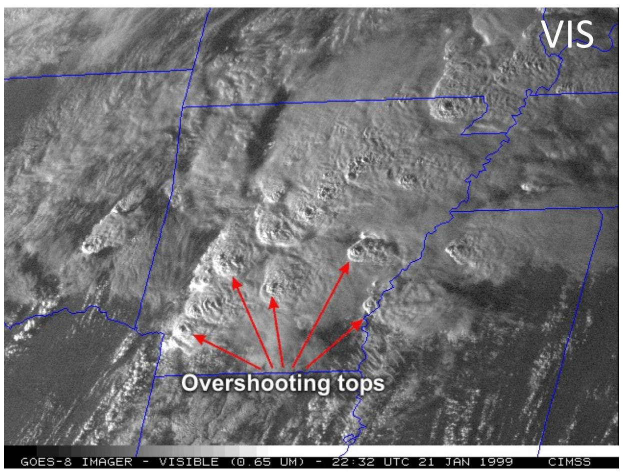
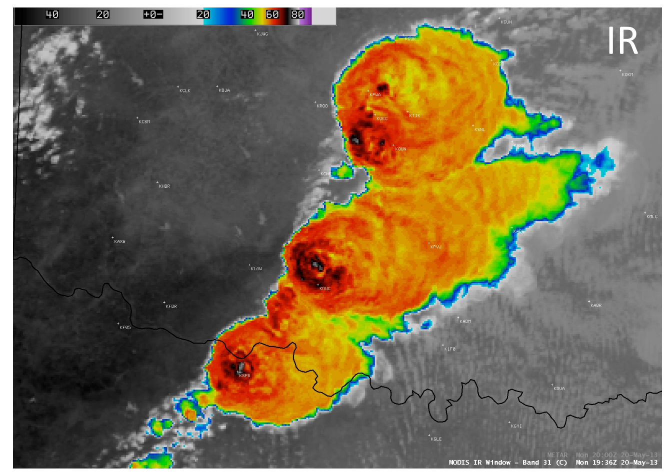
Cloud observations from space

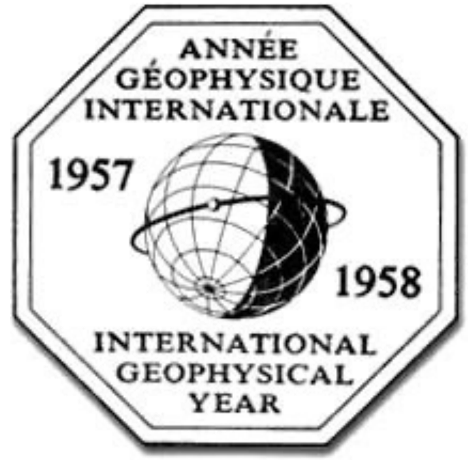


Courtney Schumacher
Texas A&M University



International Geophysical Year

- 1957-1958
- IGY was international effort to advance earth sciences
- In preparation for IGY both U.S. and Russia announced that they would launch an earth satellite



Space race

- 4 October 1957: Launch of Sputnik
  - First earth-orbiting satellite
  - Helped determine density of upper atmosphere

Birth of satellite meteorology

- 13 October 1959: US launches Explorer-7
  - Payload includes Verner Suomi and Robert Parent’s flat plate radiometer

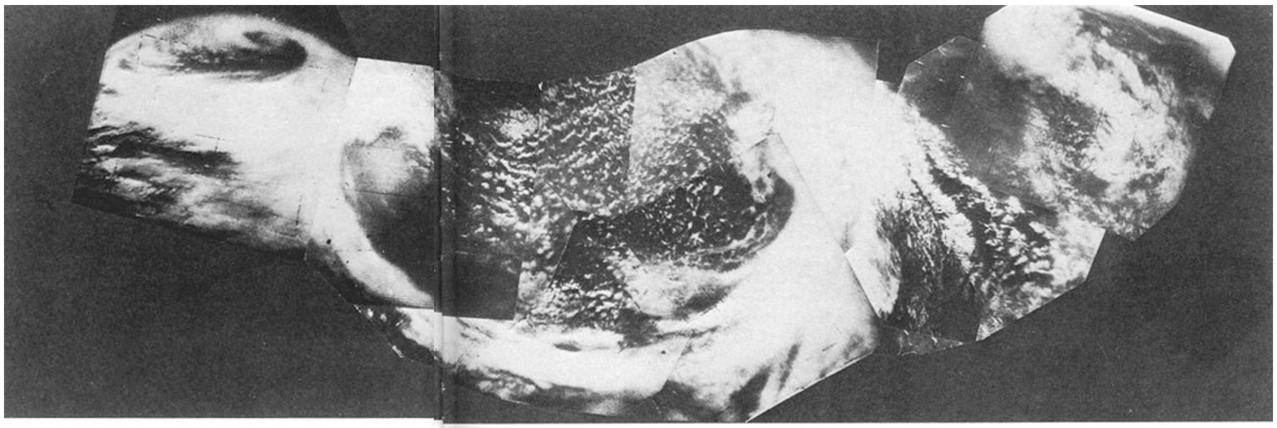
Photo credit: NASA/Courtesy of nasaimages.org

V.E. Suomi and Herman LeGow inspect Explorer 7

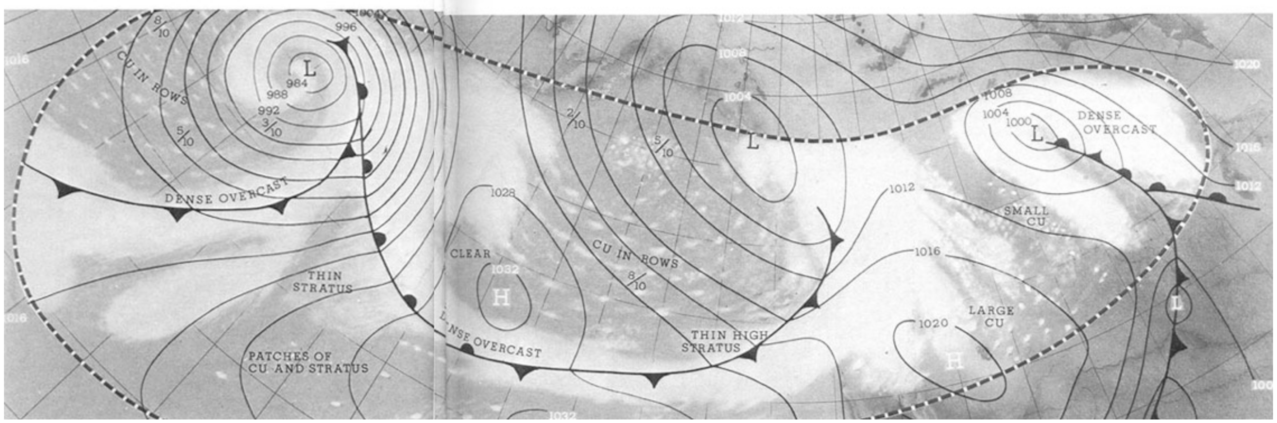
Cameras in space

- 1 April 1960: TIROS 1 - first weather satellite
  - Carried visible camera and passive IR radiometer for daytime and nighttime obs
  - Launched into low-earth orbit
  - Operated for 2.5 months
  - First of 10 TIROS satellites

Clouds and weather correlate

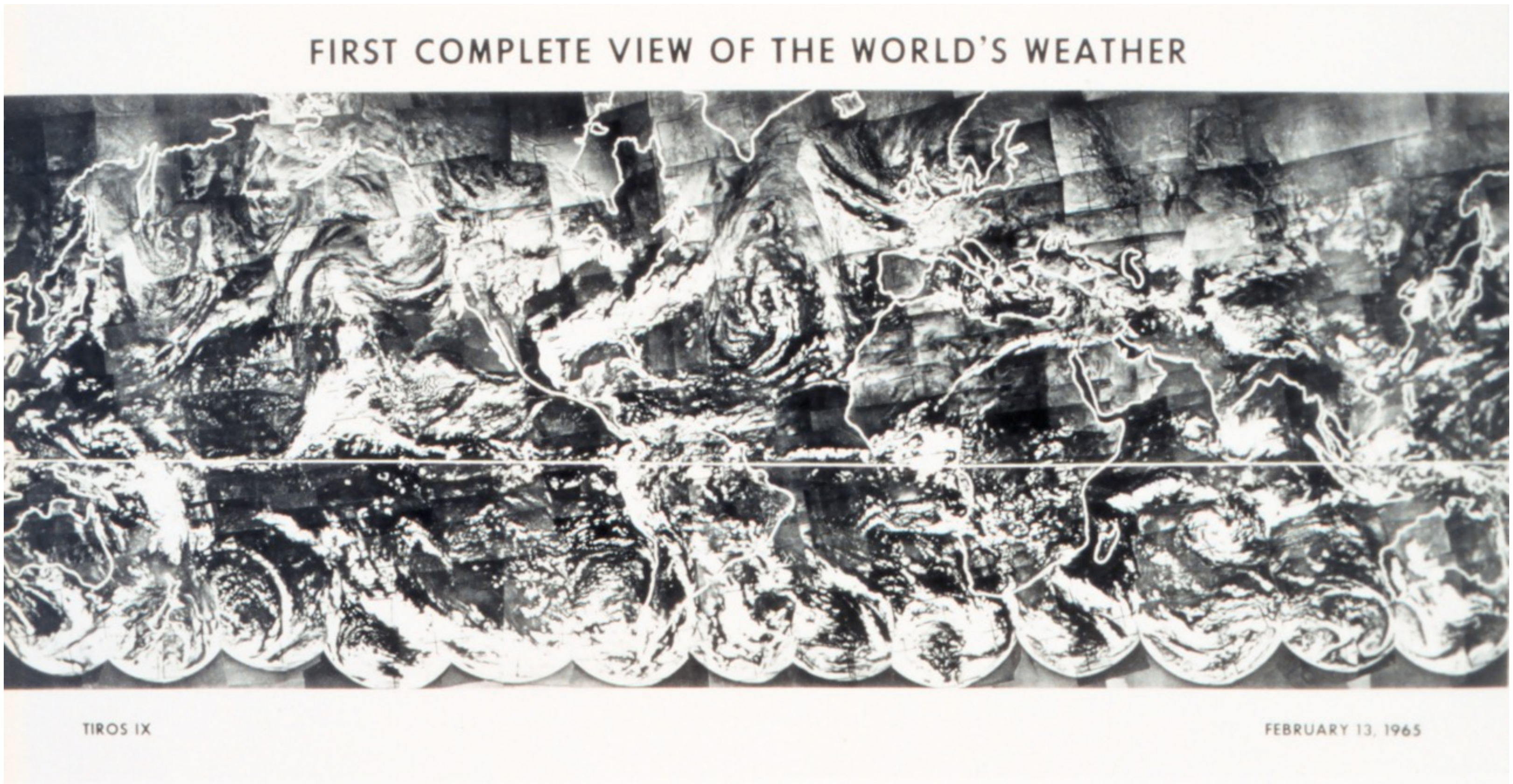


Mosaic of TIROS-1 images from May 19 and 20, 1960

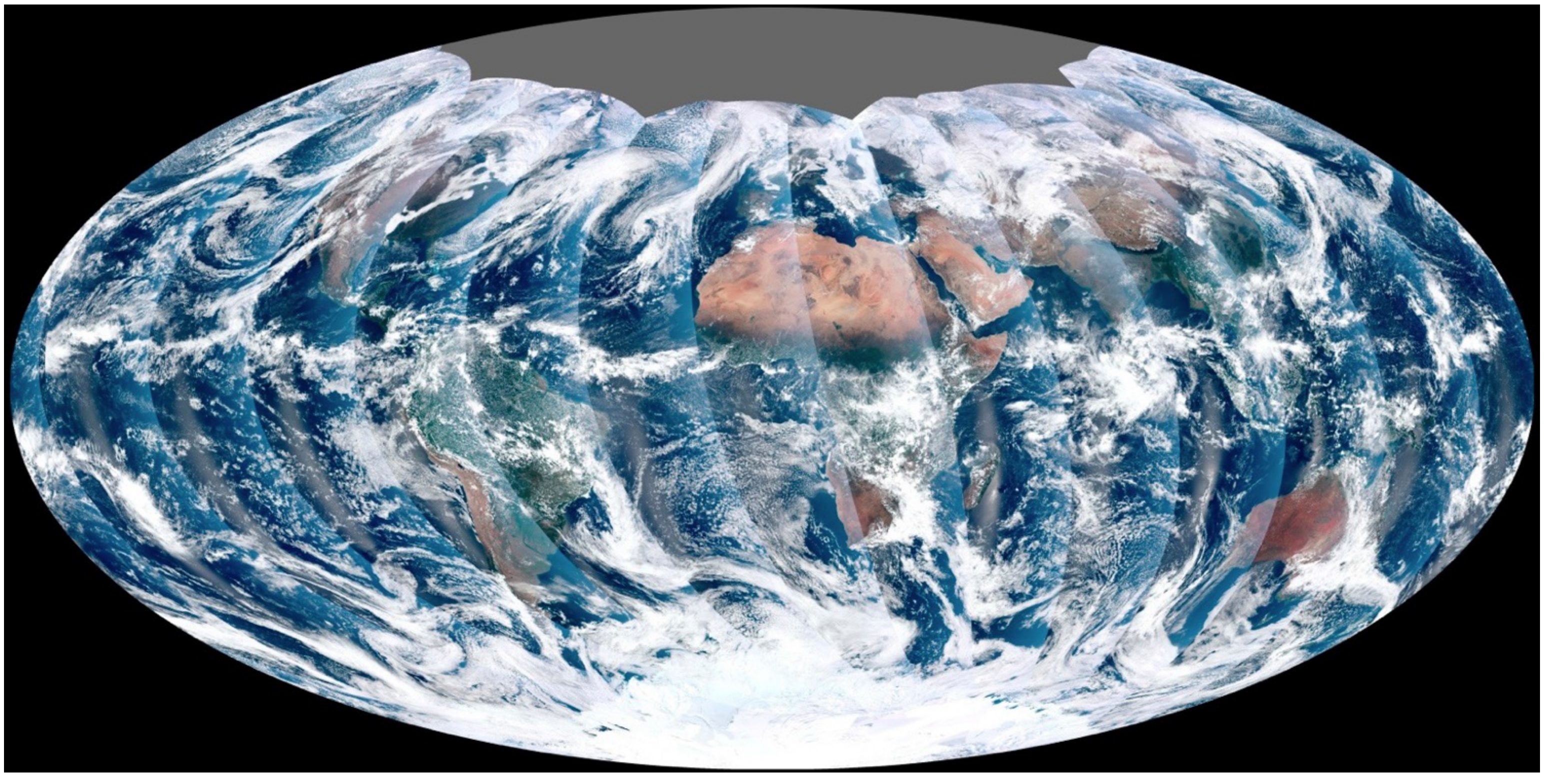


TIROS-1 cloud structure superimposed on a weather map

Historic (1965): TIROS IX (photos)

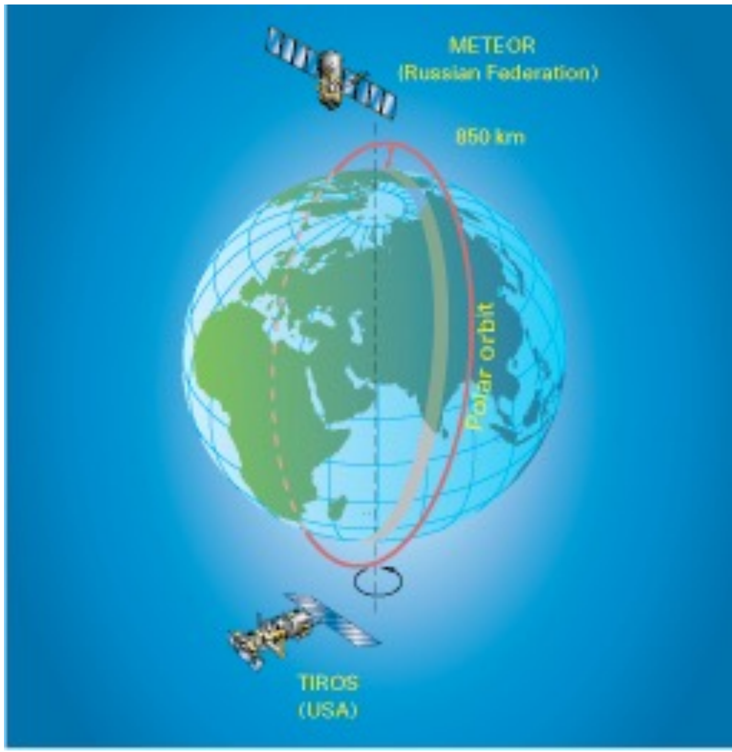


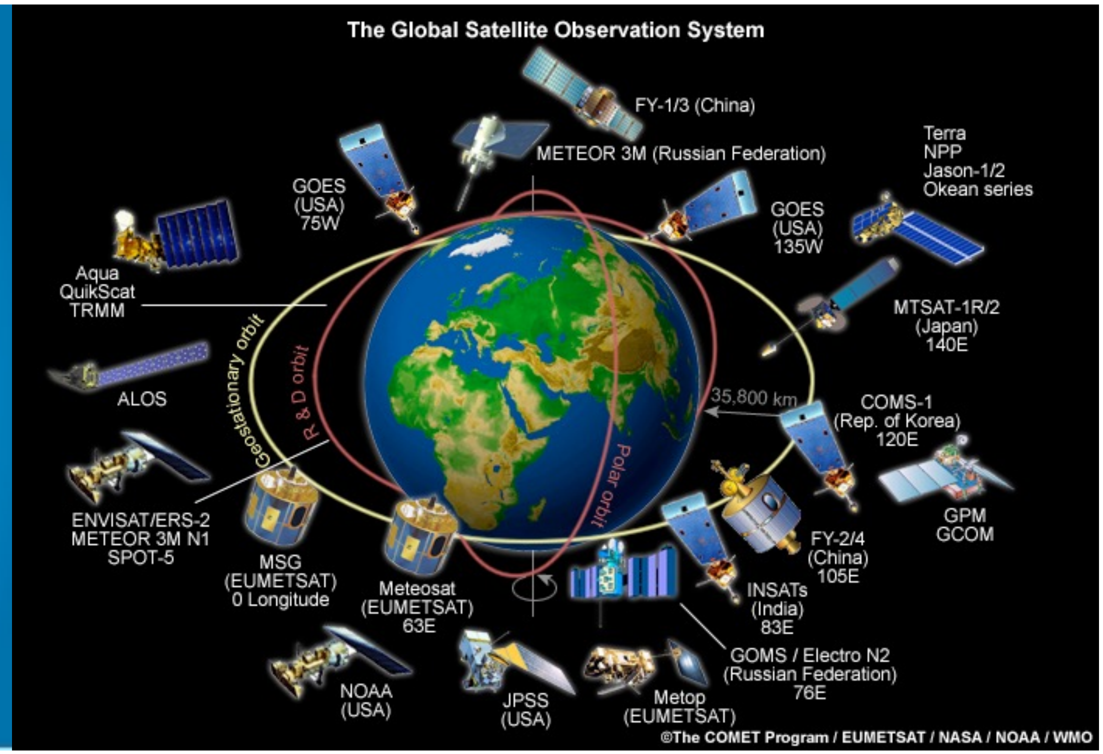
Modern day: 1-day of VIIRS (visible imagery)



