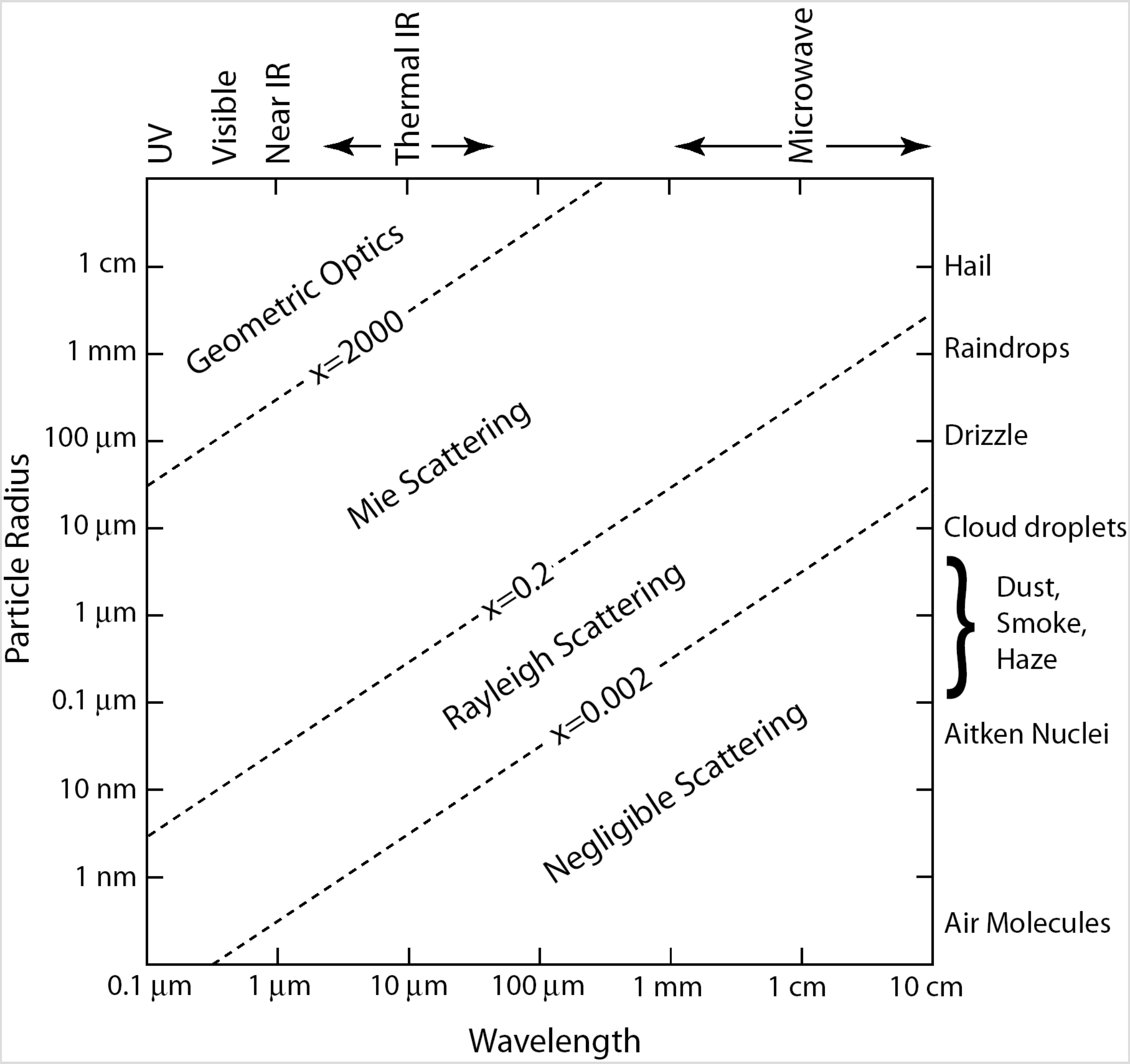
$$dI_{scat} = \frac{\beta_s}{4\pi} \int_{4\pi} p(\theta', \theta) I(\theta') d\omega' ds$$

General and Complete Form of Radiative Transfer Equation

$$dI = -\beta_e I ds + \beta_a B ds + \frac{\beta_s}{4\pi}\int_{4\pi} p(\theta', \theta) I(\theta') d\omega' ds$$

The calculation of this equation is very complex due to the existence of the scattering source term, which requires a solution for the intensity field not just in one direction along a one-dimensional path but for all directions simultaneously in three-dimensional space. One would therefore like to be able to neglect scattering (as a source, at least) whenever possible.

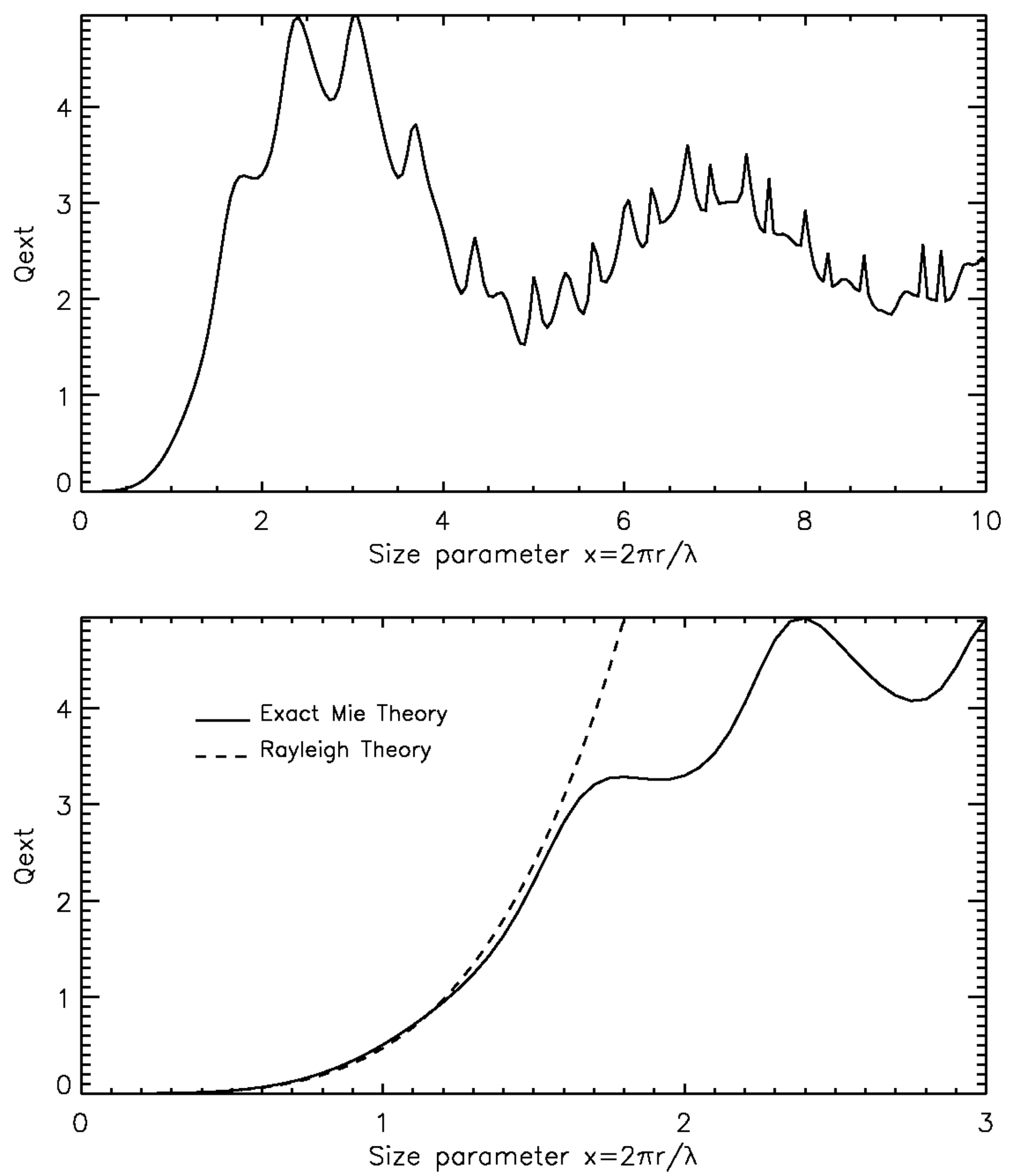
When Does Scattering Matter?



In general, particles that are far smaller than the wavelength will scatter only very weakly.

Size Paramter:

$$x \equiv \frac{2\pi r}{\lambda}$$



The extinction efficiency Q_e as a function of size parameter x for a nonabsorbing ice sphere with m=1.78, for various of x. (a) Detail for x < 10; (b) Detail for x < 3, comparing the Rayleigh (small particle) approximation and exact Mie theory.

Visible Channels

Spectrum: wavelengths around 0.5 μm

Cloud droplets are geometric scatters. A cloud only a few of tens meters thick is sufficient to scatter all of the visible radiation incident on it.

Absorption is negligible.

