Meteorological Satellites: Principles of Operation, Instruments, Orbits, and Data Types

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National Hurricane Center

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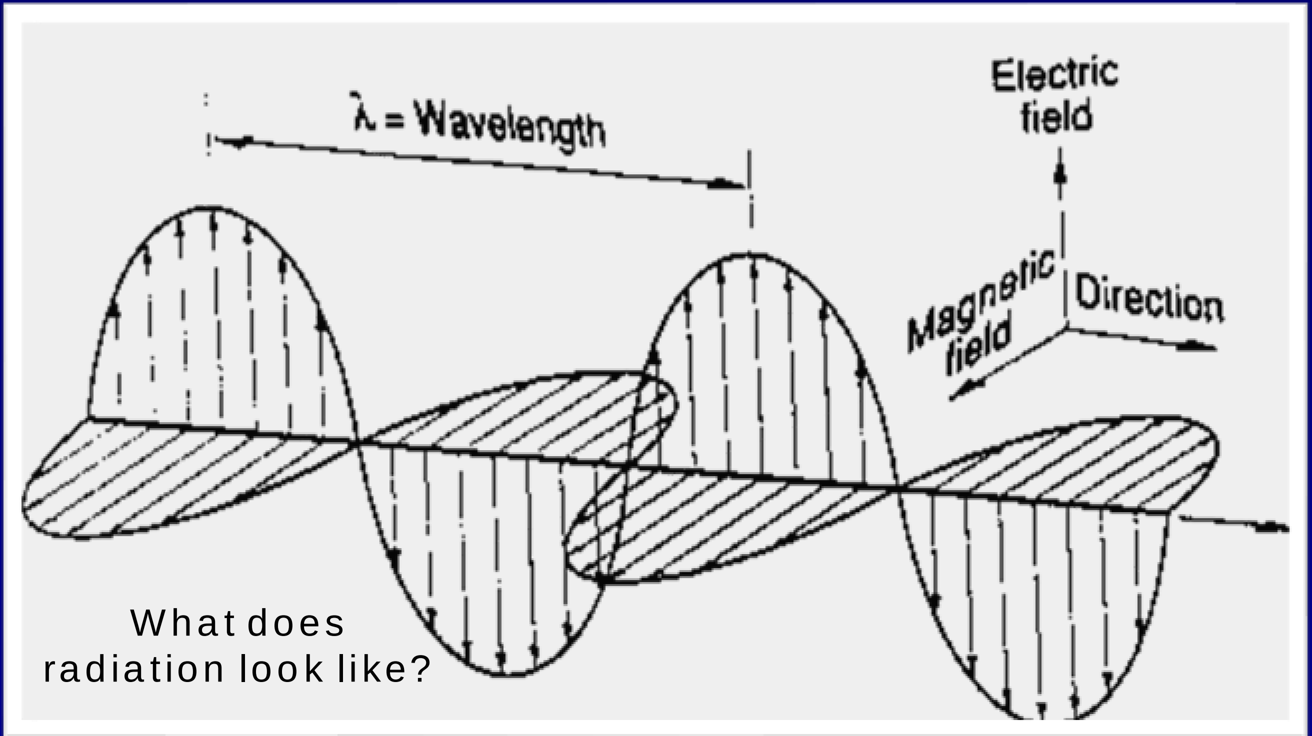
(with material borrowed from other training courses)

Outline

- **Refresher on radiative transfer – the physical basis for meteorological satellites**
  - **The electromagnetic spectrum**
  - **Basic quantities**
  - **Radiation interacting with the atmosphere**
- **Meteorological Satellites**
  - **Satellite orbits**
  - **Satellite instruments and channels**
- **Satellite Data types**

Electromagnetic Energy (Radiation)

- **All objects at temperatures above absolute zero emit radiation which moves through space, or a medium, in the form of waves with electric and magnetic fields.**
- **Radiation usually has a broad range of wavelengths that travel through a vacuum at the "speed of light" (c).**
- **The range of all possible wavelengths is described by the *electromagnetic spectrum*.**

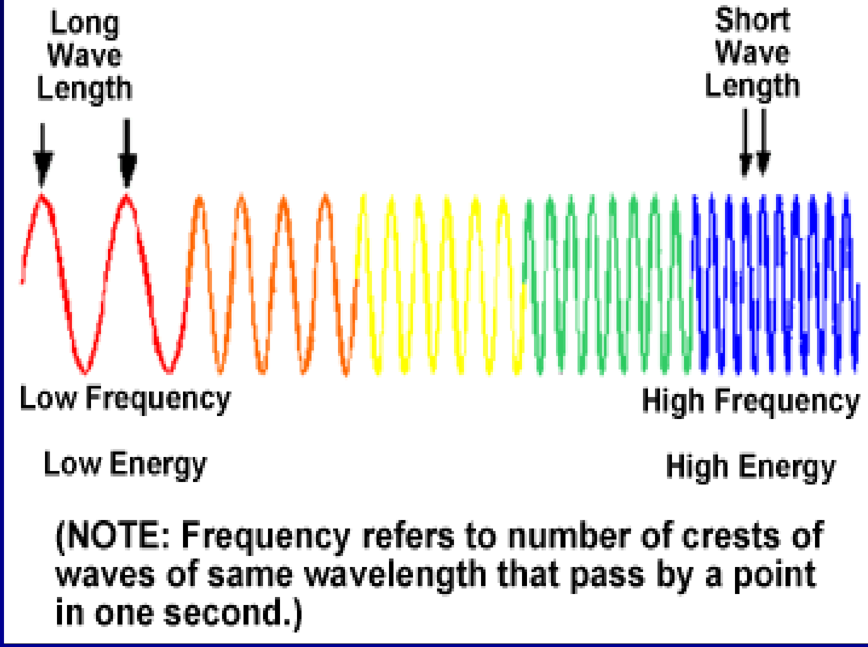


Basic Relationships and Units

wavelength

$\lambda = c/f$ Units of micrometers (10^{-6} m, µm, "microns"), Used for visible and infrared radiation

Wavelength (λ) = the distance between successive maxima in electric field strength (peak to peak)



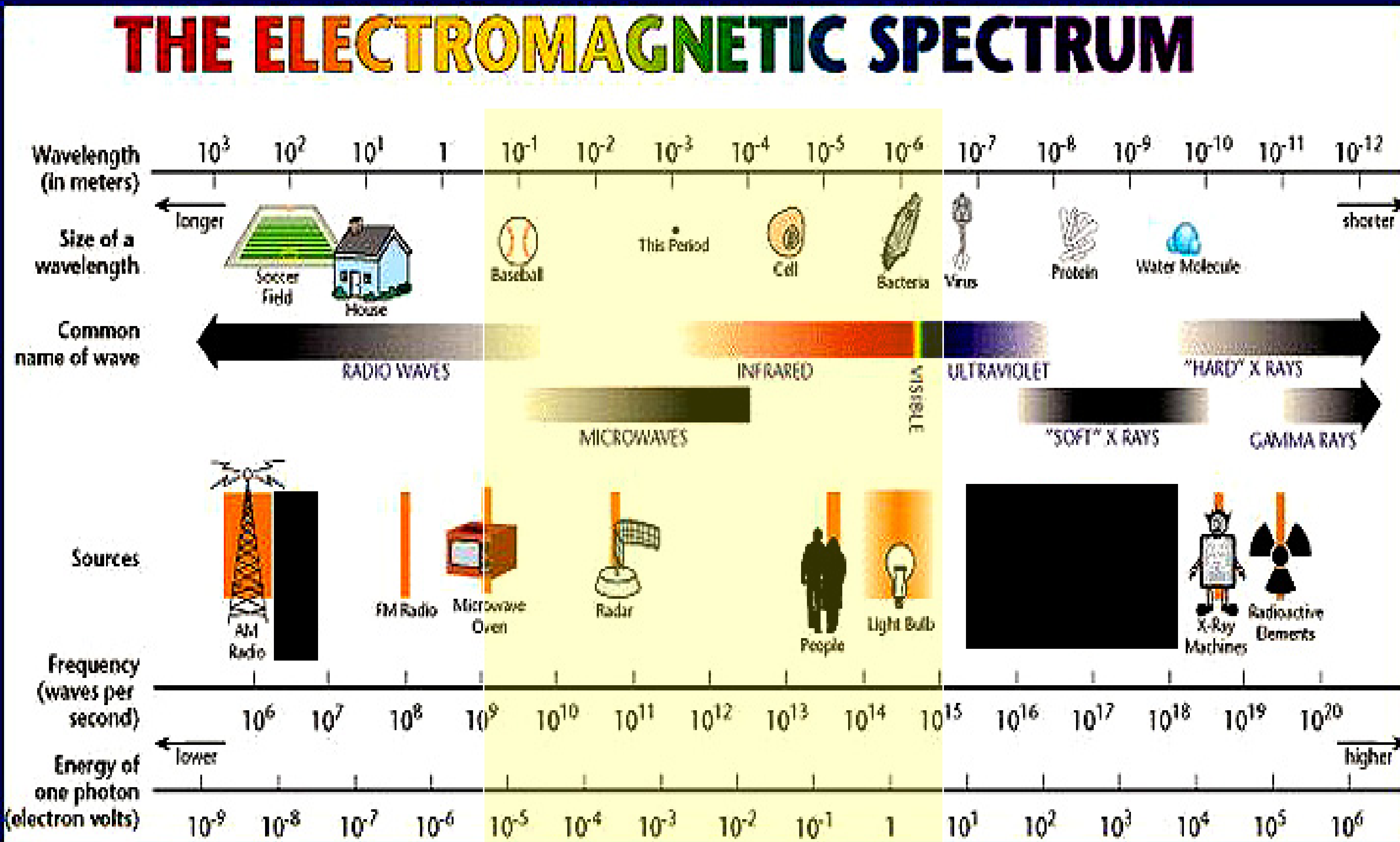
frequency

$f = c/\lambda$ Units of cycles (number of waves) per second, or hertz (Hz)

Frequency (f) = the number of waves passing a given point per unit time

Often used to describe microwaves (gigahertz, GHz = 10^9 Hz) and radio waves (megahertz, MHz = 10^6 Hz)

Meteorology primarily involves radiation within the visible, infrared, and microwave/radio portions of the electromagnetic spectrum (wavelengths from about 0.5 µm-12 cm).



Polarization

- The plane in which the electric field oscillates determines the polarization of the radiation.
- Radiation in the atmosphere is usually unpolarized, but it can become polarized due to particular wavelength-dependent interactions with surfaces or air constituents.

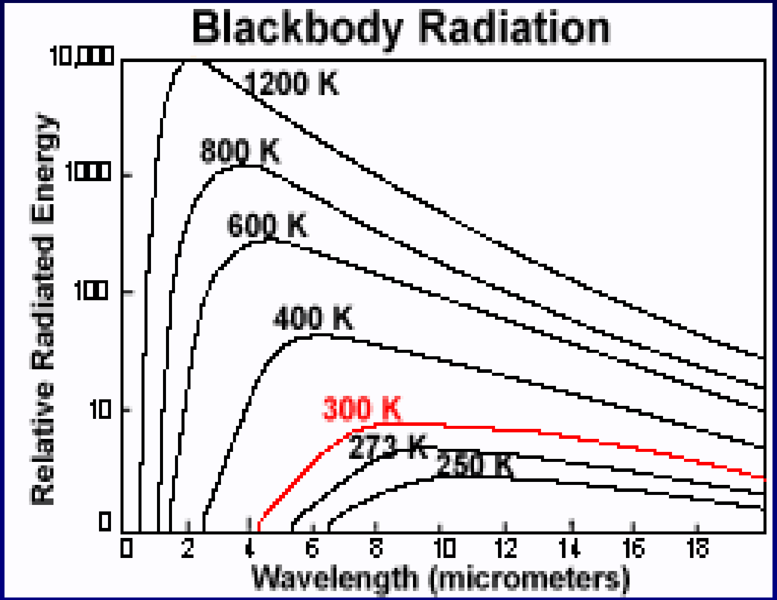
Planck Function

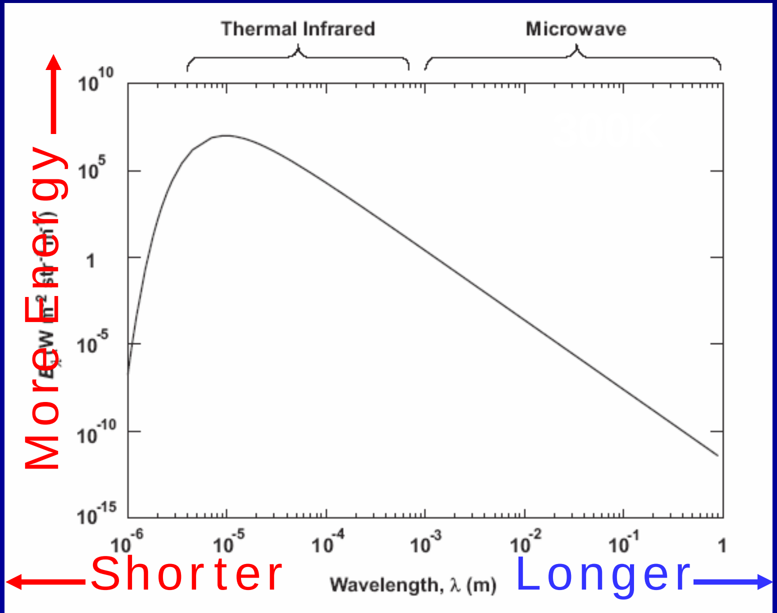
Tells you the amount of energy a blackbody object radiates at a particular wavelength, given its temperature

(A **blackbody**, an idealized radiator, emits its maximum possible radiation at all wavelengths; not all objects do this)

Hotter objects:

- Emit more energy
- Emit most of their radiation at shorter wavelengths and higher frequencies





Wien's Displacement Law

The wavelength of peak emission (λ_m) for a blackbody object is:

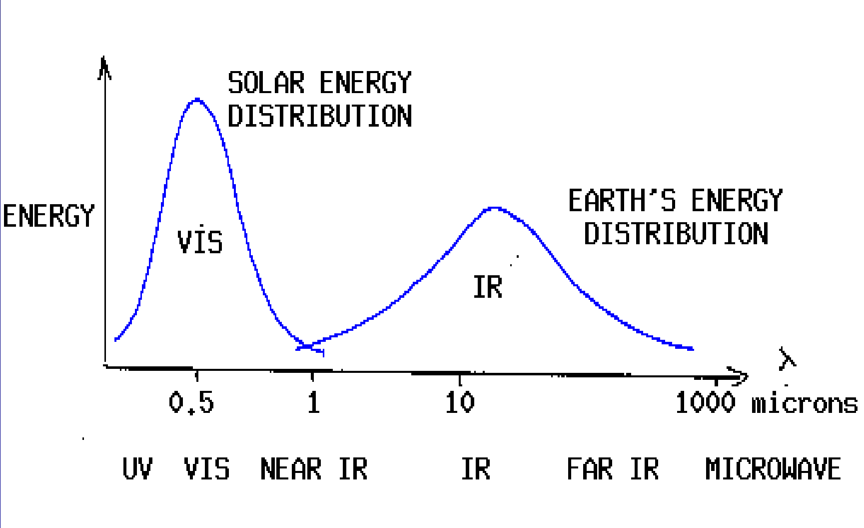
$\lambda_m = 2897 / T$

Where:

λ_m has units of μm

T is the temperature of the object in degrees Kelvin (K)

Example: The very hot Sun emits radiation concentrated at shorter wavelengths, while the much cooler earth-atmosphere system emits radiation concentrated at longer wavelengths.



Radiation Interacting with the Atmosphere

Radiation passing in any direction through the earth's atmosphere is subject to 4 processes:

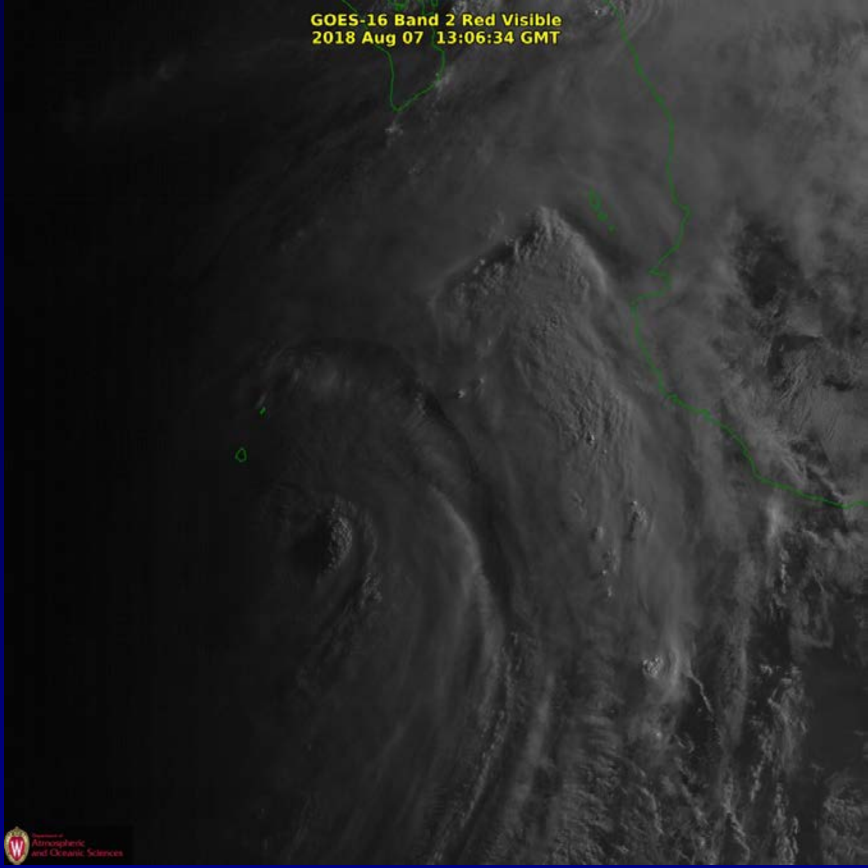
- **Reflection**
- **Scattering**
- **Absorption**
- **Emission**

These processes behave differently at various wavelengths, and they determine how remote sensing instruments work.

Reflection

Radiation sent back in the direction from which it came

- **Reflection occurs more readily as the wavelength decreases and/or size of the reflecting object increases.**
- **Albedo is the fraction of the incident sunlight that is reflected.**
- **Clouds are the primary reflectors of radiation in the atmosphere.**
- **Thick clouds reflect about twice as much visible radiation as thin clouds.**
- **Fresh white snow reflects about 75-95% of solar radiation; water reflects about 10%.**



John (2018)
Visible imagery using reflected sunlight – water/ice clouds appear bright while land/water appear dark

Scattering

Radiation diverted in various directions

- **In general, occurs when radiation strikes an object with a size similar to its wavelength.**
- **The amount and direction of scattering depends on the ratio between particle size and radiation wavelength.**

Why is the sky blue?

Why are clouds white?

Examples of Scattering

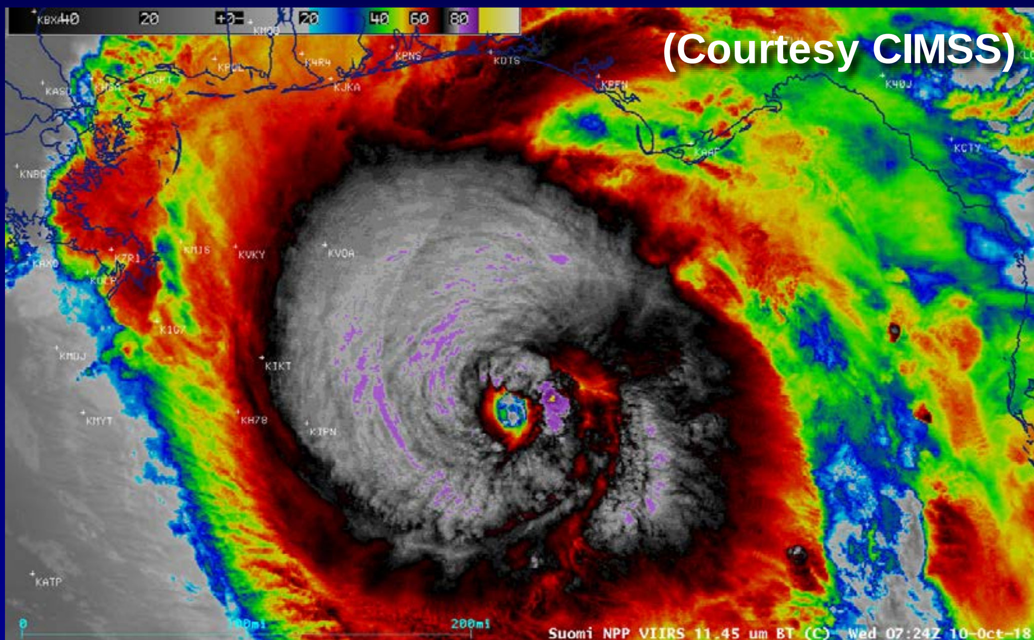
- **Air molecules and very small particles (aerosols) tend to scatter the sun's visible radiation:**
  - **Rayleigh scattering: Air molecules scatter mostly shorter-wavelength blue light (causes blue sky)**
  - **Mie scattering: Water droplets, pollen, dust, smoke scatter all visible wavelengths (cumulus clouds appear white); occurs when particles causing the scattering are larger than wavelengths of radiation striking them**
  - **Non-selective scattering: occurs in lower part of atmosphere, when particles >> incident radiation. E.g., haze**

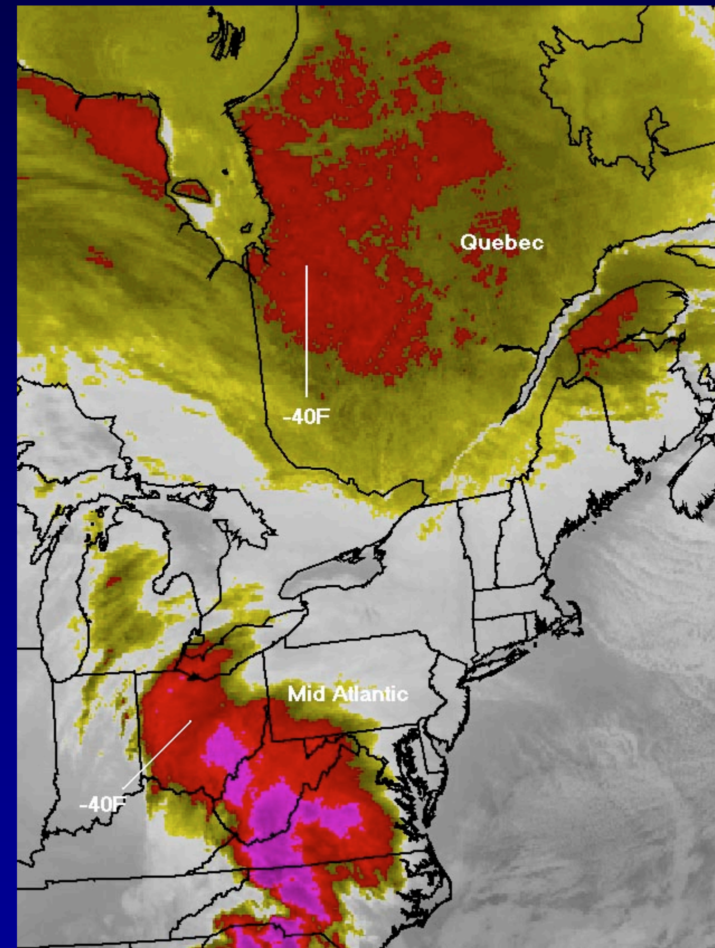
Ice particles in tall thunderstorms tend to scatter certain wavelengths of the earth's microwave radiation

Absorption and Emission

- **All objects absorb and emit radiation, with the amounts depending on the object's characteristics such as temperature, color, moisture, and texture.**
- **If an object absorbs more energy than it emits, it warms.**
- **A blackbody object absorbs and emits all possible radiation and has emissivity = 1 – no reflection or transmission.**
- **Many objects do not emit all possible radiation at certain wavelengths.**
  - **For example, oceans have low emissivity at microwave wavelengths.**
- **Absorption varies with respect to wavelength, and each atmospheric element characteristically absorbs in specific wavelength intervals called absorption bands.**
  - **For example, ozone in the upper atmosphere absorbs *only* ultraviolet radiation.**

Infrared Imagery

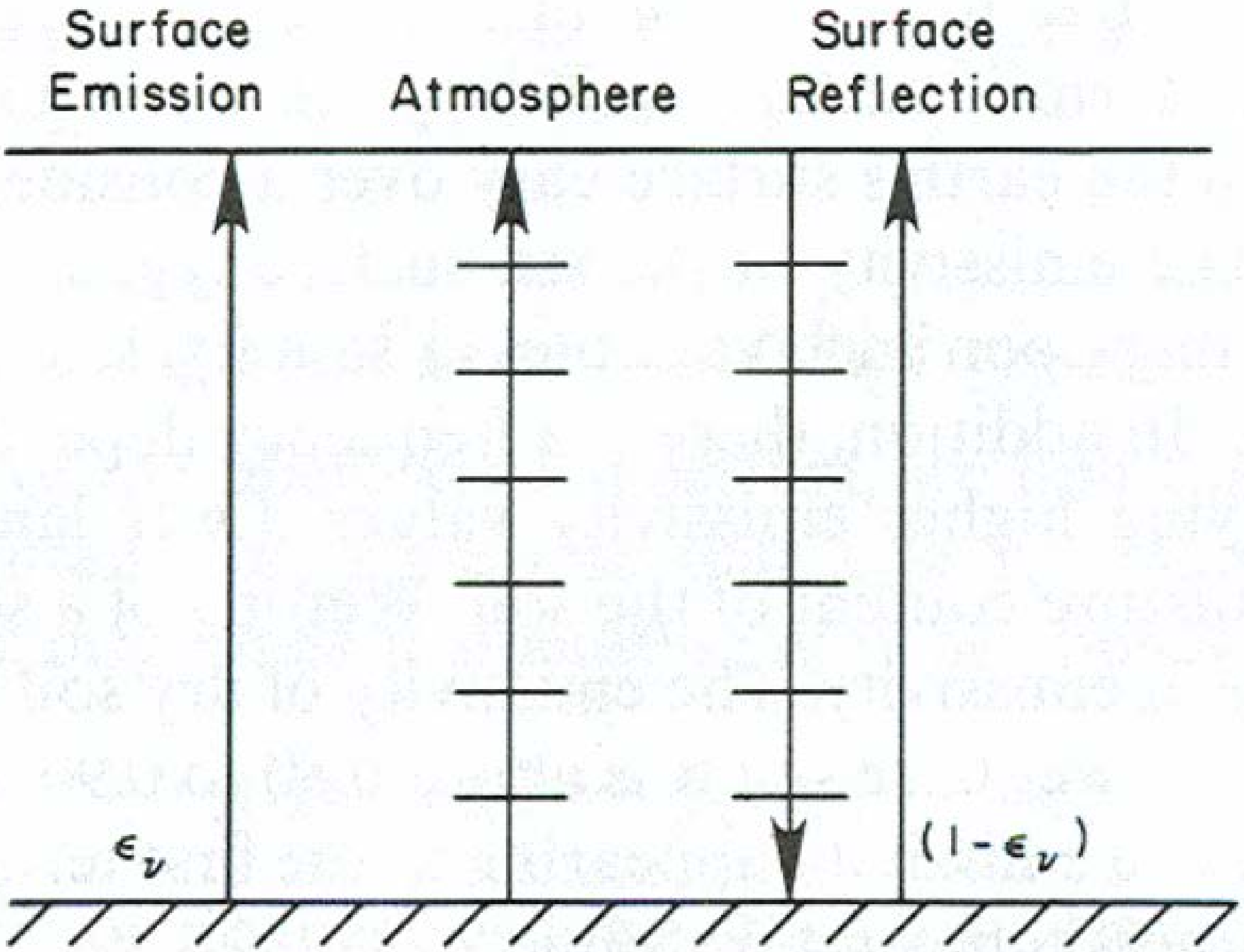




Standard infrared imagery uses wavelengths with low atmospheric absorption – "window" channels (e. g. 10.3 μm)

Radiative Transfer:

Combining the effects of emission, absorption, and reflection (non-scattering example)



Contribution of brightness temperature at the top of a clear atmosphere.