On Suomi NPP Satellite

1961 **2009**

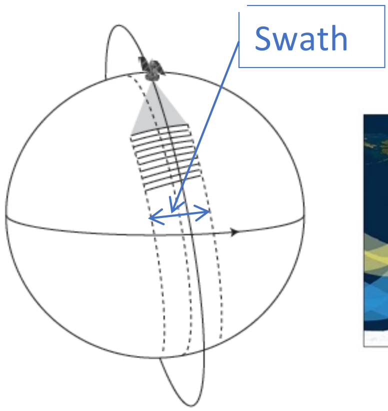




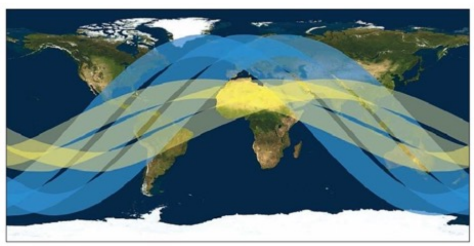
In the past many decades, the instruments and the orbits and wavelengths they use to measure weather and climate have proliferated.

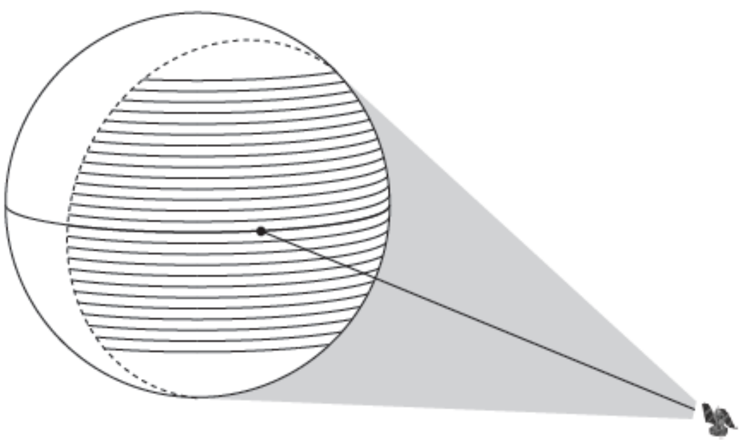
Orbits and scan geometry

Polar



Inclined





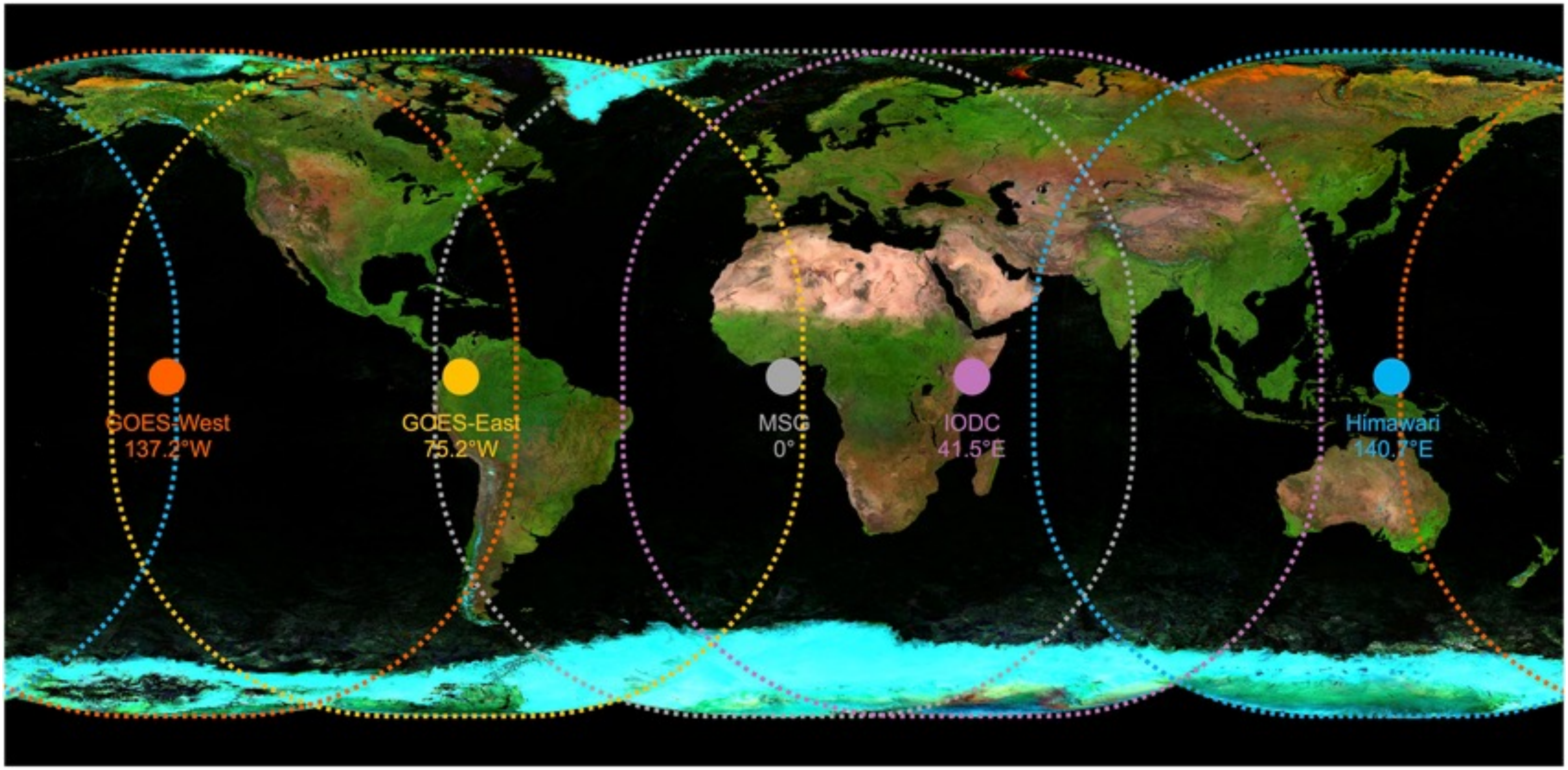
Low-earth orbit

- 300-1000 km above Earth
- Polar/sun-synchronous (same time each day, e.g., 1 am/1 pm)
- Inclined/non sun-synchronous (sampling at different times of day in precessing orbit)
- http://youtu.be/y_jM_BxQGvE

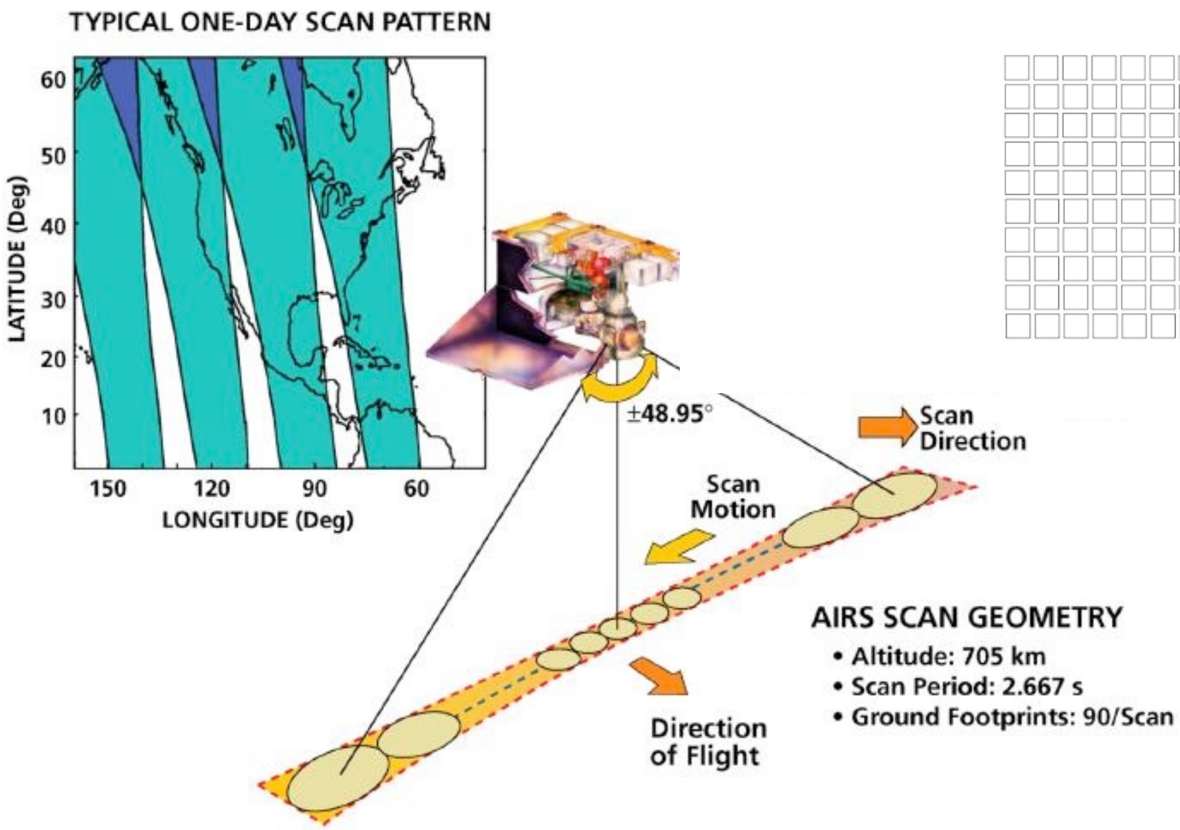
Geostationary

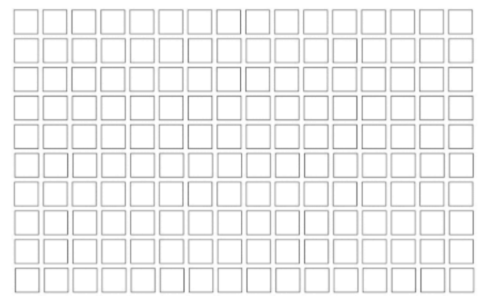
- 35,786 km above Earth
- Most of hemisphere (except poles)
- Full disk: every 15 minutes, regional: every 5 minutes, mesoscale: 30 - 60 seconds
- https://www.youtube.com/watch?time_continue=1&v=qCAPwgQR13w

Geostationary satellite coverage



Cross-track scanning

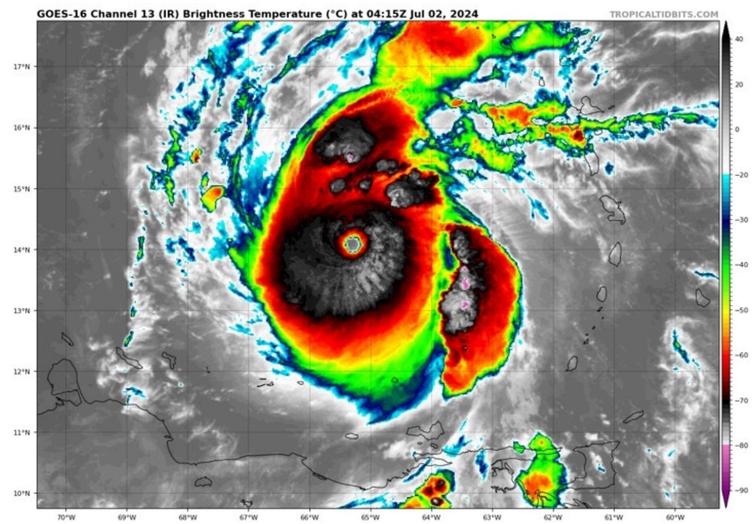




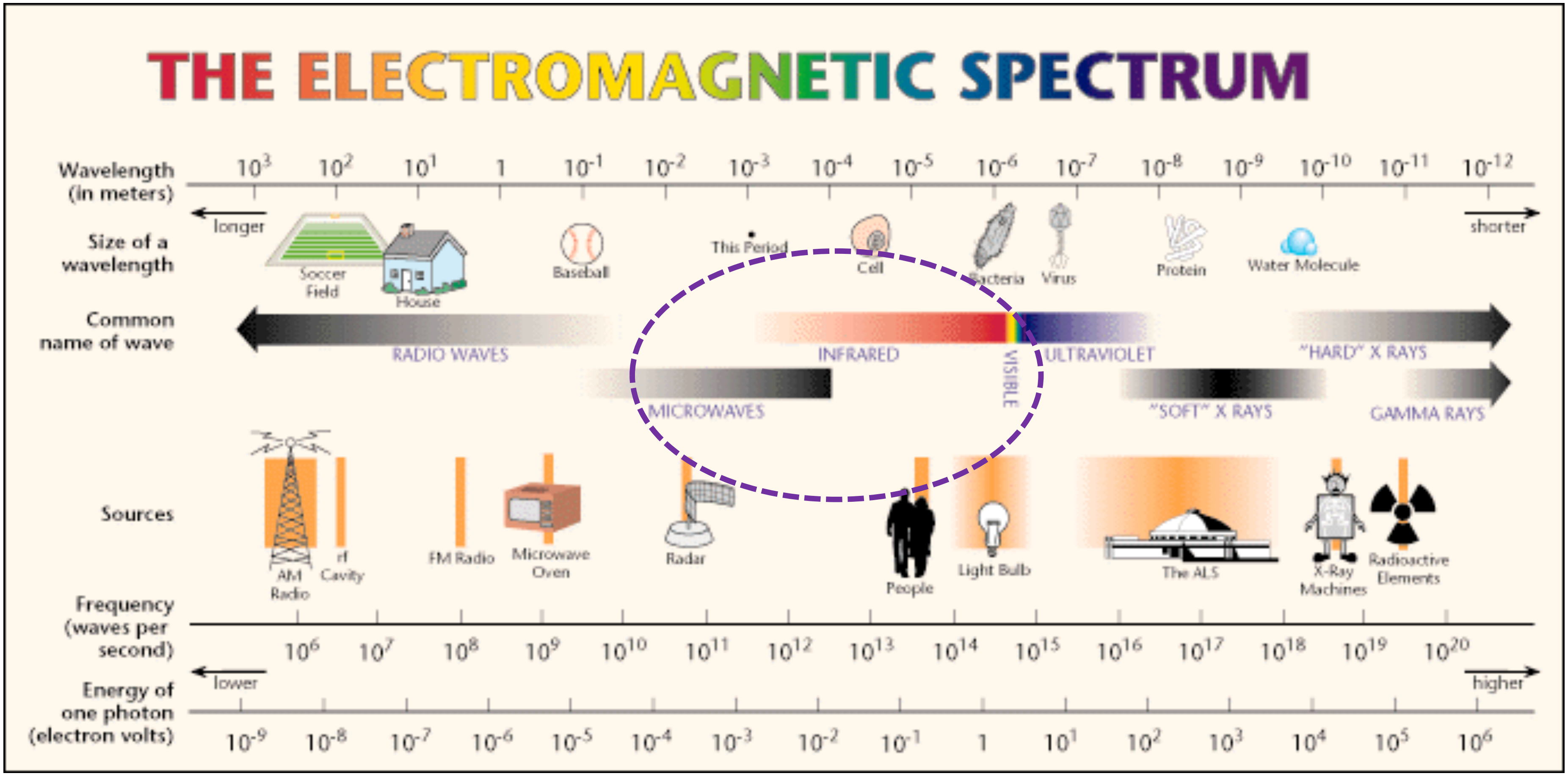
- Best resolution at nadir
- Footprints increase in size at swath's edge

Satellite architecture design/data set choices

- What are you trying to study?
  - For example: Tropical cyclone precipitation structure
  - Need to observe/resolve eyewall and rainbands
- Over what area?
  - Inclination, swath width
- How frequently do we need to observe?
  - Period
- At what spatial resolution?
  - Footprint size, number of footprints
- At what accuracy?
  - Altitude

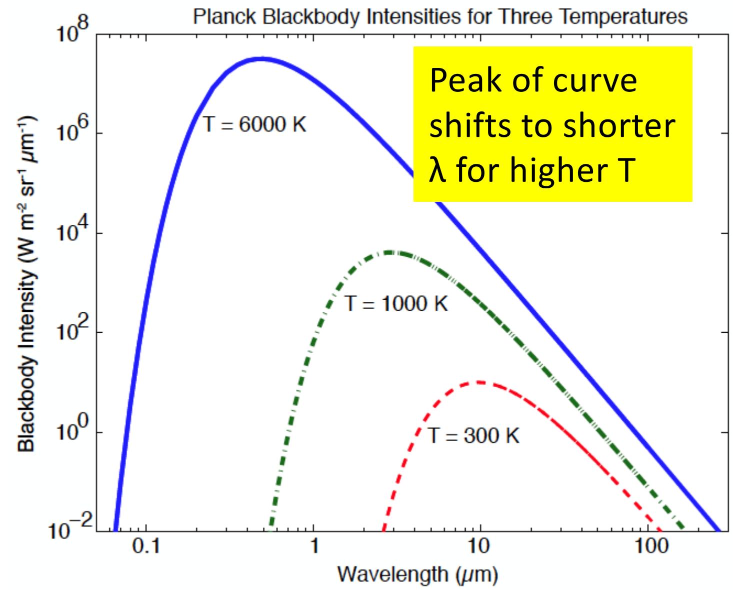


Note: Choices affect multiple categories, tradeoffs!


