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Tools for Interpreting the Atmosphere: Numerical Weather Prediction and Satellite Products

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Overview

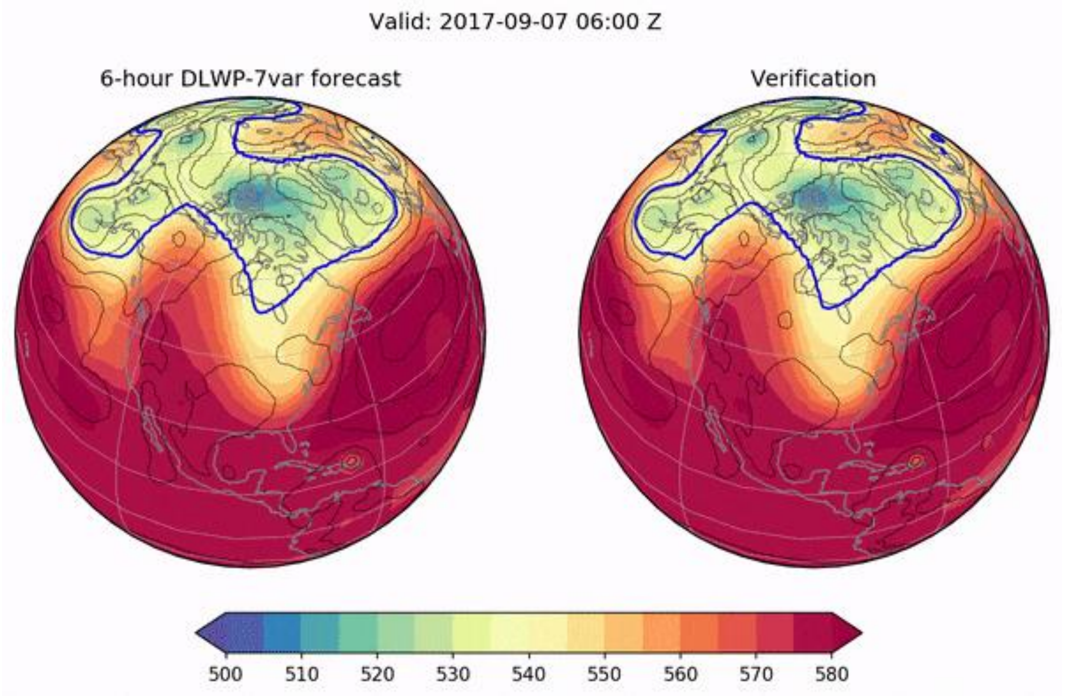
01

Numerical Weather Prediction

What is Numerical Weather Prediction (NWP)?

- The prediction of the evolution of the atmosphere by resolving the equations of fluid motion using computational techniques.

- The equations are resolved using numerical approaches, such as finite differencing and spectral modeling. The complex calculations only allowed this to become a reality during the computer era, or starting in the 1950's.



How do NWP models do their calculations?

Most atmospheric models use partial differential equations which are solved numerically. A computational grid and numerical method selected to solve the equations are based on the following criteria:

- **Accuracy**, can be estimated by comparing the numerical solution with its analytical counterpart;
- **Stability**, which often imposes a restriction on the time step;
- **Transportivity**, which requires that any perturbation is advected downwind;
- **Locality**, such that the solution of the advection problem at a given point is not significantly influenced by the field far from that point;
- **Conservation**, which requires that no gain nor loss of mass occurs during the transport;
- **Monotonicity** (shape preserving), through which the occurrence of new extrema is prohibited; these extrema (noise) are characterized by undershoots and overshoots near regions of strong gradients;
- **Efficiency**, such that the computer time consumed is not too large.

https://www.gfdl.noaa.gov/wp-content/uploads/files/user_files/pag/lecture2008/lecture15.pdf

NWP Sources of Error

- The solutions are never perfect and model solutions deteriorate with time due to the rapid growth of sources of error, starting with the fact that we cannot even measure the earth-atmosphere system with sufficient accuracy.

- Other sources of error arise from

  - The solution of the equations of motion. Approximations need to be made and they generate growing errors.

  - Parameterization of processes that cannot be resolved using the model grid and mthods.

Equations of Motion

- A set of hydrodynamical equations representing the application of Newton's second law of motion to a fluid system.

- The total acceleration on an individual fluid particle is equated to the sum of the forces acting on the particle within the fluid. Written for a unit mass of fluid in motion in a coordinate system fixed with respect to the earth, the vector equation of motion for the atmosphere is:

$$\frac{D\mathbf{u}}{Dt} = -2\Omega \times \mathbf{u} - g\mathbf{k} - \frac{1}{\rho}\nabla p + \mathbf{F},$$

where u is the three-dimensional velocity vector, Ω the angular velocity of the earth, k a unit vector directed upward, ρ the density, p the pressure, g the acceleration of gravity, and F the frictional force per unit mass.

https://glossary.ametsoc.org/

Resolving the Equations of Motion

- **Finite differencing** e.g. Regional Models with Boundaries
  - Use of grid points
  - Calculations based on differences between adjacent gridpoints
  - These are best for regional models (with boundaries

- **Spectral Models** e.g. Global Models such as the GFS Model
  - Use of waves (conversion back and forth to spectral space)
  - Better for long range forecasts
  - Best if unbounded (e.g. Global Models)

Finite Differencing (Regional Models)

- The change of a quantity in a gridpoint can be calculated by using differences between adjacent gridpoints and their evolution with time.
- These are applied to the equations of motion.
- There are different methods of different complexity and stability.