Parts of the Radiative Transfer System

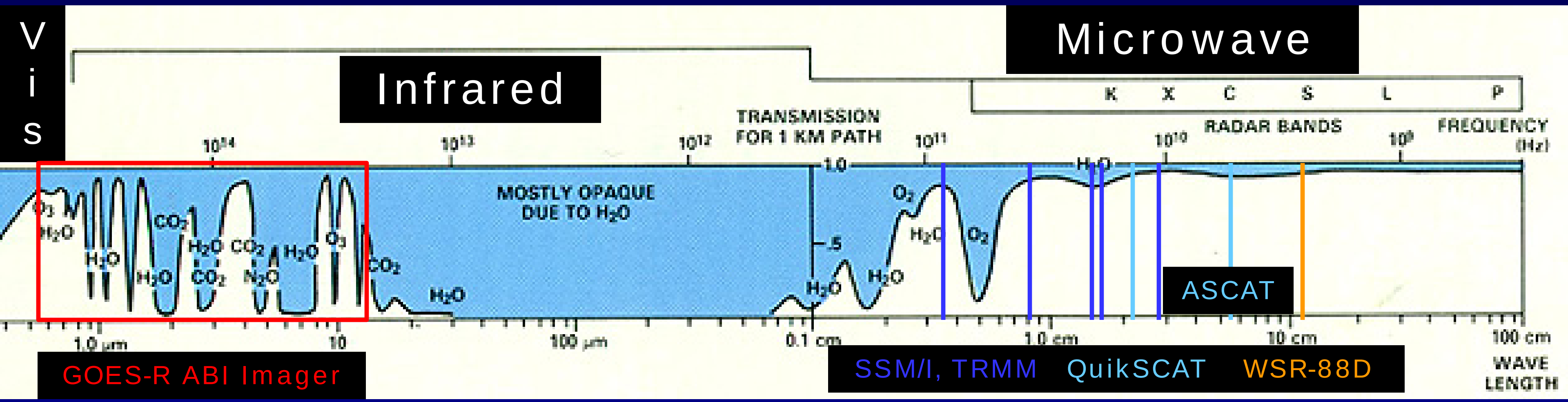
- **The Sun**

- **The atmospheric constituents:**
  - **Water vapor (varies greatly in space and time)**
  - **Liquid water and ice (clouds; also vary greatly)**
  - **Carbon dioxide (well-mixed)**
  - **Ozone**

- **The major wavelength bands of interest:**
  - **Atmospheric infrared "window" (emissions from the earth)**
  - **Water vapor infrared absorption region**
  - **Shortwave infrared region**
  - **Visible region (reflection)**
  - **Microwave region (can pass through clouds but not rain)**

- **Surfaces:**
  - **Land**
  - **Ocean**
  - **Clouds**

Atmospheric Absorption/Emission Spectrum

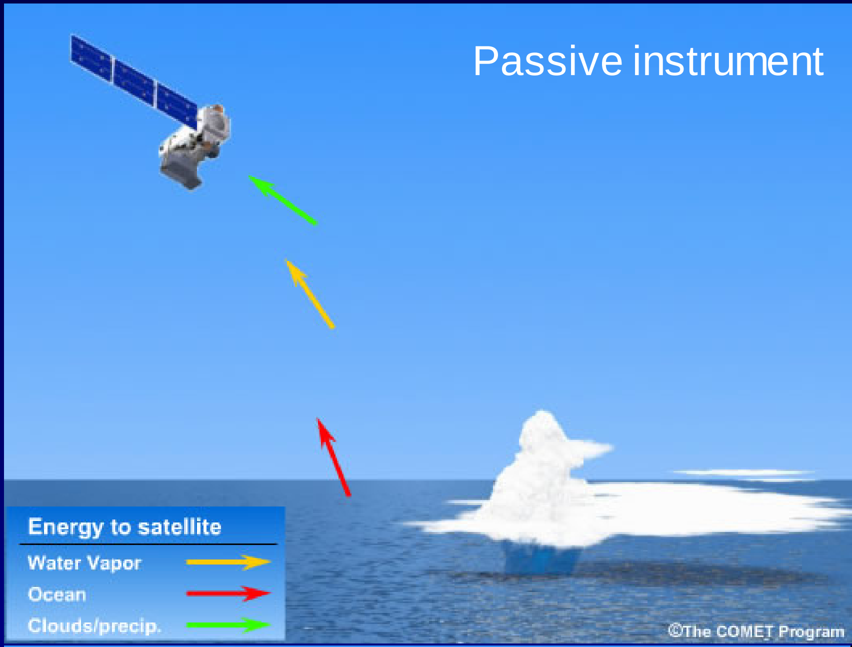


Longer wavelength

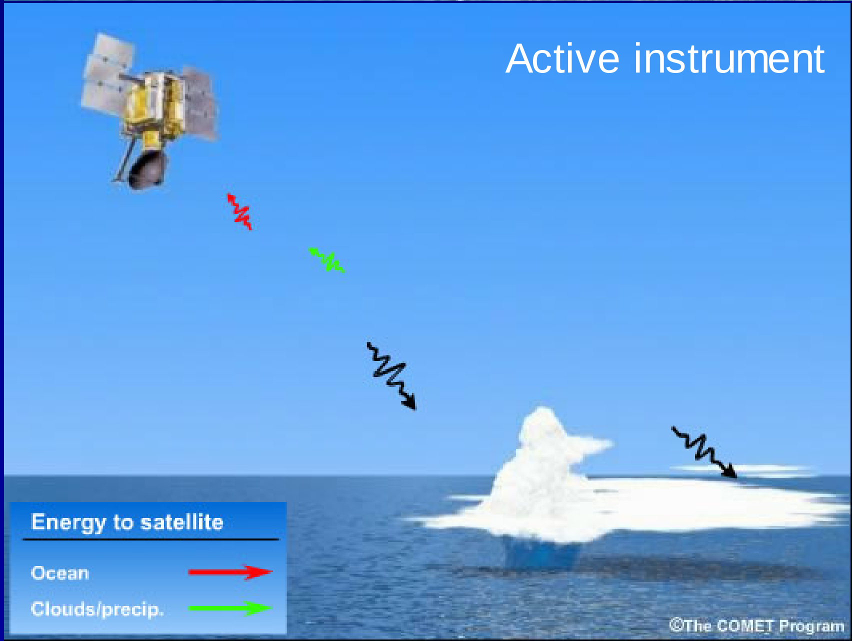
Higher frequency

Measuring Electromagnetic Energy

- **Passive Instruments:**
  - Receive radiation leaving the earth-atmosphere system
  - Measure solar radiation reflected by earth/atmosphere targets
  - Measure emitted and scattered infrared radiation
  - Measure microwave radiation resulting from emission and scattering



- **Active Instruments:**
  - Send out pulses of radiation, usually at microwave frequencies
  - Measure radiation returned to the sensor
  - Examples
    - Surface-based and airborne radars
    - Satellite scatterometers

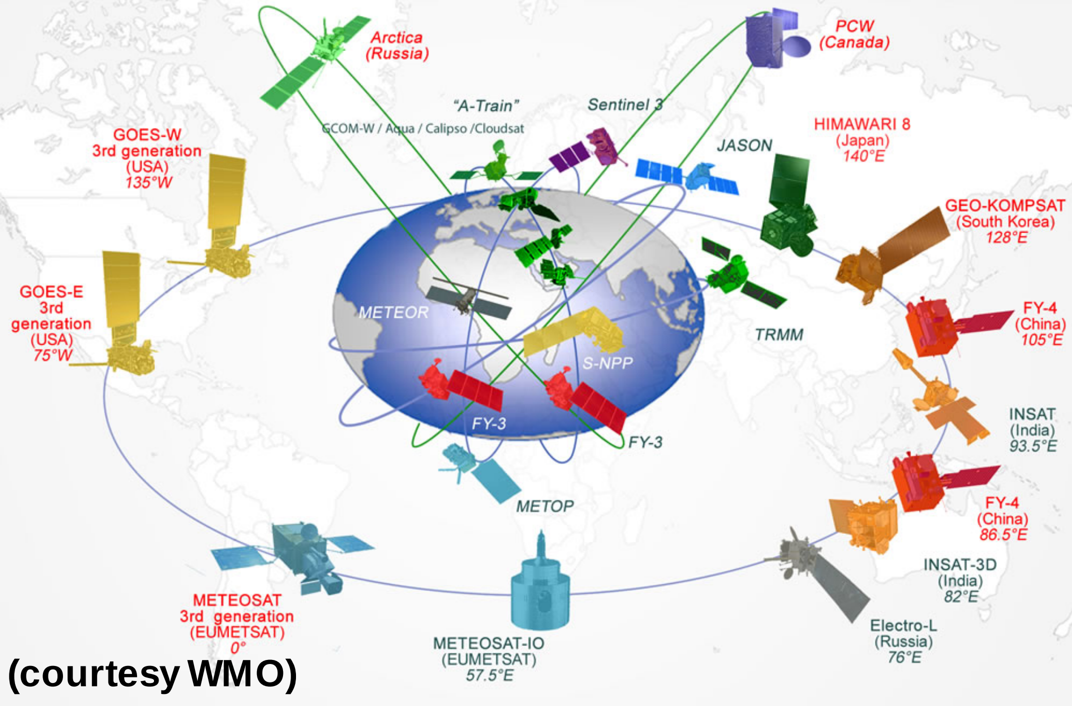


What is the single most important tool for the National Hurricane Center in monitoring its area of responsibility?

A) Geostationary Weather Satellite
B) Low Earth Orbiting Weather Satellite
C) Reconnaissance Aircraft
D) Land-based or Aircraft Radar
E) Surface Observations

Remote Sensing Satellites

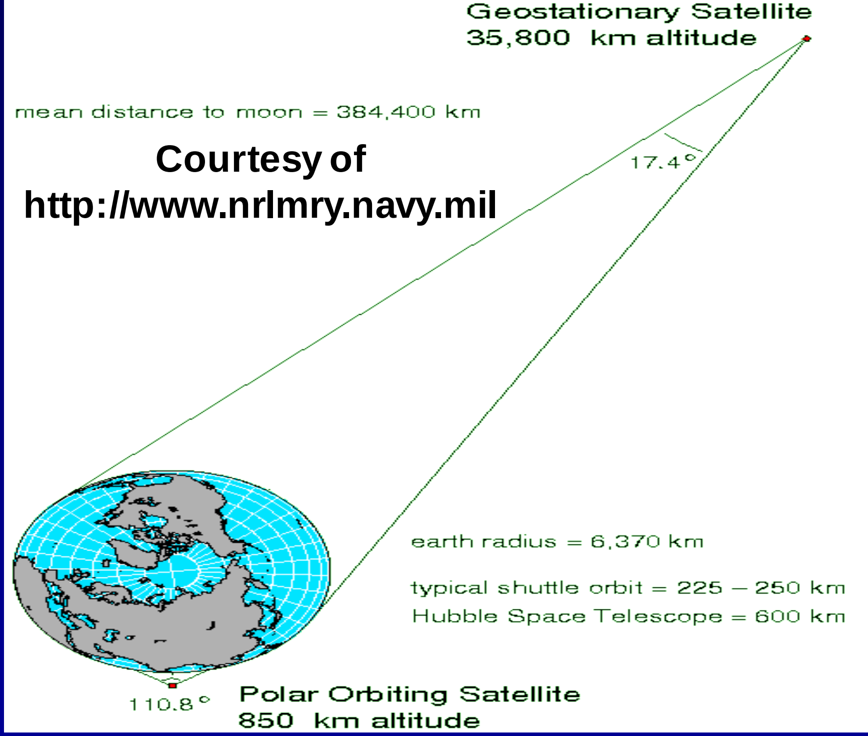
- **These “look” down from a great height and can thus see more detail depending on the height above the Earth’s surface.**
- **Remote sensing can be thought of as how to obtain information about an object of interest without being in physical contact with it.**
- **Satellite instruments can be designed to observe many types of atmospheric, oceanic, and land-surface phenomena based on the instrument frequencies chosen.**



(courtesy WMO)

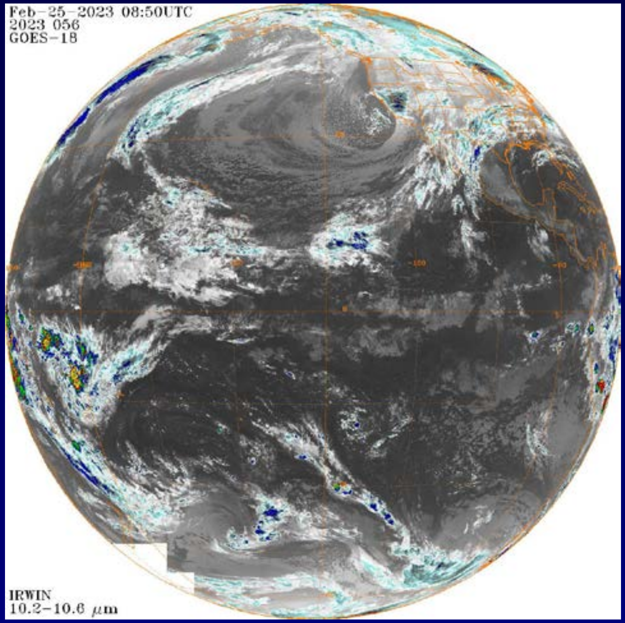
Remote Sensing Satellites - Orbits

- **Geostationary (GEO) satellites**
  - **Orbit at 35,800 km altitude over same spot on the equator**
  - **Good for continuous monitoring, less good for high resolution**
  - **Good for visible and infrared, not good for microwave**
  - **Good for passive, not good for active**
  - **Good for middle latitudes and tropics, not good for polar regions**

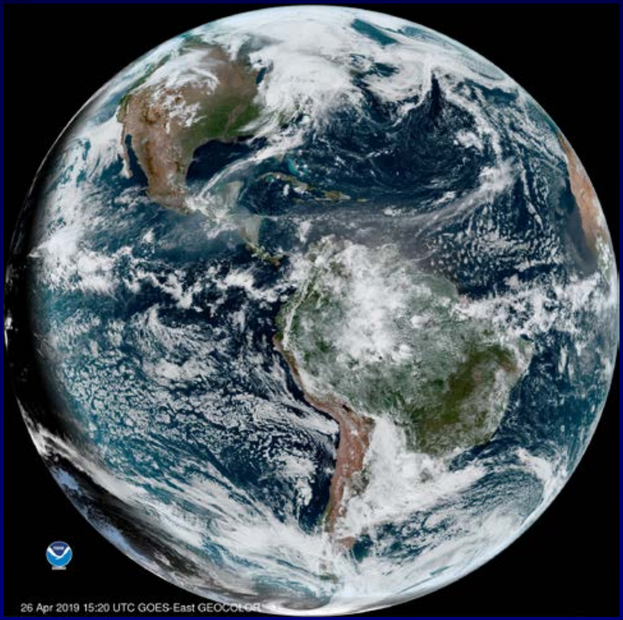


- **Low earth orbit (LEO) satellites**
  - **Good for microwave (active and passive), visible, and infrared**
  - **Lower altitude orbit, moves with respect to the Earth**
  - **Finer spatial resolution**
  - **Sees an area only twice per day (except near poles)**
  - **Limited spatial coverage (narrow data swaths)**
  - **Depending on orbital configuration, can cover nearly entire globe each day**

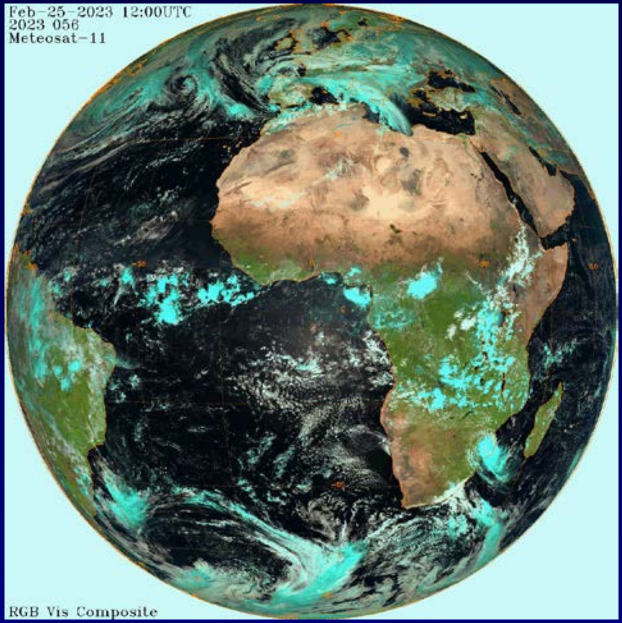
Global Coverage of Geostationary Satellites



GOES-18 137° W

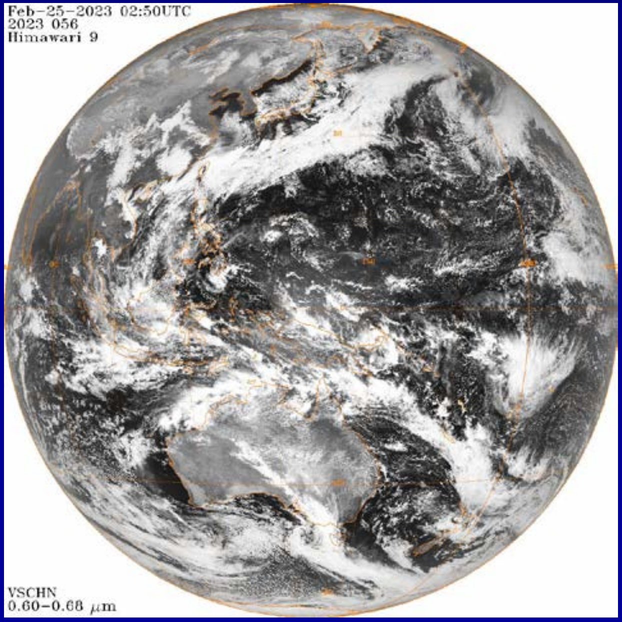


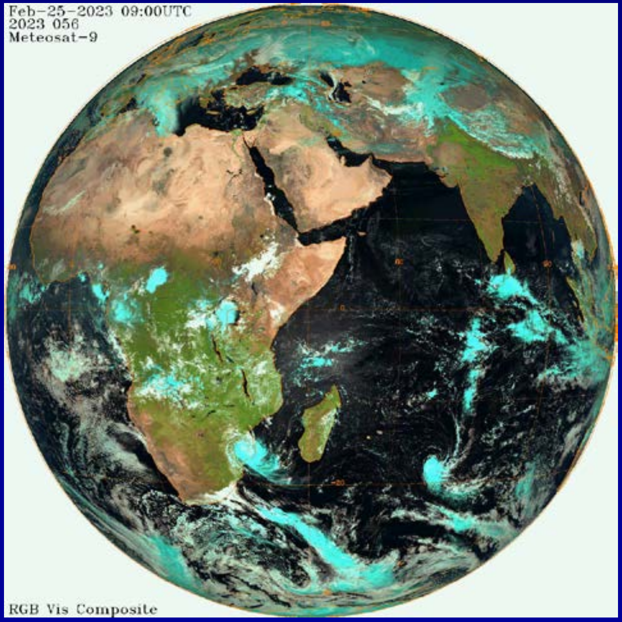
GOES-16 75° W



METEOSAT-11 0°

HIMAWARI-9
141° E

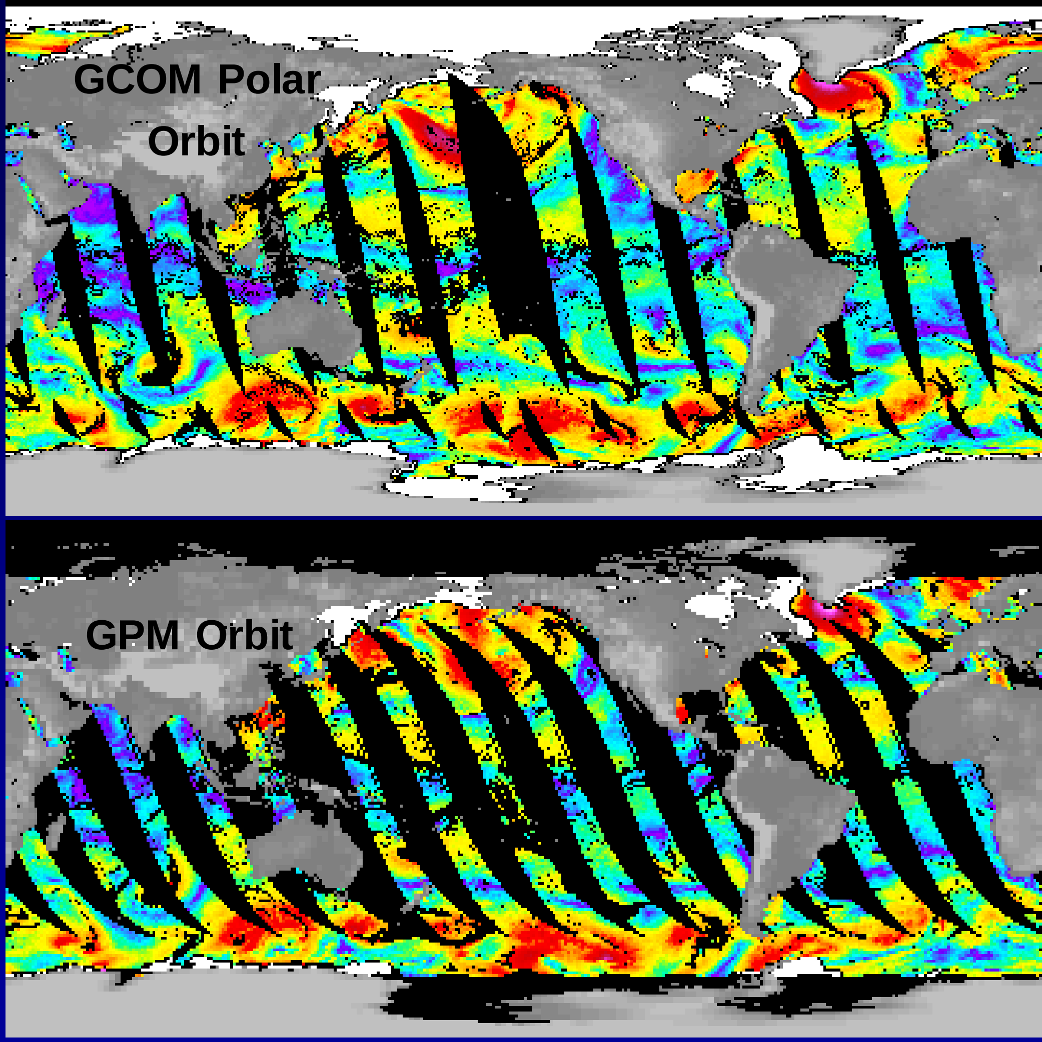




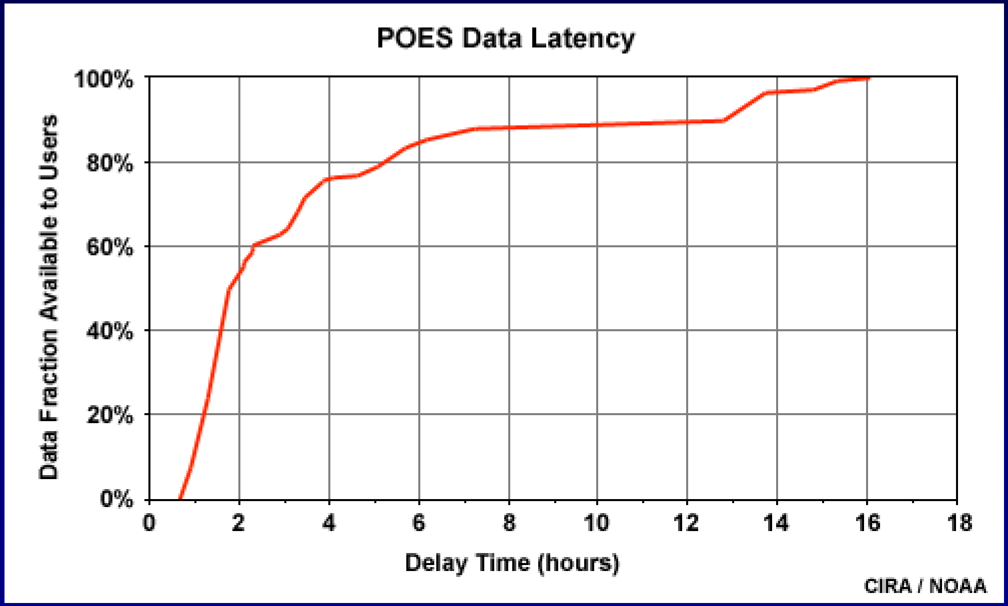
METEOSAT-9
41.5° E

Low Earth Orbiting Satellites

- **Generally fly 300-1000 miles (500-1600 km) above the surface**
- **Many LEO satellites travel over the Earth almost from pole to pole – polar orbit.**
- **Polar orbiting satellites are usually sun-synchronous (the satellite crosses the Equator at the same local time every day).**
- **Sun-synchronous satellites make about 14 orbits of the Earth a day.**
- **There are other specialized LEO satellites such as that of the Global Precipitation Mission satellite.**