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^{3} 10^{2} 10^{1} 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

Solar vs. Terrestrial

- Typical delineation
    - Shortwave radiation λ < 4 µm
    - Longwave λ > 4 µm



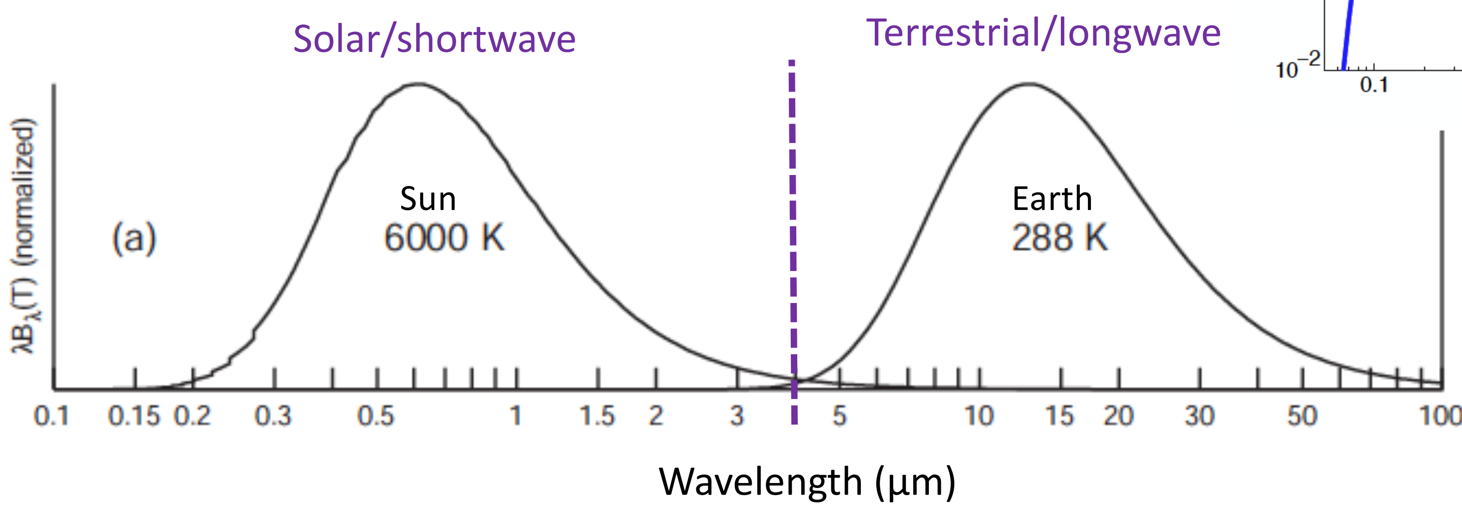


Figure 3.3 from Petty (2006)

Shortwave

Table 3.1: Regions of the electromagnetic spectrum

Region	Spectral range	Fraction of solar output	Remarks
Visible	$0.4 < \lambda < 0.7\ \mu m$	39%	Atmosphere mostly transparent
Near IR	$0.7 < \lambda < 4\ \mu m$	52%	Partially absorbed, mainly by water vapor
Thermal IR	$4 < \lambda < 50\ \mu m$	0.9%	Absorbed and emitted by water vapor, carbon dioxide, ozone, and other trace gases
Far IR	$0.05 < \lambda < 1$ mm		Absorbed by water vapor
Microwave	$\lambda > 1$ mm		Clouds semi-transparent

Petty (2006)

GOES shortwave channels (0.5-1 km, daytime only)

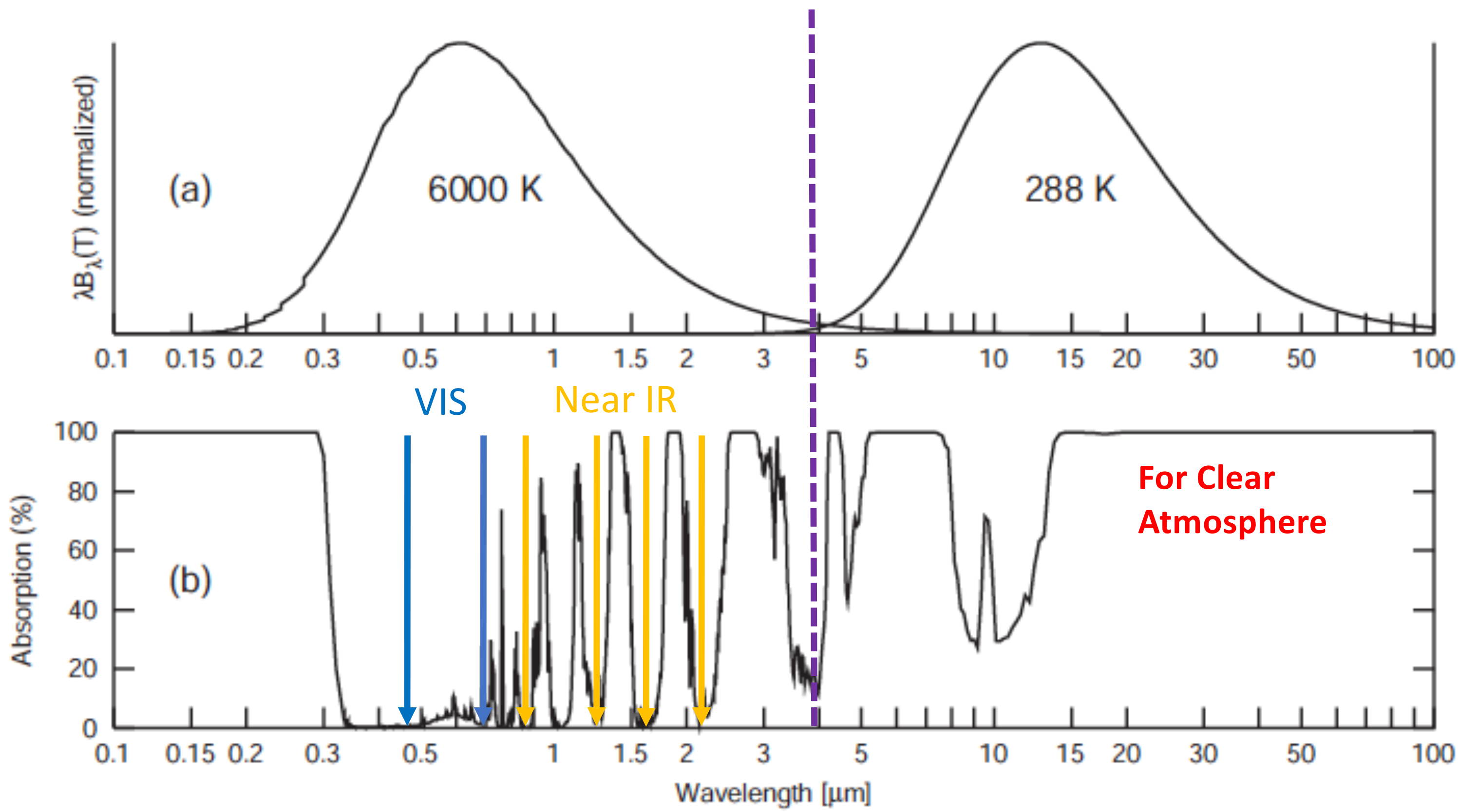
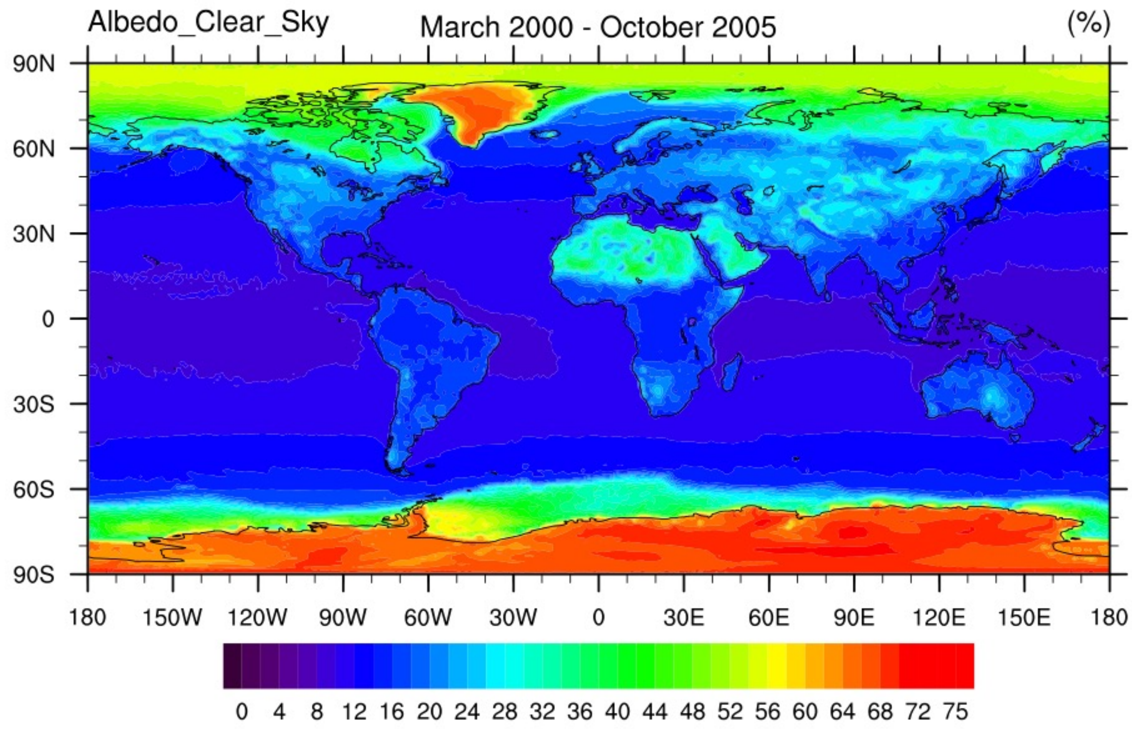
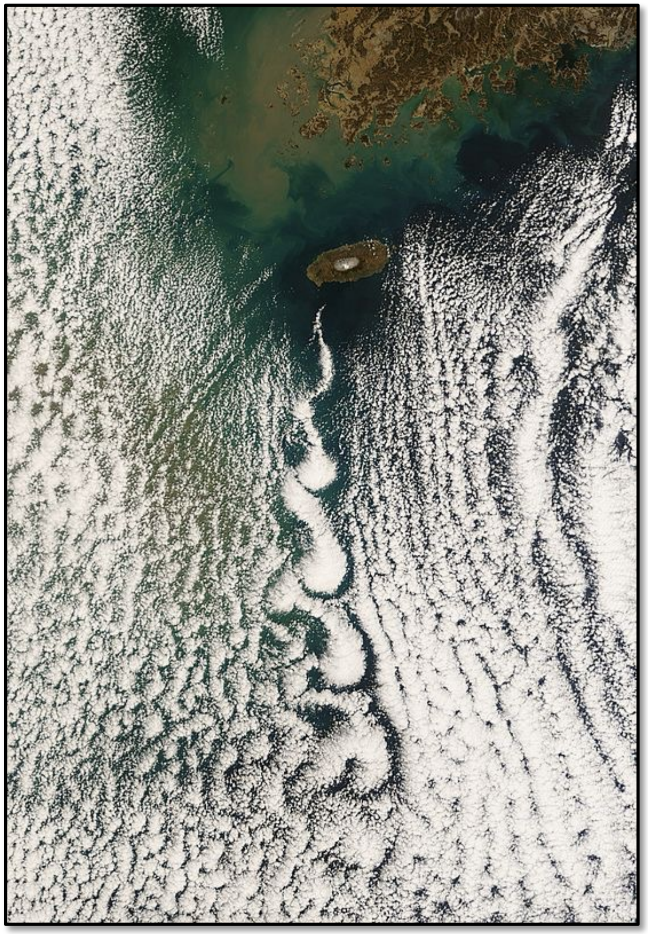


Figure 3.3 from Petty (2006)

Visible

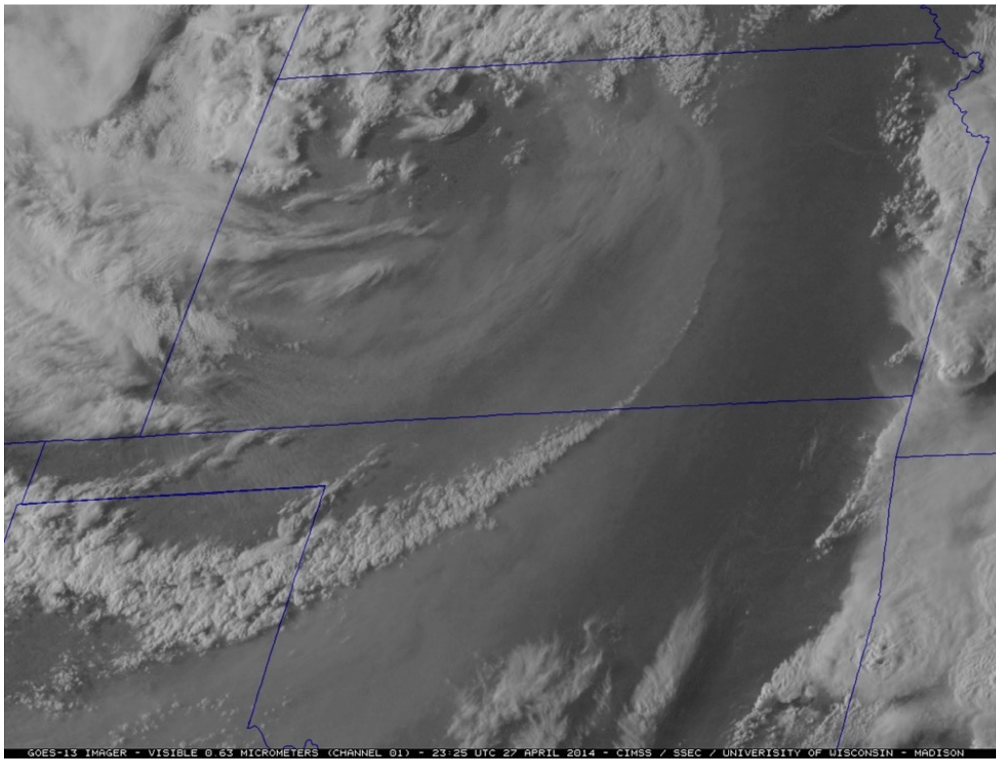
- Useful for identifying reflective surfaces
  - albedo
  - cloud structure and thickness