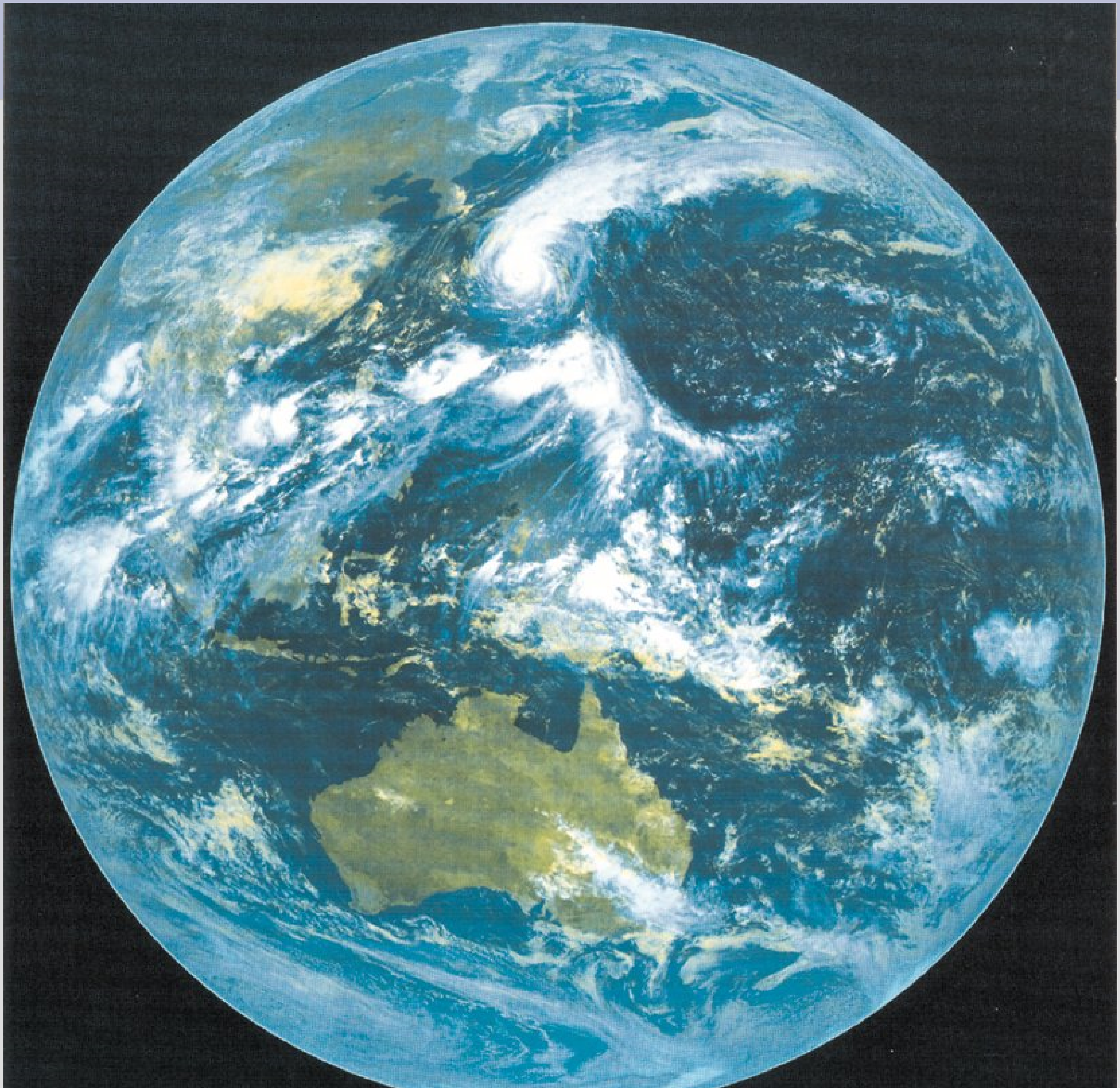
So visible channels detect sunlight reflected by clouds and the earth's surface.

Visible Image Interpretation

Thick clouds (White) are bright in the visible imagery because thicker clouds generally have higher reflectivity.

High clouds (White) are often semi-transparent and low clouds (Yellow) can be seen through them.

The land surface (Yellow) reflects sunlight less than clouds but more than the sea surface (Blue).



IR Channels

Spectrum: usually referred as the 10-12.5 μm window, in which the atmosphere is relatively transparent to the long-wave radiation from the Earth.

Cloud droplets are Mie scatters.

Clouds absorbs nearly all of the infrared radiation incident on them. They act as blackbody.

So the higher the temperature, the more intense the infrared radiation. High clouds are invariably very cold, while low clouds are much warmer. Thus, both the temperature and the height of the cloud top can be inferred from the intensity of the infrared radiation.

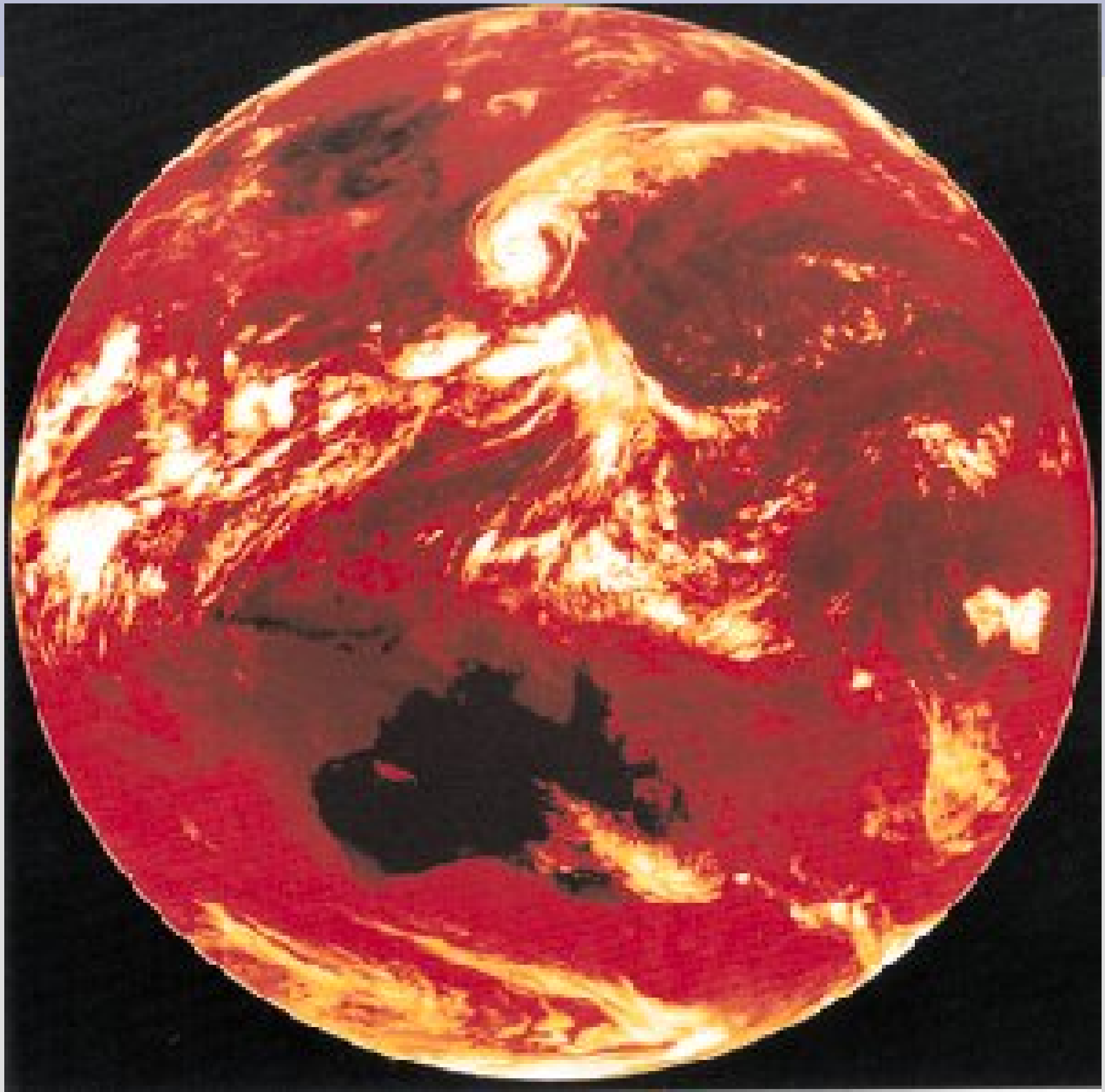
IR Image Interpretation

Thick clouds, such as those associated with the typhoon, look **white** (lowest temperature).

High clouds, which look semi-transparent in the visible imagery, are also shown **white or yellow**.

Low clouds are displayed as **red**. They may have temperatures close to that of the underlying ocean and are more difficult to identify in the infrared than in the visible imagery.

The desert in Australia is much hotter (**black**) than any cloud and shows up clearly.



IR Water Vapor Channels

Spectrum: water vapor absorption band around 6.7 µm

As absorption by water vapor is strong in this band, radiation from the low clouds and the earth's surface do not normally reach the satellite. The water vapor channels detect the radiation from high and middle clouds and from the upper and mid-tropospheric atmosphere.

The intensity of the radiation received at these channels depends on the amount of water vapor in the upper and mid-troposphere as well as the temperature of the radiation source.

The temporal changes of the humidity patterns can identify air movement and vortices even in the absence of clouds.

Water Vapor Image Interpretation

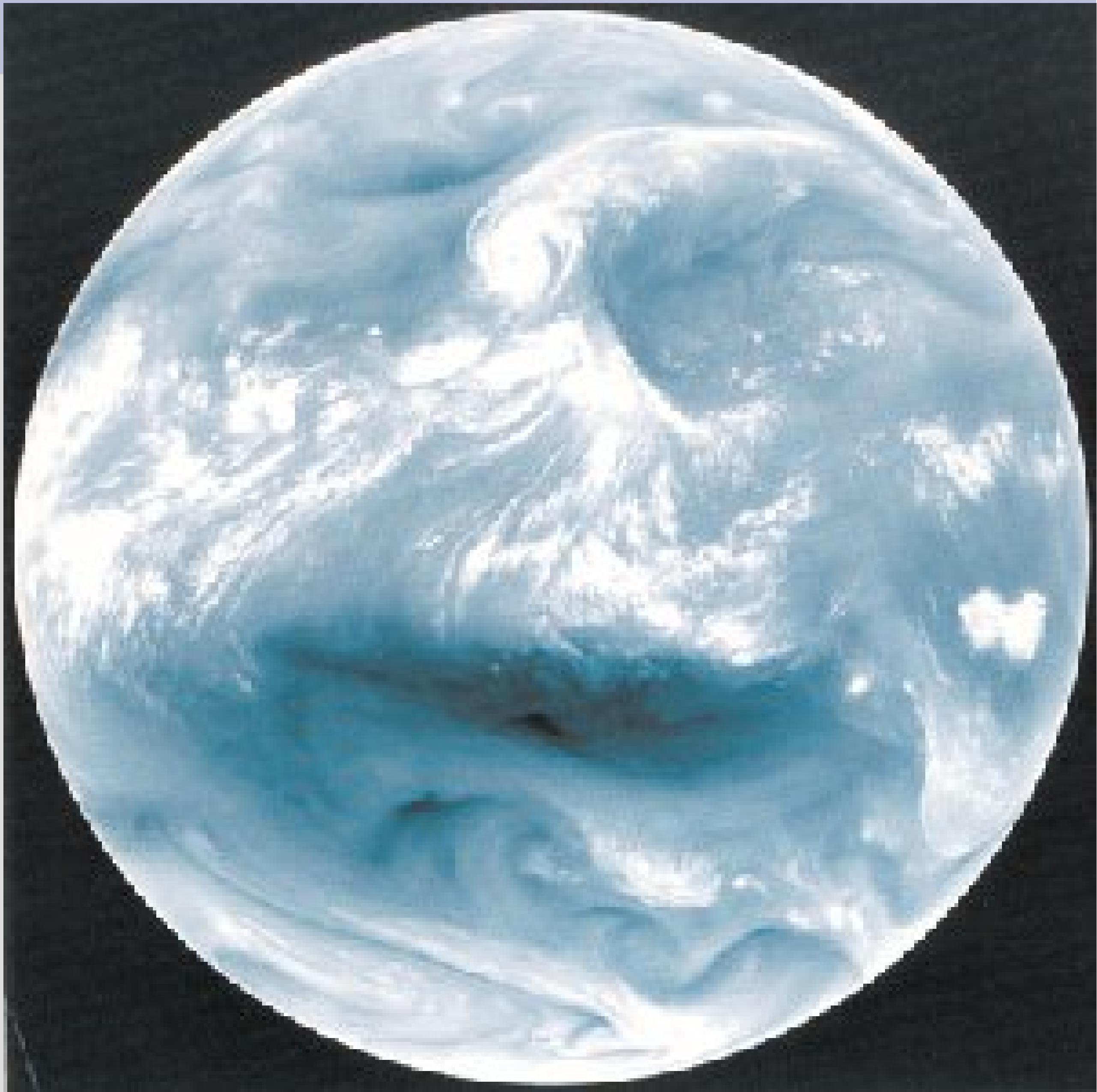
The brighter parts show the moister parts of the upper and mid-troposphere.