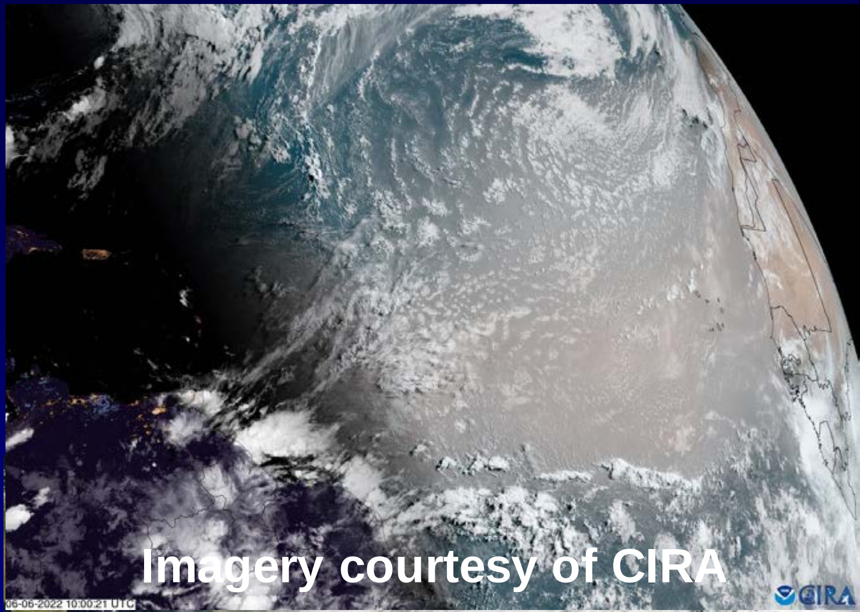
Data Latency Issue

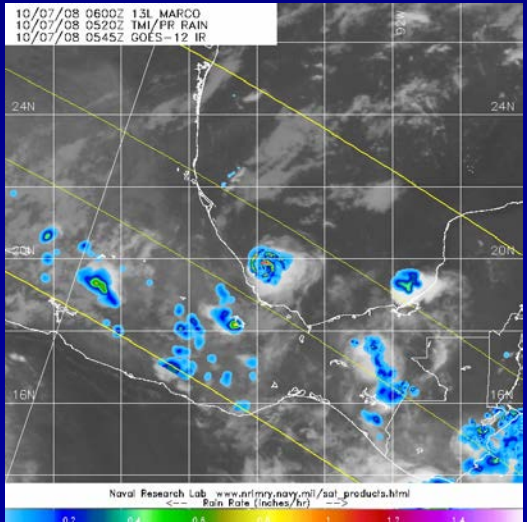


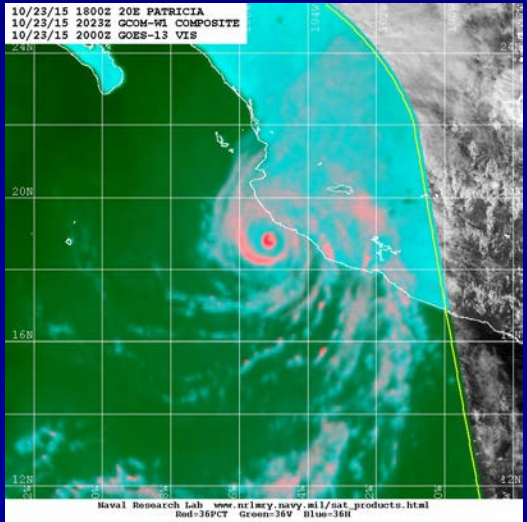
- **LEO satellites are not continuously in view of data receiving stations. They can only download data when they are in range of those stations, which leads to delays in data transmission and processing.**

Instruments - Imagers

- **An imager makes an image of some meteorological quantity.**
- ***Usually* use one wavelength/ frequency but can use combinations of wavelengths/ frequencies (multispectral)**
- **Satellite <u>imagery</u> is normally used for analysis and short-term forecasting.**





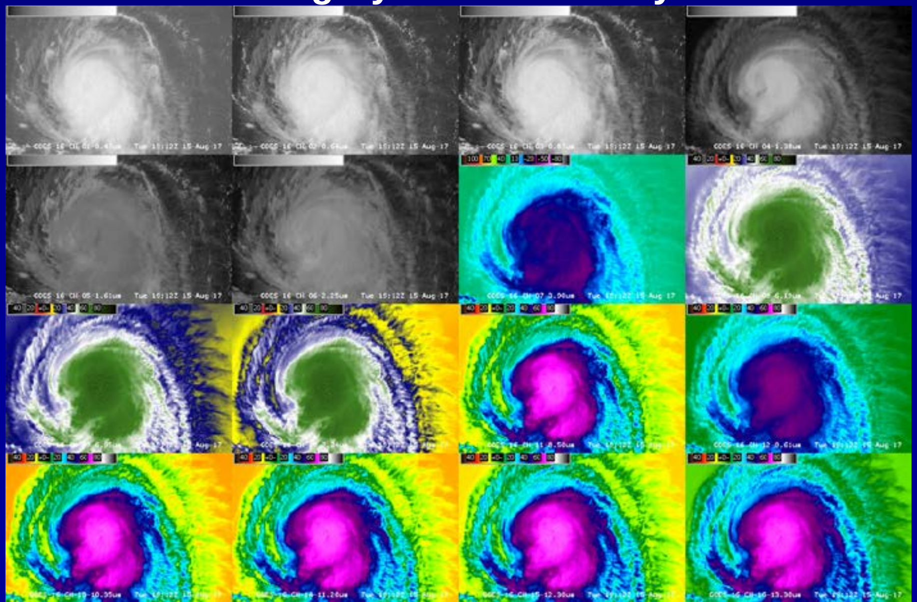


The ABI Imager

- **16 channel imager, including 11 channels not flown on GOES 13-15**
- **Increased spatial and spectral resolution over the current GOES imagers**

Table courtesy of Tim Schmit, CIMSS

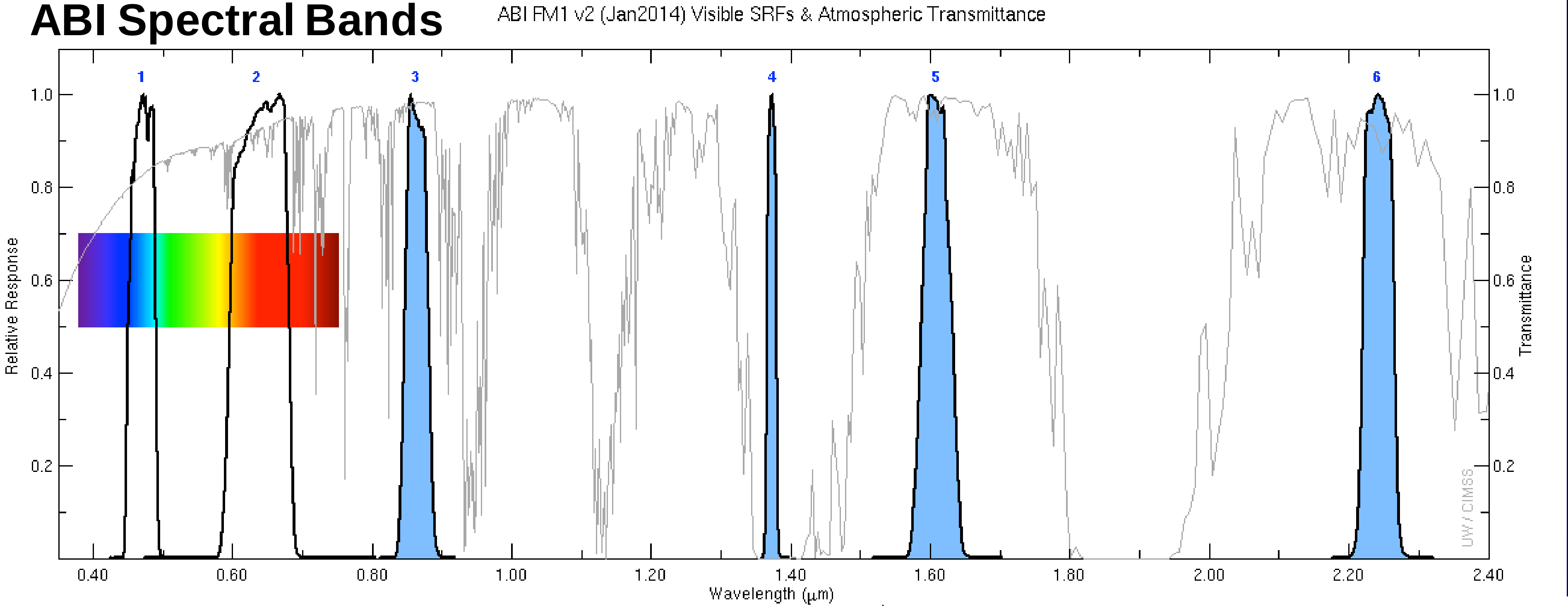
GOES-16 Imagery below courtesy of CIMSS

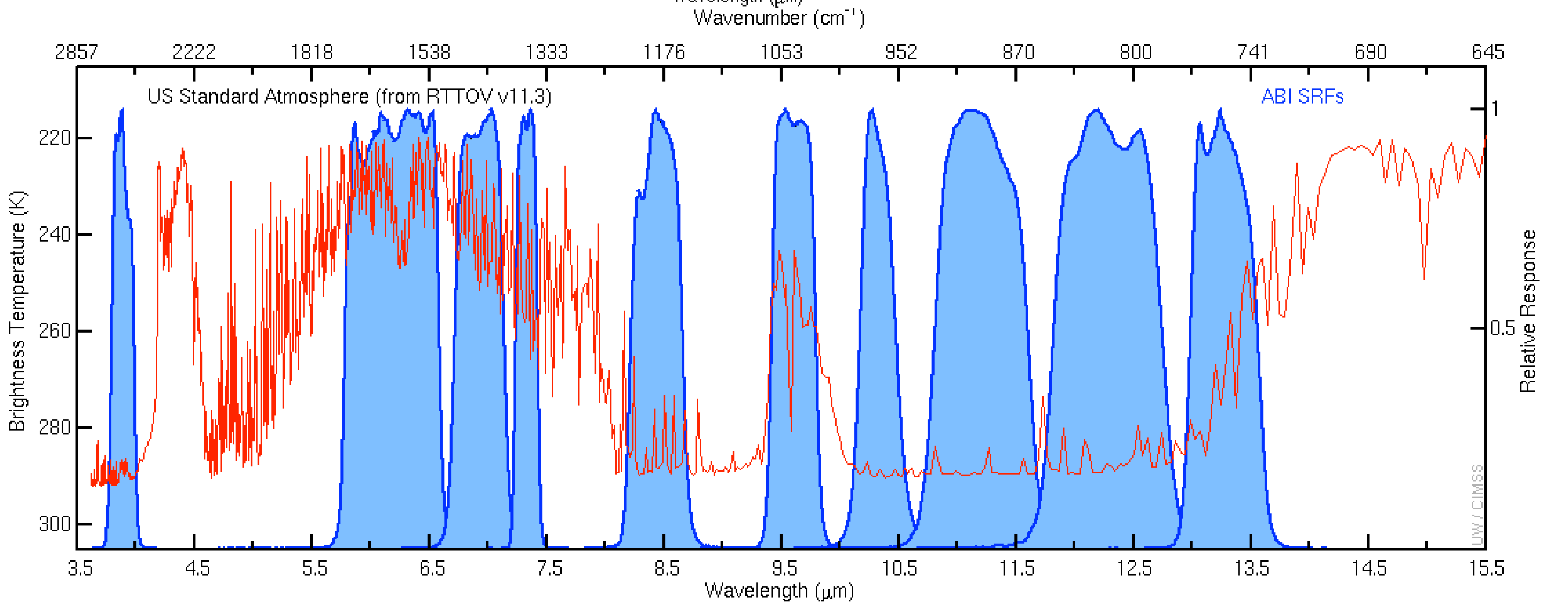


GOES-R ABI Imager Channels

Future GOES imager (ABI) band	Wavelength range (µm)	Central wavelength (µm)	Nominal subsatellite IGFOV (km)	Sample use
1	0.45–0.49	0.47	1	Daytime aerosol over land, coastal water mapping
* 2	0.59–0.69	0.64	0.5	Daytime clouds fog, insolation, winds
3	0.846–0.885	0.865	1	Daytime vegetation/burn scar and aerosol over water, winds
4	1.371–1.386	1.378	2	Daytime cirrus cloud
5	1.58–1.64	1.61	1	Daytime cloud-top phase and particle size, snow
6	2.225–2.275	2.25	2	Daytime land/cloud properties, particle size, vegetation, snow
* 7	3.80–4.00	3.90	2	Surface and cloud, fog at night, fire, winds
8	5.77–6.6	6.19	2	High-level atmospheric water vapor, winds, rainfall
* 9	6.75–7.15	6.95	2	Midlevel atmospheric water vapor, winds, rainfall
10	7.24–7.44	7.34	2	Lower-level water vapor, winds, and SO_2
11	8.3–8.7	8.5	2	Total water for stability, cloud phase, dust, SO_2 rainfall
12	9.42–9.8	9.61	2	Total ozone, turbulence, and winds
13	10.1–10.6	10.35	2	Surface and cloud
* 14	10.8–11.6	11.2	2	Imagery, SST, clouds, rainfall
* 15	11.8–12.8	12.3	2	Total water, ash, and SST
16	13.0–13.6	13.3	2	Air temperature, cloud heights and amounts

ABI Spectral Bands





Approximate spectral and spatial resolutions of US GOES Imagers

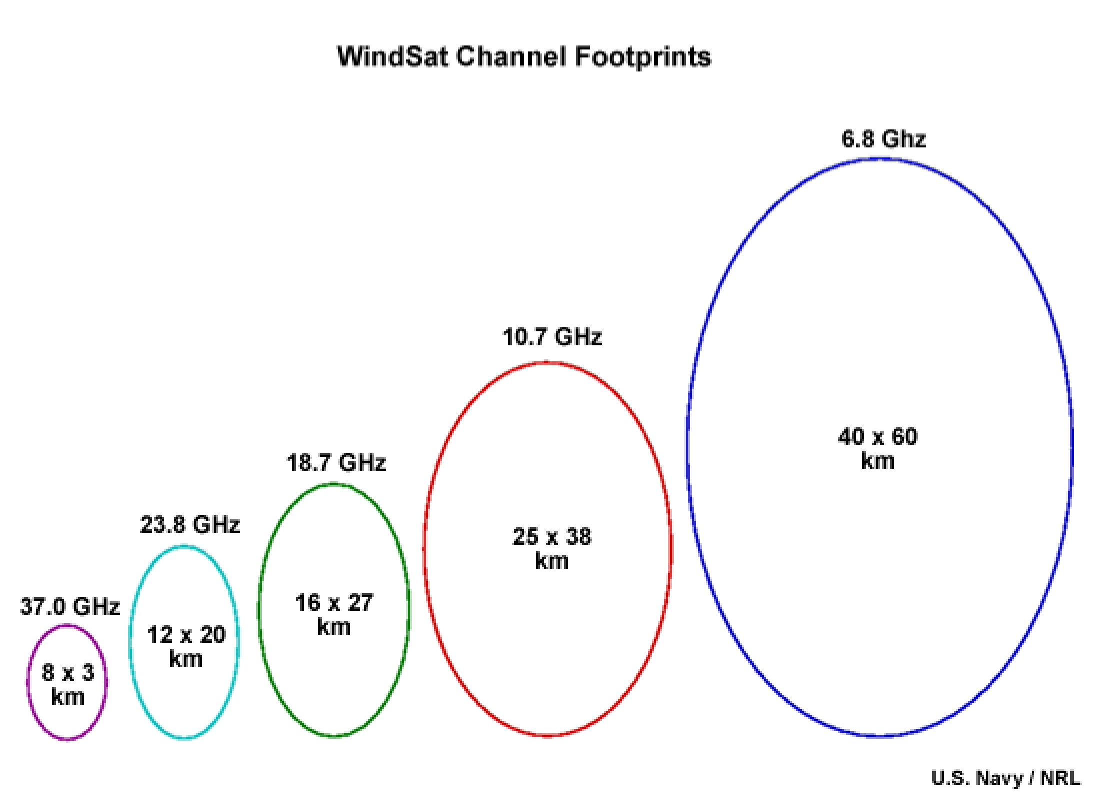
Visible / Near-IR / Infrared

~ Band Center (um)	GOES-6/7	GOES-8/11	GOES-12/N	GOES-O/P	GOES-R+
0.47					
0.64					
0.86					
1.6					
1.38					
2.2					
3.9					
6.2					
6.5/6.7/7	14km	8	4		2
7.3					
8.5					
9.7					
10.35					
11.2					
12.3					
13.3					

"MSI mode"

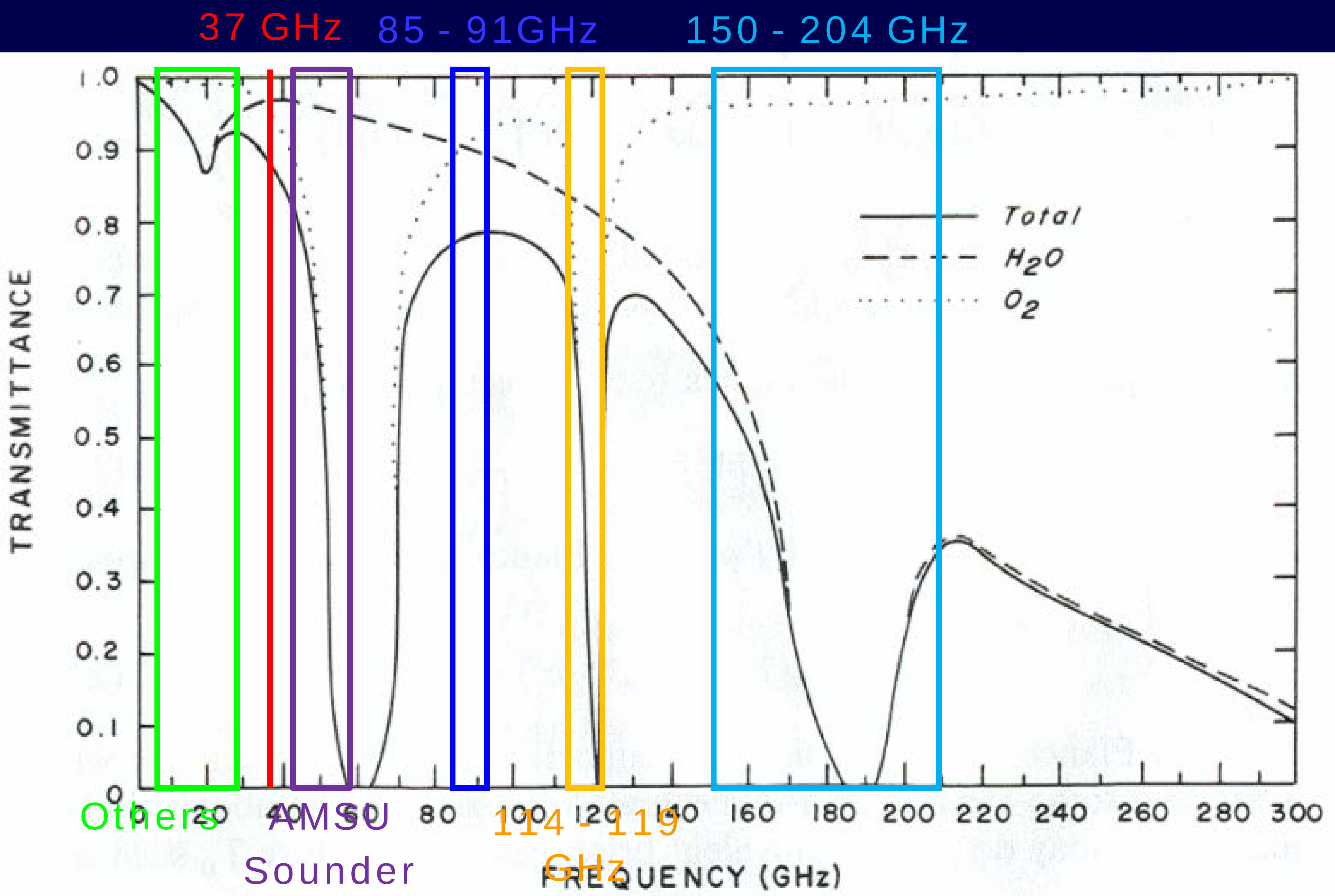
Box size represents detector size

The WindSat Microwave Imager

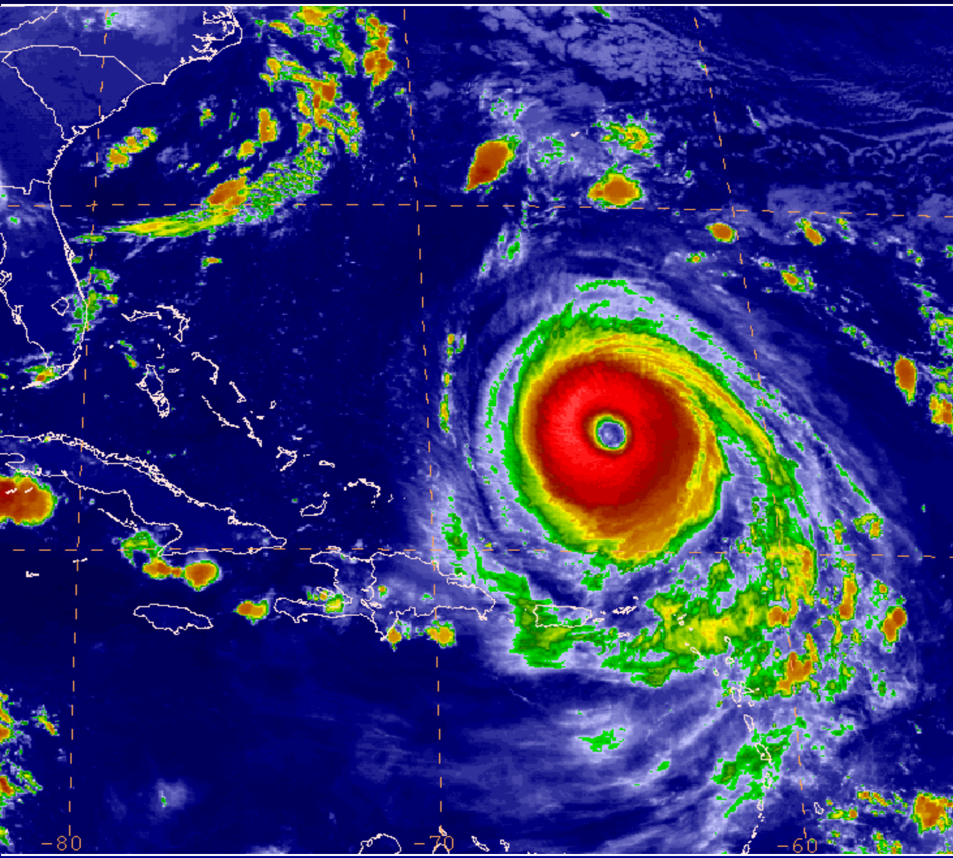


The footprint (pixel) size of the imager increases with decreasing frequency.