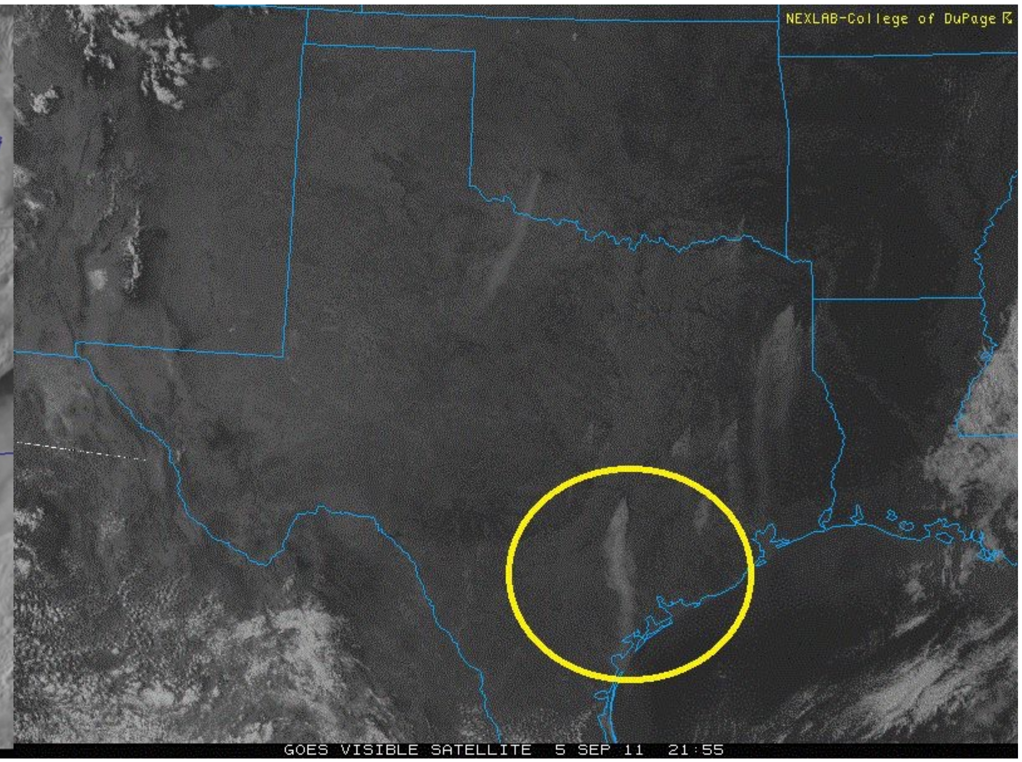




Visible

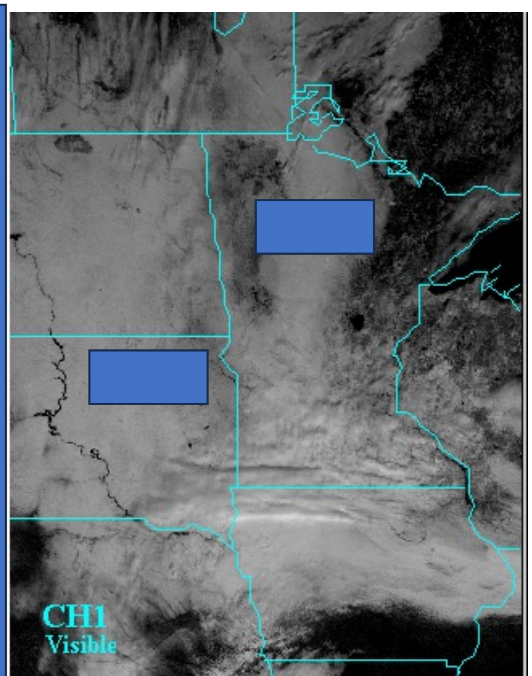
- Also good for dust and smoke





Visible + Near IR

- Together, VIS & Near IR can be used to retrieve
  - cloud vs snow
  - optical thickness (thicker clouds) and cloud phase
  - cloud particle size



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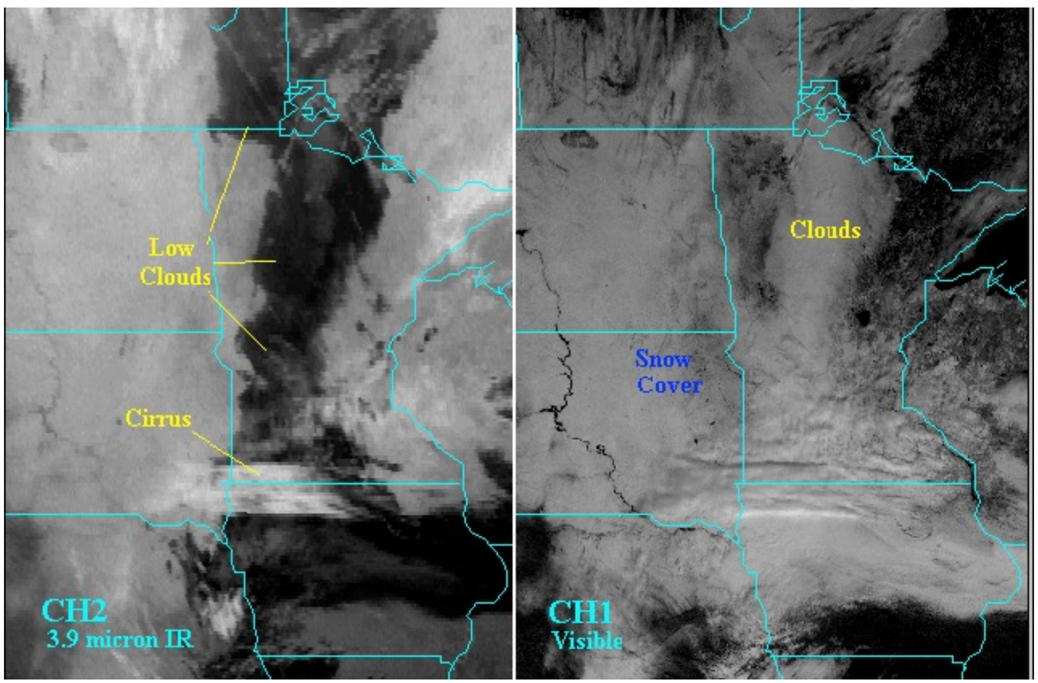
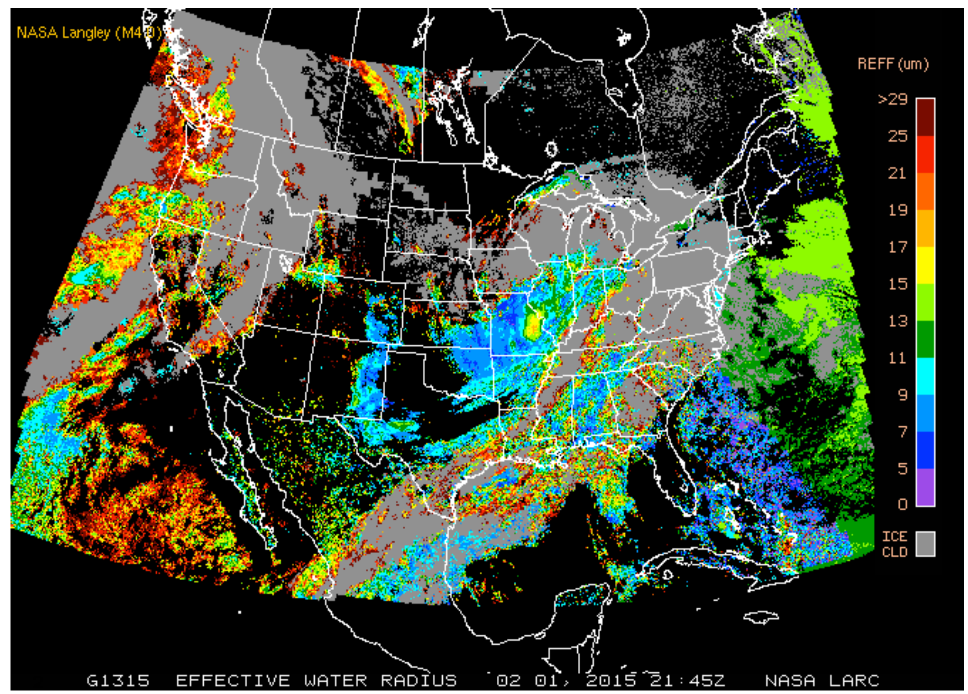


Cloud particle effective radius



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Microwave	$\lambda > 1$ mm		Clouds semi-transparent

Longwave

Petty (2006)

GOES longwave channels (2 km, day and night)

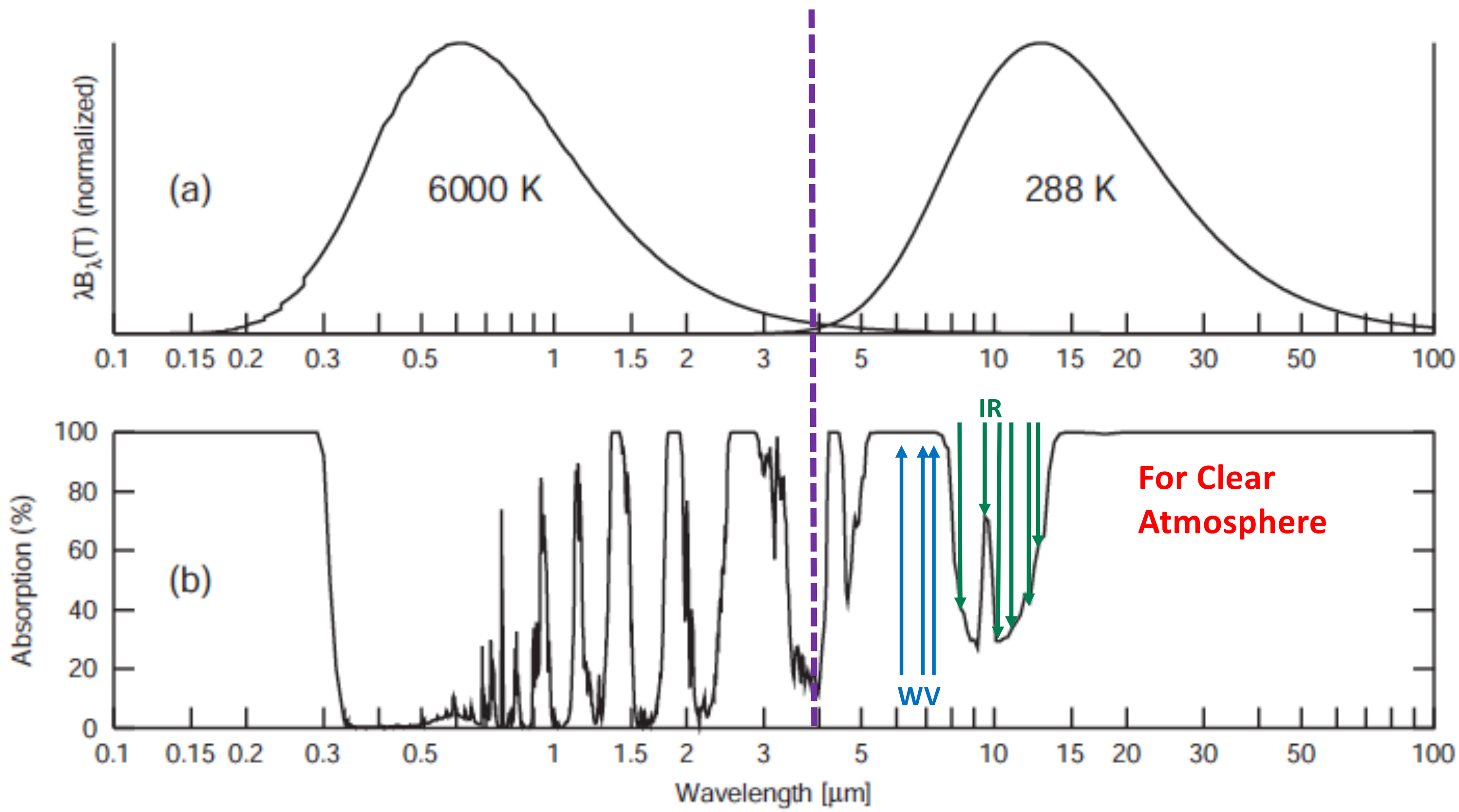
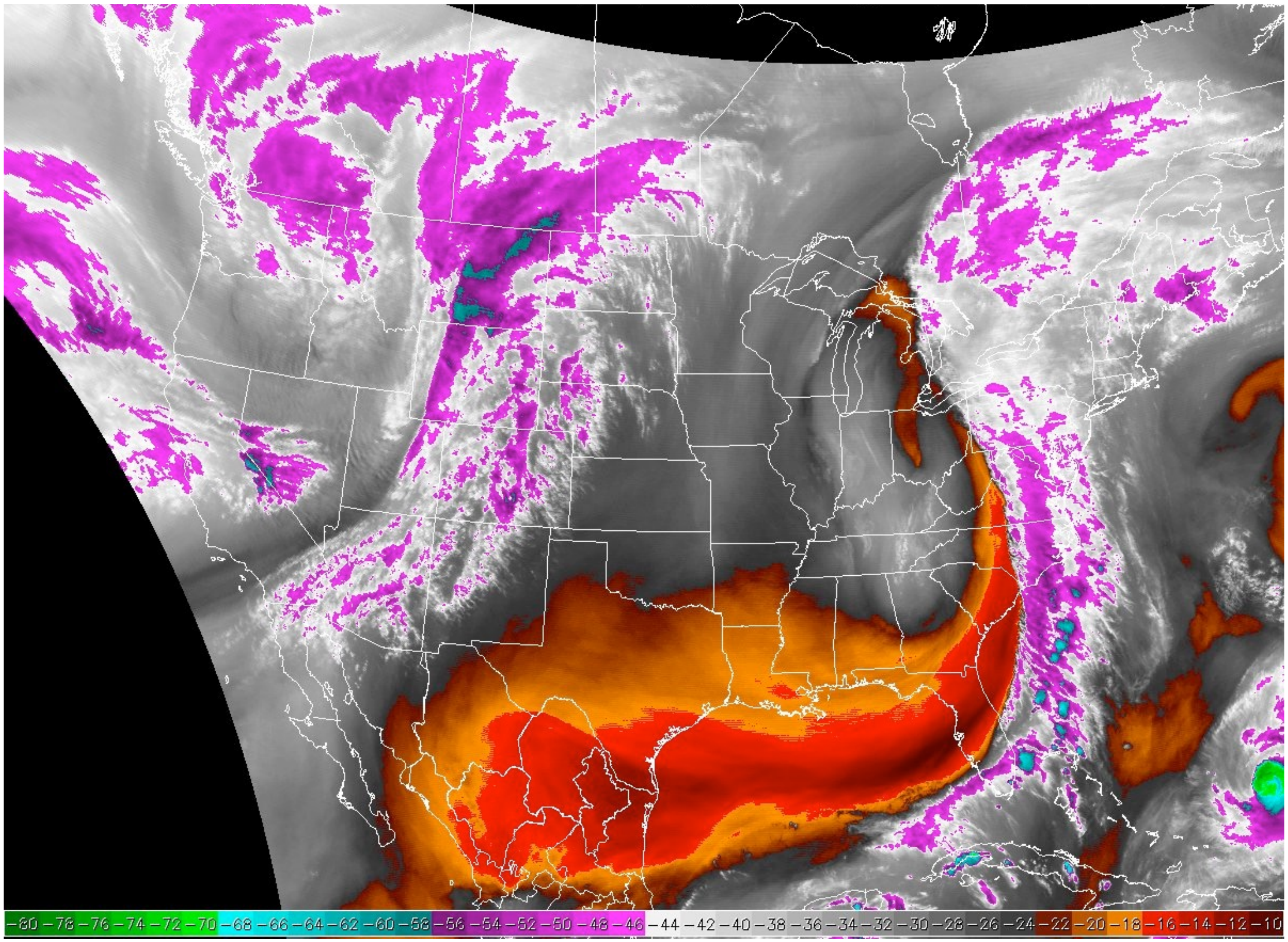
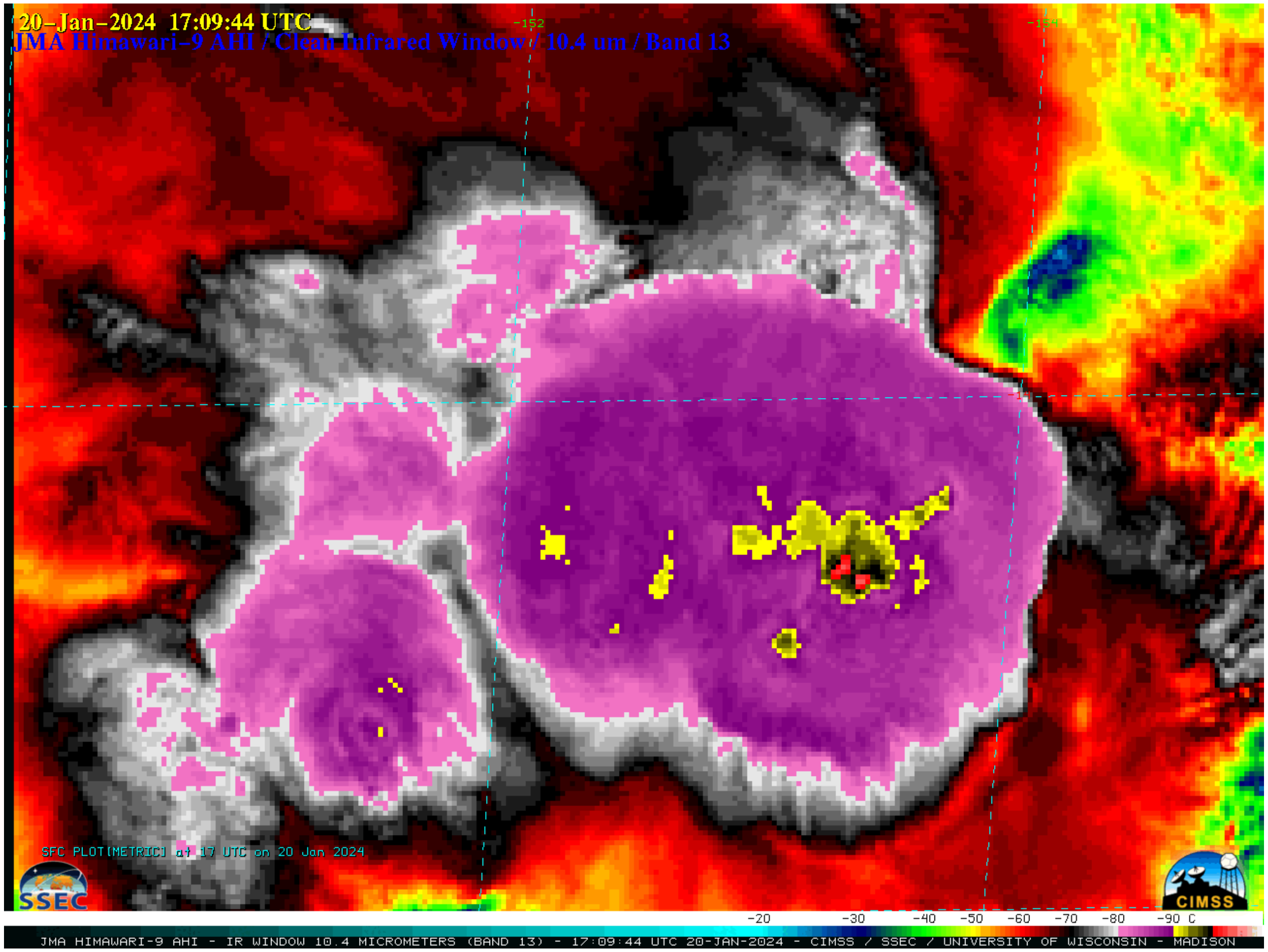