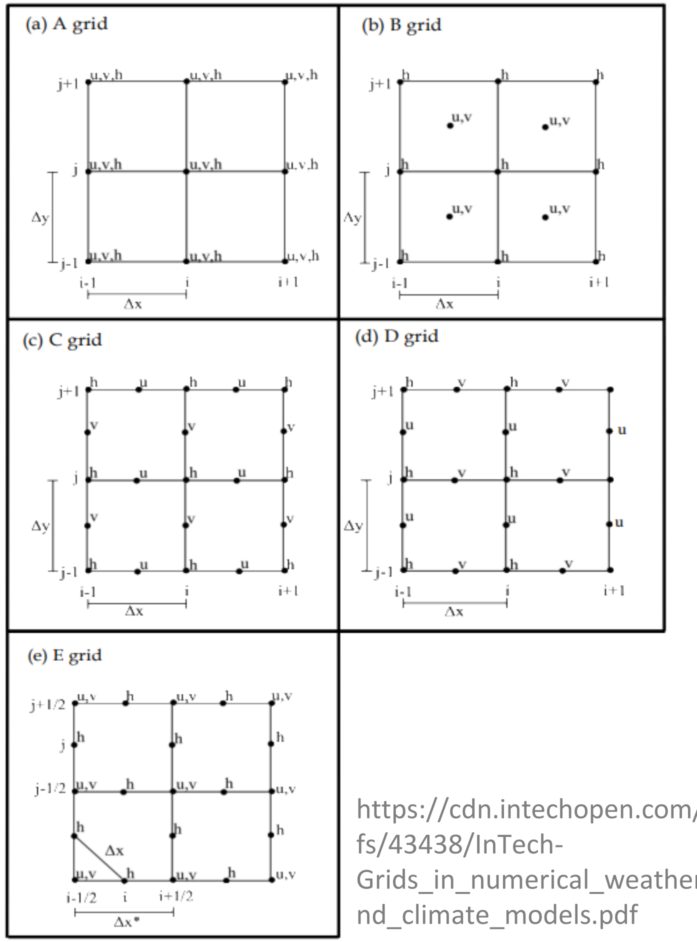
Scheme	*Algebraic Form*	*Stability*	*Accuracy*
Euler forward	$\Psi_j^{n+1} = \Psi_j^n + \frac{u\Delta t}{2\Delta x}\left(\Psi_{j-1}^n - \Psi_{j+1}^n\right)$	Unstable	$O\left(\Delta t, \Delta x^2\right)$
Upwind	$\Psi_j^{n+1} = \Psi_j^n + \frac{u\Delta t}{\Delta x}\left(\Psi_{j-1}^n - \Psi_j^n\right)$	$\frac{u\Delta t}{\Delta x} \leq 1$	$O\left(\Delta t, \Delta x\right)$
Leapfrog	$\Psi_j^{n+1} = \Psi_j^{n-1} + \frac{u\Delta t}{\Delta x}\left(\Psi_{j-1}^n - \Psi_{j+1}^n\right)$	$\frac{u\Delta t}{\Delta x} \leq 1$	$O\left(\Delta t^2, \Delta x^2\right)$
Lax-Wendroff	$\Psi_j^{n+1} = \Psi_j^n + \frac{u\Delta t}{2\Delta x}\left(\Psi_{j-1}^n - \Psi_{j+1}^n\right) +$		
	$\frac{1}{2}\left(\frac{u\Delta t}{\Delta x}\right)^2\left(\Psi_{j-1}^n - 2\Psi_j^n + \Psi_{j+1}^n\right)$	$\frac{u\Delta t}{\Delta x} \leq 1$	$O\left(\Delta t^2, \Delta x^2\right)$
Crank-Nicholson	$-\frac{u\Delta t}{2\Delta x}\Psi_{j-1}^{n+1} + 2\Psi_j^{n+1} + \frac{u\Delta t}{2\Delta x}\Psi_{j+1}^{n+1} =$		
	$\frac{u\Delta t}{2\Delta x}\left(\Psi_{j-1}^n - \Psi_{j+1}^n\right)$	Stable	$O\left(\Delta t^2, \Delta x^2\right)$
Chapeau (FEM)	$\left(\frac{1}{3} - \frac{u\Delta t}{2\Delta x}\right)\Psi_{j-1}^{n+1} + \frac{4}{3}\Psi_j^{n+1} + \left(\frac{1}{3} + \frac{u\Delta t}{2\Delta x}\right)\Psi_{j+1}^{n+1} =$		
	$\left(+\frac{1}{3} - \frac{u\Delta t}{2\Delta x}\right)\Psi_{j-1}^n + \frac{4}{3}\Psi_j^n + \left(\frac{1}{3} - \frac{u\Delta t}{2\Delta x}\right)\Psi_{j+1}^n$	Stable	$O\left(\Delta t^2, \Delta x^4\right)$

https://www.gfdl.noaa.gov/wp-content/uploads/files/user_files/pag/lecture2008/lecture15.pdf