Thick clouds and high clouds are seen **white** (similar to IR and visible images). The earth's surface and low clouds are undetectable .

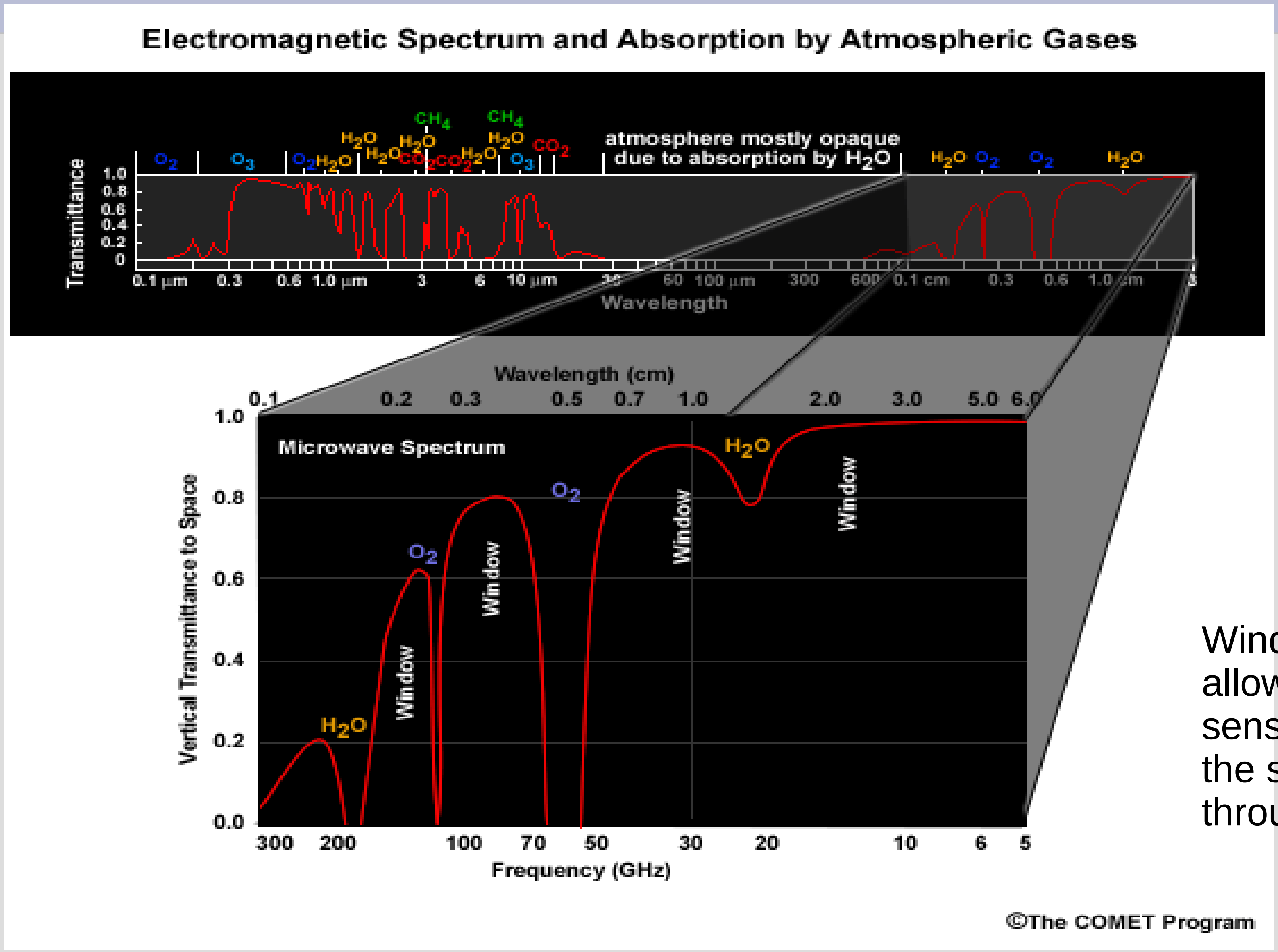
Grey shades corresponding to water vapor amounts are seen where there are no high and middle clouds.

In the southern hemisphere, **dark areas** can be seen, associated with dry upper air.

Many vortices of grey shades are also seen, associated with upper tropospheric lows.



Microwave Channels



Window channels allow the satellite sensors to "see" the surface, even through clouds.

Microwave Channels

Non-raining clouds are nearly transparent (no absorption, no scattering), but raining clouds are not. Thus microwave is very useful to detect precipitation.

Passive microwave sensors detect the microwave scattering and emission signatures of liquid water or ice particles.

In 10 GHz channel, ice scattering can be neglected. Only emission from rain and liquid water and background (ocean or land) is significant.

The 22 GHz channel is sensitive to water vapor .

The 19 and 37 GHz channels are sensitive to both emission from rain particles and scattering from ice particles.

The 85 GHz and above channels are mainly sensitive to scattering from ice particles.

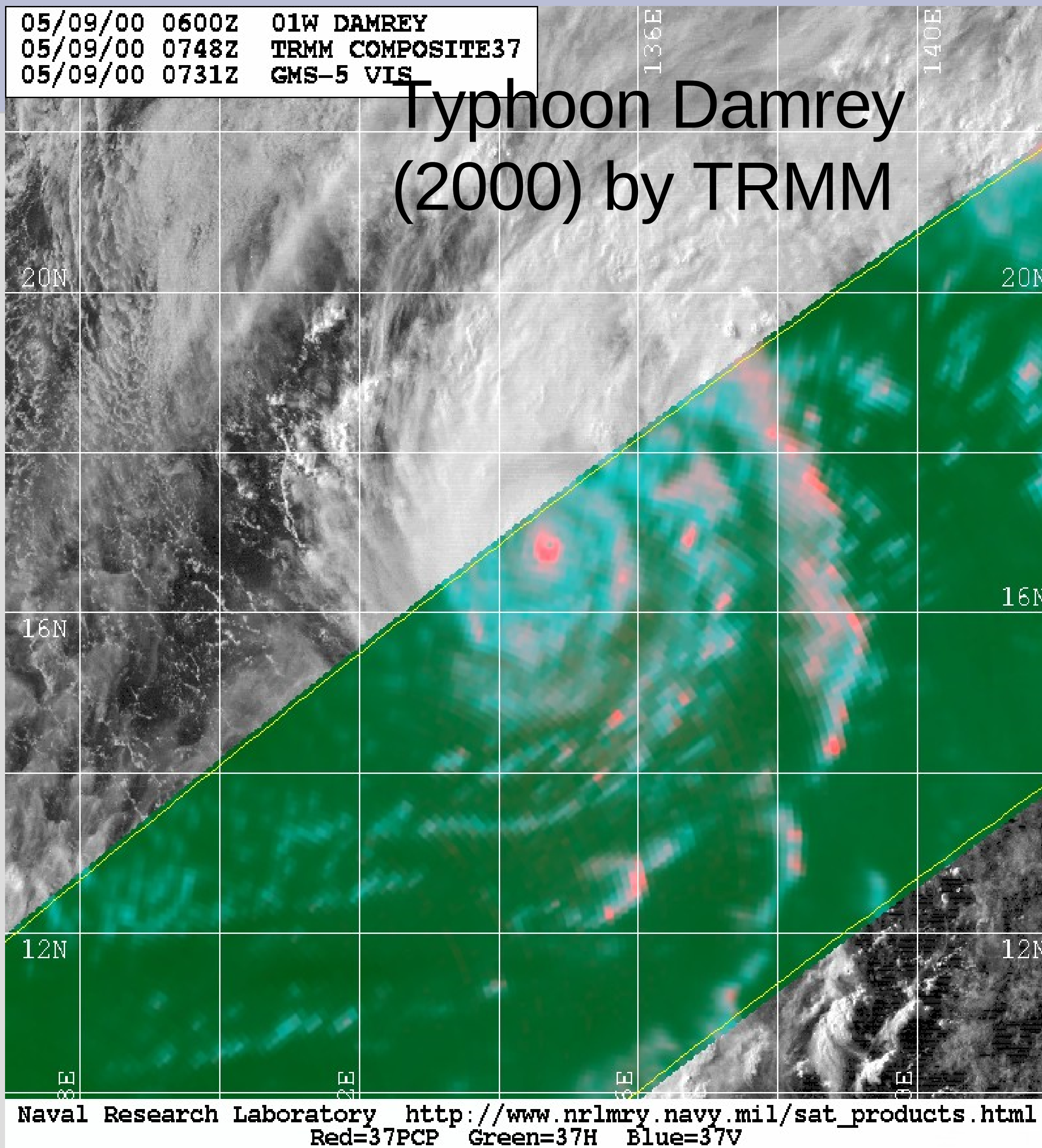
37 and 85 GHz Polarization Corrected Temperature (PCT)

Unlike the infrared where convection appears cold, and the sea surface warm, in the microwave both deep convection and the sea surface can be cold.

PCT (Spencer et al. 1989) is defined by a combination of V & H brightness temperatures to remove the cold sea surface effect.

In Navy’s TC webpage, on the 37 PCT color product, the sea surface shows up as green, stratiform rain/clouds show up as light green, and deep convection shows up as pink.