Figure 3.3 from Petty (2006)

IR water vapor at mid/upper levels



IR brightness temperature in window region



https://cimss.ssec.wisc.edu/satellite-blog/archives/56584

- Representative of cloud top temperature
- Intermittent convective bursts (and overshooting tops) within growing cold canopy over Coral Sea
- Coldest observed brightness temperature by geostationary satellite (-103.83ºC)

Climatology of Aqua/MODIS coldest cloud tops

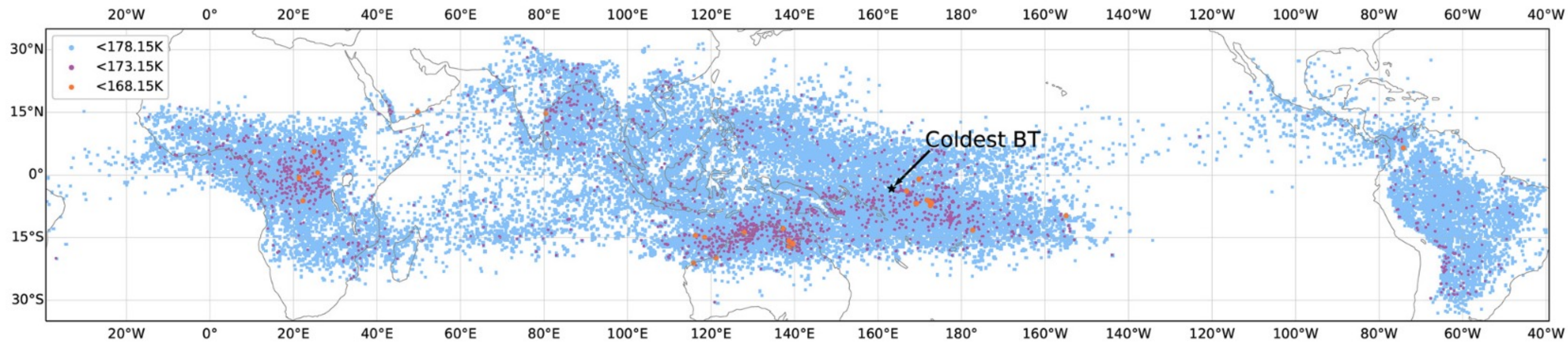


Figure 4. A map of all particularly cold brightness temperatures (BTs) recorded by the MODIS instrument aboard NASA's Aqua satellite between August 2004 and August 2020. The location of the cold BT discussed in this study is shown by the red star. Areas outside 30° North/South latitude are excluded, as no extreme cold BTs were recorded there. Similar, regional, data for AHI is shown in Figure S4. AHI, Advanced Himawari Imager; BT, brightness temperature.

Proud and Bachmeier (2021)

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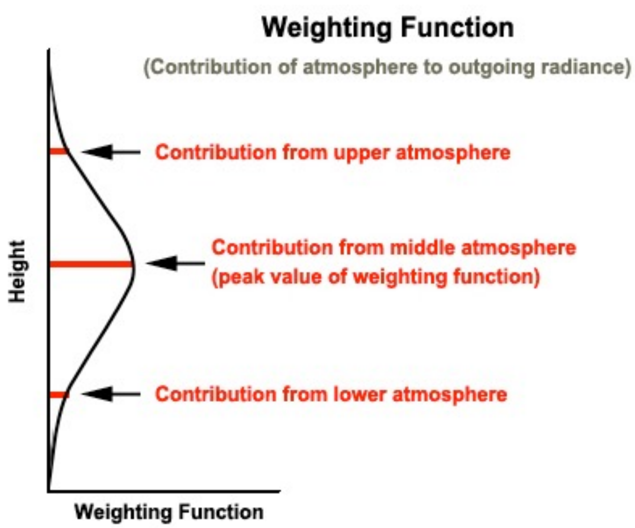
Longwave (Microwave row) — Or < 300 GHz

Petty (2006)

Weighting functions

- Represent contribution of atmospheric layers to measured intensity (I_λ)
- Peak higher in atmosphere the closer a channel is to center of absorption band

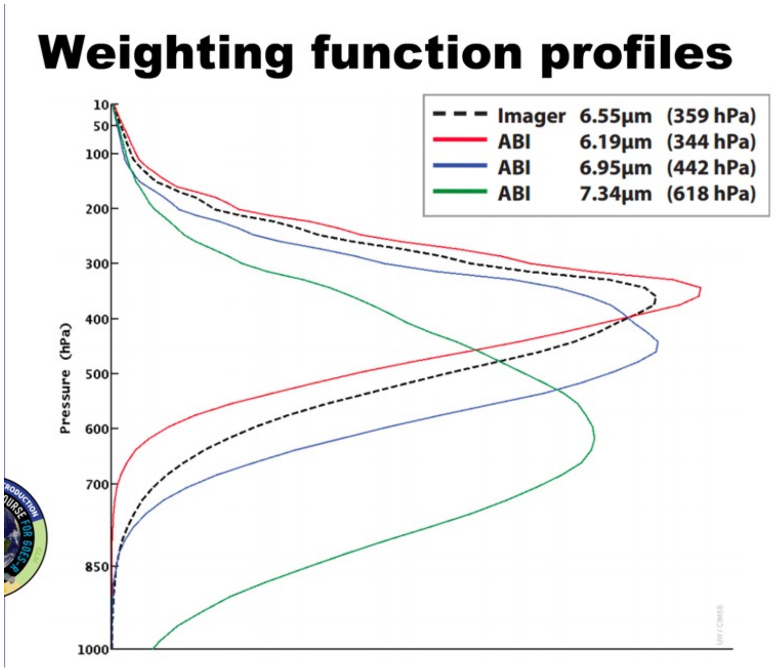
Example



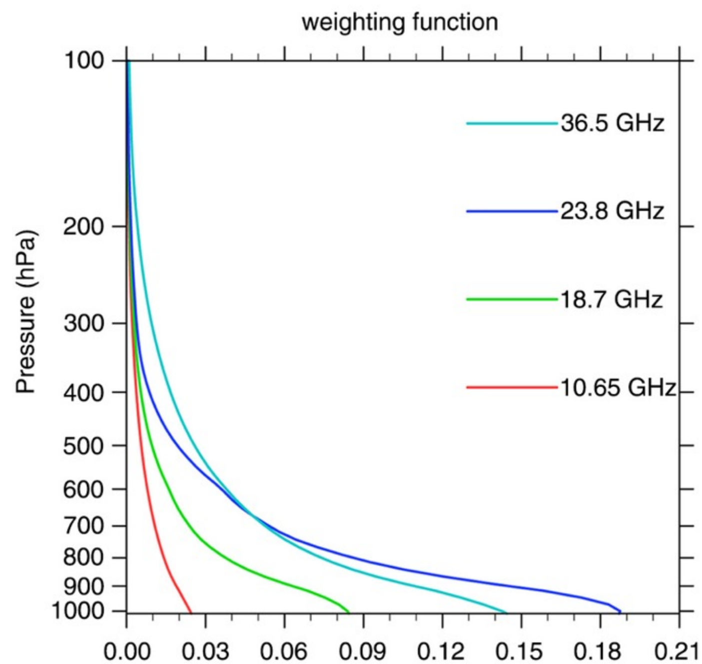
- **More attenuation of radiation from lower levels (small contribution to measured I_λ)**
- **Small contribution from upper levels (less absorber)**
- **Peak represents region of atmos that contributes most to I_λ**

Weighting functions

GOES IR



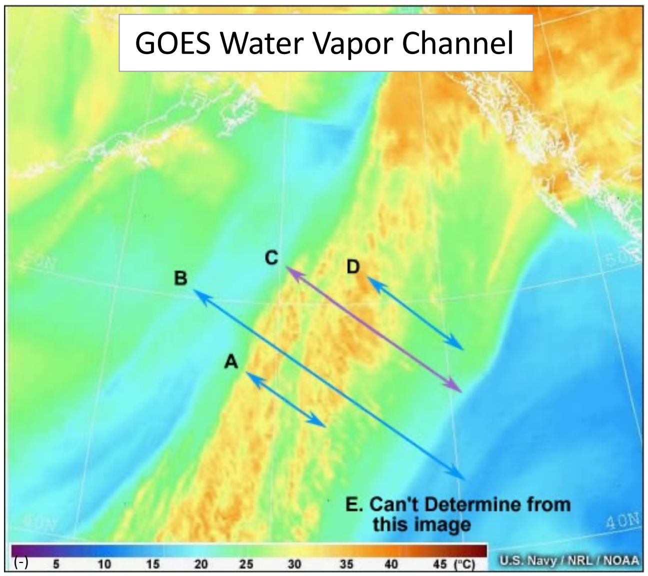
AMSR2 Passive MW

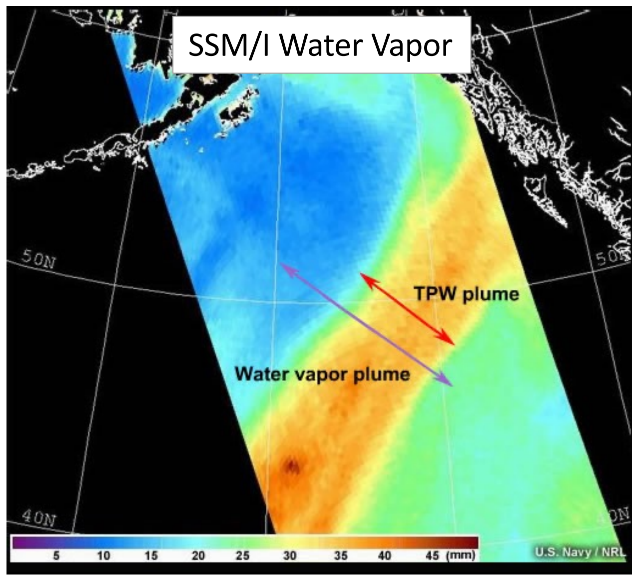


Better measure of water vapor near the surface

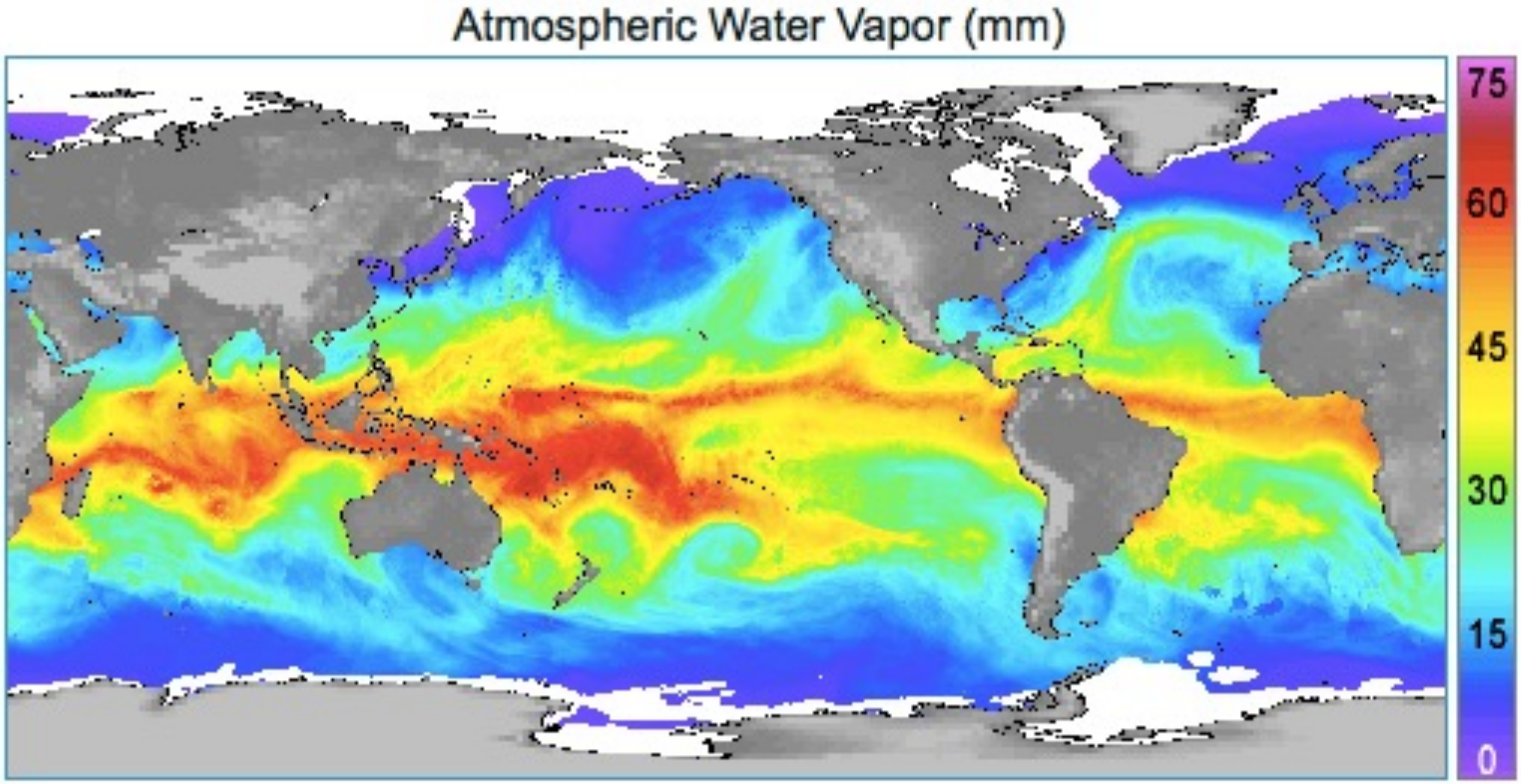
Total Precipitable Water

- 23 GHz
  - Sees entire atmospheric column (transmissivity≈0.85)
  - However, coarser resolution than IR and passive MW instruments not on geostationary satellites (only low-earth orbit)