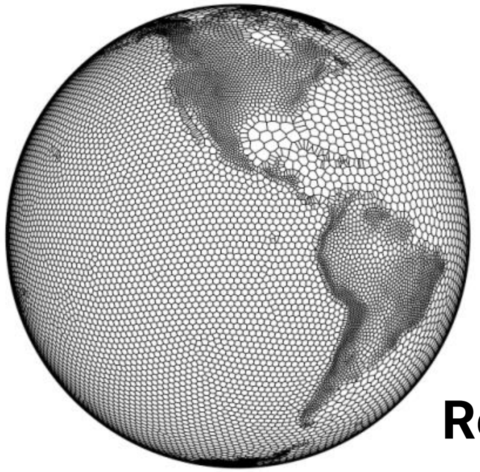
Grids in NWP Models

- NWP models have different types of grids.
- Square grids are the most simple (right), and there are different types, where specific sets of data (u, v for winds and h for other variables) are located in different positions to facilitate the calculation of future values using finite differencing.

Square Grids



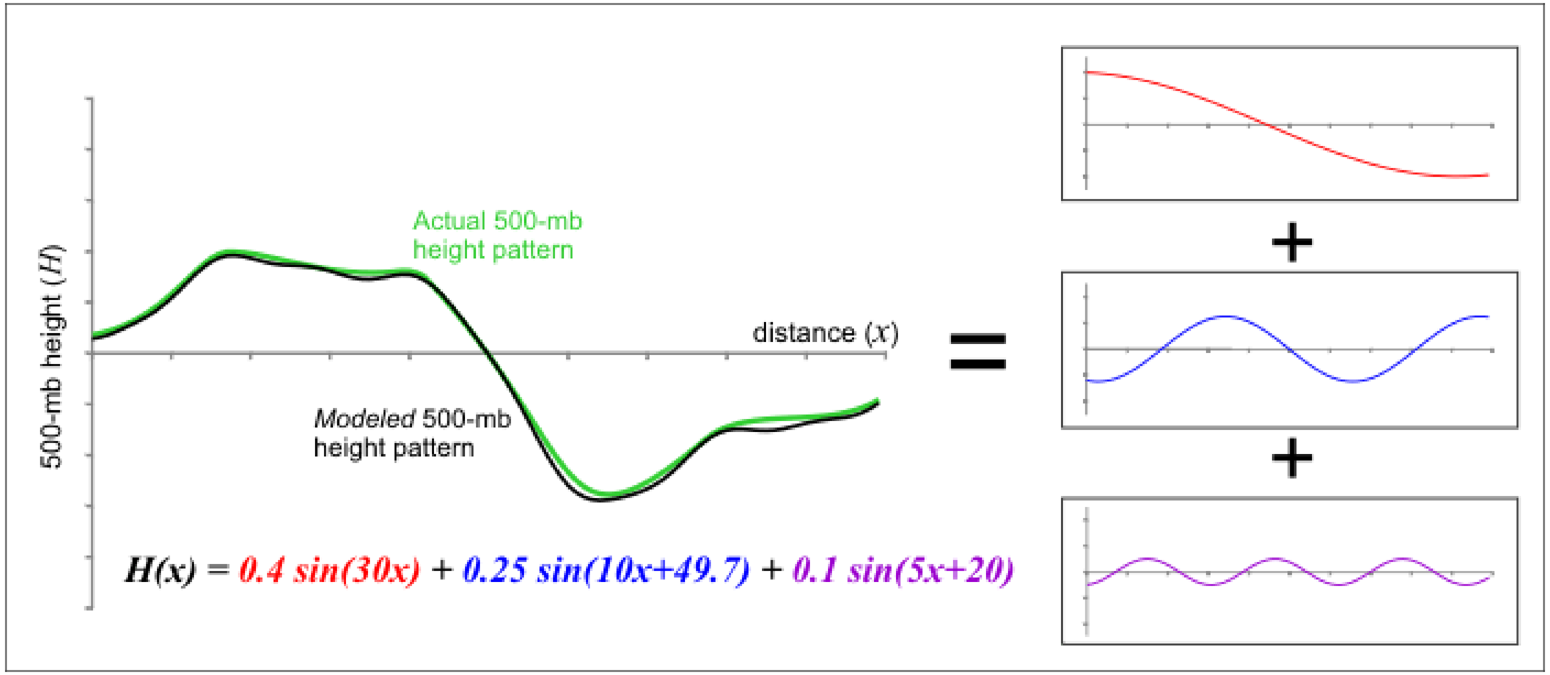
https://cdn.intechopen.com/pdfs/43438/InTech-Grids_in_numerical_weather_and_climate_models.pdf



- There are many more complex types of grids, such as the "refined mesh", which uses higher resolution in regions of interest.