37 GHz Image Interpretation



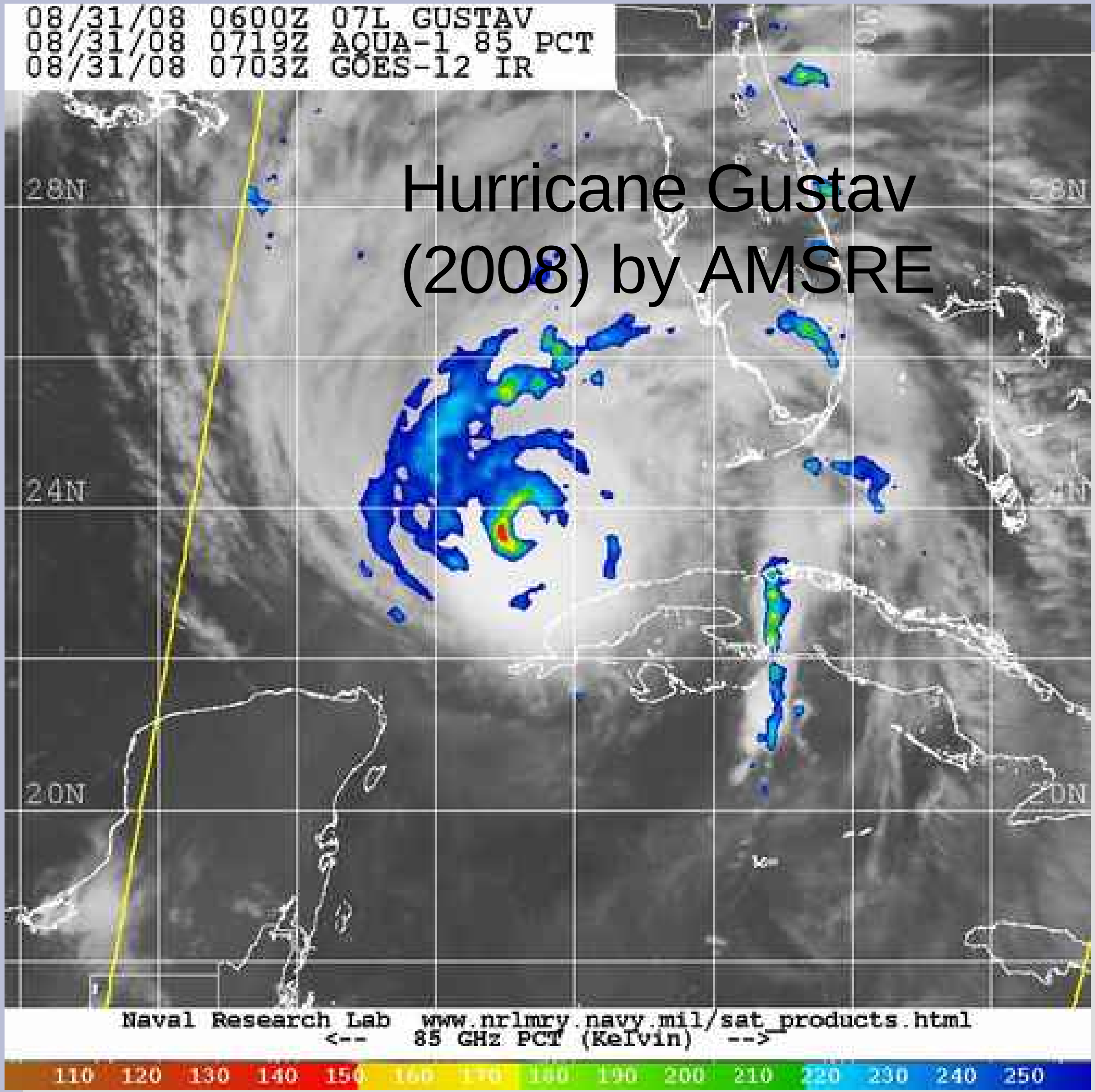
Typhoon Damrey (2000) by TRMM

At 37 GHz:

1. Water clouds and precipitating clouds appear warm against a relatively cold ocean

2. Imagery resolves details missed by 85-91 GHz, for example, low-level clouds and rain

85 GHz Image Interpretation



At 85-91 GHz:

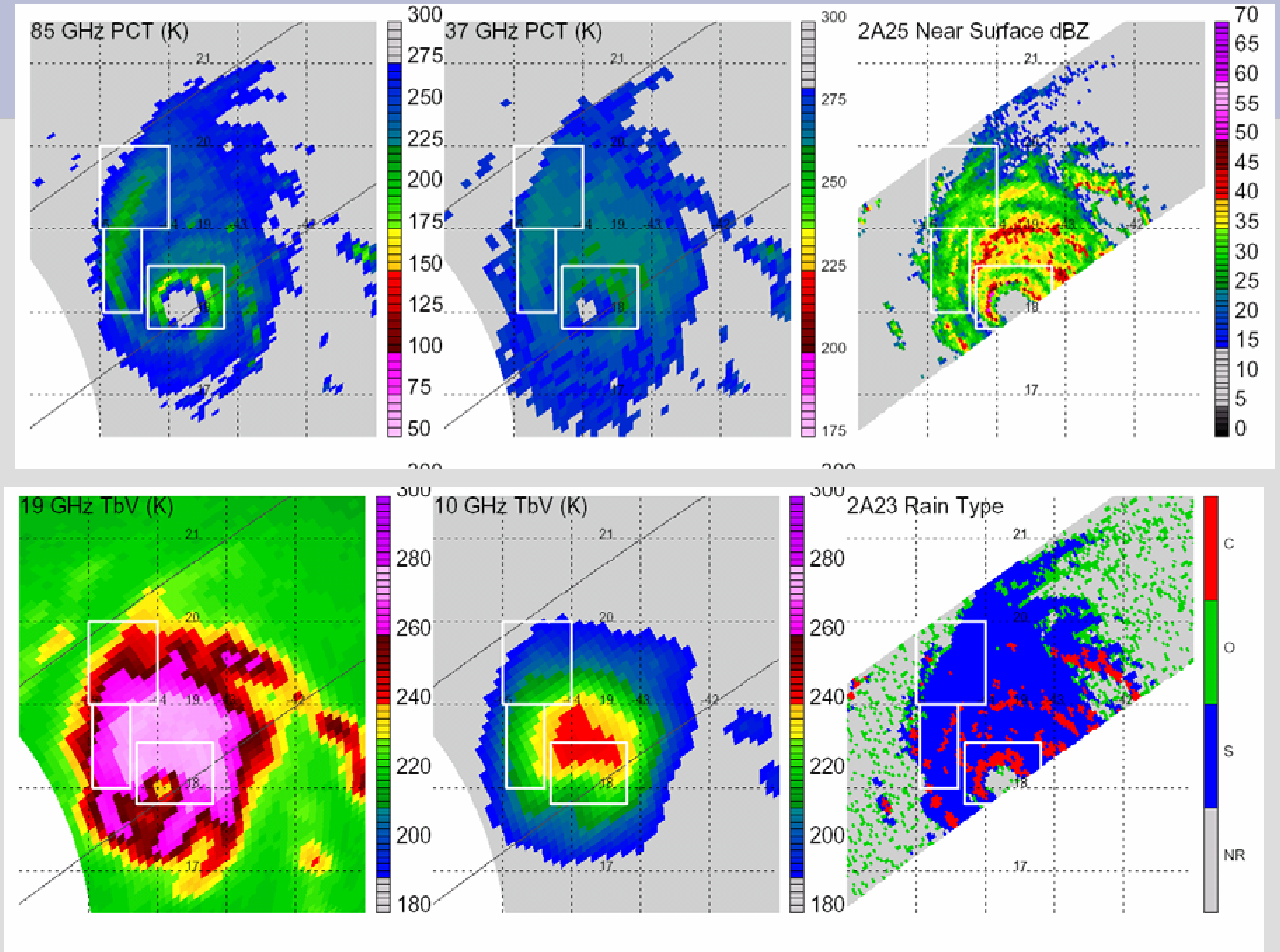
1. Deep convection appear relatively cold

2. Imagery can penetrate thin cirrus canopies and reveal internal storm structure

3. Imagery is able to distinguish deep convection, but can not always see low-level circulations when associated primarily with low-level water clouds

4. Spatial resolution is higher than for imagery at lower microwave frequencies

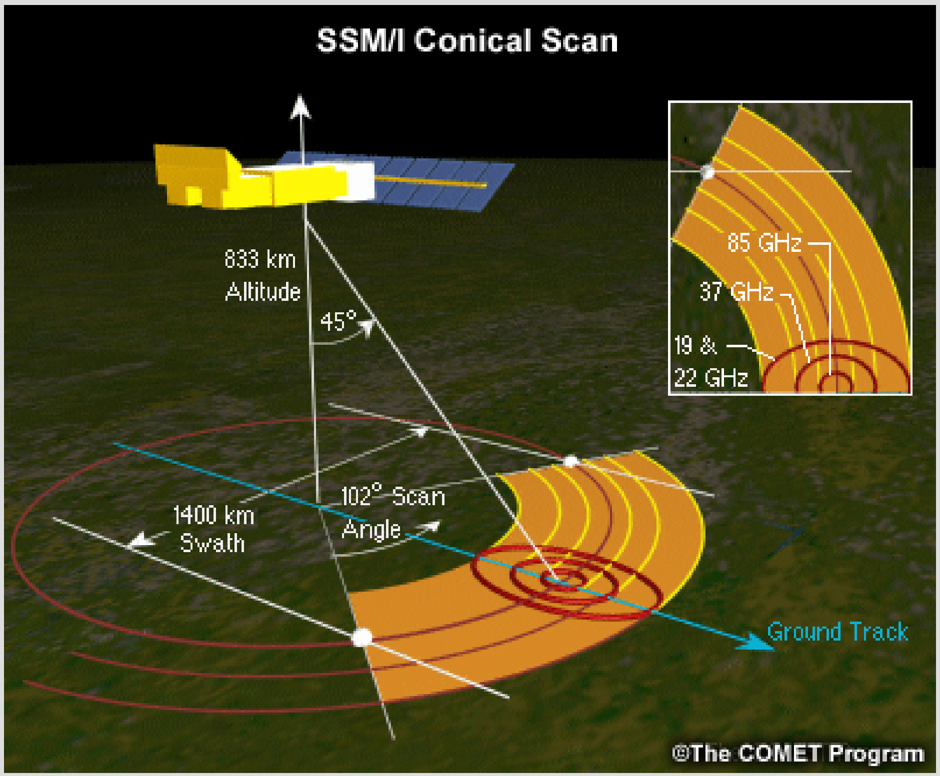
TRMM 10, 19, 37, 85 GHz: Hurricane Isabel (2003)