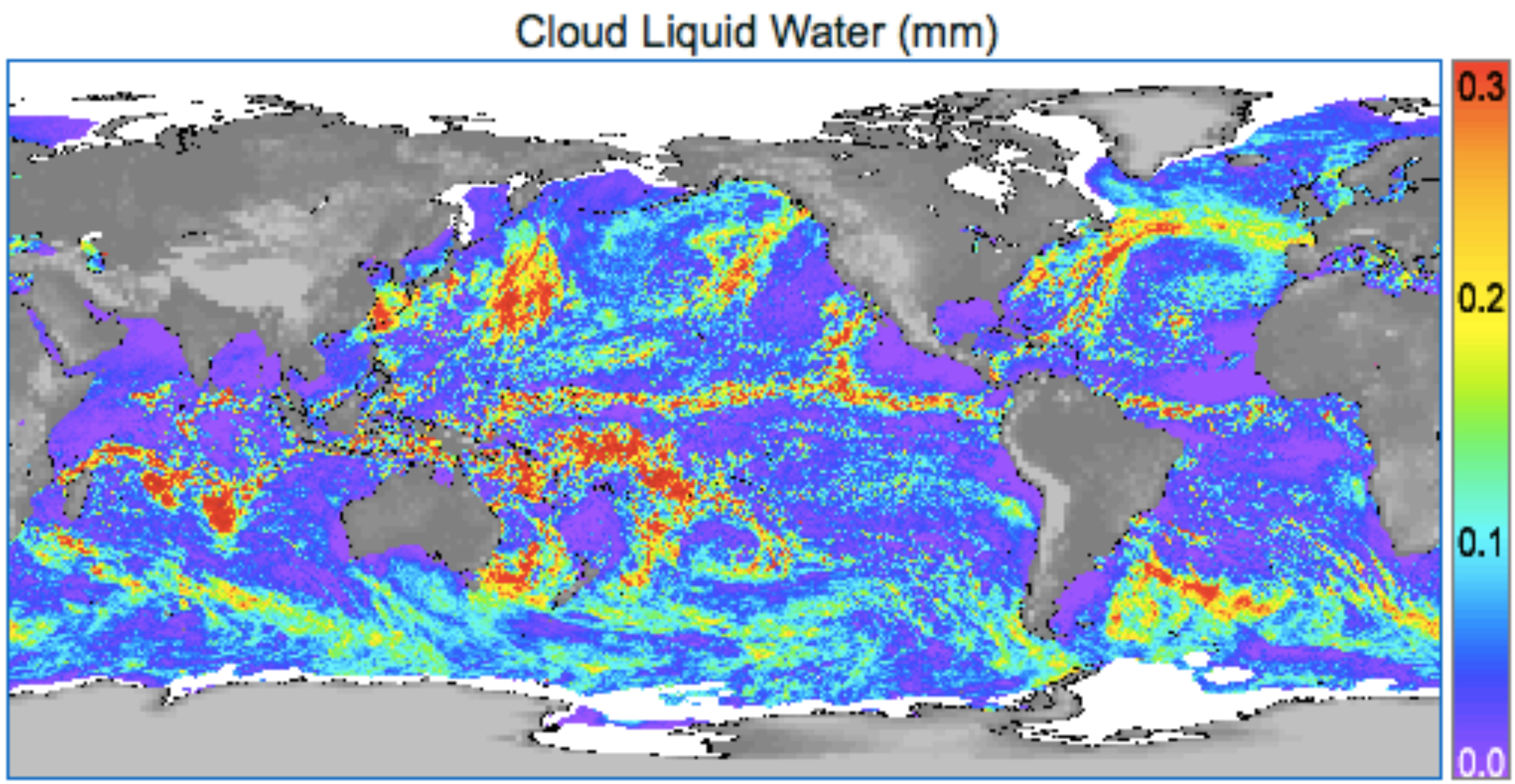




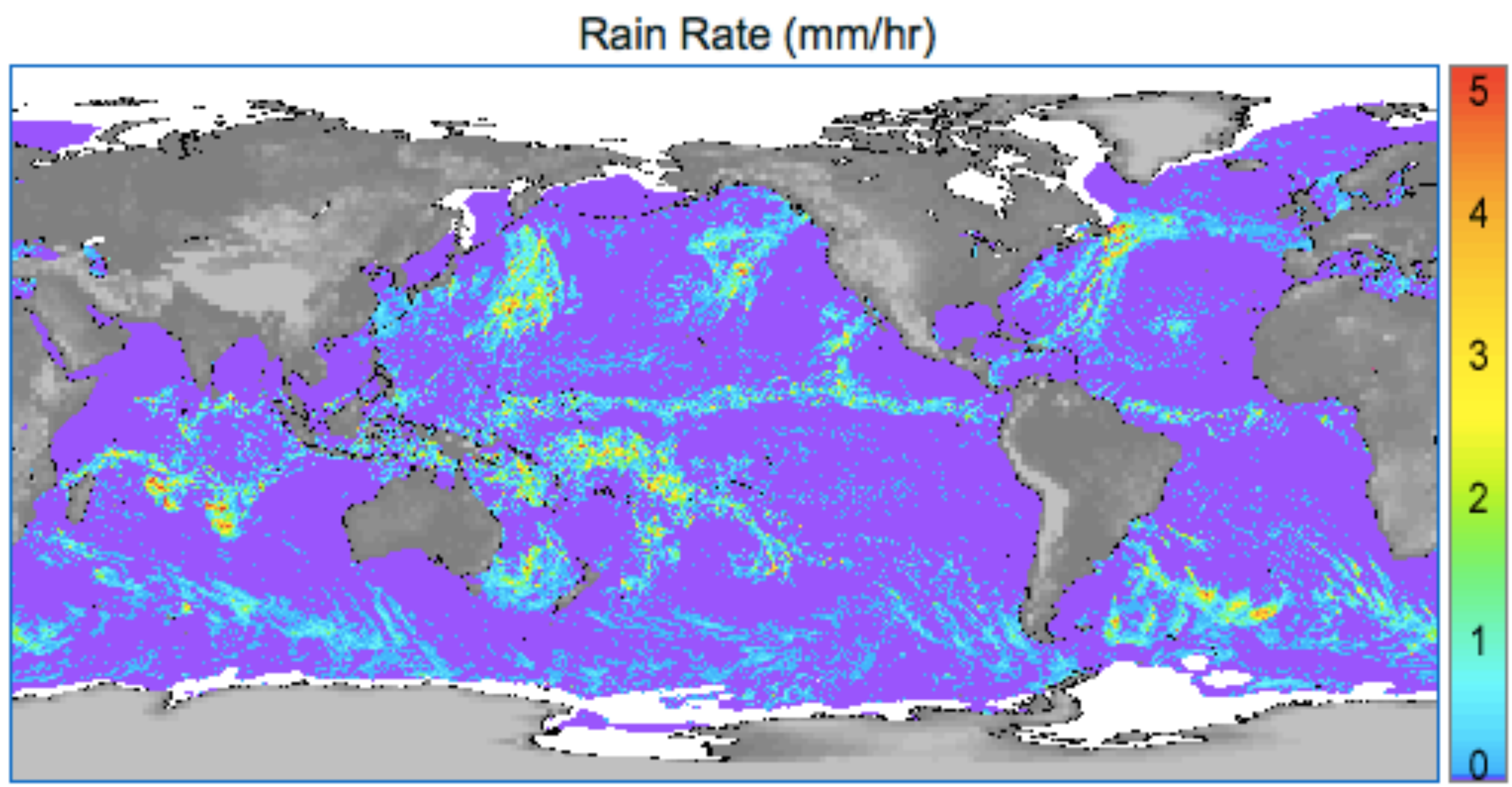
Passive MW Integrated Water Vapor



Passive MW Liquid Water Path

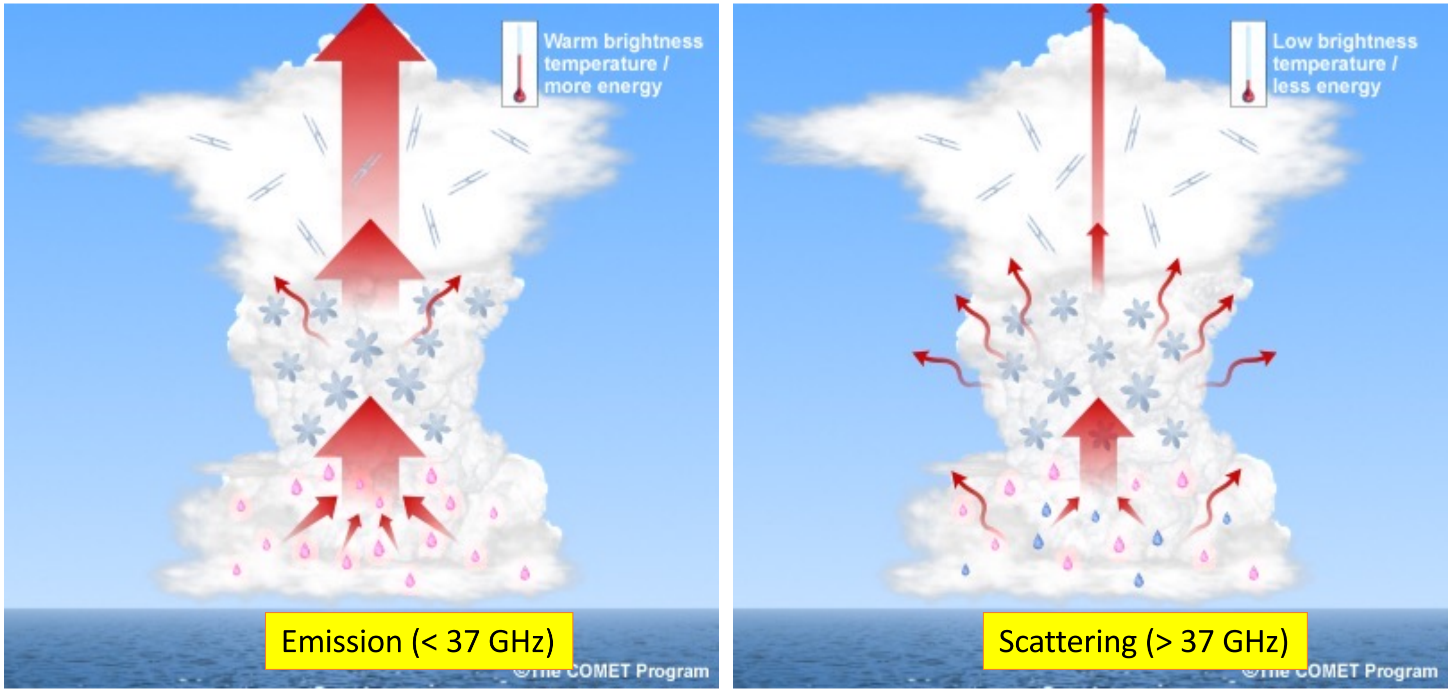


Passive MW Rainfall



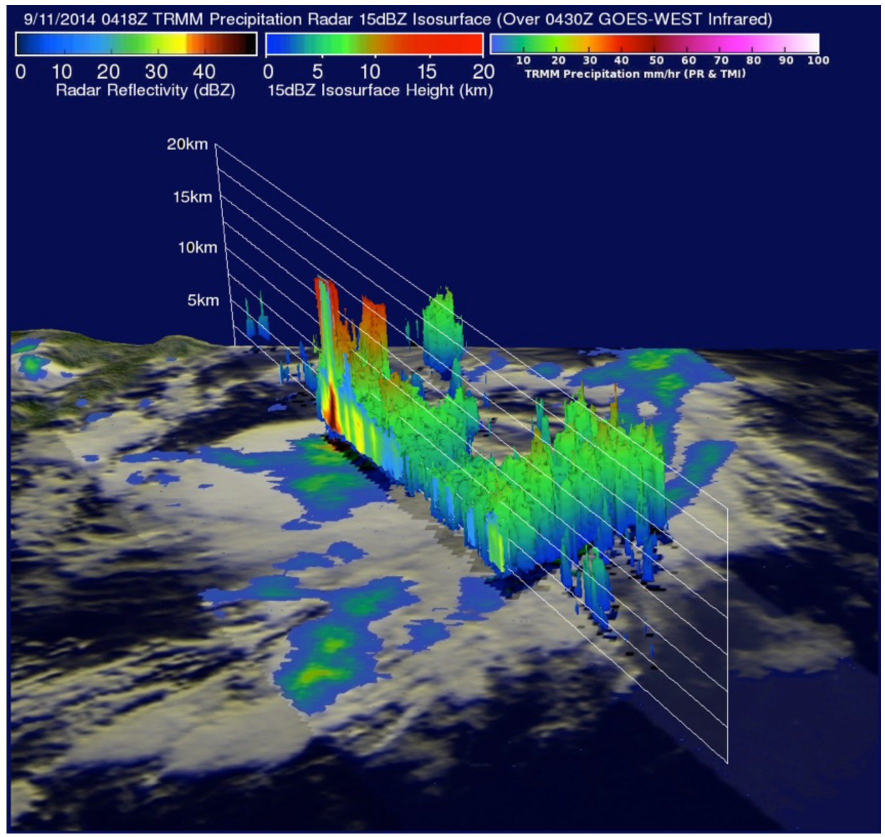
Passive MW Rainfall

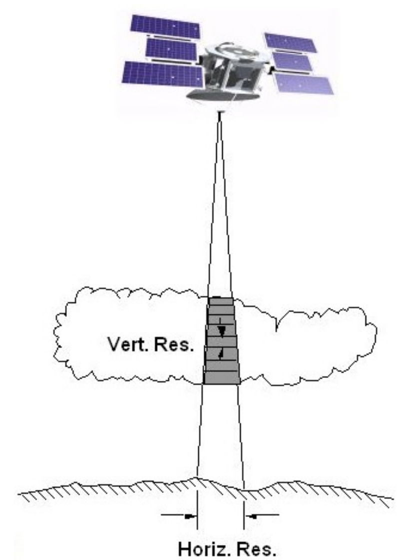
- ν < 37 GHz referred to as emission channels since the rainfall signature is primarily due to emission (used over ocean only)
- Higher ν referred to as scattering channels since their rainfall signals rely on ice scattering (land and ocean)



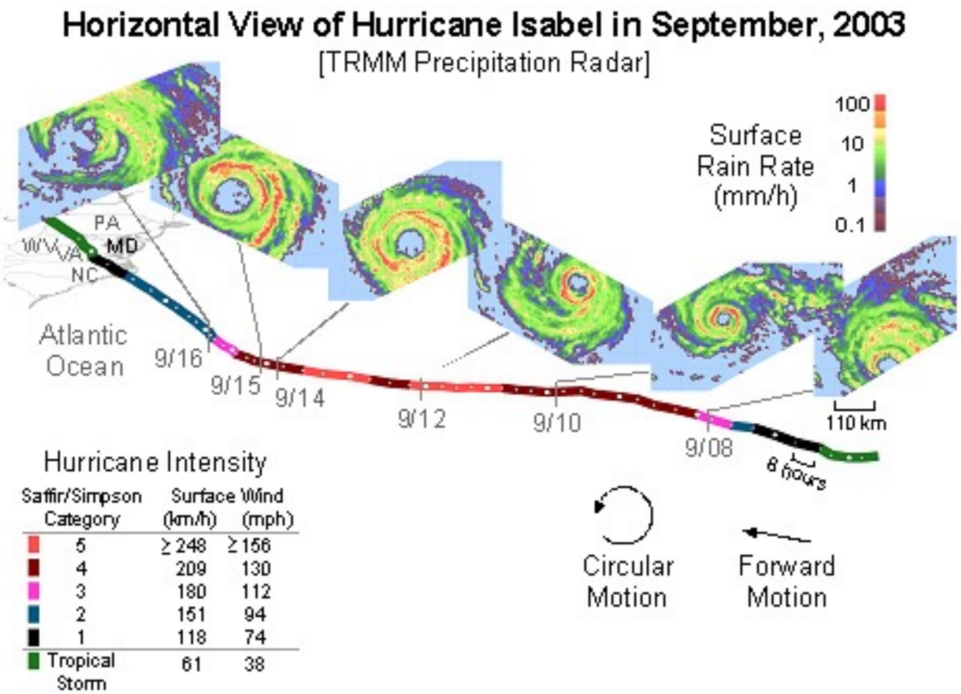
Active MW remote sensing (i.e., radar)

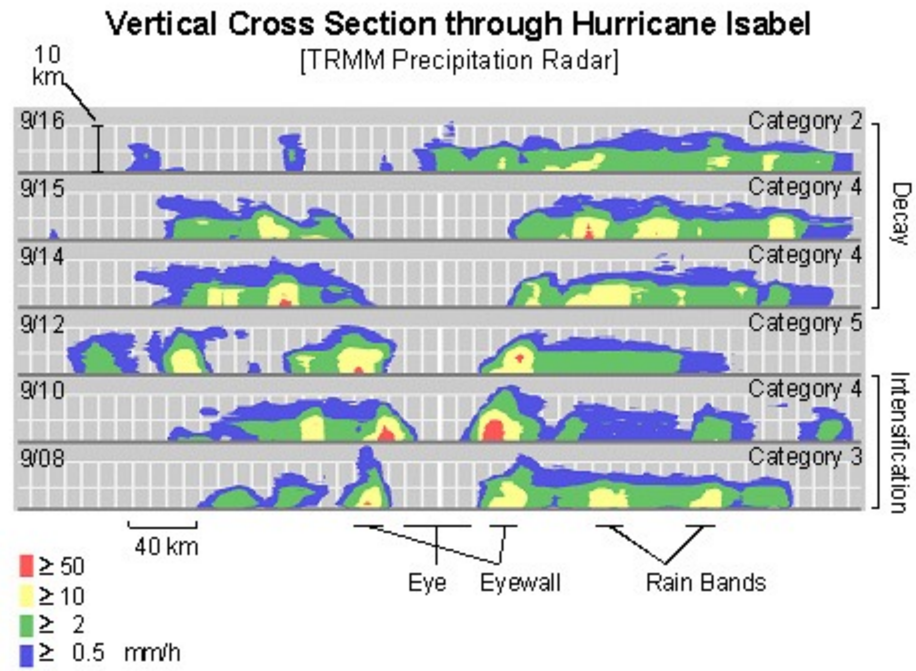
- 3D view!
- TRMM (launched late 1997) and GPM (still in orbit) carry precipitation radars
- CloudSat (and recently EarthCare) carry cloud radars
- Upcoming research radar missions include INCUS and AOS





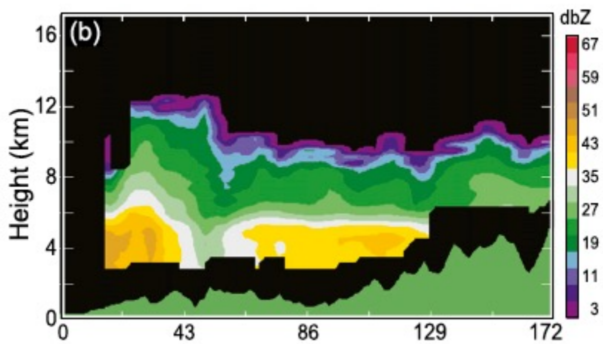
TRMM PR snapshots of Isabel



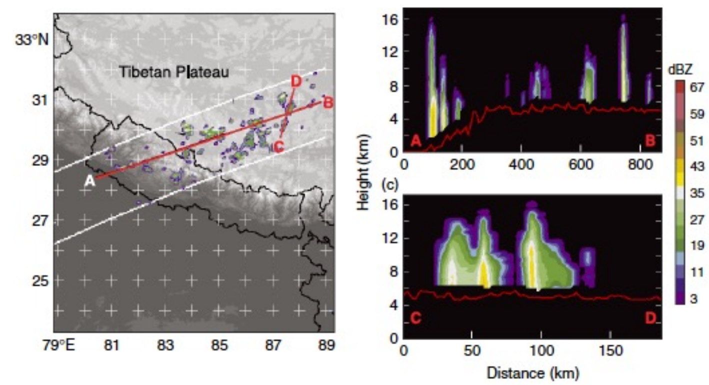


PR allows 3D view of storms well as snapshots of evolution of 3D structure

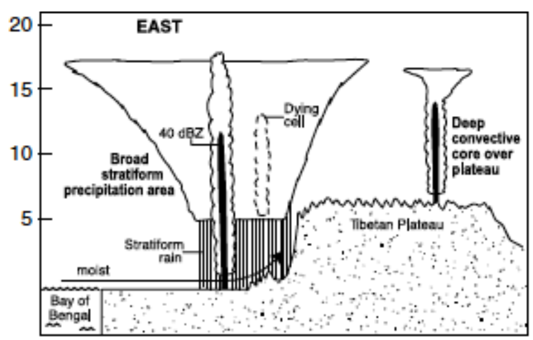
TRMM PR cross sections over western Nepal