Refined Mesh

Spectral models add waves



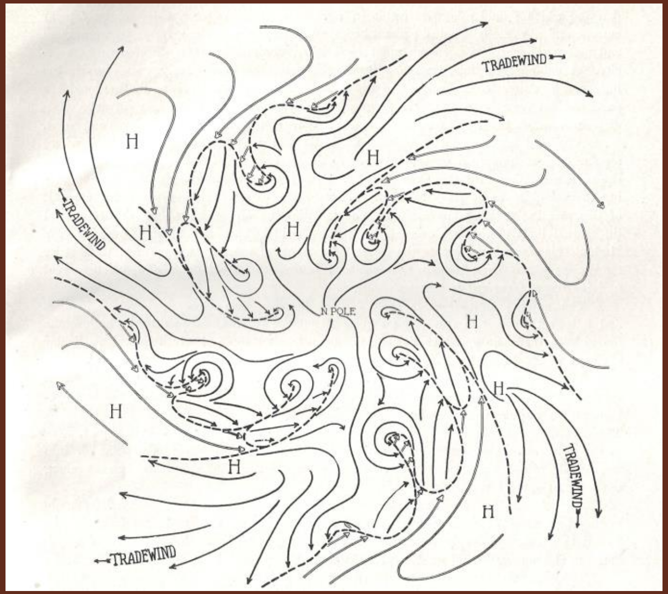
A spectral model attempts to replicate wavelike patterns in key atmospheric variables (here, a sample 500-mb height line represented by the green curve) by adding together simple wave functions (red, blue, and purple curves). The resulting sum (black curve) usually represents the observed pattern fairly well, depending on the number of simple waves contained in the sum. The model then uses the relatively simple mathematical equation describing the sum in its computations.

https://www.e-education.psu.edu/

History of Numerical Weather Prediction

History of NWP

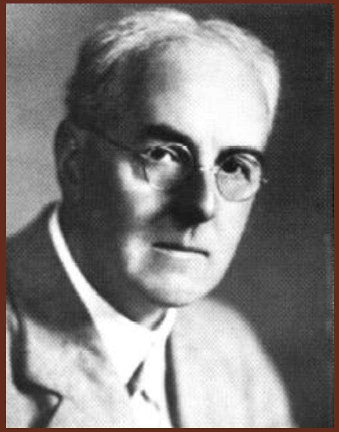
- Weather observations started in the 1700s, and became routine in the mid-1800s when links between weather observed in remote stations showed that the migration of weather systems could be used to forecast.
- The telegraph revolution in the mid-1800s allowed the generation of weather maps quickly, which helped with their use to forecasting the weather.
- Yet by the late 1800s, no one had linked atmospheric behavior with equations and physics.



1904: Application of Laws of Physics

- The Norwegian Wilhem Bjerkness (1862-1951) was the first to apply the laws of physics to describe motion of the atmospheric fluid.
- In 1904, he was the first to propose the concept of NWP, in which the atmophere can be represented as a 3-D fluid and its evolution can be based on an initial value problem.
- In the 1920's, Lewis Richardson was the first to propose the application of mathematical equations to forecast the weather. The idea was revolutionary, but required rapid calculations and there were no means to do that.

Wilhem Bjerkness



Lewis Richardson

1950: Computer Revolution

- NWP was able to develop rapidly as soon as the computer revolution started.
- Jule Charney was the leader of the NWP revolution, starting the development of numerical weather prediction models, applying the Bjerkness's and Richardson's work into concrete results.
- The initial models had a very coarse resolution, and the forecast failed quickly due to rapidly growing errors and also limitations sampling the earth-atmosphere system.