Microwave Transmittance

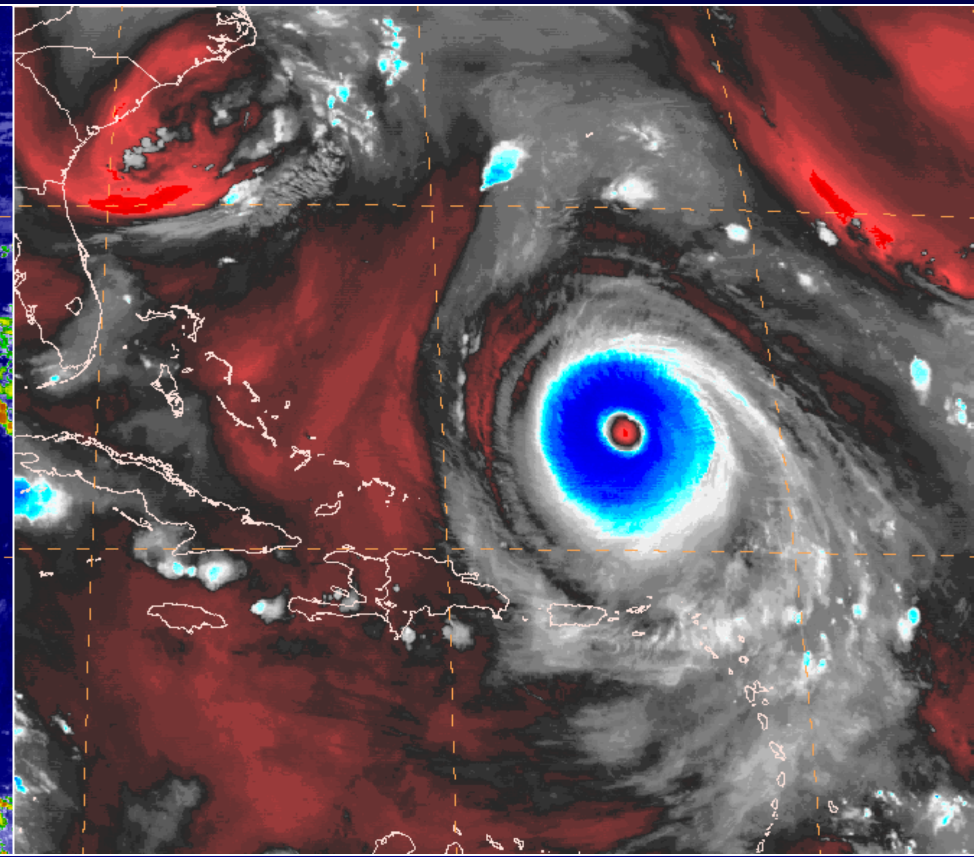


Are we looking at levels or layers?



Conventional IR 10.7 μm

More of a level quantity.



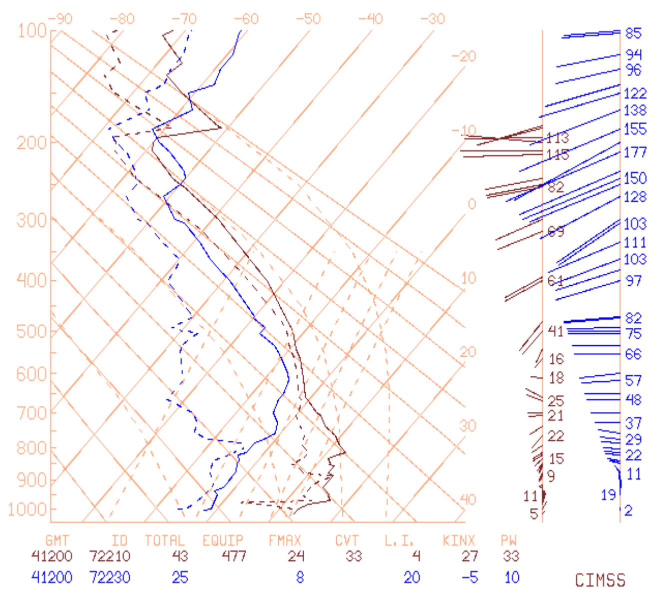
Water Vapor IR 6.5 μm

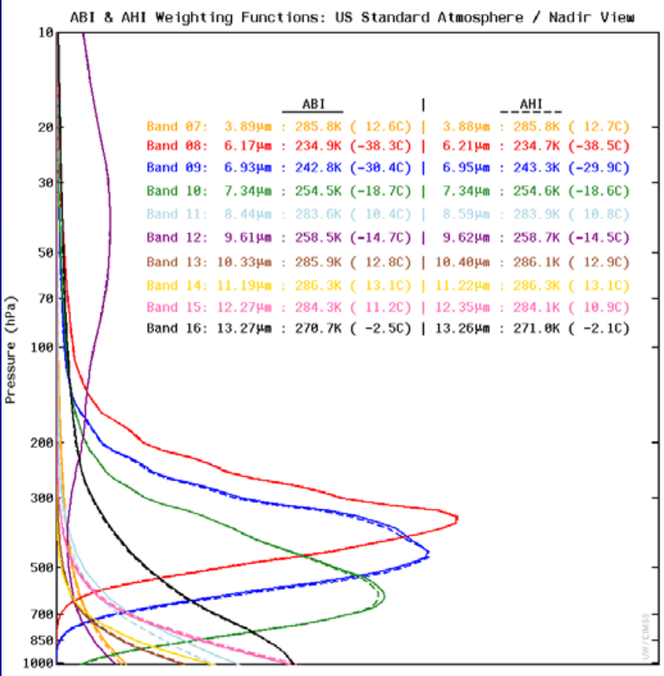
More of a layer quantity.

GOES-12 0600 UTC 14 Sep 2003

Weighting Functions

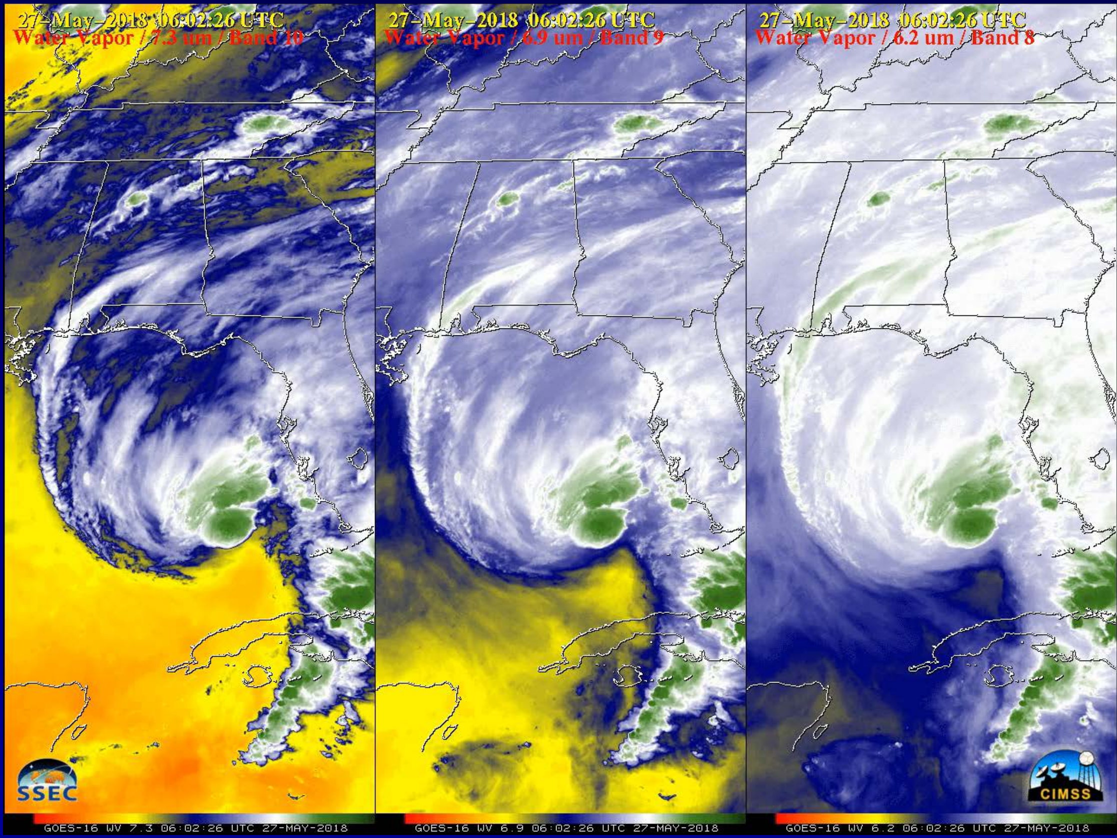
- ***Weighting function*, the derivative of transmittance with respect to height, specifies the relative contribution that each atmospheric layer makes to the radiation emitted to space.**
- **The weighting function determines those regions of the atmosphere which are sensed from space at a particular wavelength λ.**
- **Since water vapor concentrations are highly variable, weighting functions dependent on them will also vary by location.**
- **A good choice of λ on satellite instruments allows for atmospheric vertical profiling or "sounding".**





Water Vapor Imagery

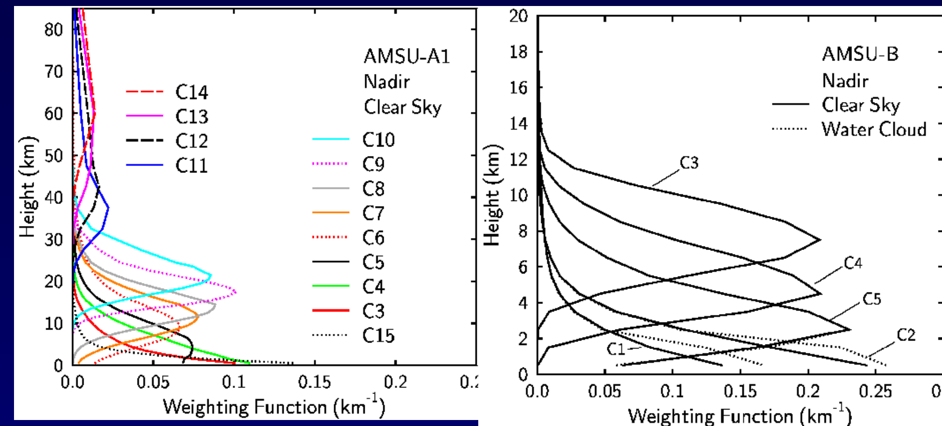
- **λ =6.5 μm is sensitive to water vapor in the mid to upper troposphere (generally 200-500 mb).**
- **Other wavelengths have peak sensitivity at other levels – the ABI has three channels for low/mid/ high-level water vapor.**
- **Water vapor imagery can reveal features that don't generate visible clouds.**
- **Animation can reveal steering flows, shearing winds, dry intrusions, or outflow for TCs.**



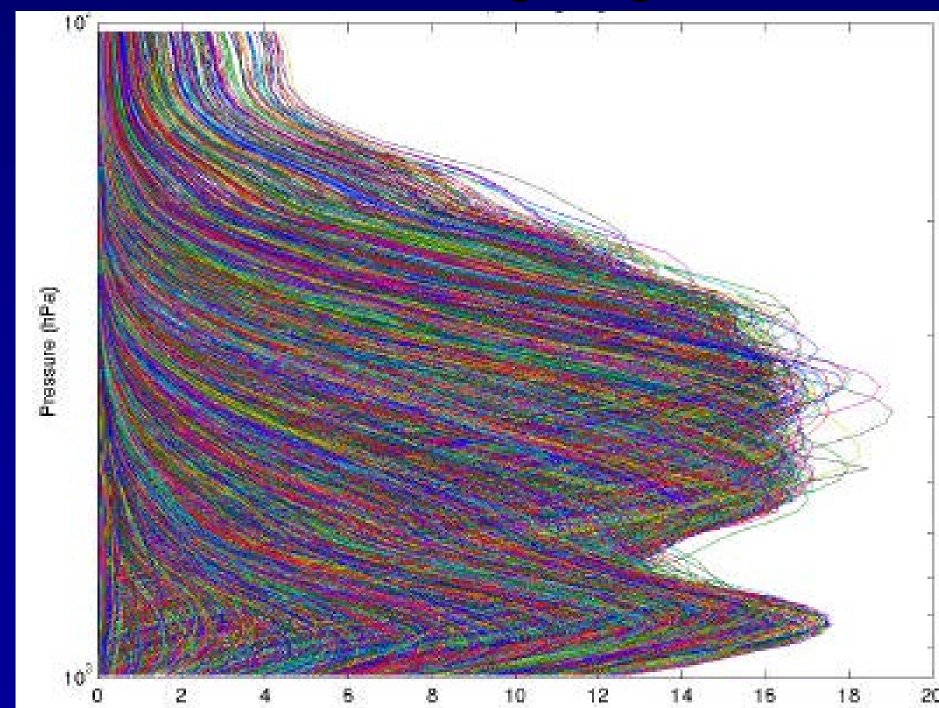
Alberto (2018) GOES WV channels (courtesy CIMSS)

Instruments - Sounders

- **Sounder – Makes a vertical profile of a meteorological quantity - usually uses combinations of infrared or microwave frequencies**
- **Satellite <u>soundings</u> can be used for analysis and short-term forecasting, and are also assimilated into numerical weather prediction models**
- **Infrared-based sounders cannot sound through clouds, while microwave sounders like AMSU are affected by heavy precipitation**
- **Hyperspectral sounders like AIRS or IASI use interferometry to create thousands of channels**



AMSU vertical weighting functions



Hyperspectral weighting functions

Types of Satellite Data

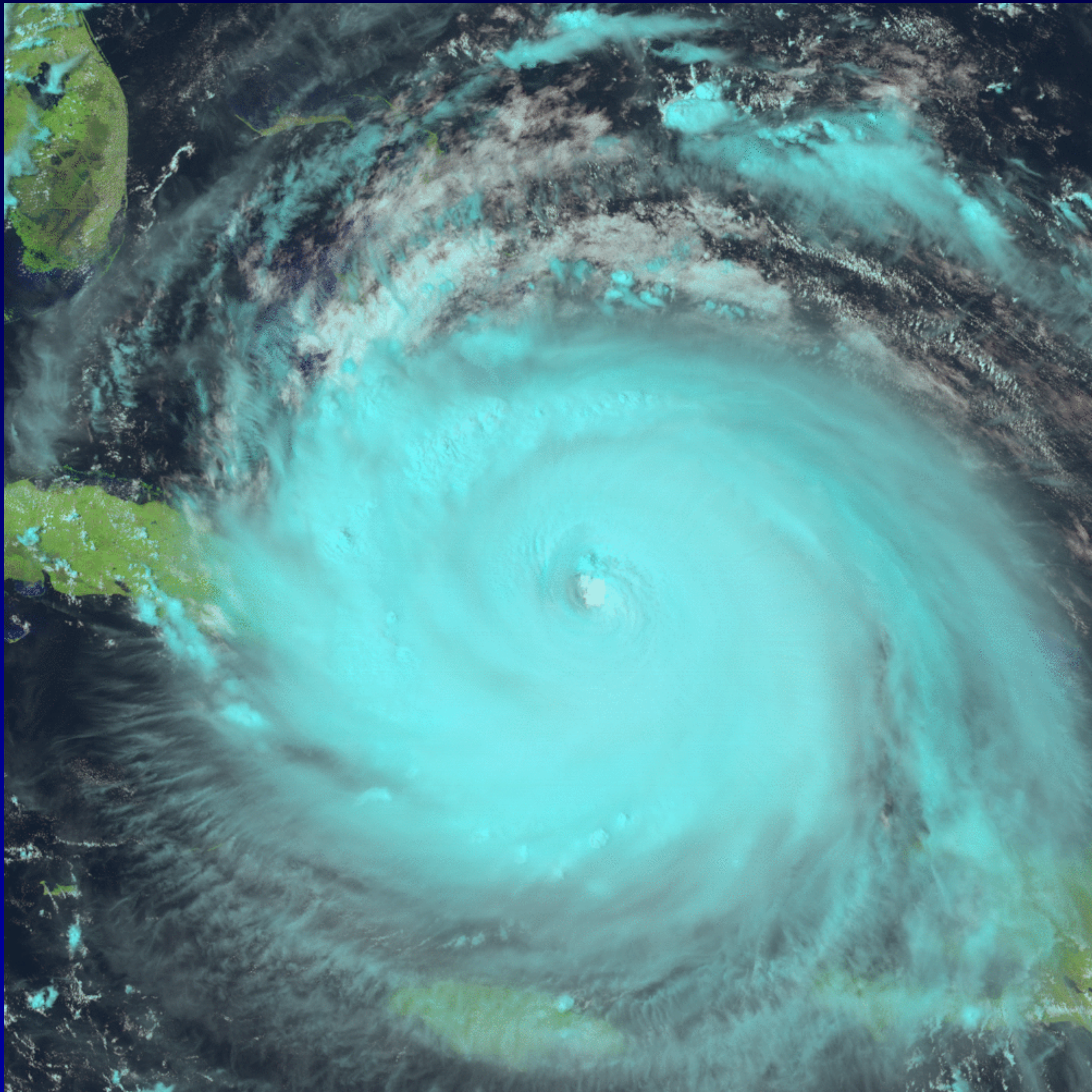
- **Imagery: Visible (VIS), Infrared (IR), Water Vapor (WV), Shortwave Infrared (SWIR), Microwave (MW), Multispectral – most meteorological satellites**
- **Satellite Atmospheric Winds: from multiple images (VIS, IR, WV) - geostationary satellites, some LEO satellites near the poles**
- **Sea Surface Temperatures (IR, MW) - GOES, NOAA, GPM, GCOM, METOP, NPP/JPSS**
- **Ocean Surface Wind Speeds (MW) * - DMSP, GPM, GCOM, METOP, CYGNSS, SMAP, SMOS**
- **Precipitation Estimates (IR, MW) * - geostationary satellites, GPM (including the <u>Precipitation Radar</u>), GCOM, DMSP, METOP**

Types of Satellite Data

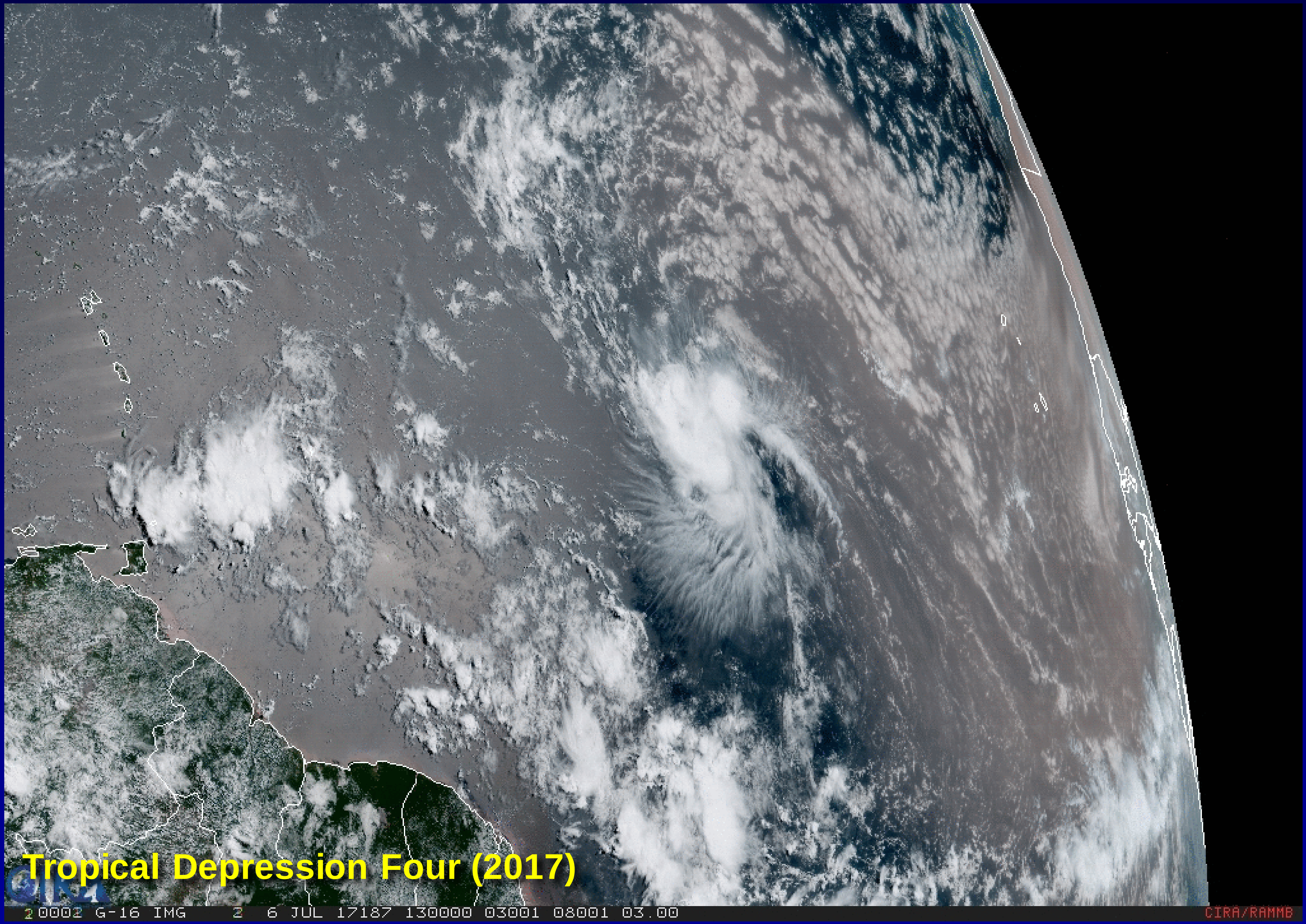
- **Tropical Cyclone Intensity Estimates (VIS, IR, MW) * - geostationary satellites, NOAA (Advanced Microwave sounding Unit or AMSU), DMSP (SSM/IS), GPM, GCOM, METOP, NPP/JPSS (ATMS)**
- **Satellite Vertical Soundings (IR, WV, MW) - GOES, NOAA, DMSP, METOP, Aqua, NPP, JPSS**
- **Ocean Wave Heights (Jason 3, Cryosat-2, Altika, Sentinel-3)**
- **Oceanic Heat Content (Jason 3, Cryosat-2, Altika, Sentinel-3)**
- **Atmospheric moisture – COSMIC**
- **Lightning – GOES-R series**
- ***Other Derived Products: Aerosol detection and thickness, cloud top parameters, stability indices, volcanic ash detection, fire detection.***