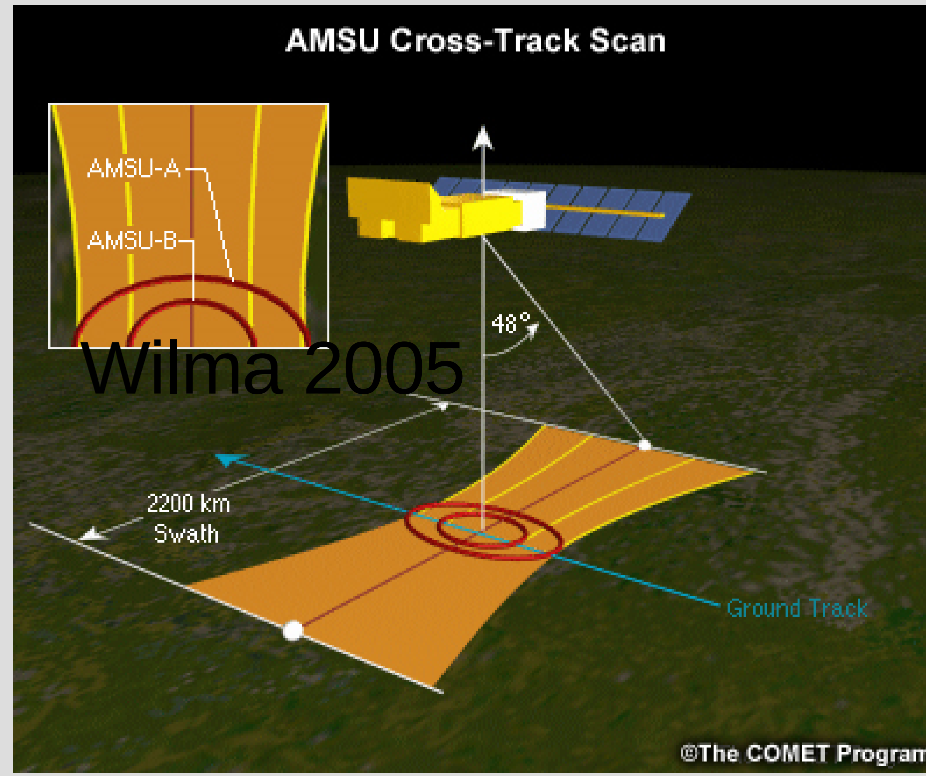


Summary of Passive Microwave Instrument Characteristics

	SSM/I	AMSU-B	TRMM TMI	AMSR-E
Spectral bands	19, 22, 37, 85 GHz	89, 150, and three at ~ 183 GHz	10.7, 19, 22, 37, 85 GHz	6.9, 10.7, 18.7, 23.8, 36.5, 89 GHz
Horizontal Resolution (at nadir)	12.5 - 50km	16.3km	4.6 x 6.95 km at 85.5 GHz to 45 km at 10.7 GHz	6 x 4km at 89GHz to 74 x 43 km at 6.9GHz
Swath Width	1400km	2343 km	780 km	1440 km

Effects of Instrument Scanning Geometry





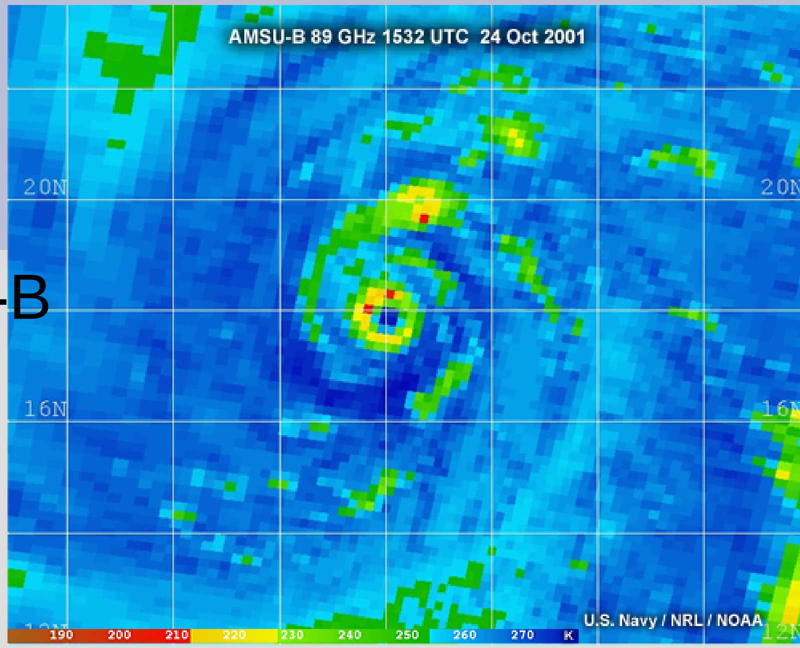
Constant Ground Resolution
Narrower swath