Jule Charney

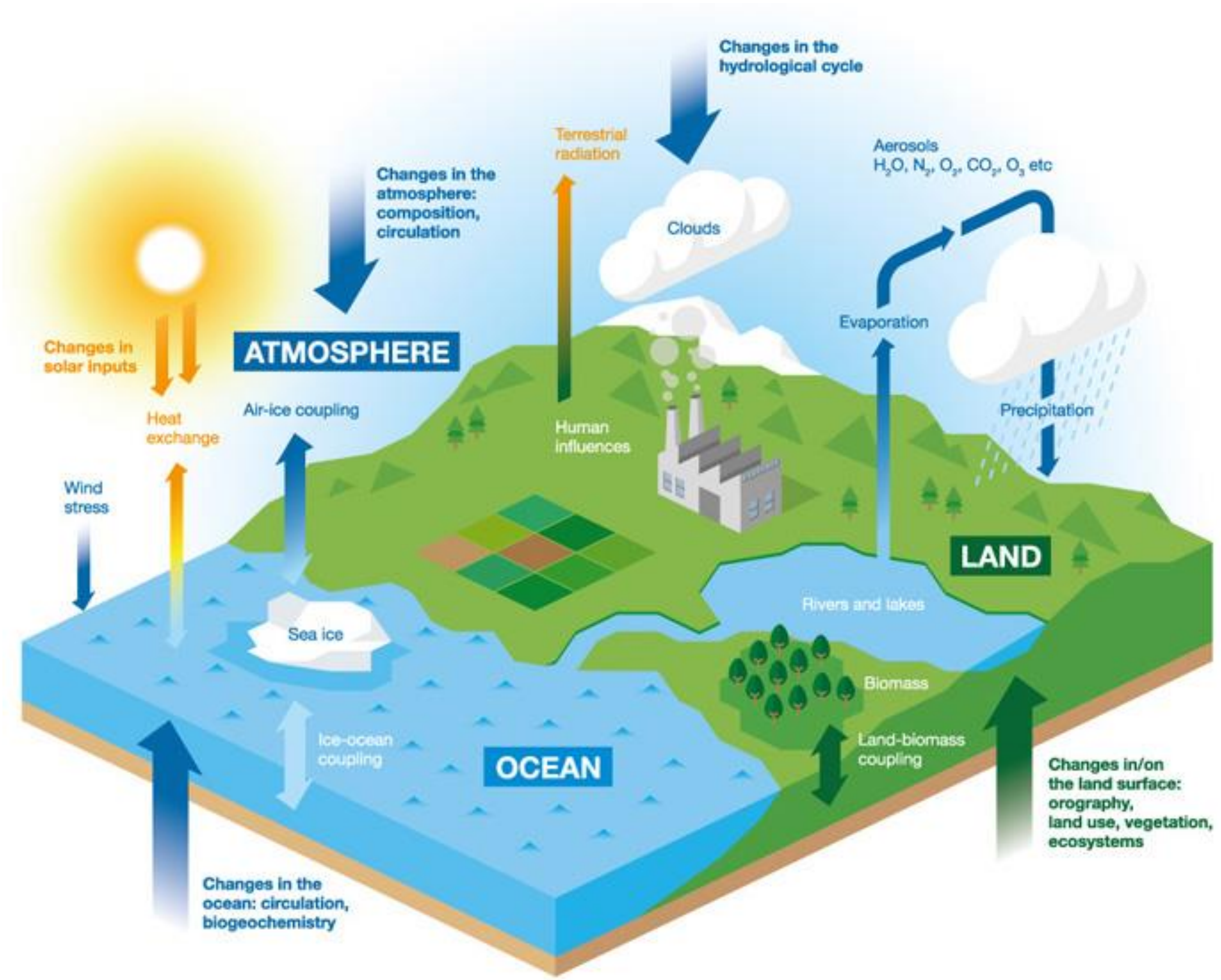
Improvements since the 1970s

- 1970's marked the satellite era. Since then, the ability to improve the representation of the earth-atmospheric system for initializing models has increased, especially since the 1990s.
- Polar orbiting satellites play a major role as they are able to measure more variables with better vertical resolution, thanks to microwave sensors. By 2022, 85% of observations ingested into models arose from polar satellites.
- Models and data disemination have also improved rapidly since the 1990s due to the technoligical revolution that rapidly increased computing capacity and the dissemination of internet.

Data Assimilation

- It is the ingestion of observations into a NWP model, to represent the current state of the earth-atmosphere system and allow the model to resolve the evolution based on these conditions.

- The more reliable observations, the better the representation of the initial conditions for the model. But there are other aspects to be considered to limit the generation of errors once models resolve the equations of motion.