GOES-R Super-Rapid Scan Capabilities

Hurricane Irma September 2017 – 1-min multispectral rapid-scan imagery



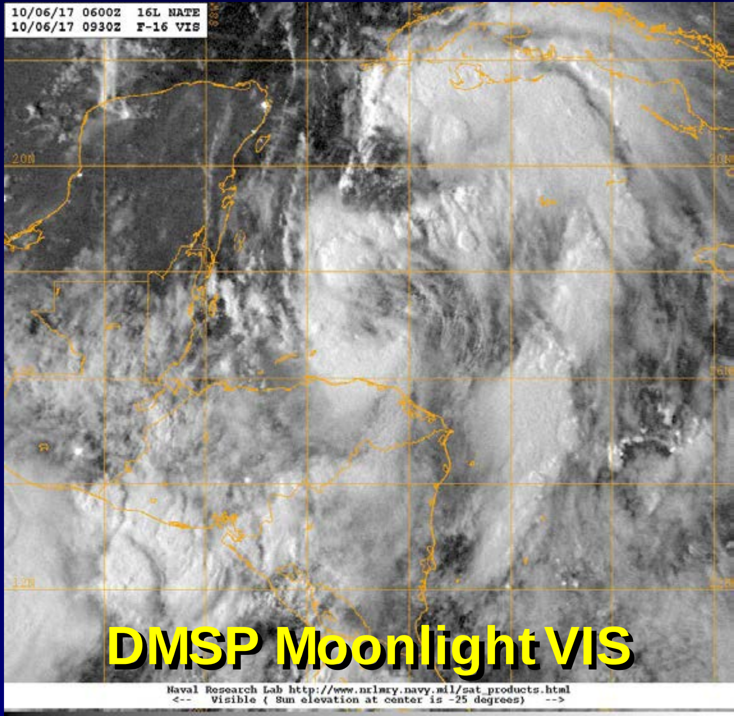
Pseudo-Natural (Geo) Color Imagery

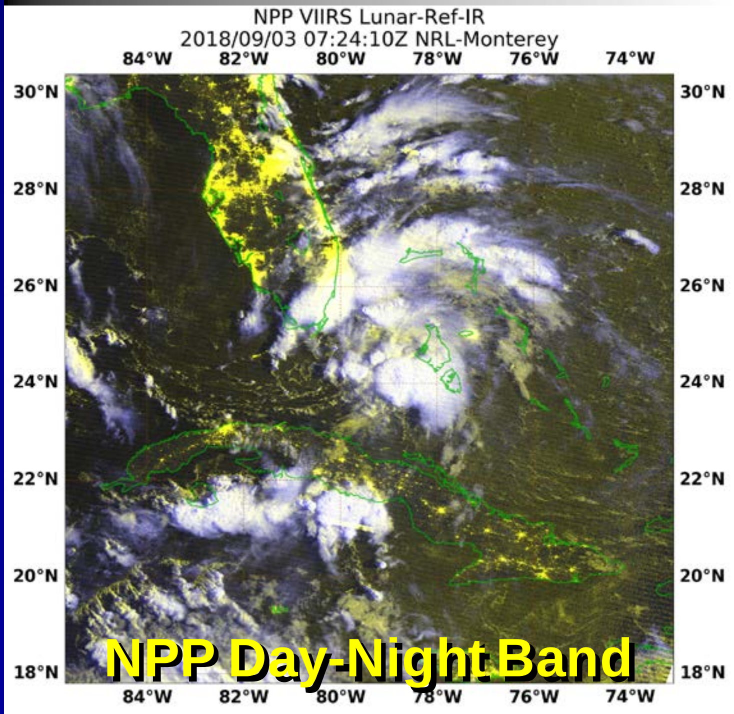


- **The ABI does not have a channel for green visible imagery, so it cannot make true/natural color visible images. (The Himawari-8 imager includes a green channel.)**
- **Data for the green channel can be estimated from other channels to create pseudo-natural color imagery.**

Day-Night Band Imagery

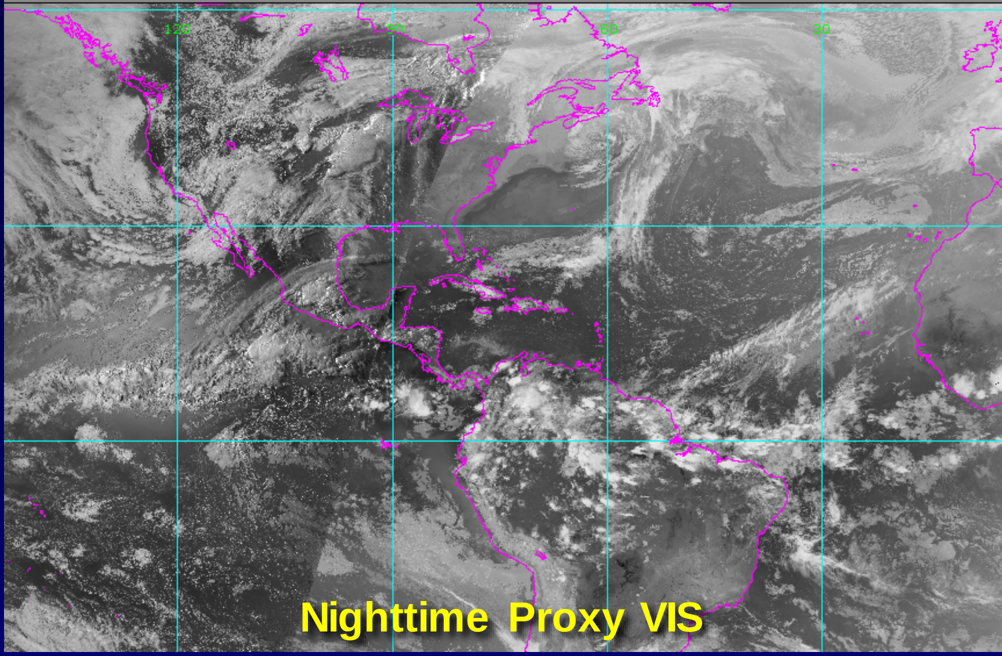
- **DMSP and NPP/JPSS satellites have the ability to take visible images by reflected moonlight.**
- **This allows the resolution of visible imagery at night, which is useful for diagnosing the structure of tropical cyclones and other weather systems.**



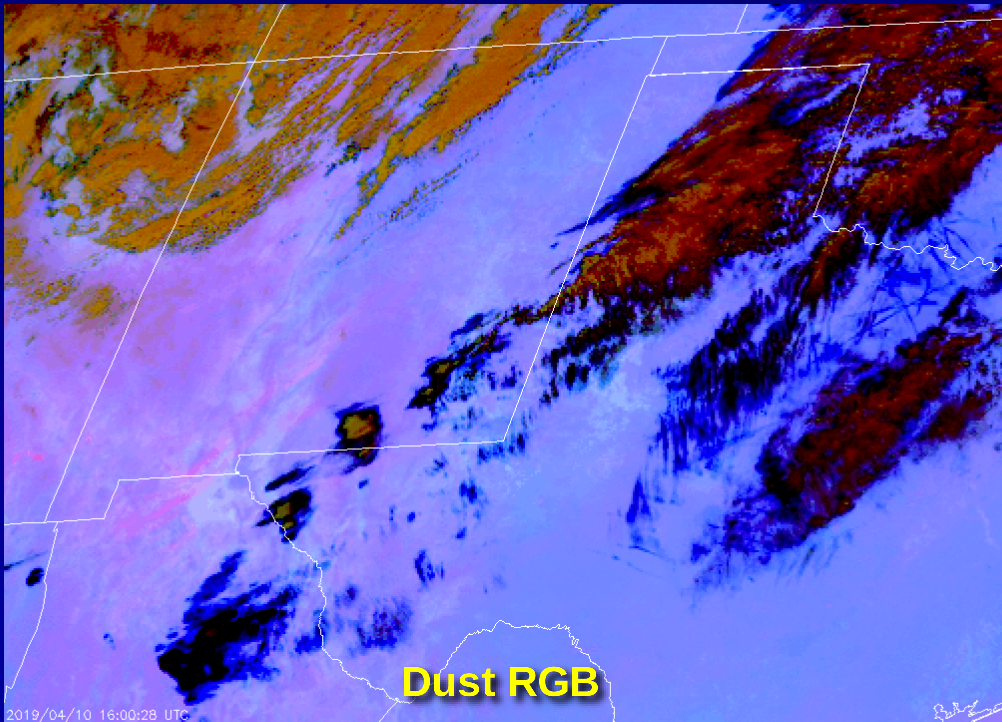


Multi-spectral Imagery

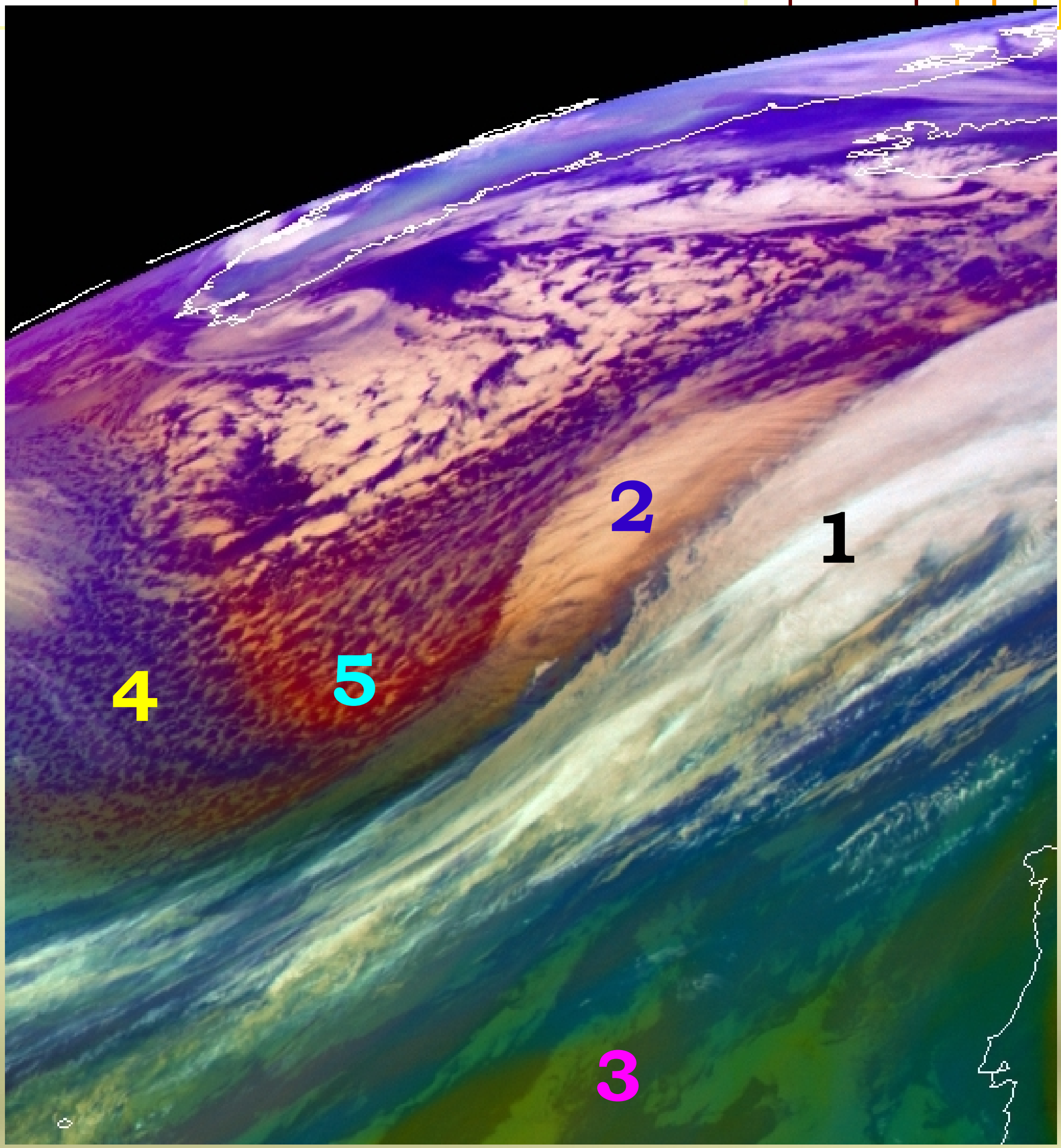
- **Combinations of channels can show important features that a single channel cannot, such as enhanced convection or aerosols.**
- **Properly using radiative properties can maximize image amount of information in an image.**
- **Nighttime visible is an example, as well as the Dust RGB.**



(Both courtesy of CIRA)



Airmass RGB: Colour Interpretation

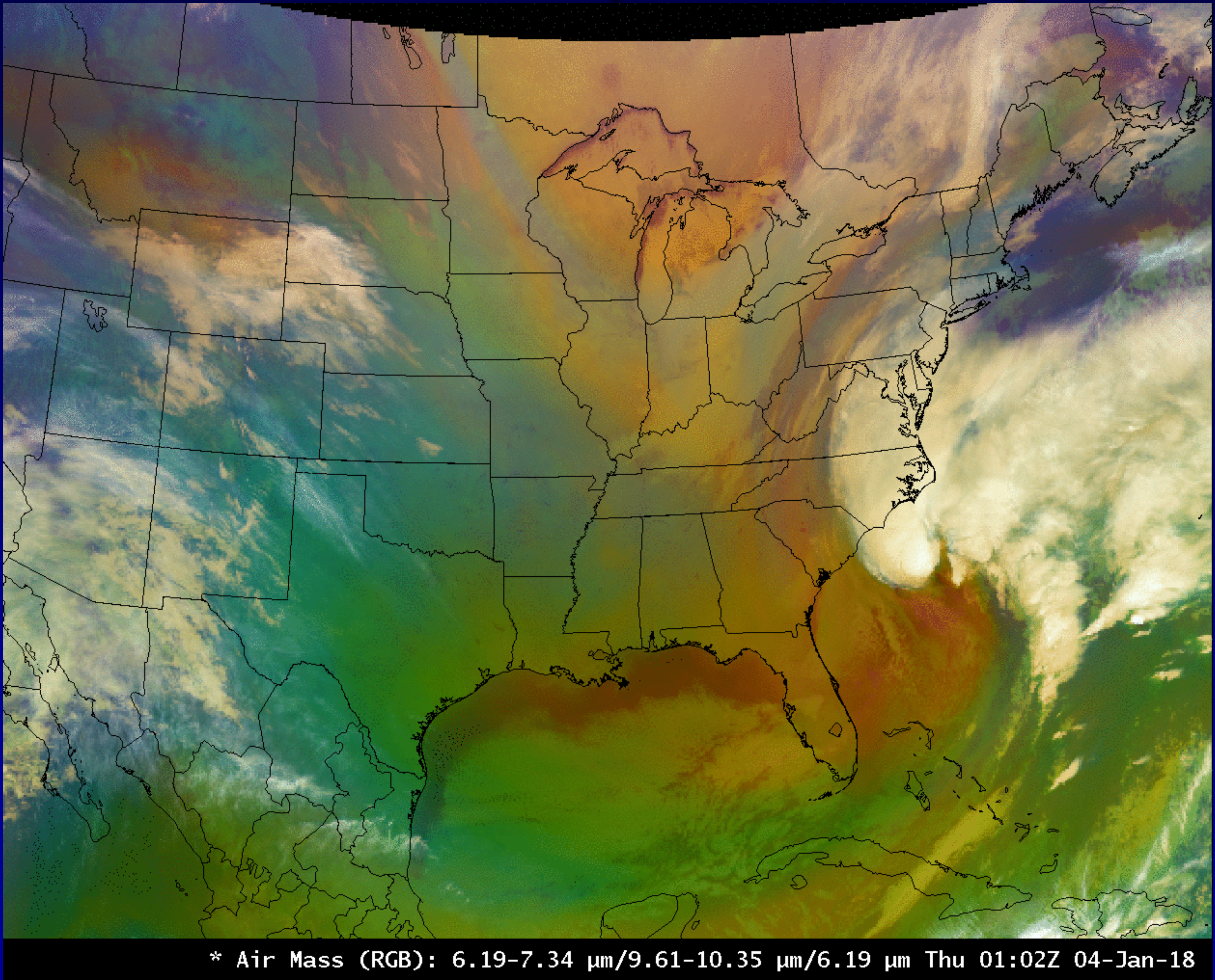


1 = high clouds
2 = mid-level clouds
3 = warm airmass, high tropopause
4 = cold airmass, low tropopause
5 = dry descending stratospheric air

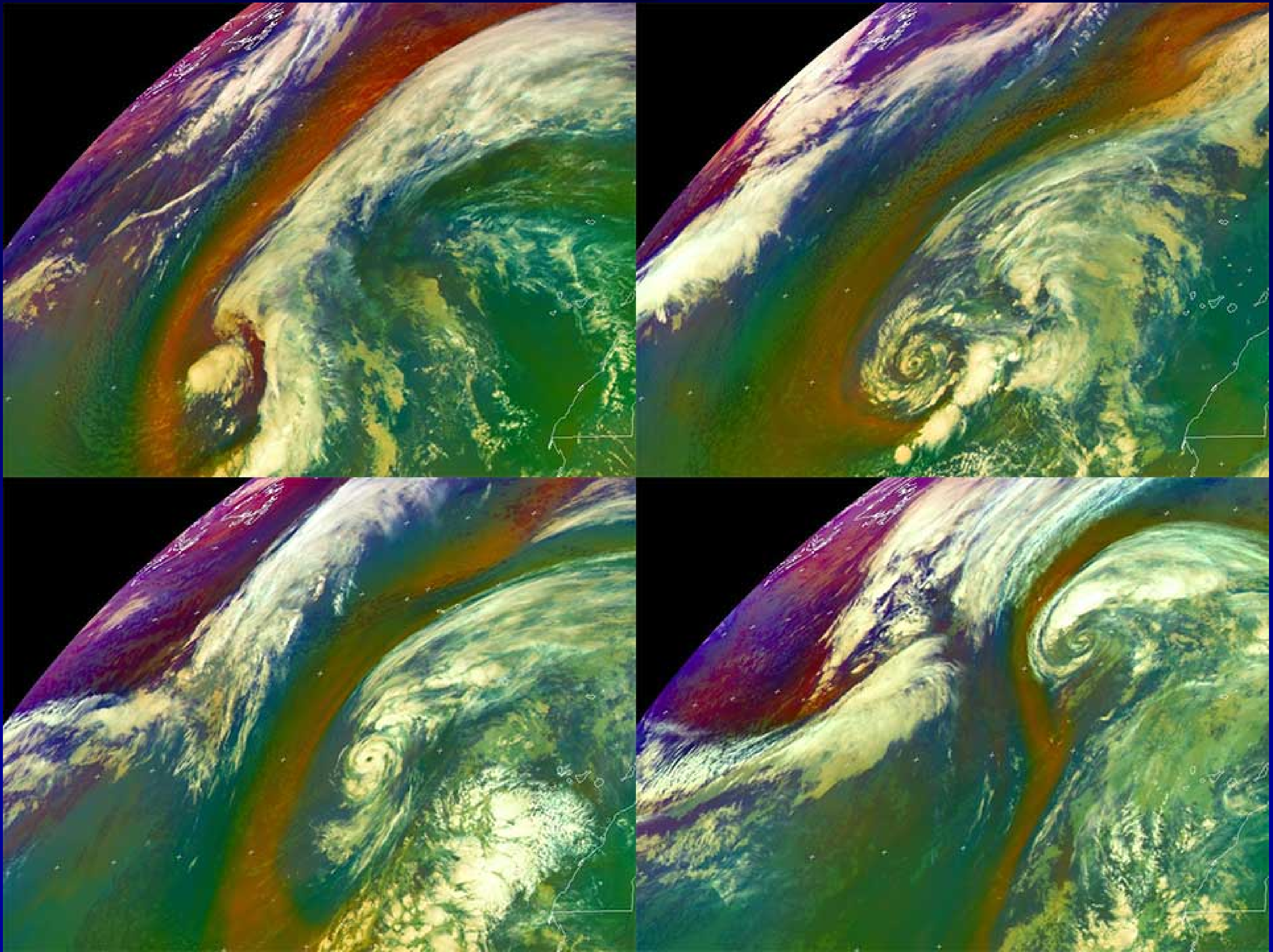
MSG-1
07 January 2005
15:00 UTC
RGB Composite
R = WV6.2 - WV7.3
G = IR9.7 - IR10.8
B = WV6.2

EUMETSAT

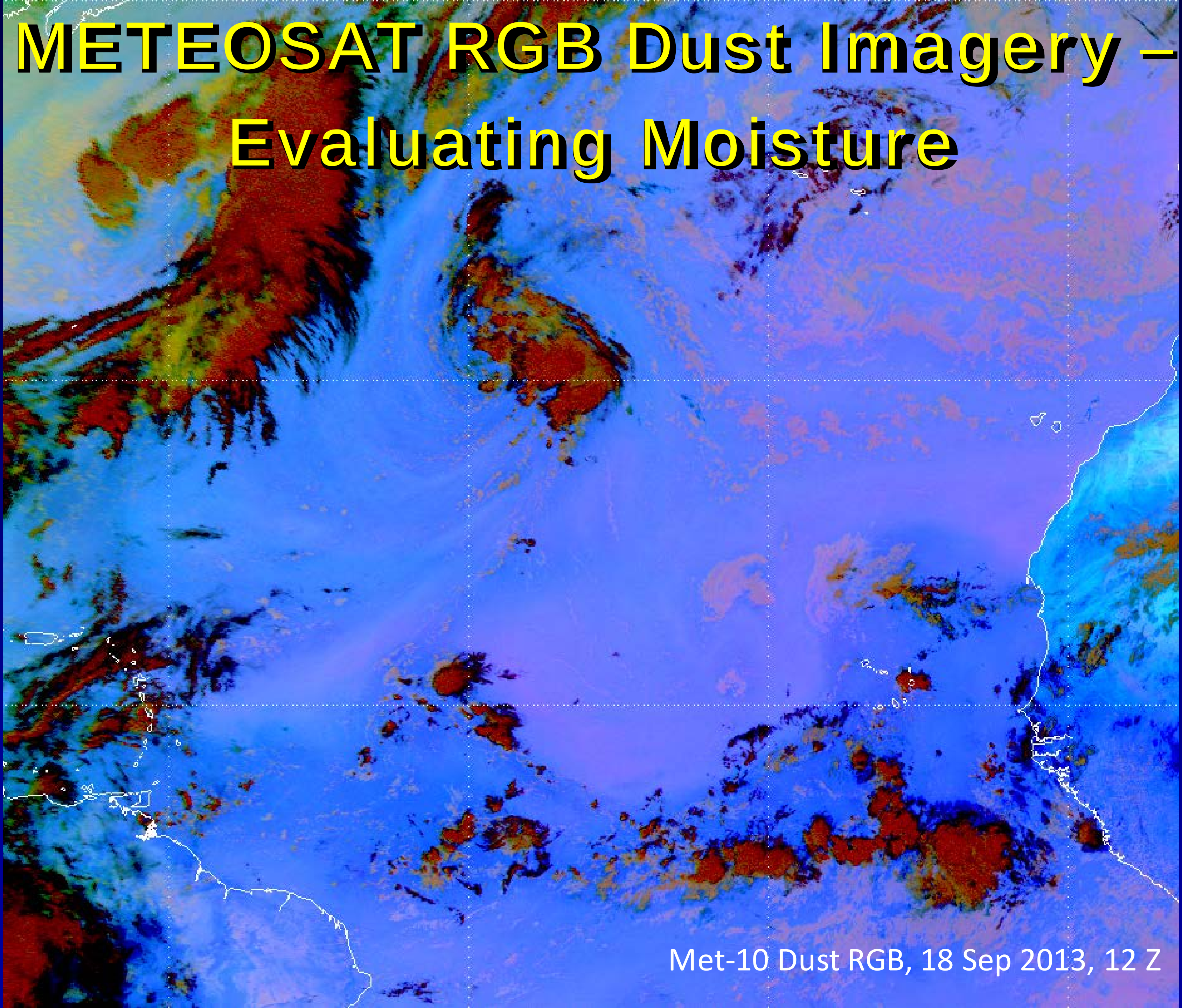
RGB Airmass Product – January 2018 Explosive Cyclogenesis



RGB Airmass Images of Alex (2016)