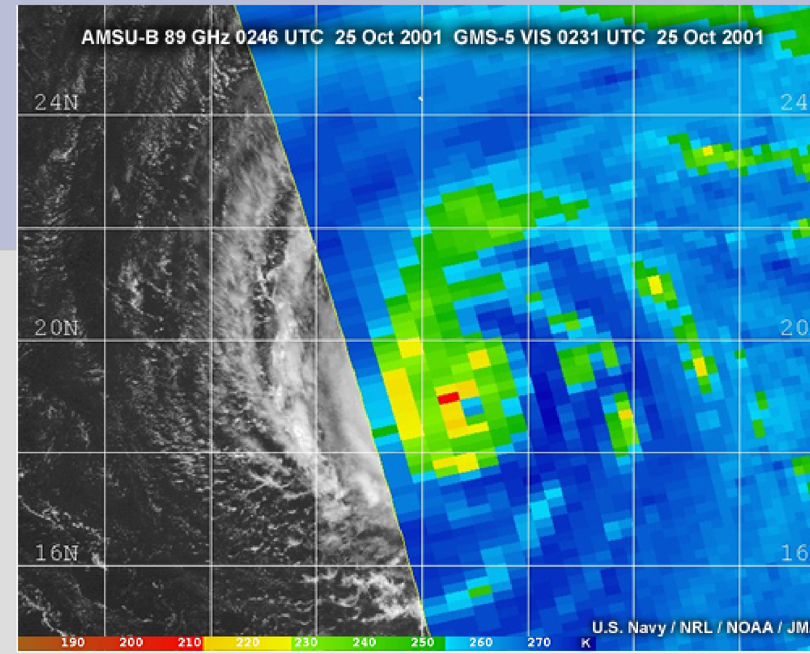
Edge Effect
Wider swath

Center

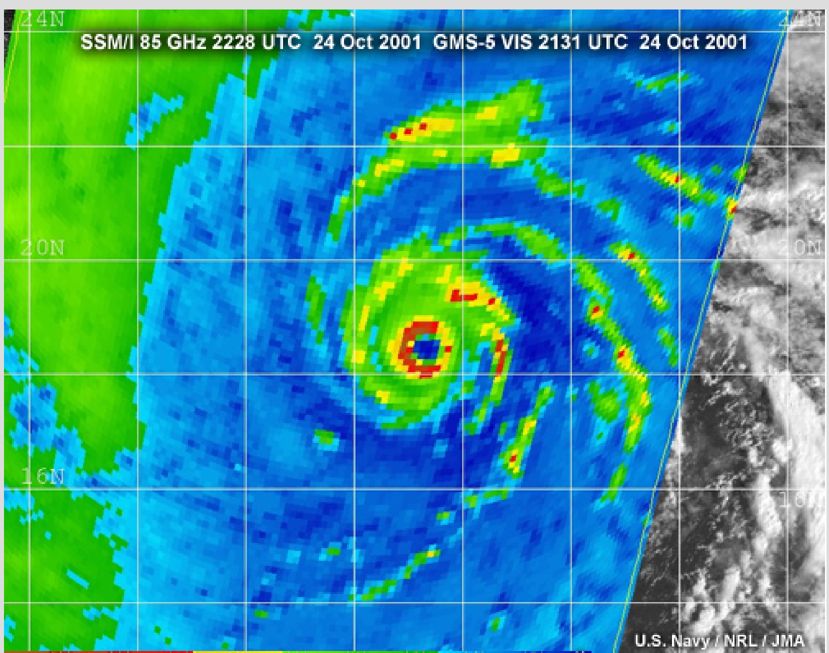
Edge

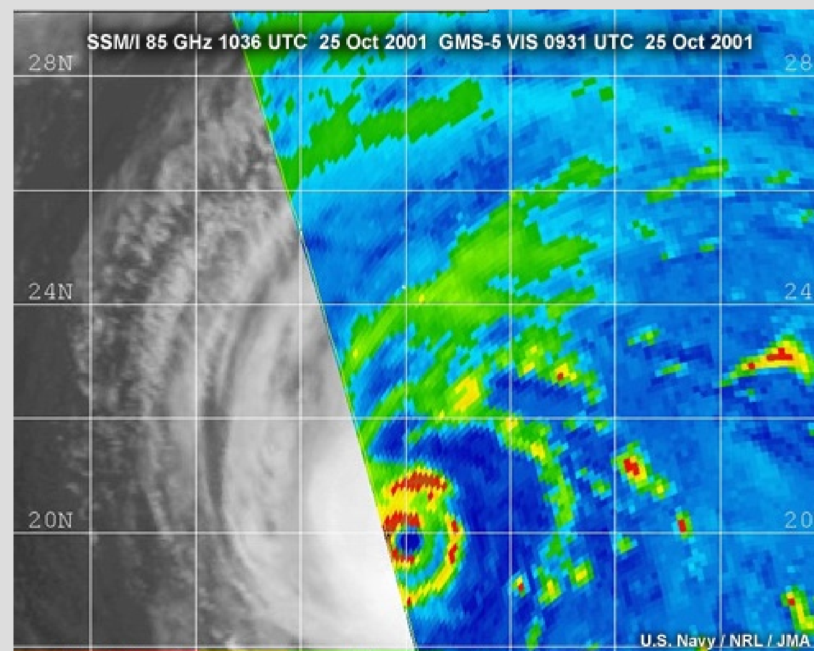
AMSU-B



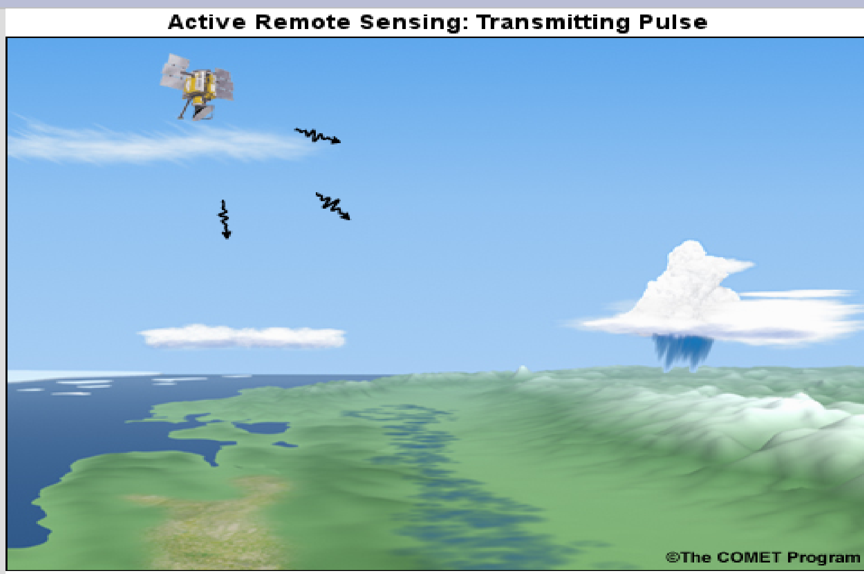


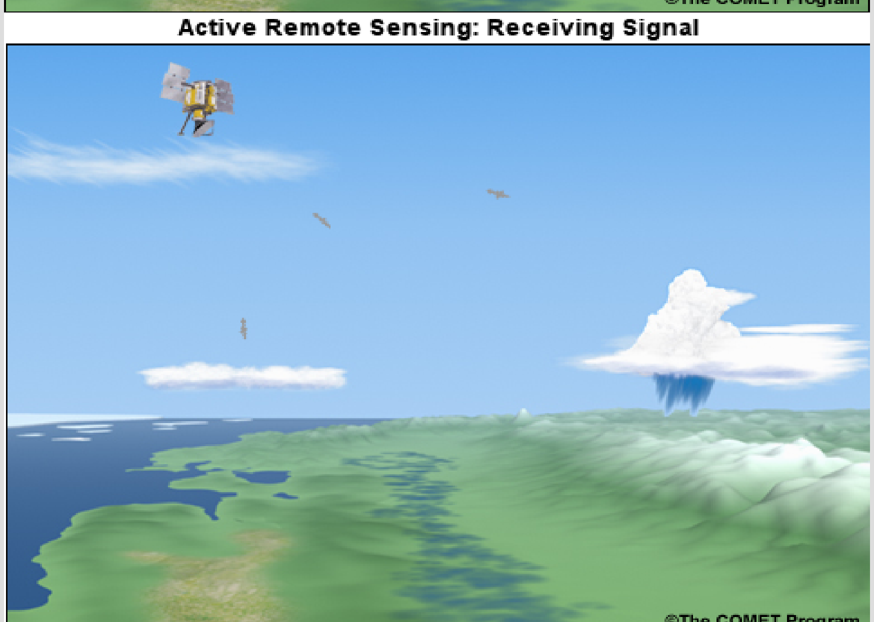
SSM/I

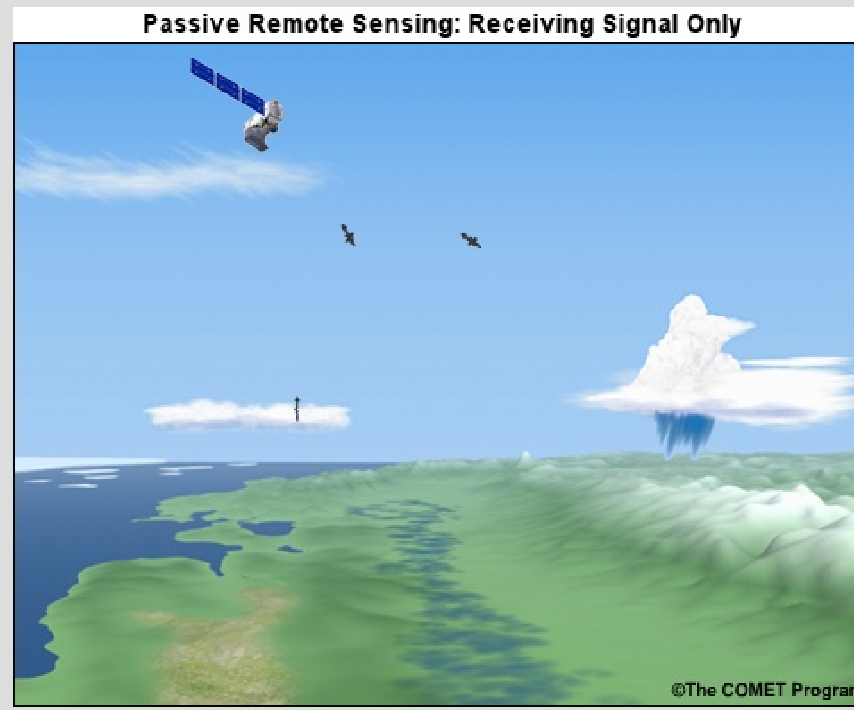




Passive vs. Active Microwave Remote sensing







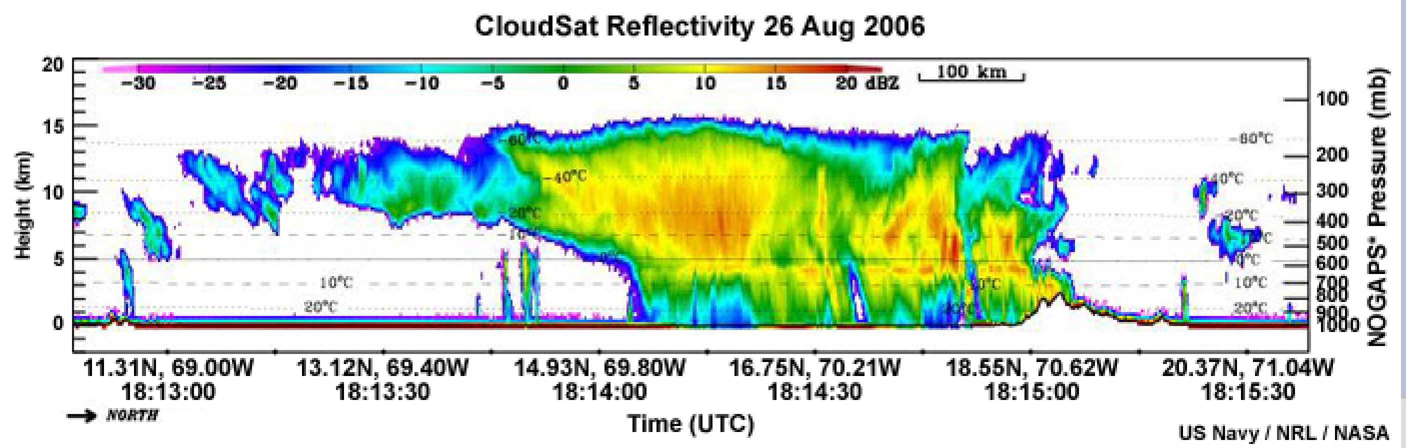
Radar (Active Microwave)

Frequencies: TRMM PR: 13.8 GHZ (wavelength: 2.17 cm)
CloudSat CPR: 94 GHz (wavelength: 3.19 mm, only small drizzles and cloud droplets are in Rayleigh regime: x<1)

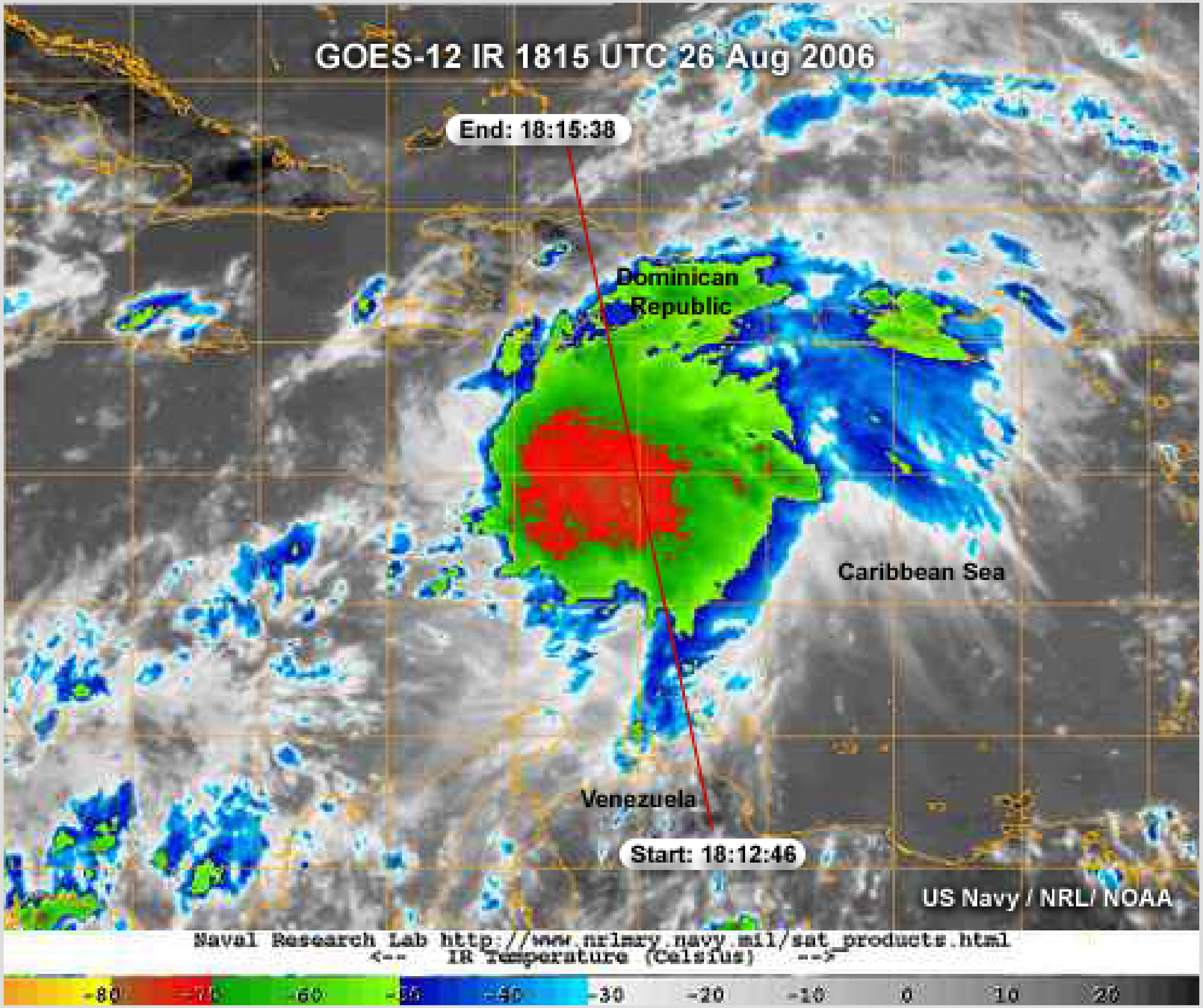
Radar measures the backsattering of cloud and precipitation particles. Radar theory is based on Rayleigh scattering. Ze is proportional to D^6.