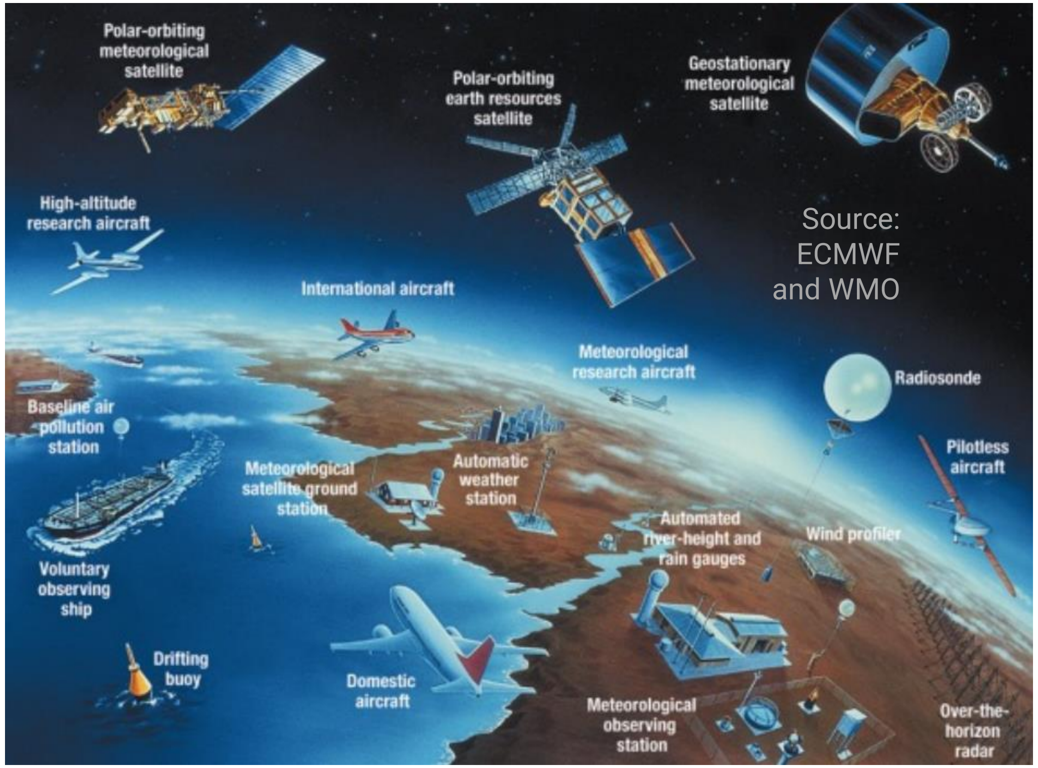
Which data is used to feed the models?

Satellite measurements
Fill in gaps

SURFACE
- Surface observations

ATMOSPHERE
- Upper air observations (radiosondes and pilot balloons)
- Aircraft observations

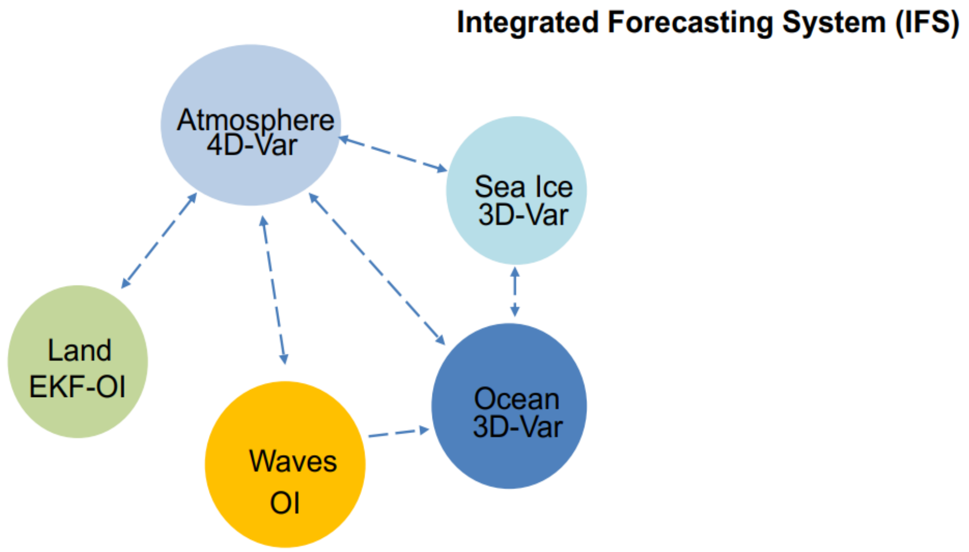
OCEAN
- Buoys
- Ship observations



Source: ECMWF and WMO

How is data assimilated?

- An initial forecast is used.
- The forecast is adjusted based on observations.
- Techniques used include 3D-Var, 4D-Var, Ensemble Kalman Filter (EKF) and Optimal Interpolation.
- The adjusted forecast is fed into the model.



- Coupled assimilation developments for NWP and reanalyses
- Importance of interface observations (e.g. SST, sea ice, snow, soil moisture)

ECMWF

Problems of assimilating too much or too little

- Adding too much detailed information
  - Positive: More realistic representation of the atmosphere
  - Negative: Large values and sharp gradients can generate errors when resolving the equations, which can grow rapidly with time.
- Rejecting too many observations by labeling them as "bad data"
  - Positive: Limits the growth of errors when solving the equations.
  - Negative: Misses on important details that could improve the forecast.

Global and Regional Models

- **Global models** cover the entire globe and are resolved using spectral modeling techniques.
  - Examples: GFS, ECMWF, UKMET, CMC, JMA, ICON, etc
- **Regional Models** cover smaller areas, and require the use of boundary conditions for their initialization.
  - The placement of the boundary matters. Best to place boundaries in region of limited moise generated by features such as complex orography, coastlines, etc.