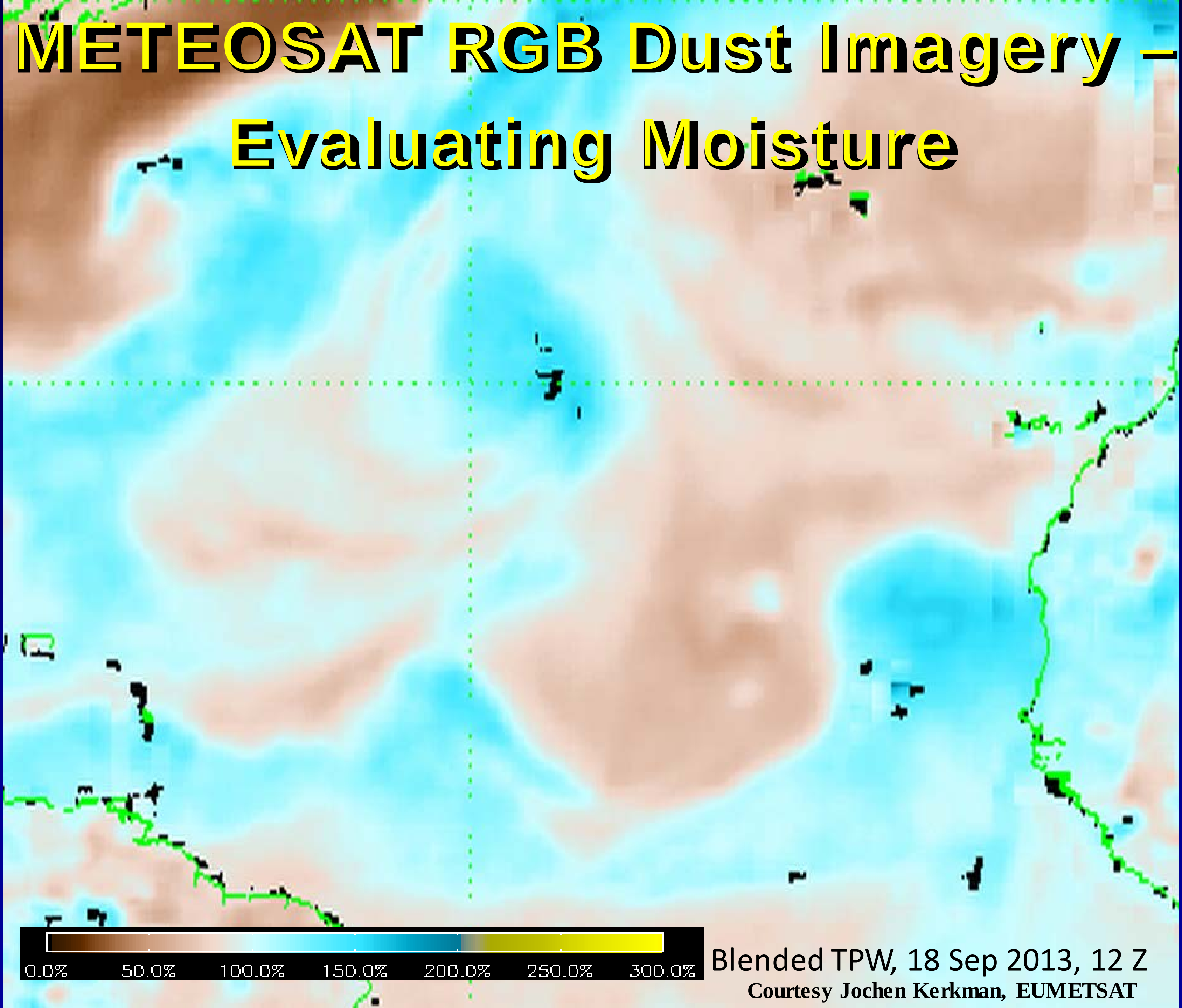


METEOSAT RGB Dust Imagery – Evaluating Moisture



Met-10 Dust RGB, 18 Sep 2013, 12 Z

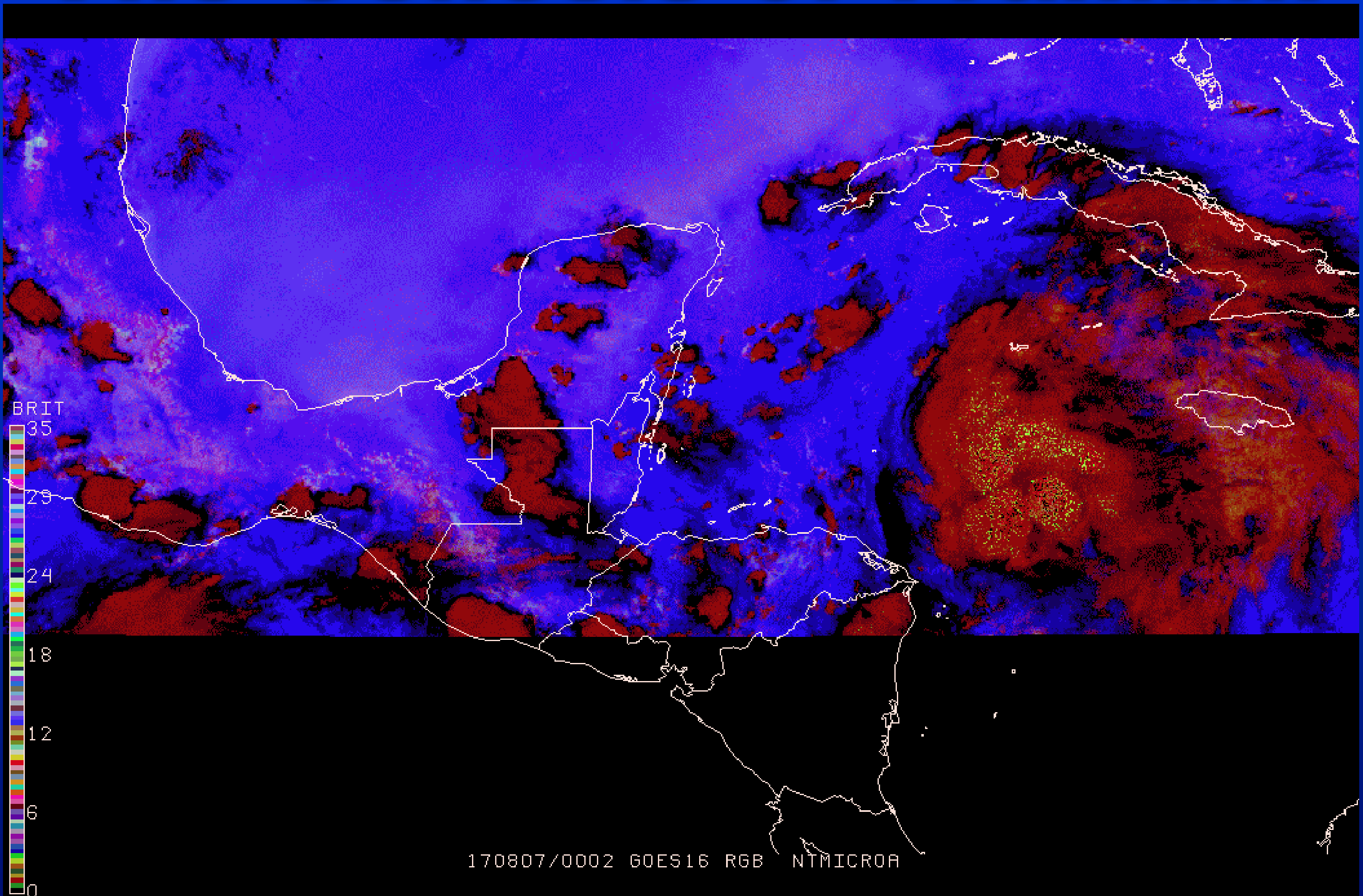
METEOSAT RGB Dust Imagery – Evaluating Moisture



Blended TPW, 18 Sep 2013, 12 Z

Courtesy Jochen Kerkman, EUMETSAT

The Genesis of Franklin

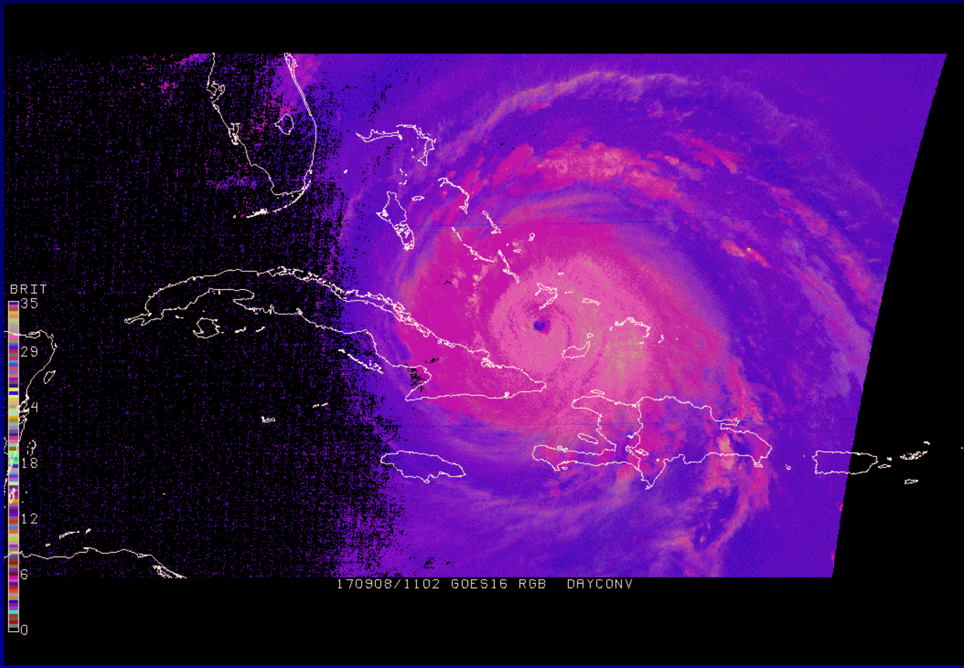


RGB Night Microphysics imagery courtesy of NASA SPoRT

“However, the new GOES-16 nighttime microphysics imagery clearly shows low clouds moving from west to east on the south side of the alleged center, which is suggestive of a closed low-level circulation.”

Daytime Convective Storms Product

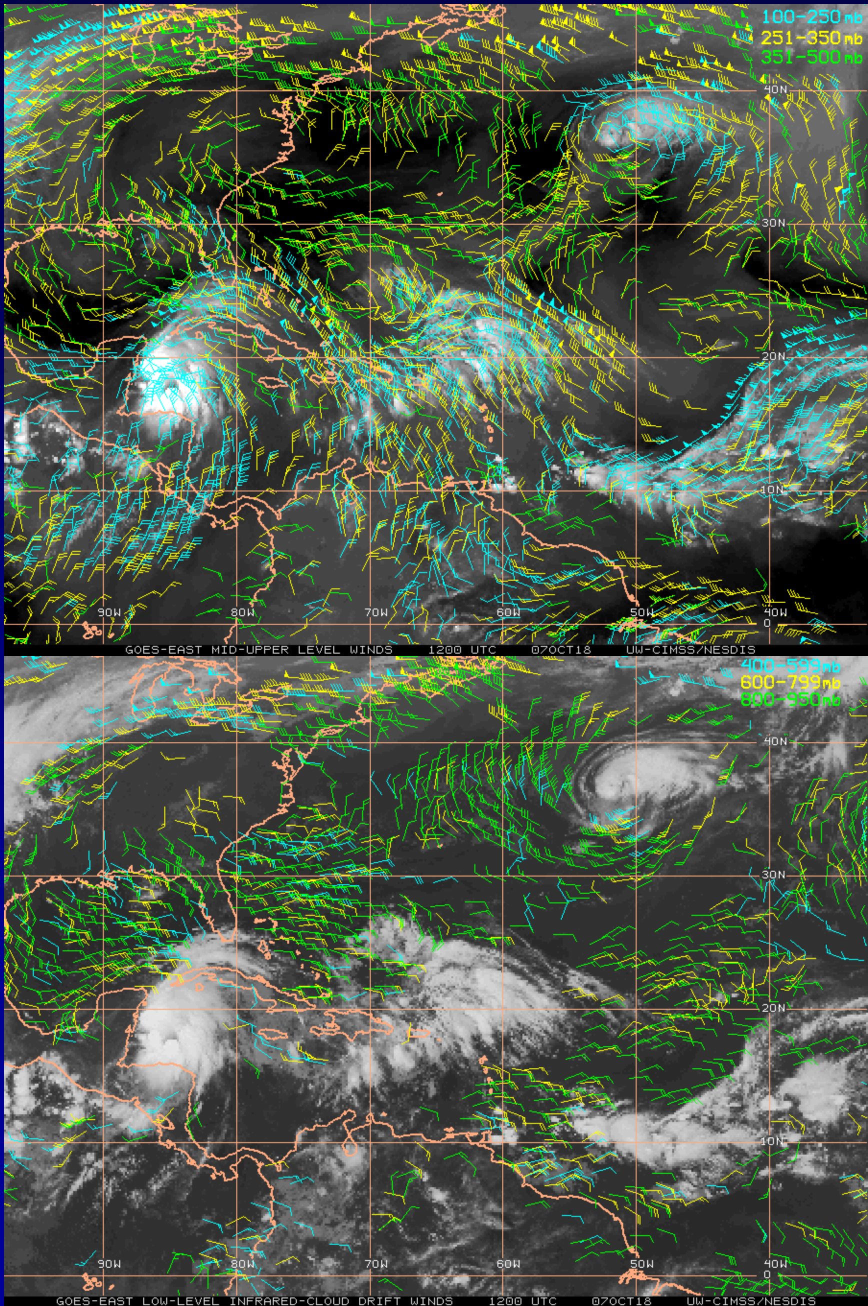
- Provides information about
  - Cloud top particle size (related to updraft strength)
  - Cloud top phase
  - Precipitation
- Tropical applications
  - Cloud discrimination (convective, stratiform)
  - Genesis and intensity forecasting
- Generated from MSG SEVIRI channels WV6.2, WV73, IR3.9, IR10.8, NIR1.6, VIS0.6
- Highlights differences between dry, tropical, and cold air masses



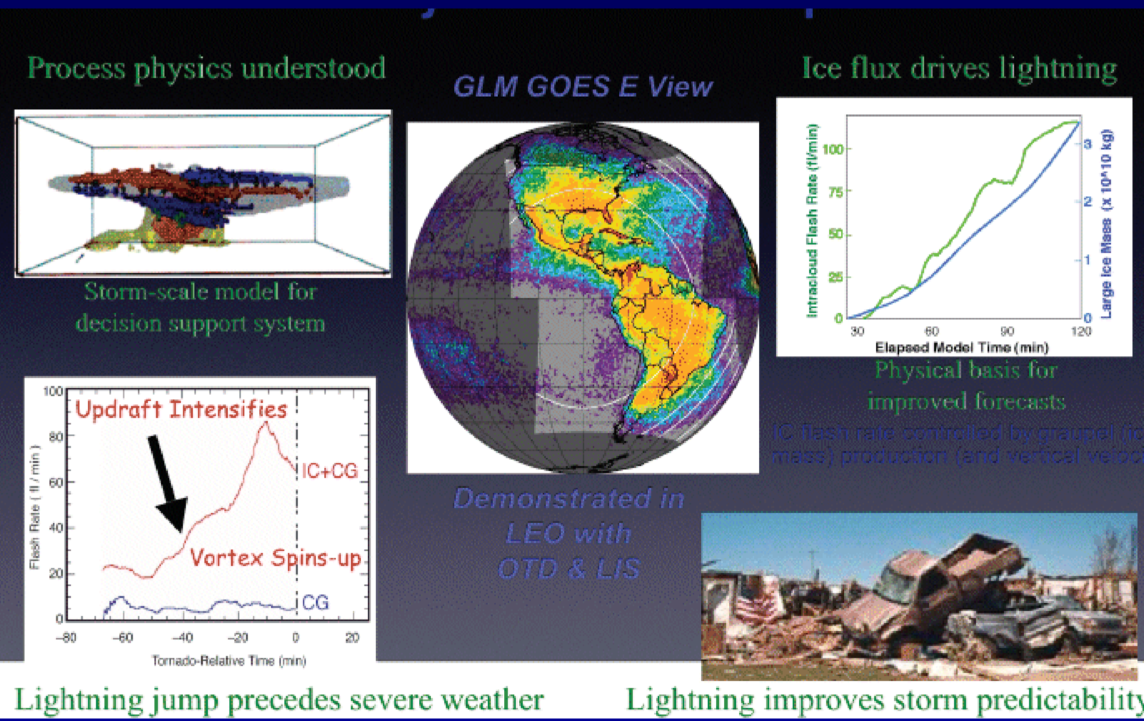
Irma (2017)

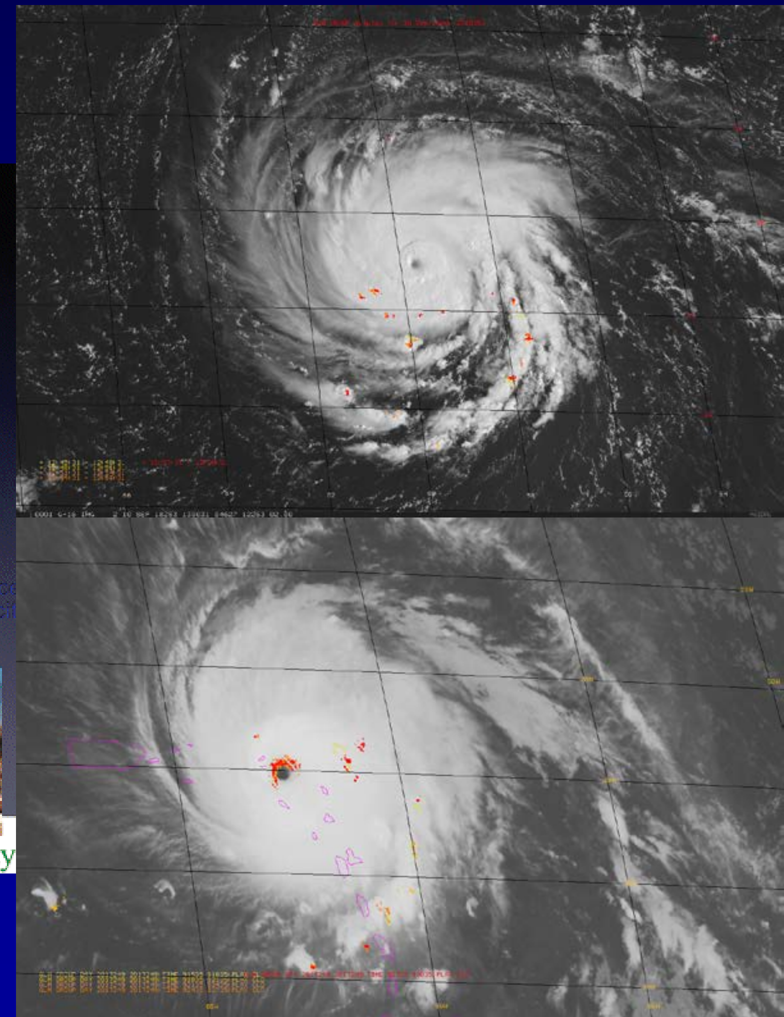
Satellite-derived Winds

- **Satellite winds (also known as atmospheric motion vectors) are computed from displacement of targets on successive geostationary images.**
- **Targets include clouds in visible or infrared imagery and features in water vapor imagery.**
- **Temperature of cloud or water vapor feature is used for height assignment.**
- **Satellite winds can show tropical cyclone steering, shearing, and outflow patterns, but cannot be made below the central cirrus canopy of a TC.**
- **Satellite winds are used for analysis as well as to initialize numerical weather prediction models.**
- **Reference: Velden et al., BAMS, 1997**



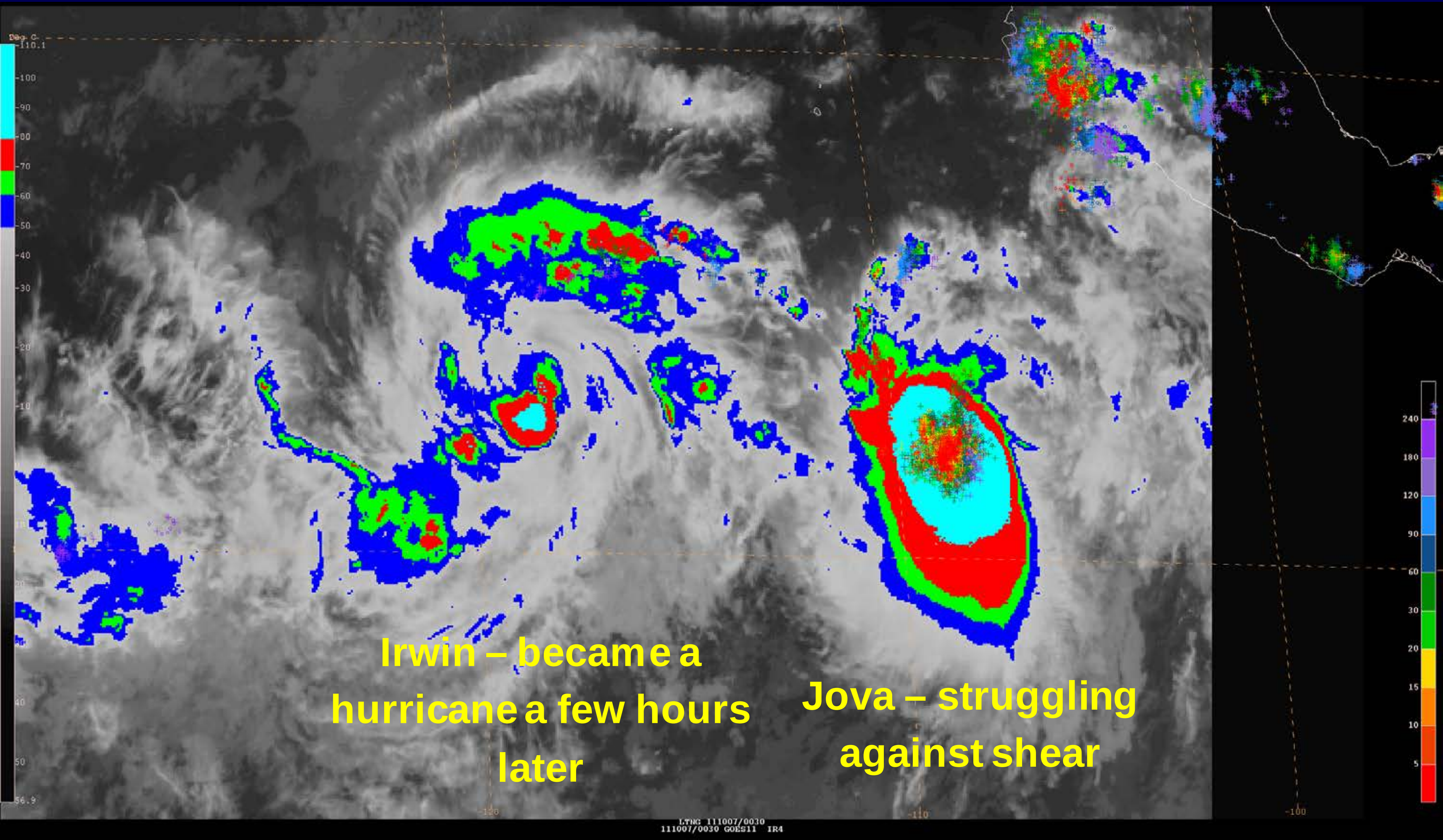
Geostationary Lightning Mapper (GLM) - Continuous GEO Total Lightning helps identity severe storm potential



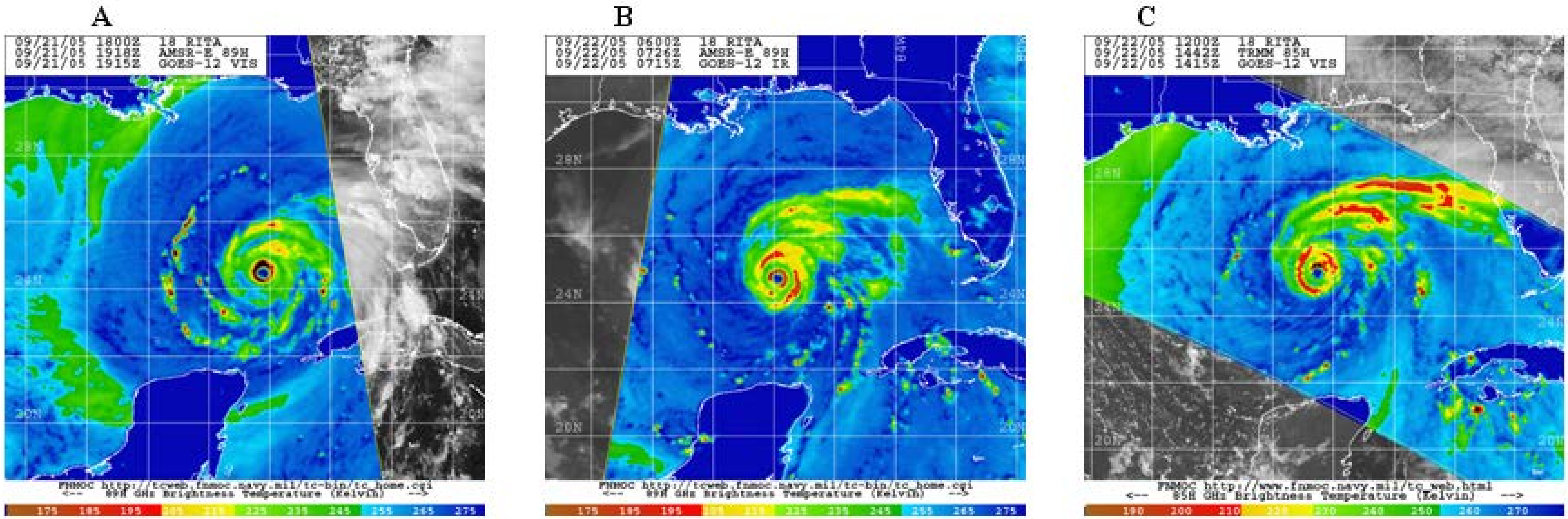


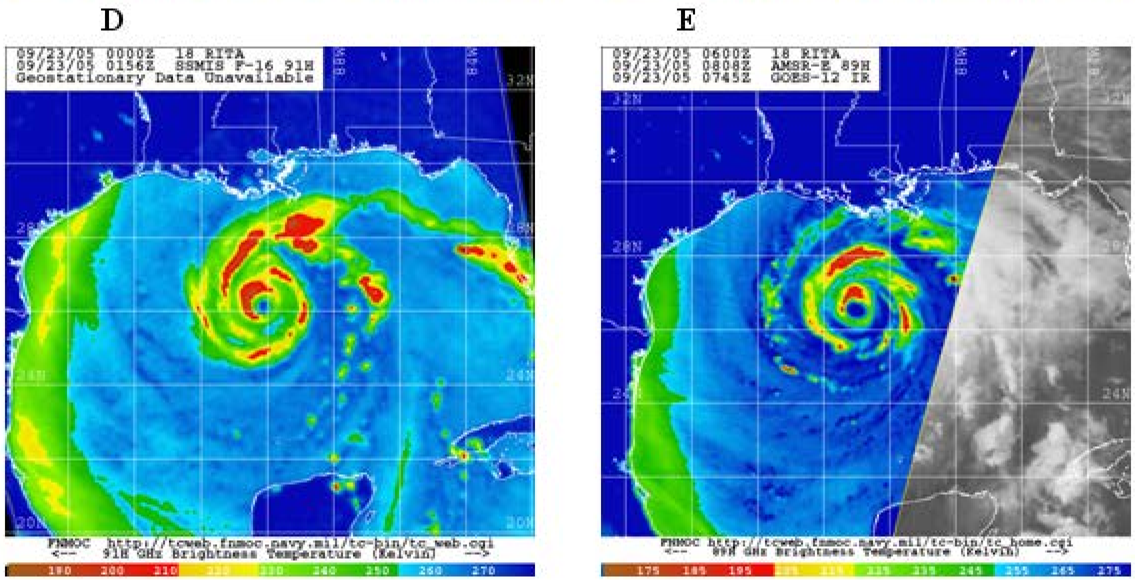
Florence (2018) top and Irma (2017) bottom – both courtesy of CIMSS

An Example of Lightning in Eastern Pacific Tropical Cyclones



Microwave imagery of TCs



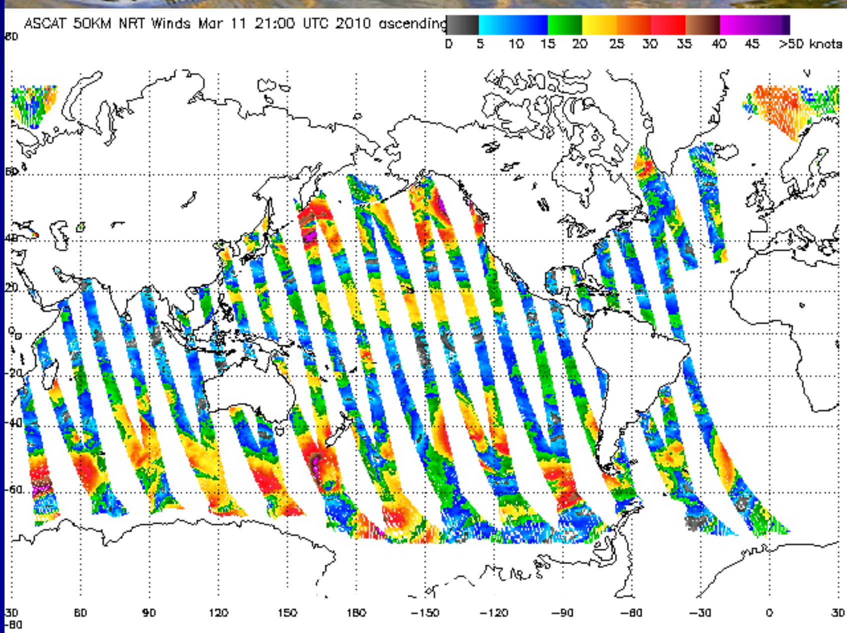


Images provided by the Fleet Numerical Meteorology and Oceanography Center (FNMOC).