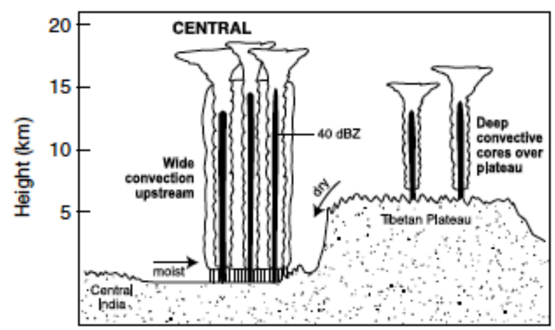


Houze et al. (2017)



Houze et al. (2007)



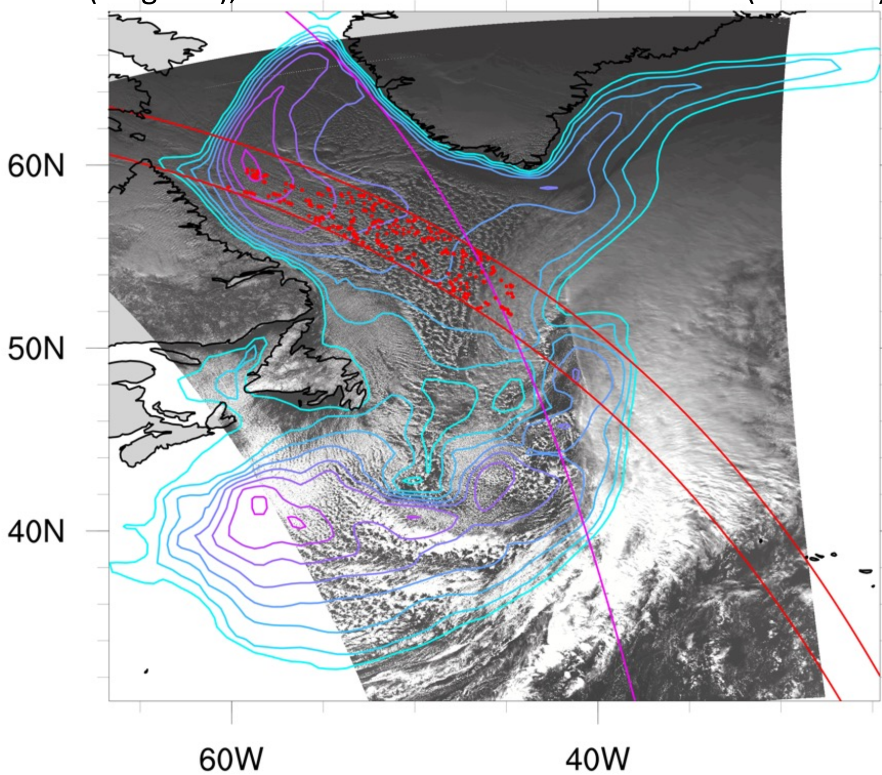


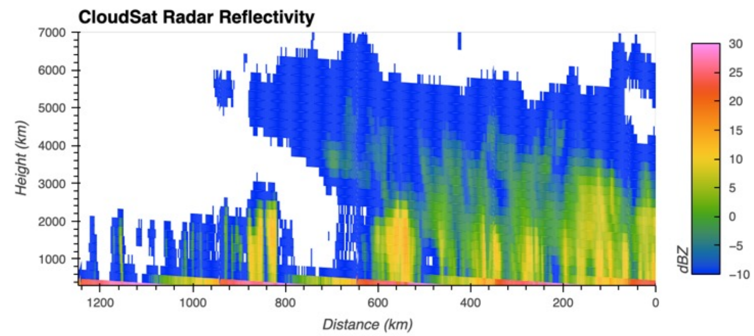
PR shows different convective organization depending on large-scale flow

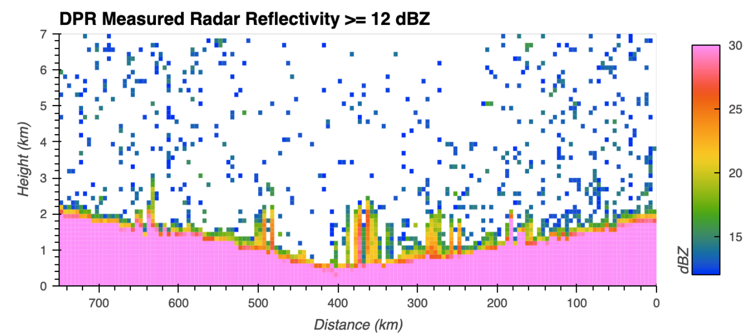
*See also more studies by Houze's group, Shrestha and Deshar 2014, etc.

GPM DPR cross sections over Labrador Sea during marine cold air outbreak

MODIS visible imagery with DPR swath (red), CloudSat nadir curtain (magenta), and MCAO contours from MERRA-2 (contours)



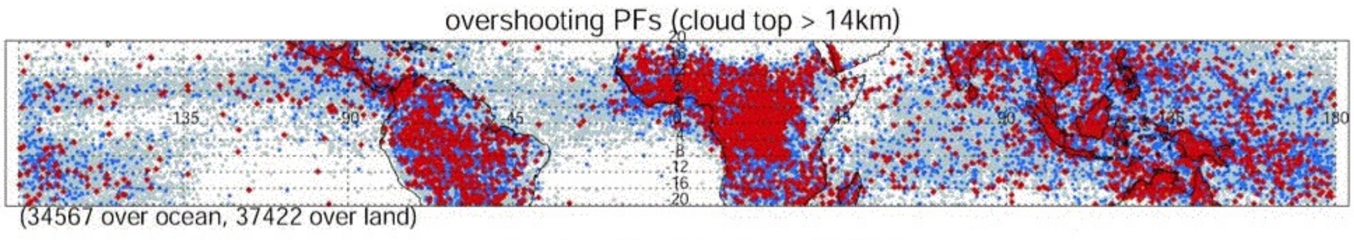




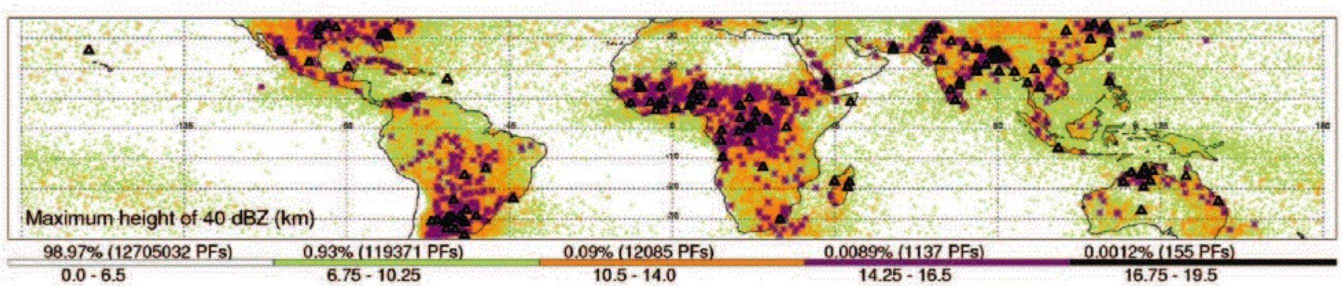
Funk and Schumacher (in preparation)

DPR can sense small precipitating convective cells close to nadir, CloudSat much more sensitive (but nadir only)

Intense storms w/ Precipitation Feature (PF) database



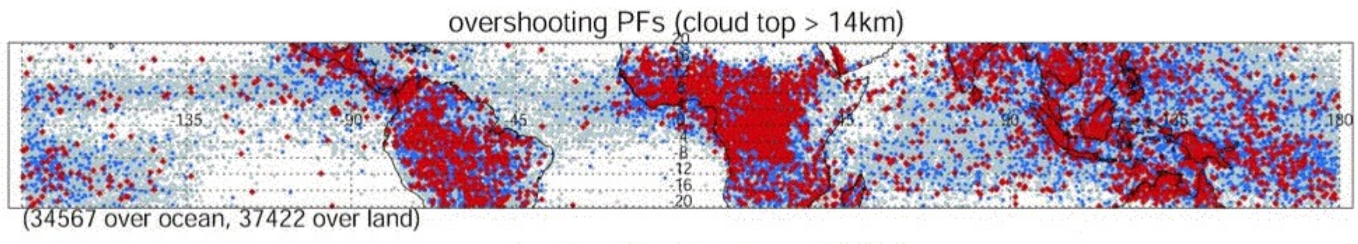
Liu and Zipser (2005)



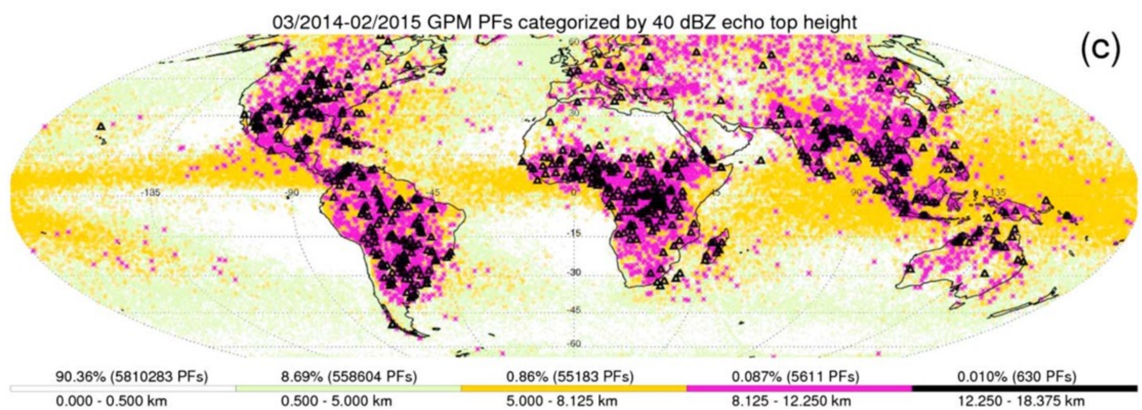
Zipser et al. (2006)

- Overshooting convective tops and the most intense storms in the tropics occur over land, esp. Africa

Intense storms w/ Precipitation Feature (PF) database



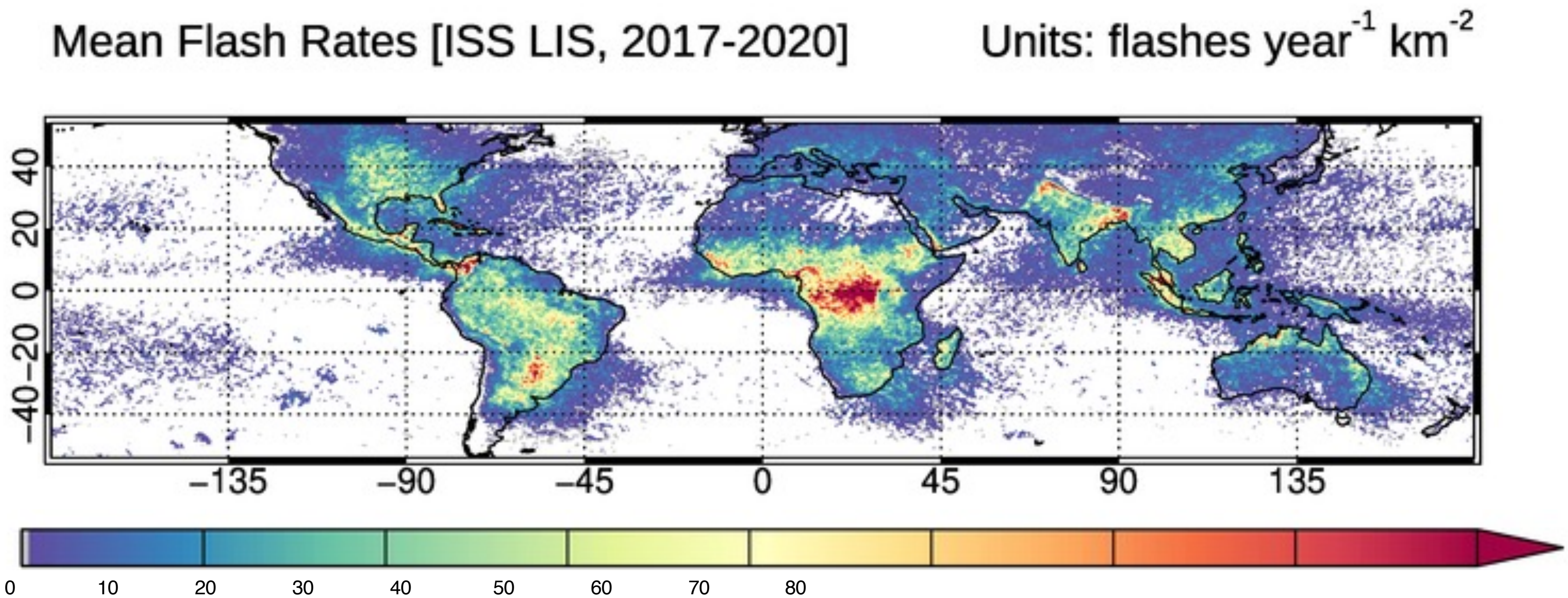
Liu and Zipser (2005)



w/ GPM

Liu and Zipser (2015)

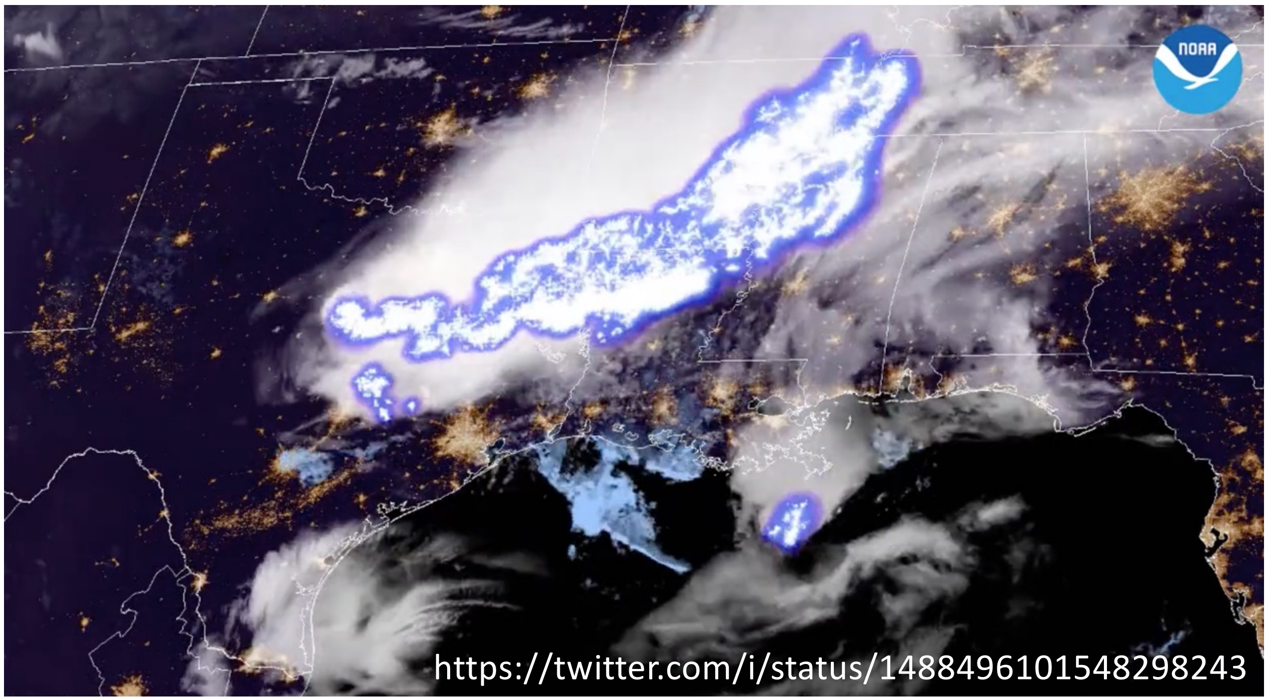
ISS LIS lightning



- Lightning also strongest over land, with maxima where strongest convection and overshooting occur

Geostationary lightning mapper

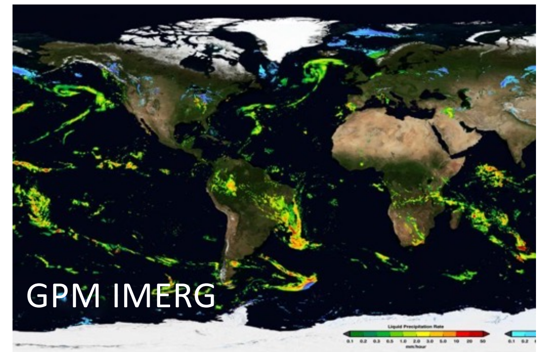
New world record for the longest lightning flash

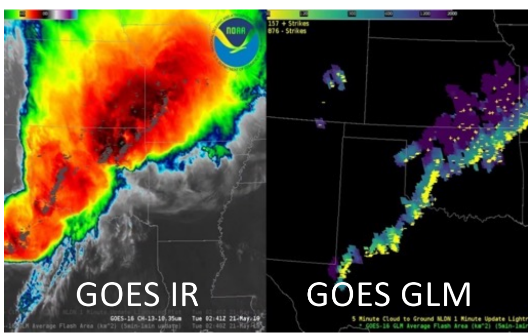


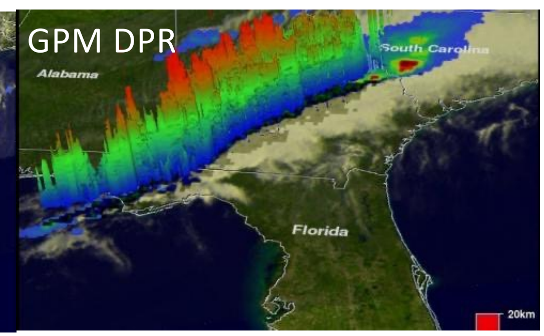
On 7 February 2022, the World Meteorological Organization announced that a single bolt on 29 April 2020 stretched over 767 kilometers across Texas, Louisiana, and Mississippi

How is convection best characterized from space?