At 13.8 GHz, PR is useful for measuring precipitating clouds.

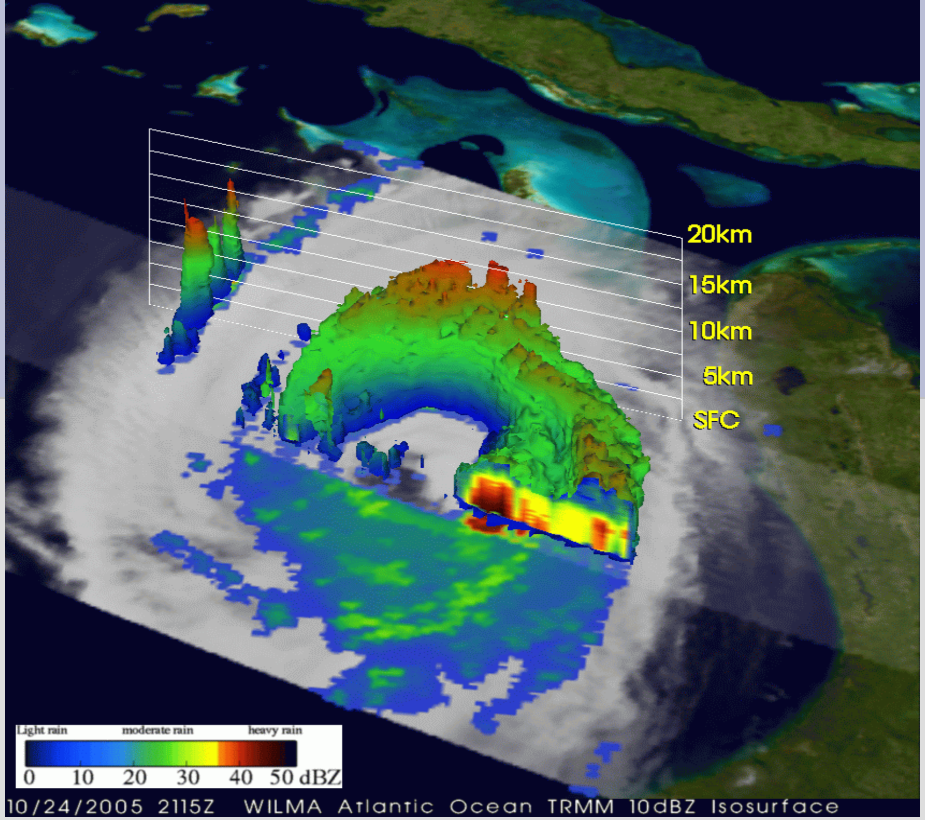
At 94 GHz, CPR is useful for detecting cloud particles. The signal is attenuated (absorbed) severely when looking through raining clouds.



CloudSat Reflectivity 26 Aug 2006
Height (km)
NOGAPS* Pressure (mb)
100 km
20 dBZ
11.31N, 69.00W
18:13:00
13.12N, 69.40W
18:13:30
14.93N, 69.80W
18:14:00
16.75N, 70.21W
18:14:30
18.55N, 70.62W
18:15:00
20.37N, 71.04W
18:15:30
NORTH
Time (UTC)
US Navy / NRL / NASA



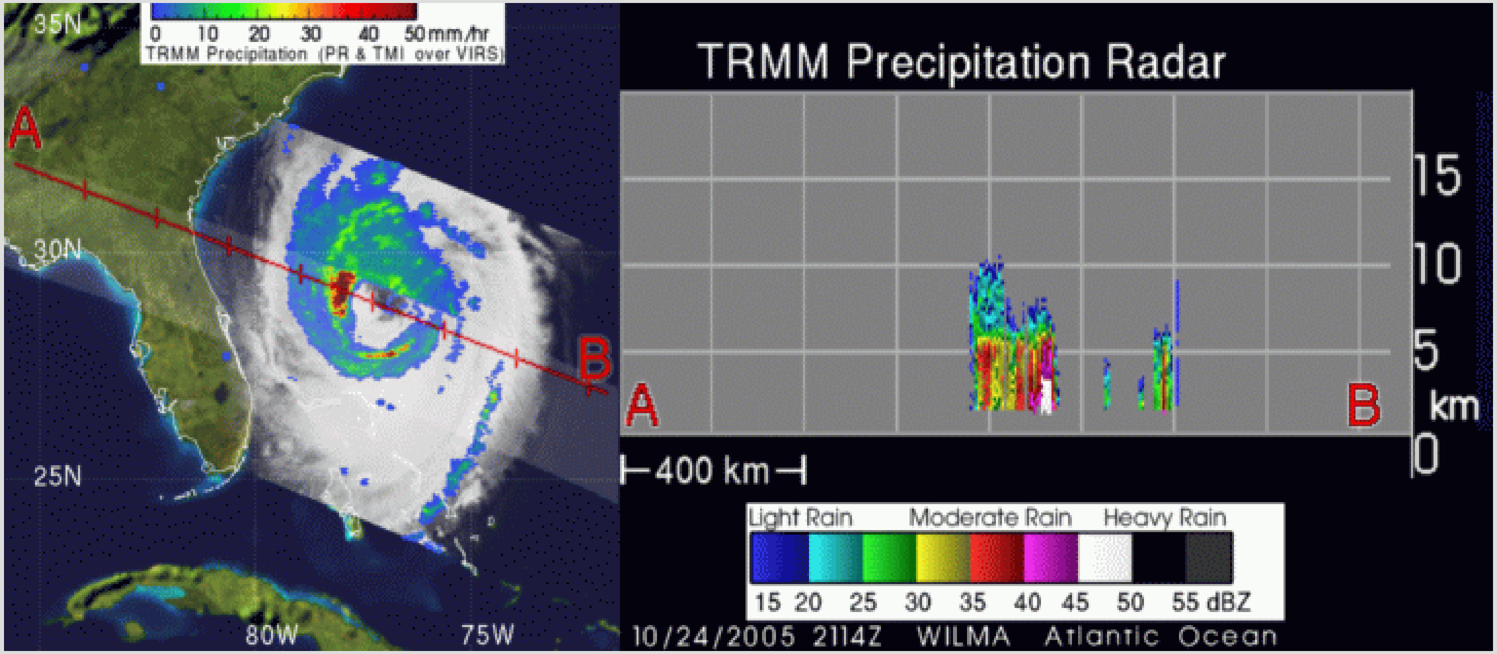
GOES-12 IR 1815 UTC 26 Aug 2006
End: 18:15:38
Dominican
Republic
Caribbean Sea
Venezuela
Start: 18:12:46
US Navy / NRL/ NOAA
Naval Research Lab http://www.nrlmry.navy.mil/sat_products.html
<-- IR Temperature (Celsius) -->



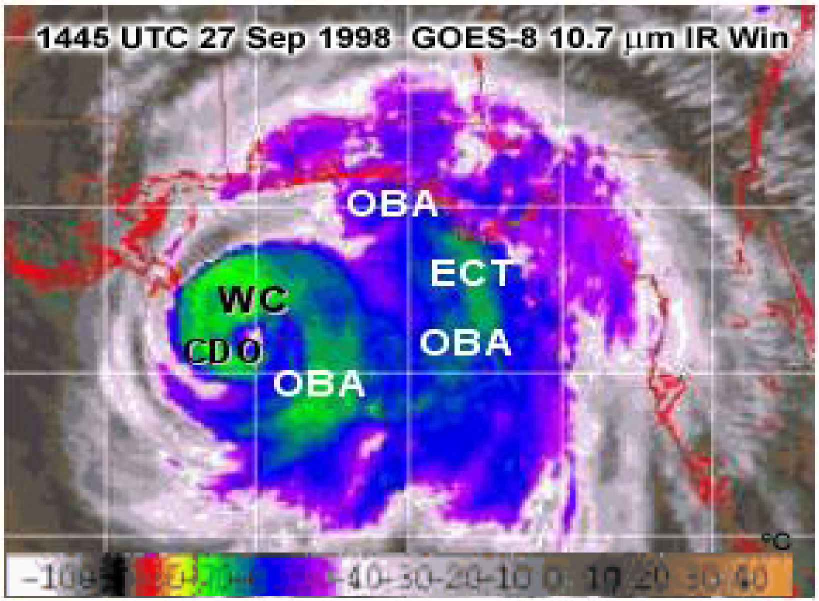
TRMM PR 3D Animation For Ike:

http://trmm.gsfc.nasa.gov/trmm_ra

Wilma 2005



Rainfall Retrieval from IR



Hurricane Cloud Signatures

Cloud Signature	Subjective rain rate
Central Dense Overcast	12.5-51 mm h^{-1} (0.50-2 in h^{-1})
Wall Cloud	25-76 mm h^{-1} (1-3 in h^{-1})
Outer Band Area	2.5-51 mm h^{-1} (0.10-2 in h^{-1})
Embedded Convective Tops	1.25-102 mm h^{-1} (0.05-4 in h^{-1})