Certain microwave frequencies can see through the ice clouds at the top of a tropical cyclone.

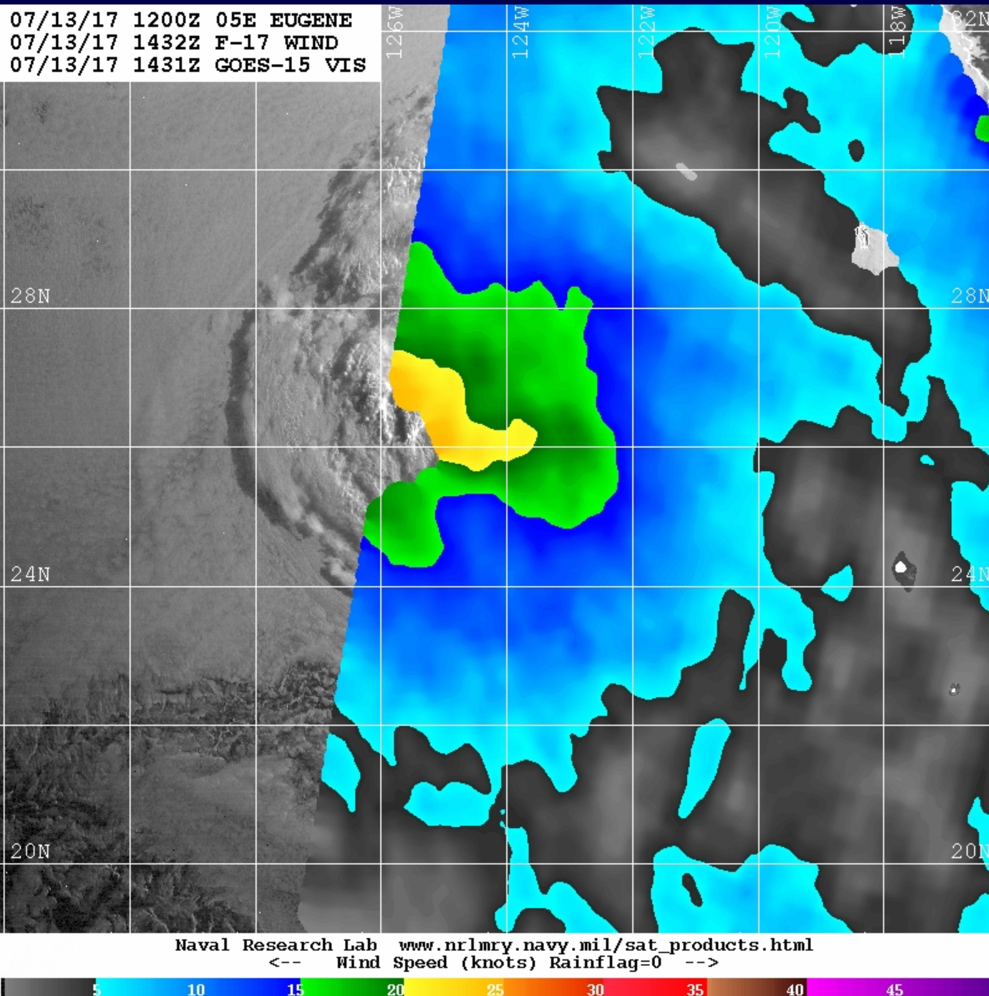
Figure 4. Series (in order A-E) of 85-91 GHz passive microwave images of Hurricane Rita during 21-23 September 2005.

Scatterometry and Scatterometers

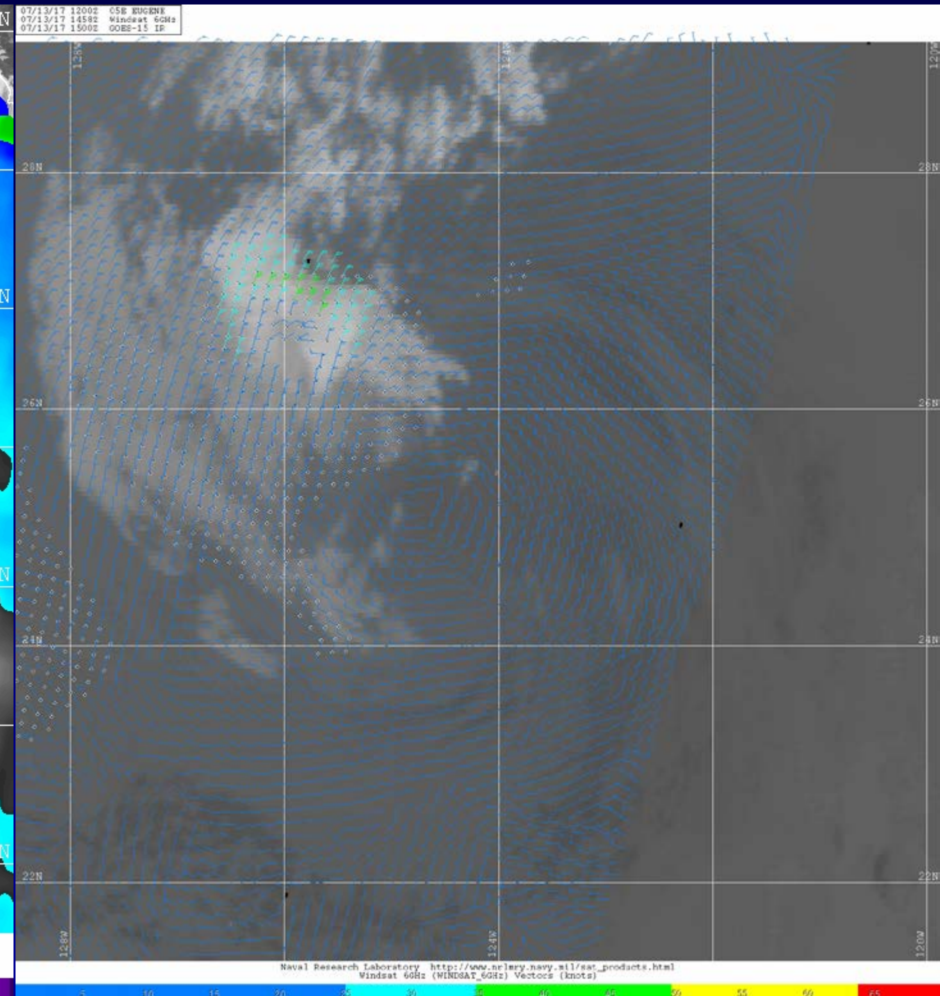


- **Small-scale roughness elements are scatterers.**
- **Fundamental assumption/ paradigm: small-scale roughness elements on the ocean surface are function of local wind speed/ direction.**
- **Radar pulses can measure these roughness elements and return estimates of wind speed/direction. Instruments that do this are called <u>scatterometers.</u>**
- **Currently active scatterometers fly on the METOP and Chinese FY LEO series satellites.**

Passive Ocean Surface Winds



SSM/IS Winds – Eugene (2017)

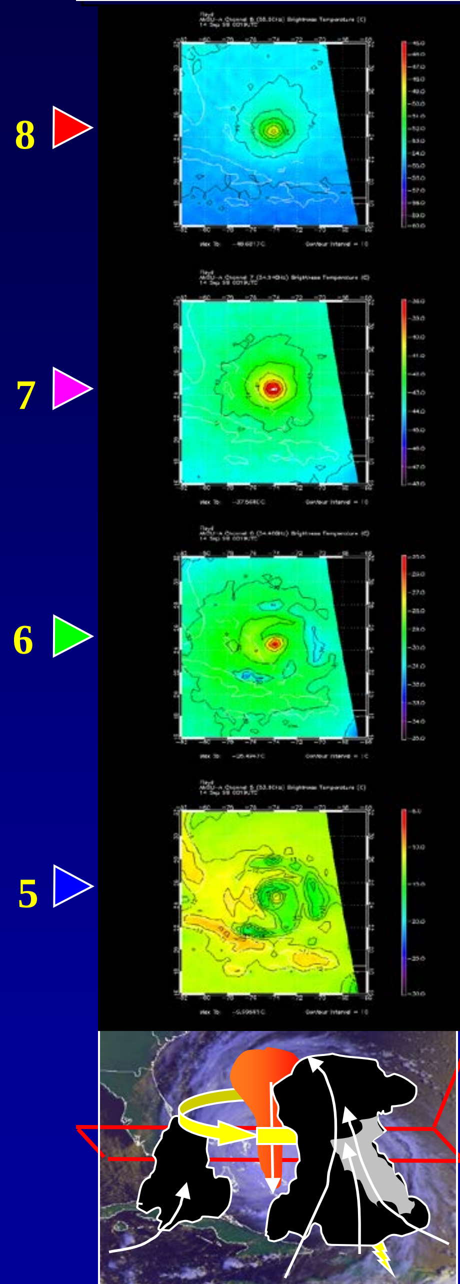


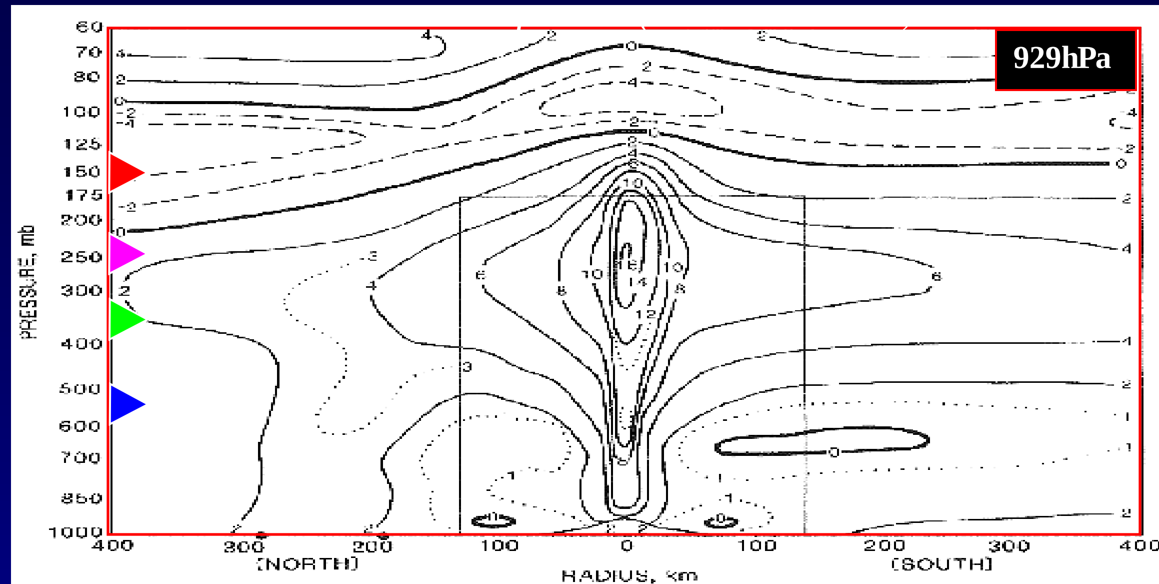
Windsat vector winds – Eugene (2017)

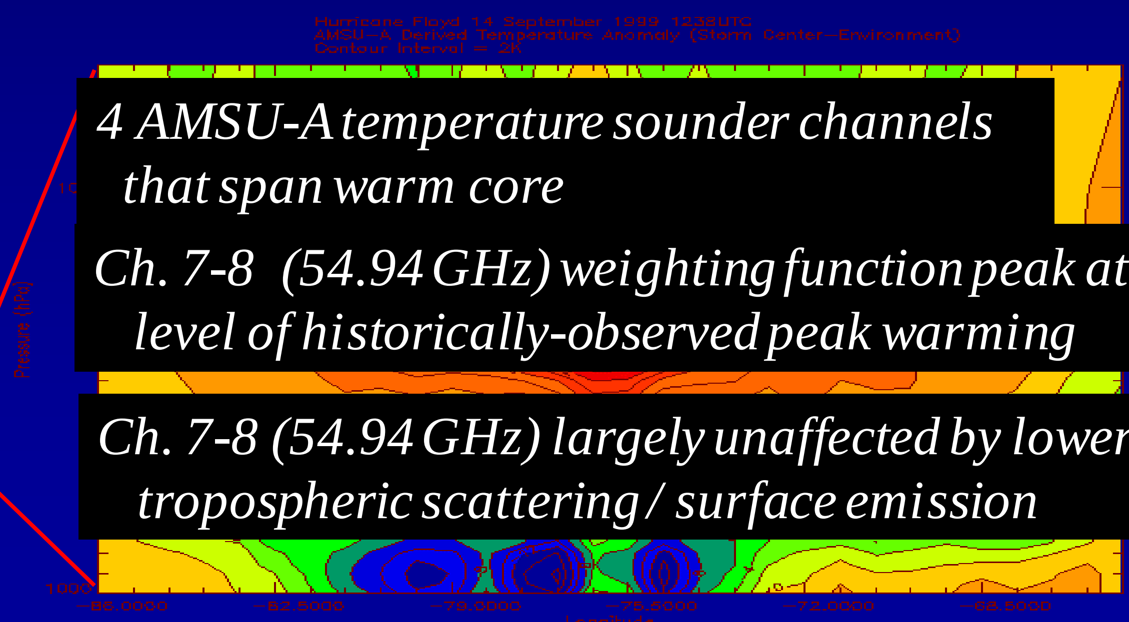
Passive microwave winds work best in areas of dry weather.

Hurricane Floyd Sept 14 1999

AMSU-based intensity estimates from CIMSS and CIRA







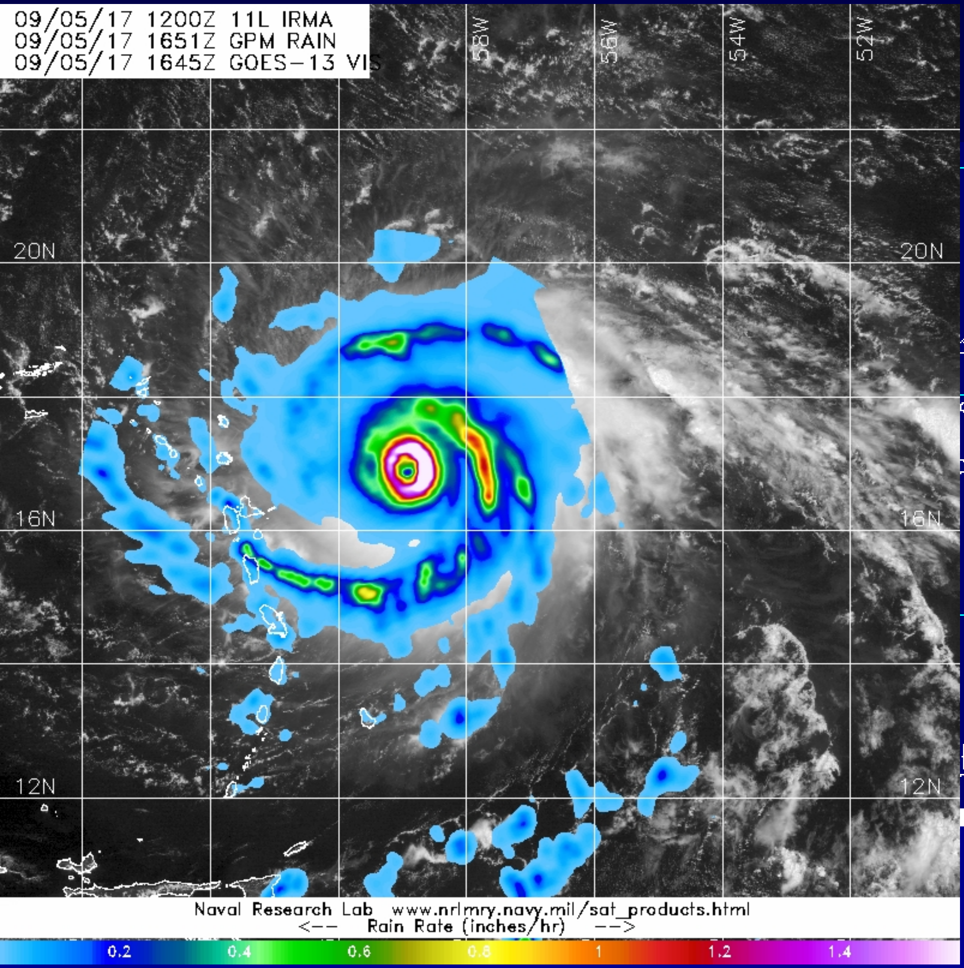
4 AMSU-A temperature sounder channels that span warm core

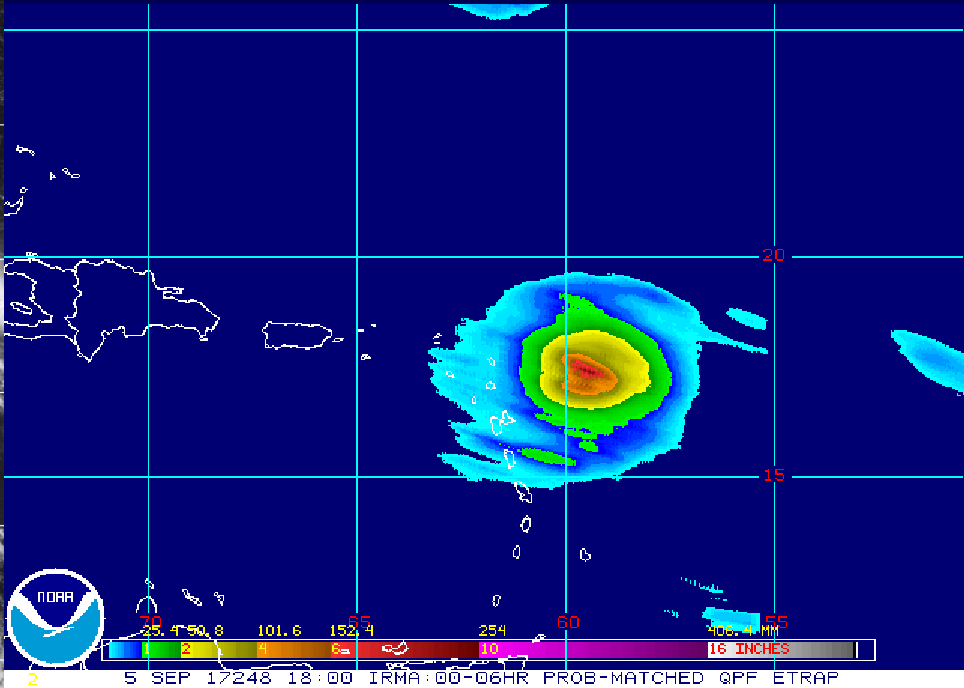
Ch. 7-8 (54.94 GHz) weighting function peak at level of historically-observed peak warming

Ch. 7-8 (54.94 GHz) largely unaffected by lower tropospheric scattering / surface emission

Slide courtesy of Velden et al CIMSS/NRL

Microwave Satellite Rainfall Estimates



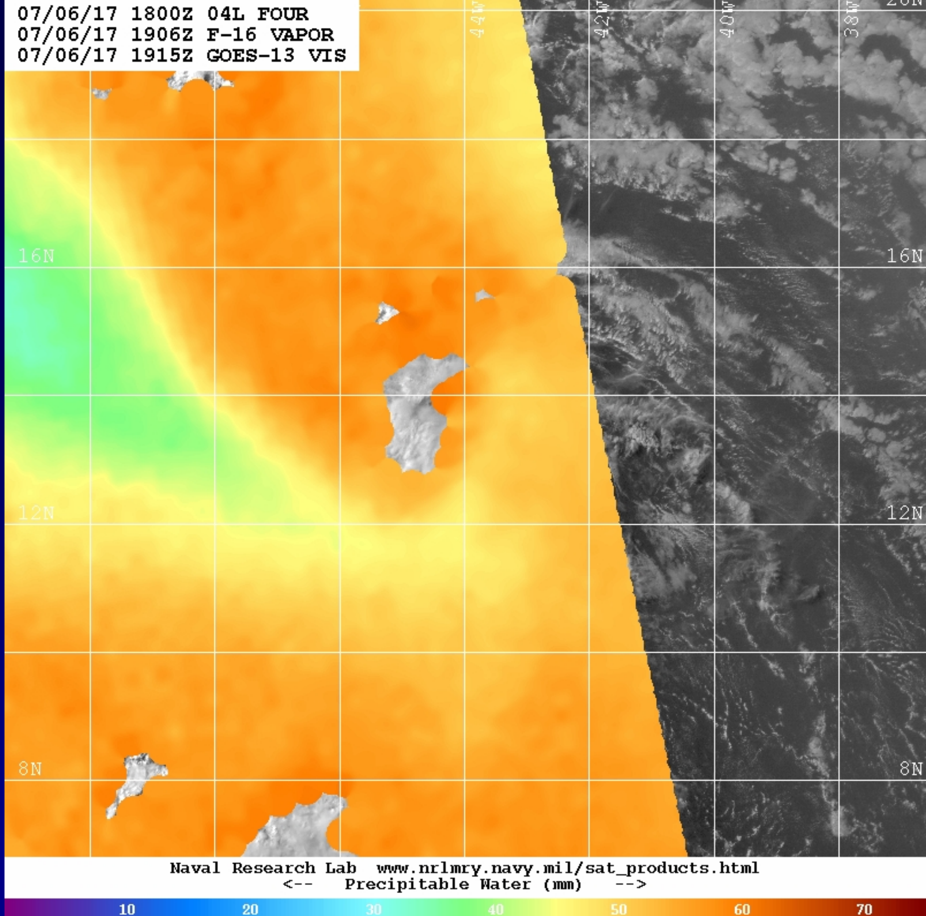


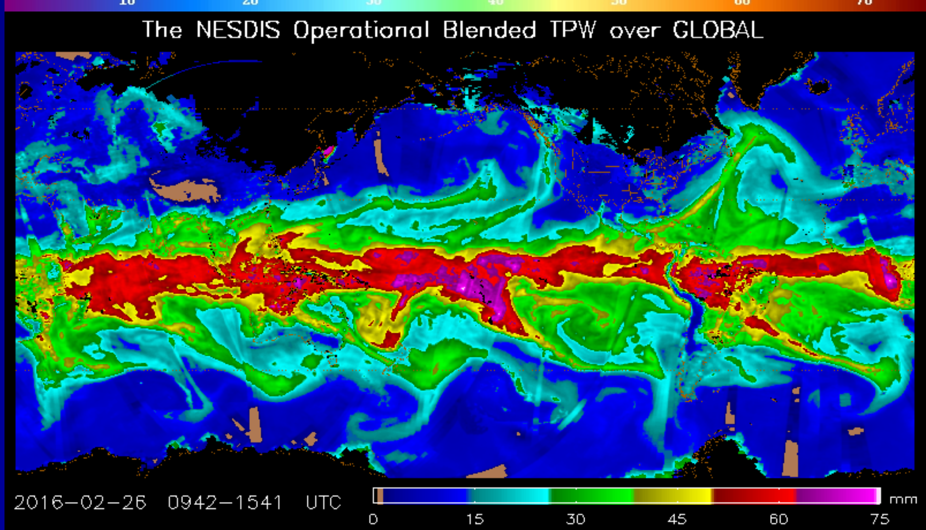
Observed Rainfall Rate **Forecast Precipitation Totals**

The Ensemble Tropical Rainfall Potential (eTRaP) technique is based on extrapolation of microwave convective patterns into the future.