Some Global Models

UKMET

- Horiz. Resolution: 10km
- Vertical Resolution : 70
- Forecasts up tp 6 days
- Runs 4 times a day

GFS

- Horiz. Resolution: 13 km
- Vertical Resolution: 127
- Forecasts up to 384h
- Runs 4 times a day

ECMWF

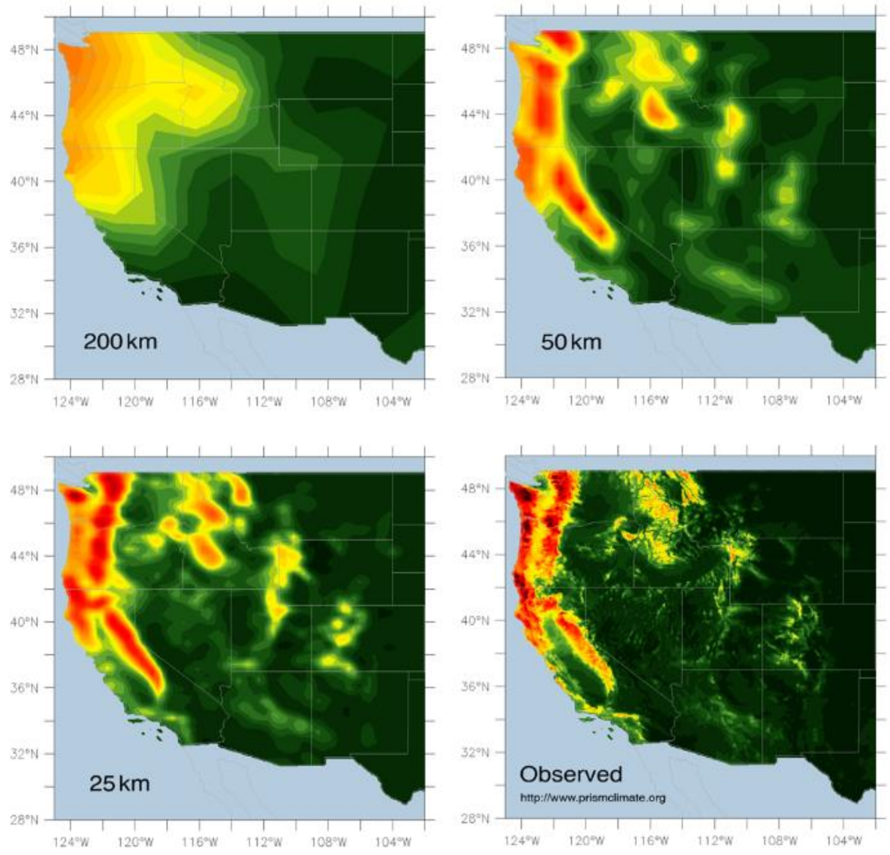
- Horiz. Resolution: 9 km
- Vertical Resolution: 137
- Forecasts up to 384h
- Runs 4 times a day

Model Resolution

- **Horizontal Resolution (dx,dy):** Represents the separation between gridpoints (data points) in a model.

- The larger the separation, the smaller/coarser the resolution.

- Finer grids produce more accurate results, but can also generate larger calculation errors, especially when sharp gradients are introduced in the equations.



Current model resolution (200 km) compared to high-resolution models (50 km and 25 km) and observed data

Observed data provided by PRISM Climate Group, Oregon State University.