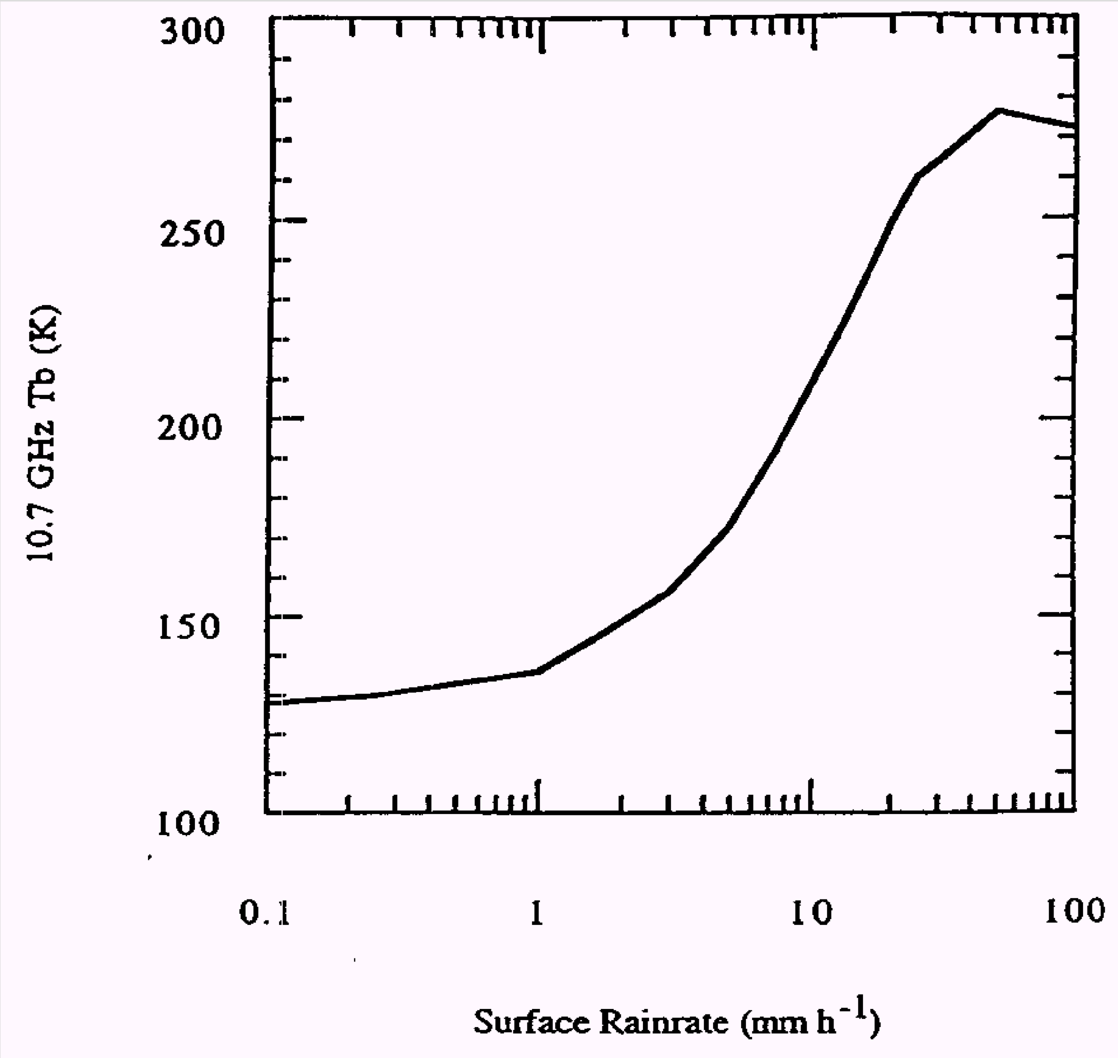
NOAA

IR cloud top temperatures are averaged over various areas and times. Those averages are then compared with precipitation measurements to arrive at an operational temperature-precipitation correlation. One example of this is the **GOES Precipitation Index (GPI),** which uses 235K as the IR temperature with the best correlation to average precipitation for areas spanning 50-250 km over 3-24 hours.

Advantage: High temporal resolution

Disadvantage: Clouds with high cloud top temperature is not necessarily clouds producing heavy rainfall.

Rainfall Retrieval from Passive Microwave: Emission-based



McGaughey et al. 1996

Emission-based algorthms are based on 10 & 19-GHz or lower channels.

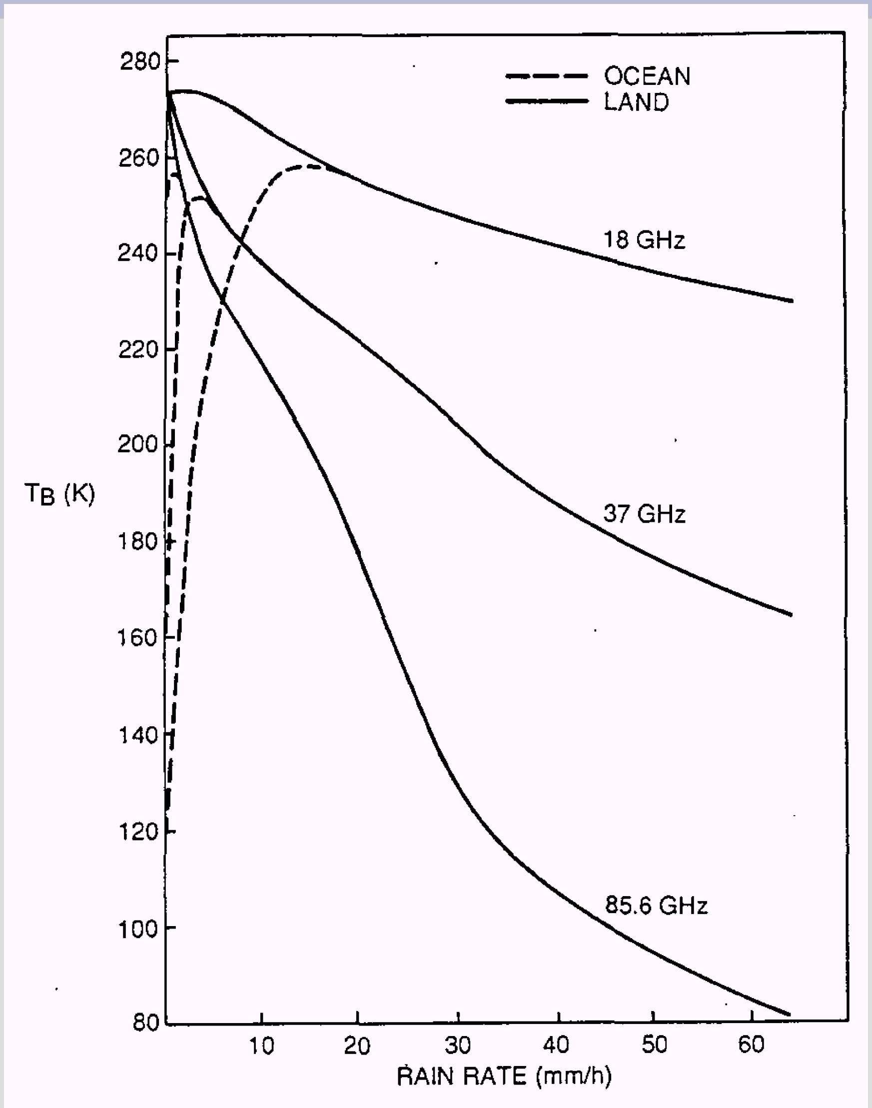
Advantage: Nearly linear relationship up to 50 mm/h without saturation at 10 GHz

Disadvantages:

1.Low spatial resolution: 72x43 km^2 at 10GHz; 35x21 km^2 at 19 GHz; Beamfilling problem.

2. Doesn’t work for over land

Rainfall Retrieval from Passive Microwave: Scattering-based



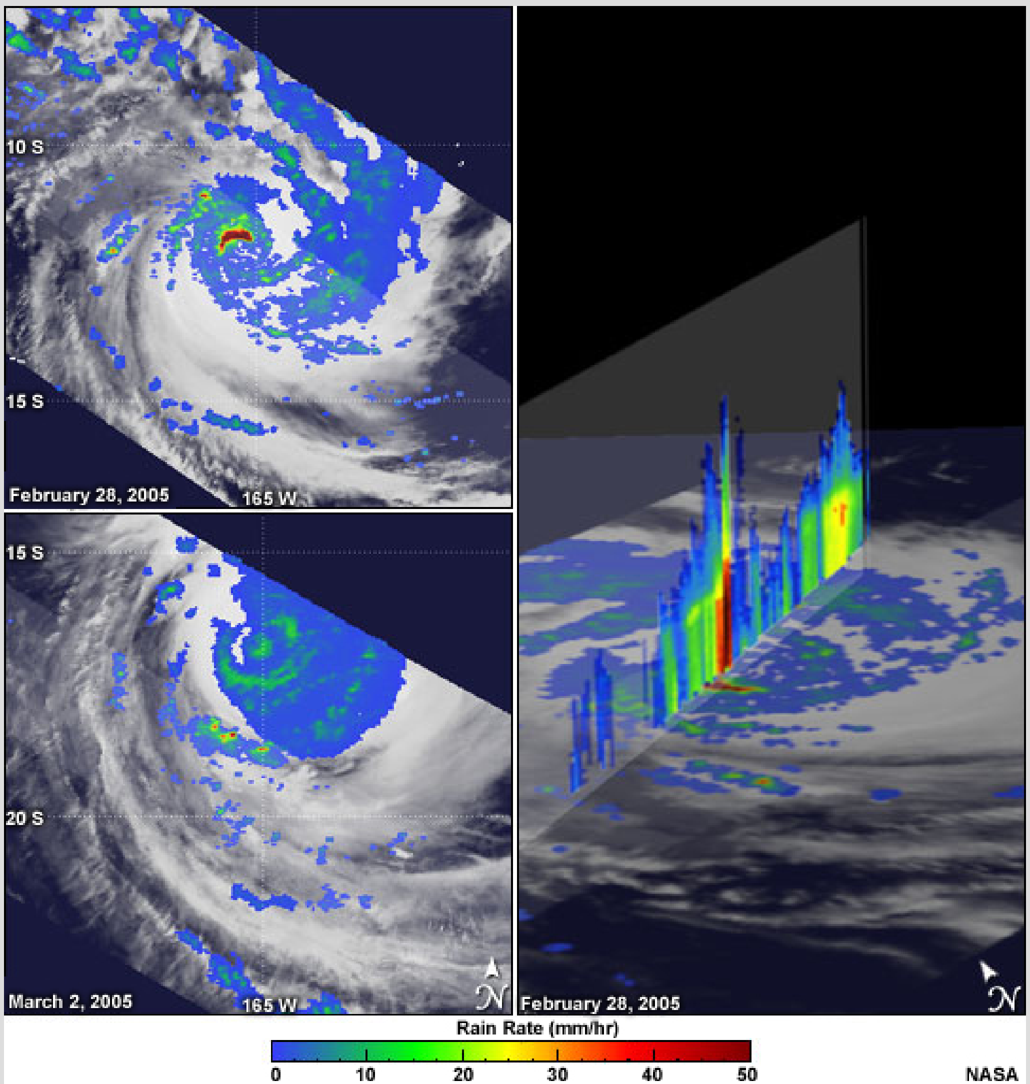
Spencer et al. 1989

Scattering-based algorithms use microwave observations at high frequencies (greater than 37 GHz).

Advantages:
1. Higher spatial resolution;
2. works for both over land and over ocean.

Disadvantage:
The direct relationship is actually between Tb and total ice water instead of rain rate.

Rainfall Retrieval from Radar



TRMM PR 2A25 rain algorithm: Assuming different particle size distributions for different rain types to get Z-R relationships.

Advantages:
1. Higher spatial resolution: 4~5 km;
2. 3D structure;
3. works for both over land and over ocean;
4. Generally, it’s more accurate than passive microwave retrievals.

Disadvantage:
PR’s swath is narrow: 217 km

JAXA Tropical Cyclone Database Webpage

http://sharaku.eorc.jaxa.jp/TYP_DB