- Geosynchronous data, convection tracking algorithms
  - Mostly characterizes anvil tops, but doesn't adequately describe convective organization
- Lightning (GLM and similar sensors)
- Spaceborne passive microwave in low-earth orbit
- Spaceborne radar (TRMM PR, GPM DPR, AOS PMM)
- Commercial constellations (Ka-band radars, high-frequency radiometers)
- Multi-satellite merged rainfall (e.g., IMERG)



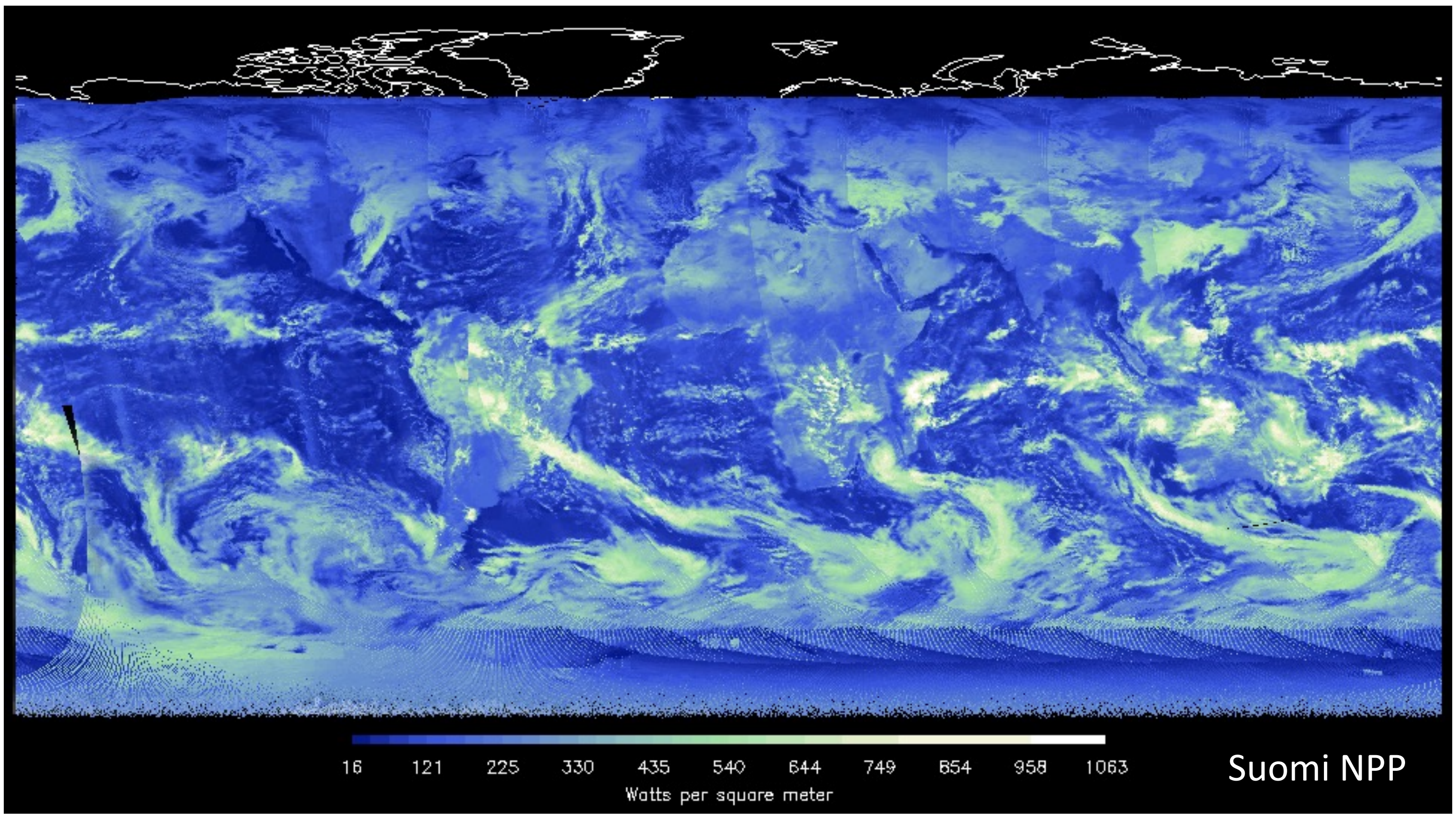




Adapted from Scott Braun slide

CERES broadband radiances

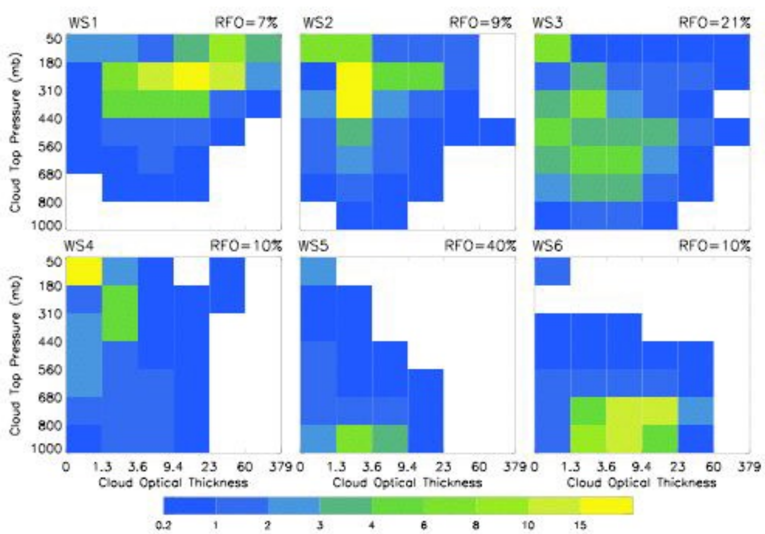
Shortwave TOA flux

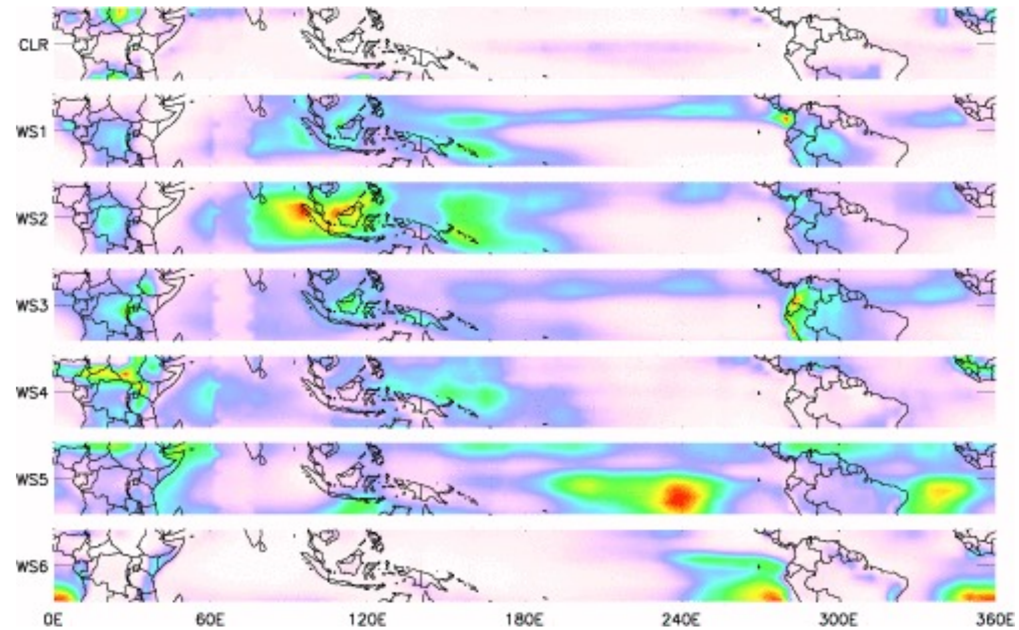


Tropical weather states

Optical thickness

Cloud top pressure

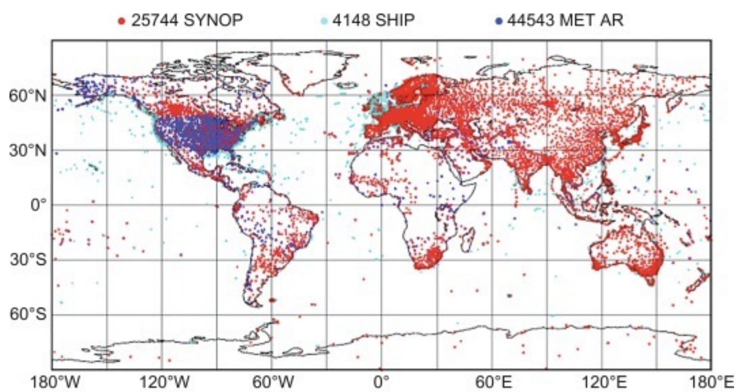


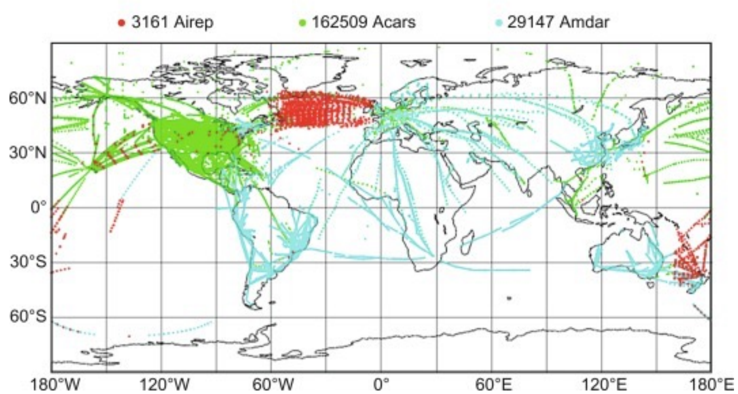


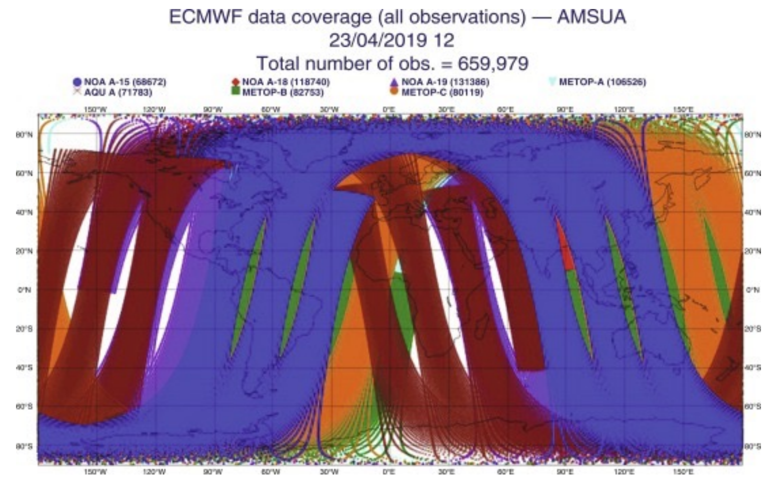
- Uses patterns of cloud property joint distributions to identify distinct states of the tropical atmosphere

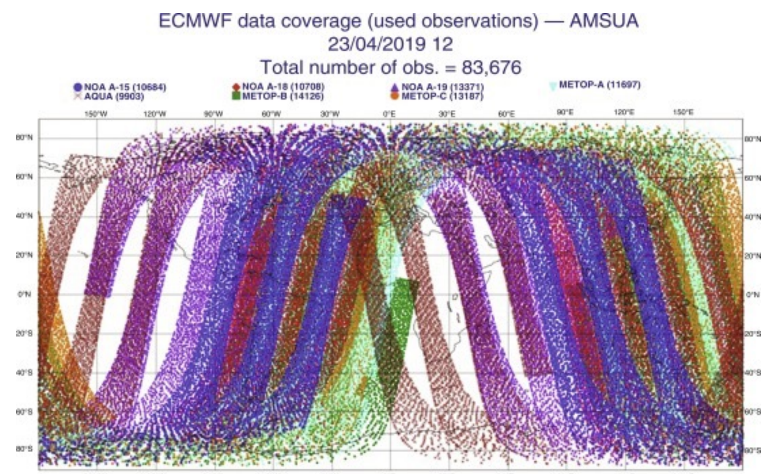
e.g., Jacob and Tselioudis et al. (2003)

Example day of ECMWF data assimilation



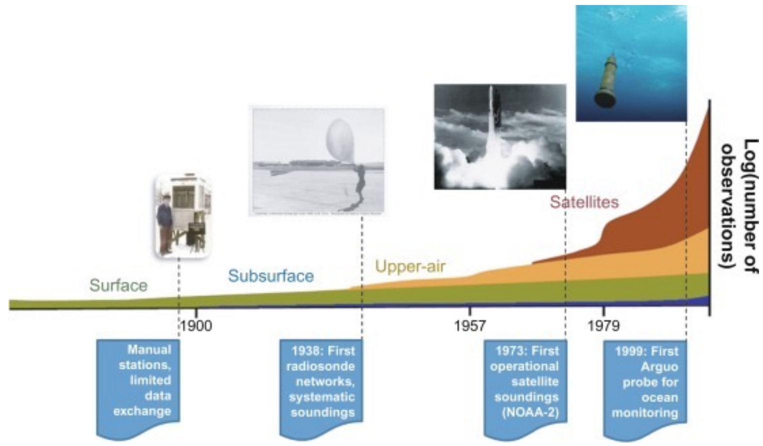


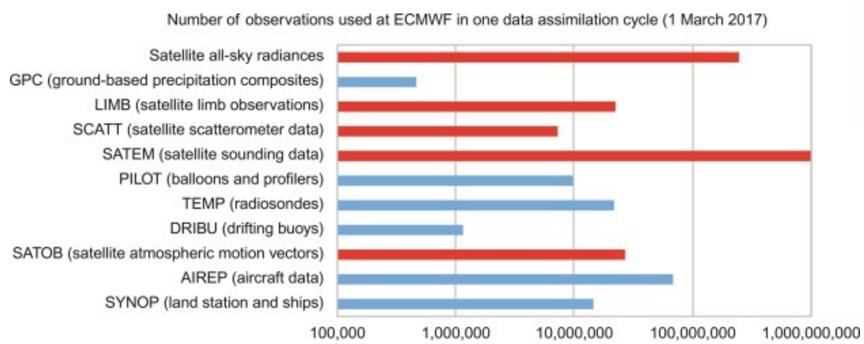




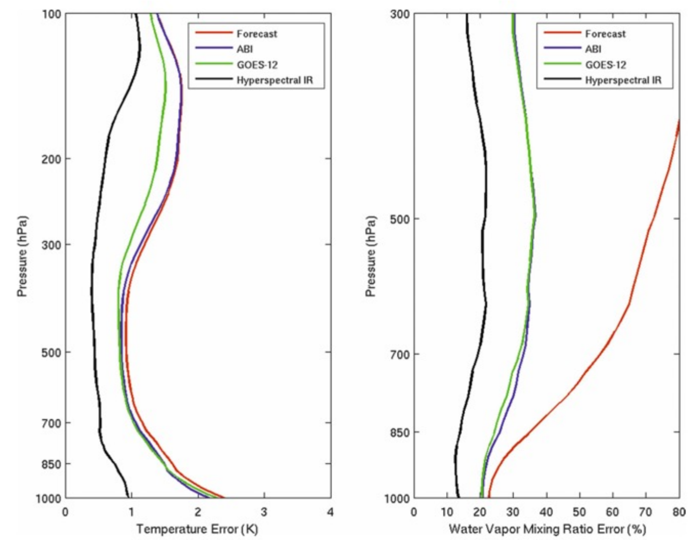
Buizza (2021)

Importance for NWP





Buizza (2018)



Schmit et al. (2008)