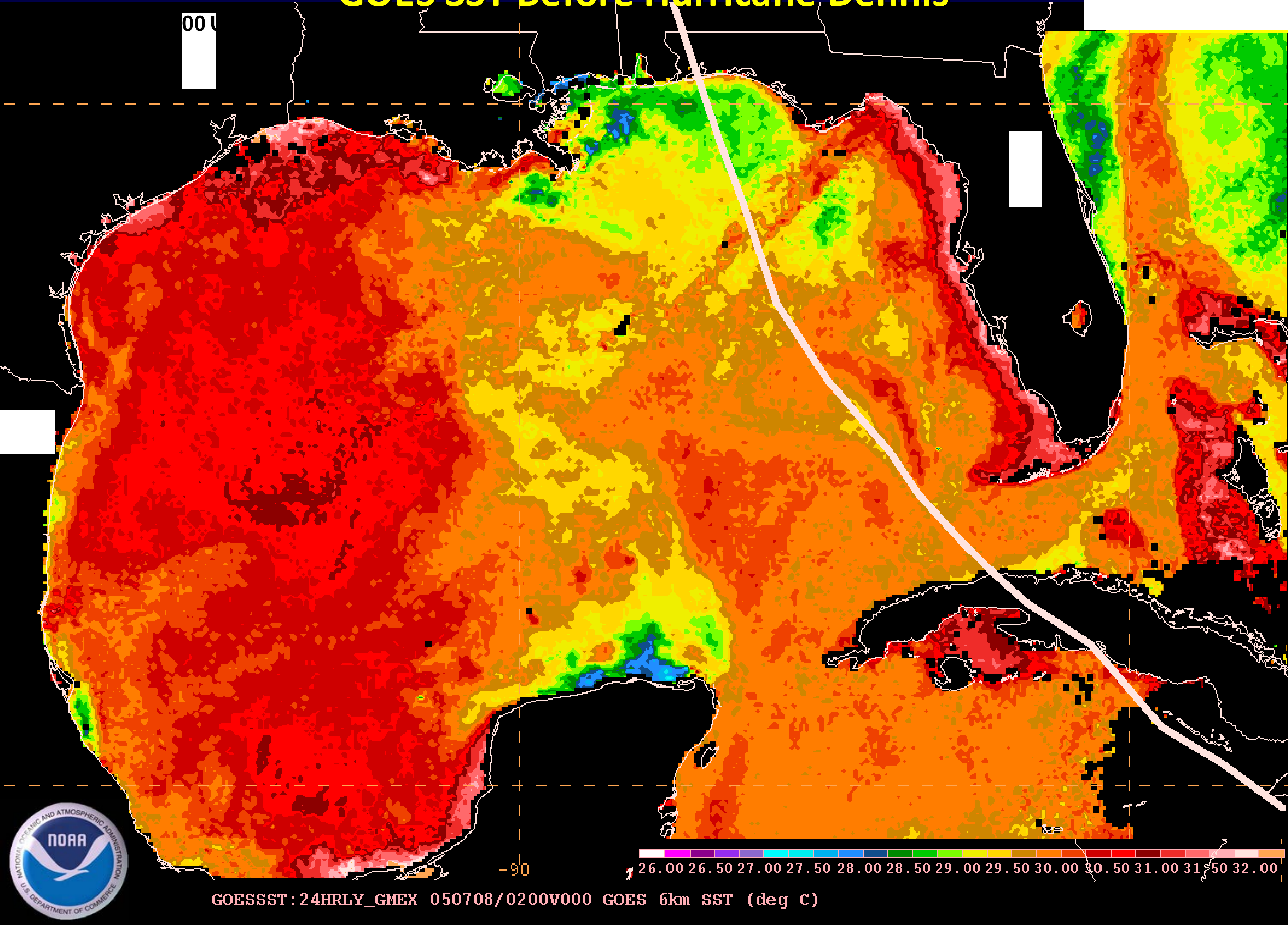
Total Precipitable Water Products

- Microwave sounders measure radiation emitted from moisture, which allows for determination of the total amount of water and water vapor in a column of atmosphere – the total precipitable water (TPW).
- The TPW is used to track moist and dry air masses in weather systems, for determination of cyclone structure, and determination of how much atmospheric moisture is available to become rain.

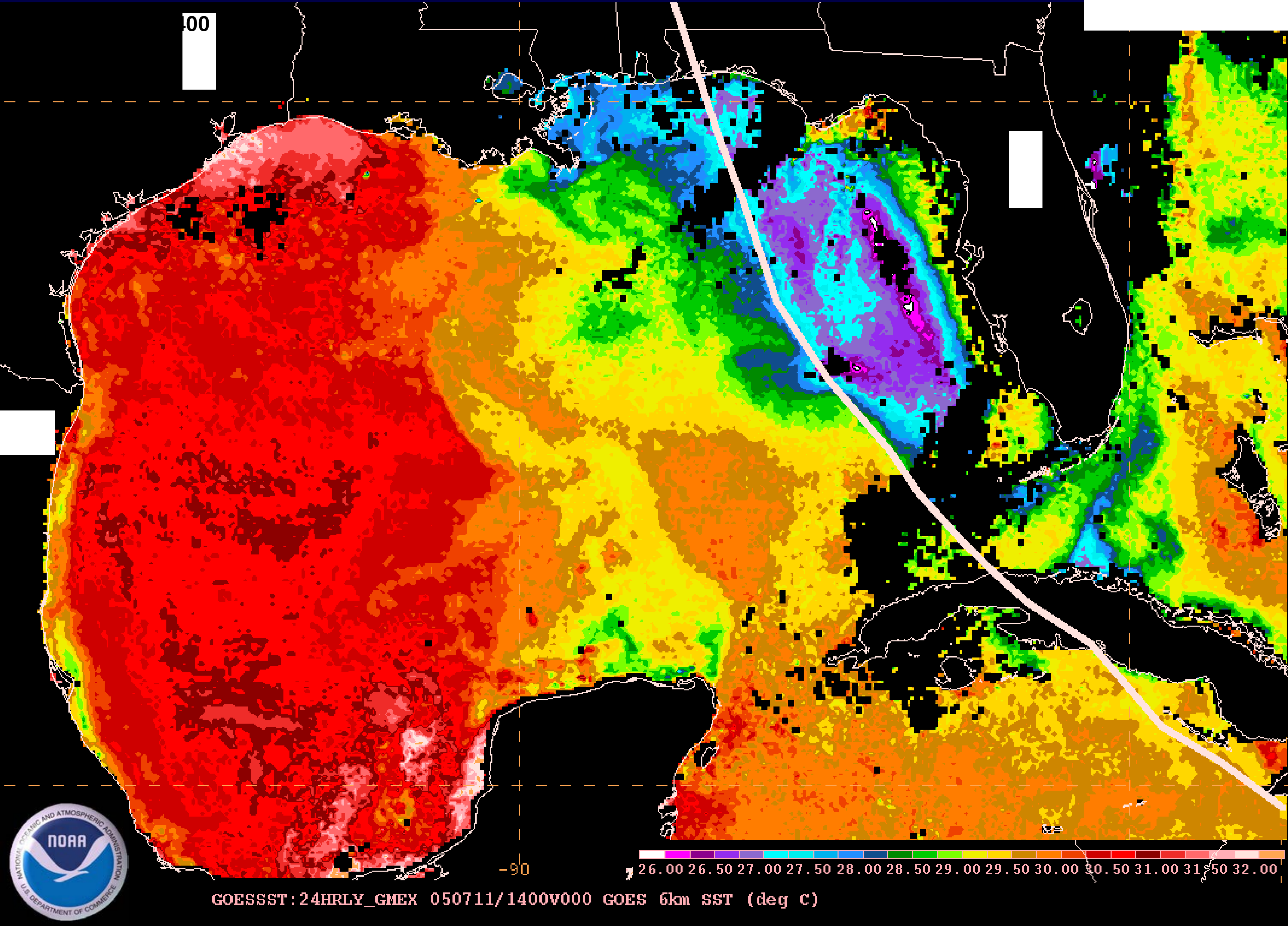




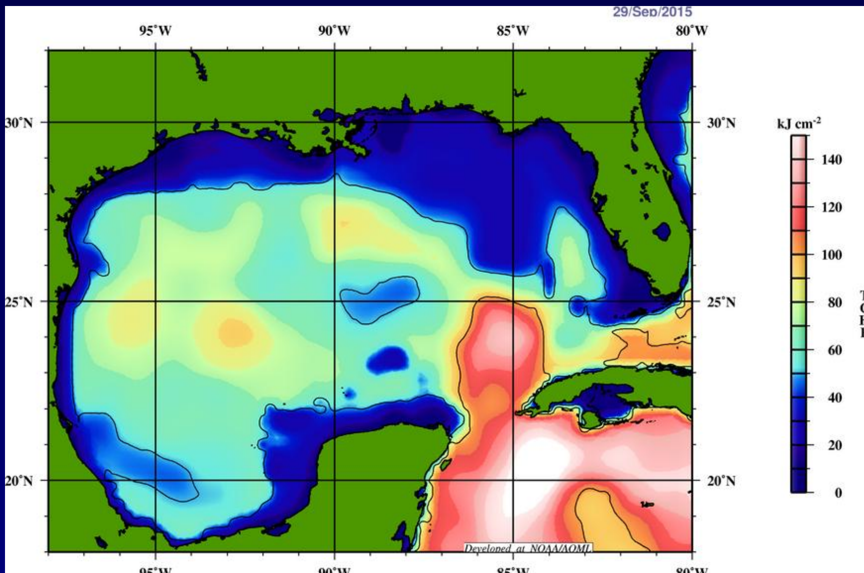
GOES SST Before Hurricane Dennis



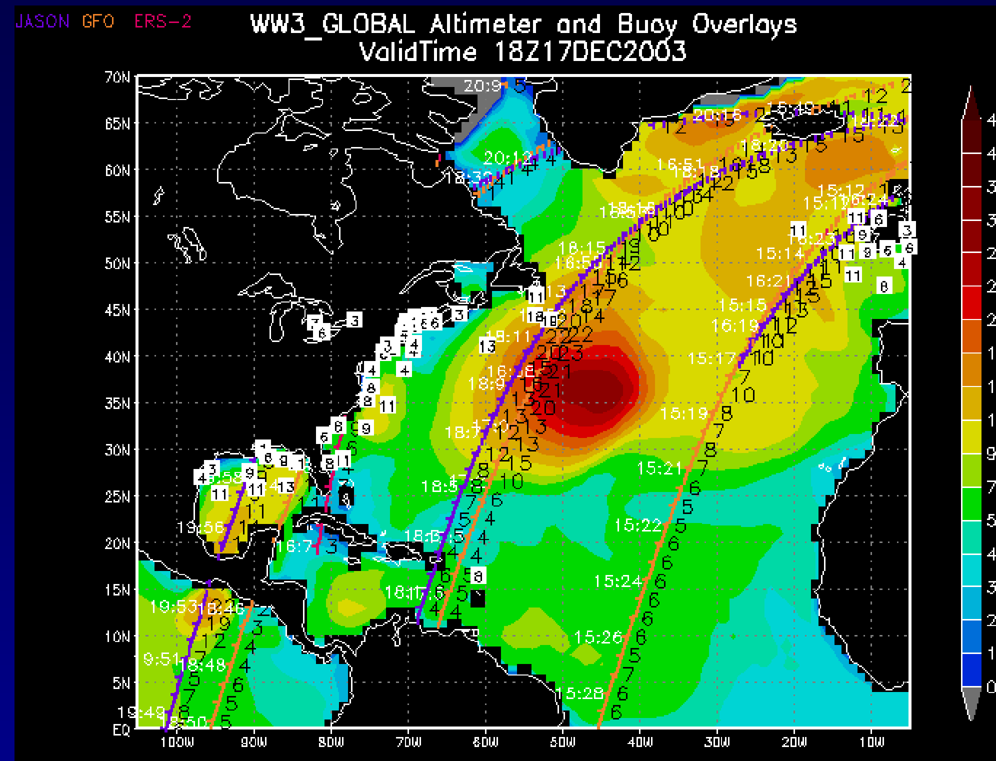
Hurricane Dennis' Cool Wake



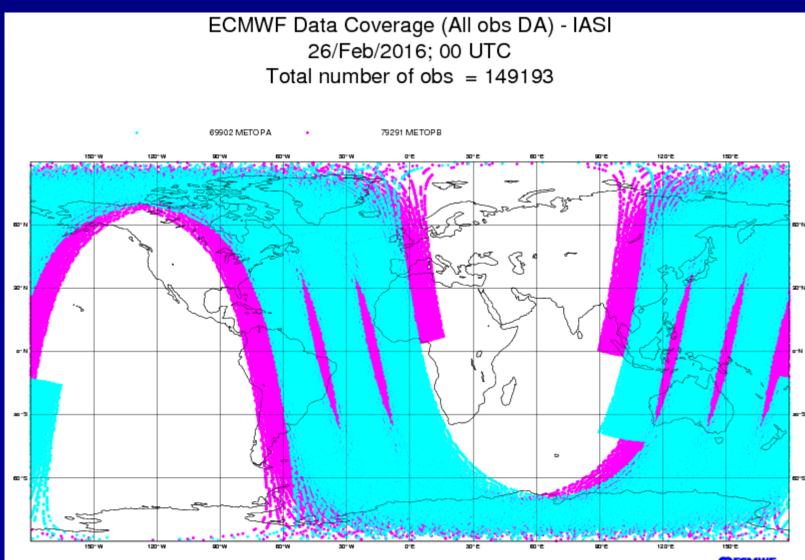
Other useful satellite data



Ocean height and heat content for TC intensity forecasting



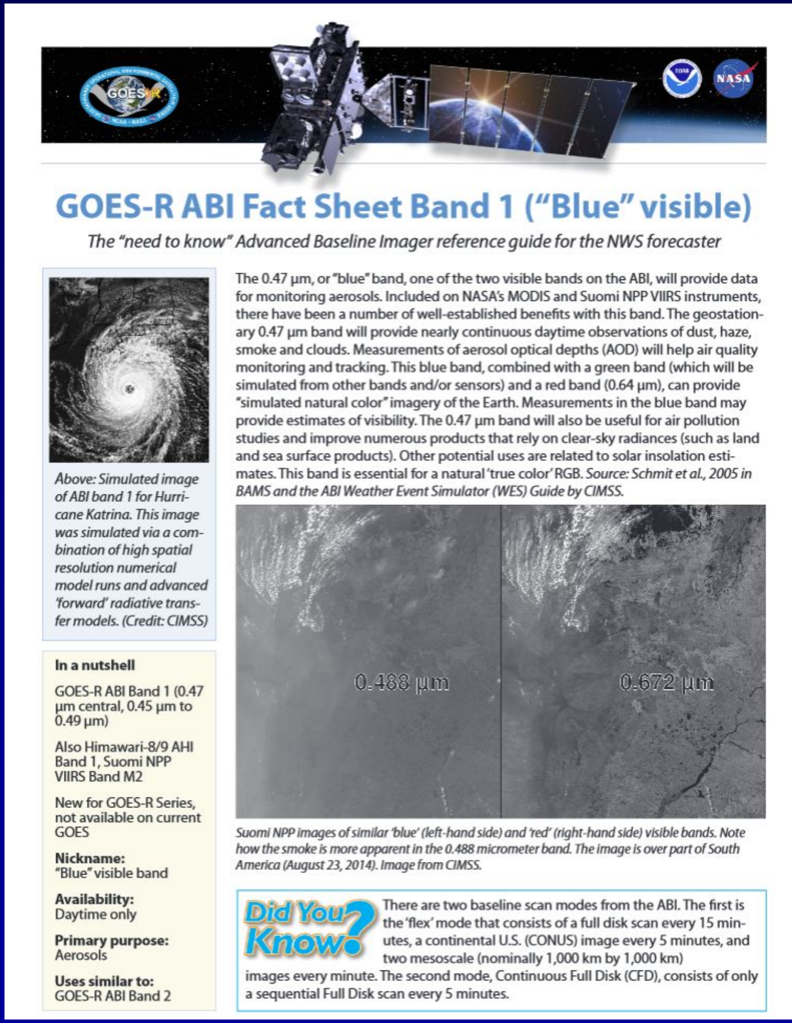
Radar altimeter wave heights



Satellite temperature and moisture soundings for use in numerical models – not used directly at NHC but of vital importance in forecasting

Additional Training for GOES-R

- GOES-R Training Portal - http://www.goes-r.gov/users/training.html
- COMET MetEd Course - https://www.meted.ucar.edu/training_course.php?id=42
- CIRA Training Course for GOES-R - http://rammb.cira.colostate.edu/training/visit/training_sessions/satfc-g.asp
- ABI Facts Sheets - http://www.goes-r.gov/education/ABI-bands-quick-info.html
- CIRA Satellite Library - https://satlib.cira.colostate.edu
- CIMSS Satellite Blog - http://cimss.ssec.wisc.edu/goes/blog/



GOES-R ABI Fact Sheet Band 1 ("Blue" visible)

The "need to know" Advanced Baseline Imager reference guide for the NWS forecaster

Above: Simulated image of ABI band 1 for Hurricane Katrina. This image was simulated via a combination of high spatial resolution numerical model runs and advanced 'forward' radiative transfer models. (Credit: CIMSS)

The 0.47 µm, or "blue" band, one of the two visible bands on the ABI, will provide data for monitoring aerosols. Included on NASA's MODIS and Suomi NPP VIIRS instruments, there have been a number of well-established benefits with this band. The geostationary 0.47 µm band will provide nearly continuous daytime observations of dust, haze, smoke and clouds. Measurements of aerosol optical depths (AOD) will help air quality monitoring and tracking. This blue band, combined with a green band (which will be simulated from other bands and/or sensors) and a red band (0.64 µm), can provide "simulated natural color" imagery of the Earth. Measurements in the blue band may provide estimates of visibility. The 0.47 µm band will also be useful for air pollution studies and improve numerous products that rely on clear-sky radiances (such as land and sea surface products). Other potential uses are related to solar insolation estimates. This band is essential for a natural 'true color' RGB. *Source: Schmit et al., 2005 in BAMS and the ABI Weather Event Simulator (WES) Guide by CIMSS.*

0.488 µm | 0.672 µm

Suomi NPP images of similar 'blue' (left-hand side) and 'red' (right-hand side) visible bands. Note how the smoke is more apparent in the 0.488 micrometer band. The image is over part of South America (August 23, 2014). Image from CIMSS.

In a nutshell

GOES-R ABI Band 1 (0.47 µm central, 0.45 µm to 0.49 µm)

Also Himawari-8/9 AHI Band 1, Suomi NPP VIIRS Band M2

New for GOES-R Series, not available on current GOES

Nickname: "Blue" visible band

Availability: Daytime only

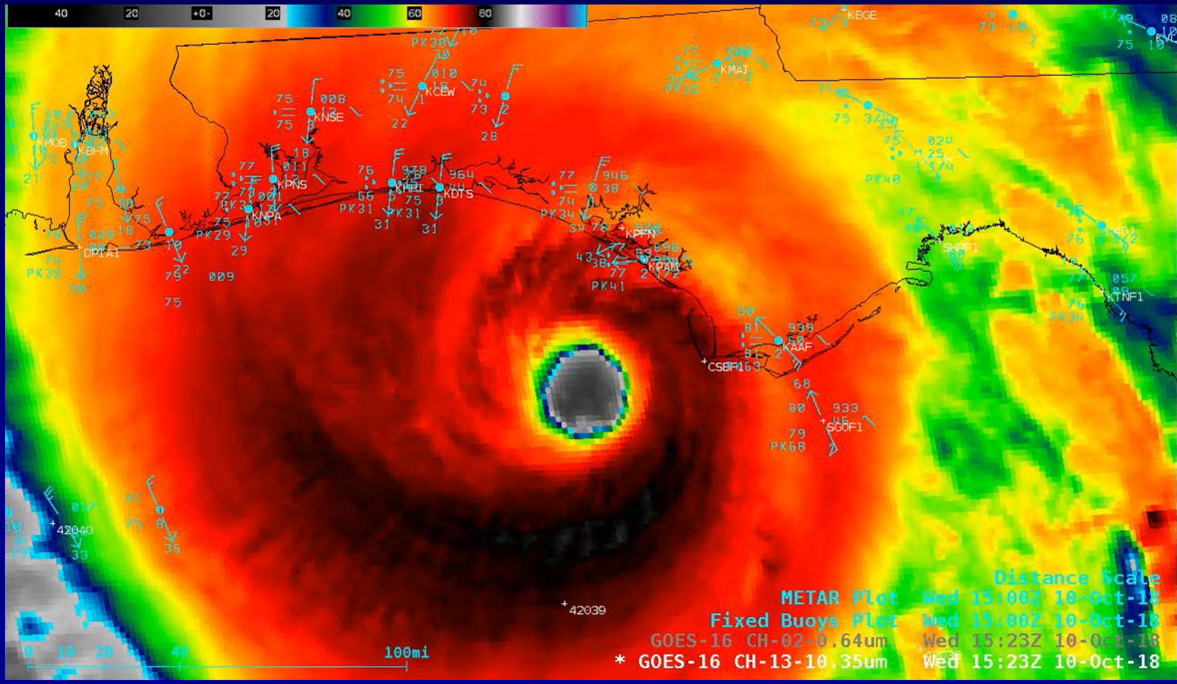
Primary purpose: Aerosols

Uses similar to: GOES-R ABI Band 2

Did You Know? There are two baseline scan modes from the ABI. The first is the 'flex' mode that consists of a full disk scan every 15 minutes, a continental U.S. (CONUS) image every 5 minutes, and two mesoscale (nominally 1,000 km by 1,000 km) images every minute. The second mode, Continuous Full Disk (CFD), consists of only a sequential Full Disk scan every 5 minutes.

Conclusions

- **Remote sensing satellites use principles of radiative transfer when designing the instrument and the desired portions of the electromagnetic spectrum.**
- **Much of the TC forecast process is based on satellite data.**
- **The GOES-R satellites create new ways to monitor the tropical cyclone and the nearby environment.**

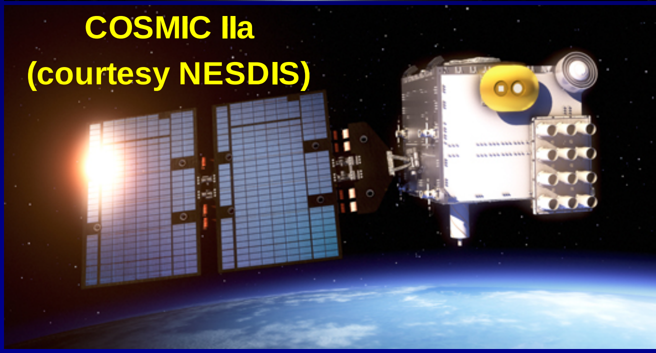


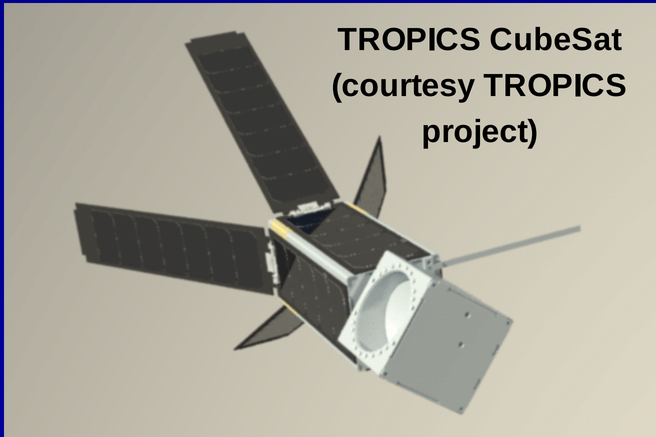
Michael (2018) rapid scan imagery (courtesy CIMSS)

The Future – A Partial List

- <u>**Geostationary Satellites:**</u>
  - **Additional satellites of the various current series**
  - ***European Meteosat Third Generation***
  - **China FY-3 Rainfall Measurement**
  - **China FY-4 Microwave**
  - **Next Generation INSAT**

- <u>**LEO Satellites:**</u>
  - **Additional satellites of the various current series**
  - **European METOP Second Generation**
  - **US Defense Weather Satellite System**
  - **COSMIC IIa**
  - ***TROPICS CubeSats***
  - **Several new scatterometer satellites**





How many channels does the GOES-R series ABI imager have?

A) Five channels
B) Sixteen channels
C) More channels than you can conveniently count

Questions?