https://www.gfdl.noaa.gov/climate-modeling/

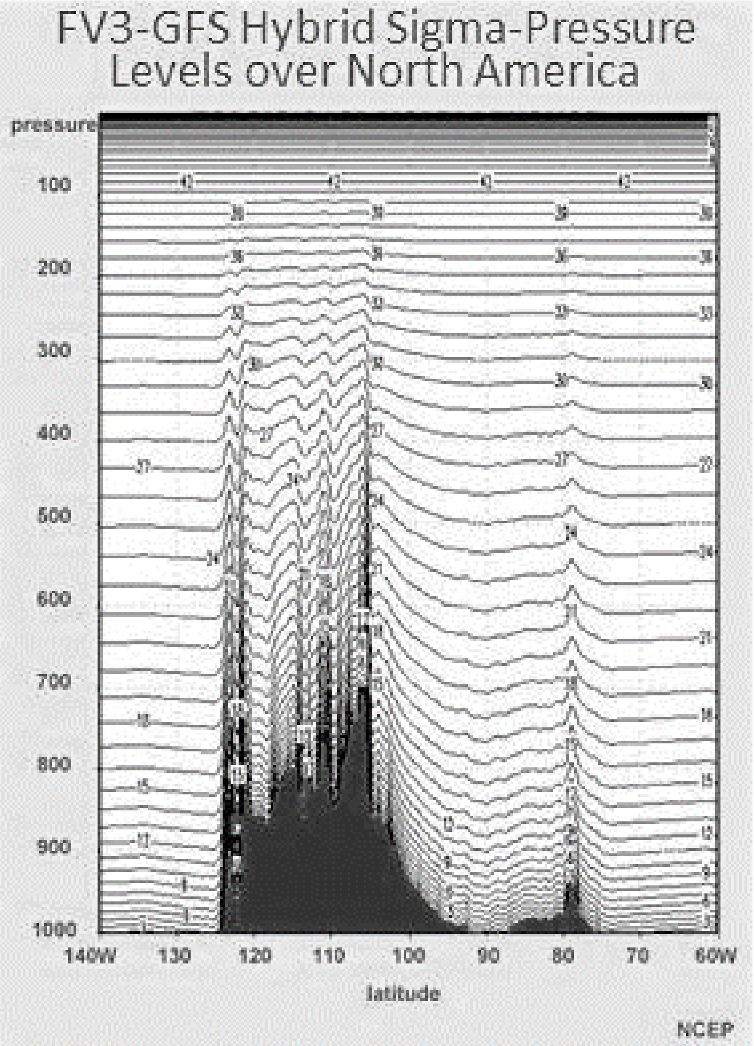
GFS Model V16

Operational since 22 March 2021

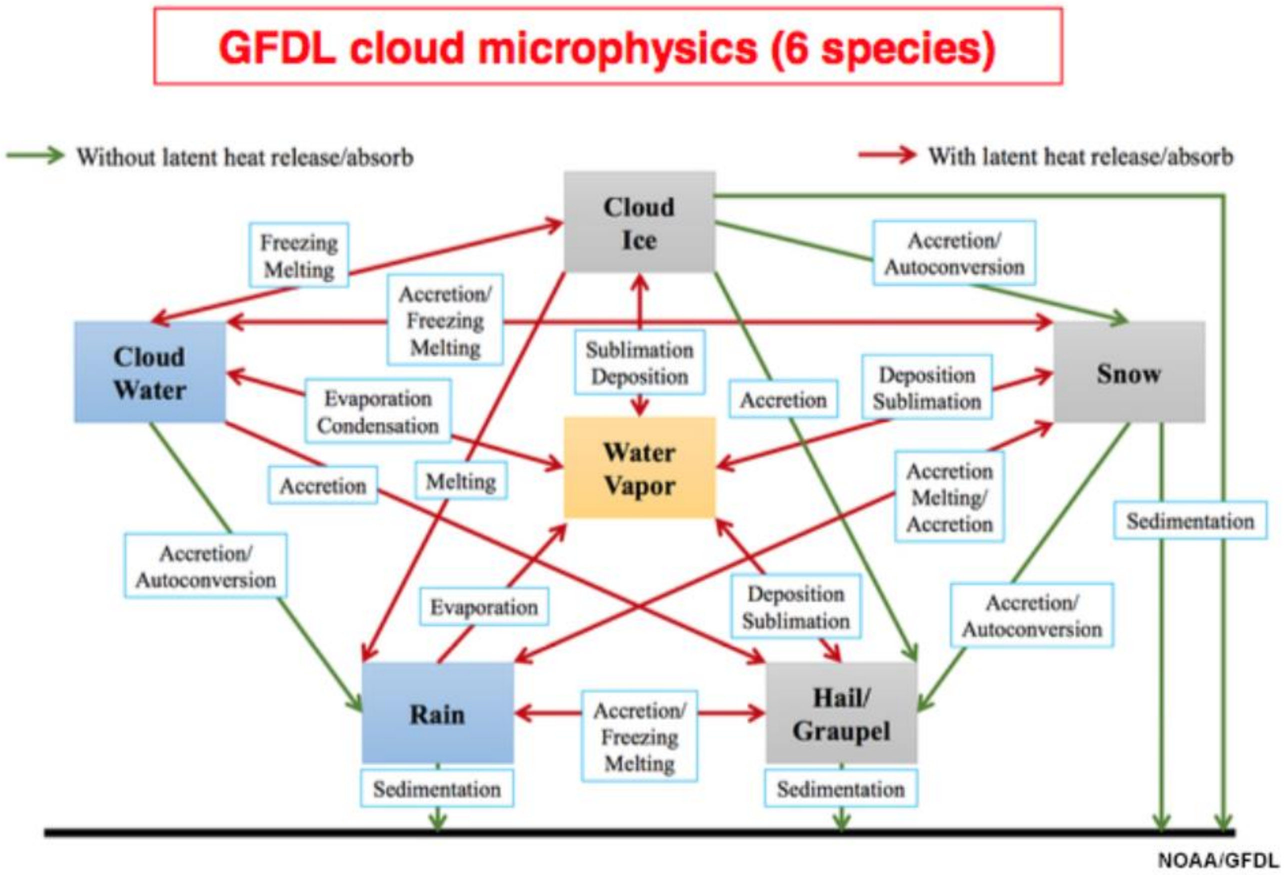
Improvements from GFS V15:

- Increased vertical resolution: 64 to 127 and the model top is extended from the upper stratosphere to the mesopause (~80 km height)

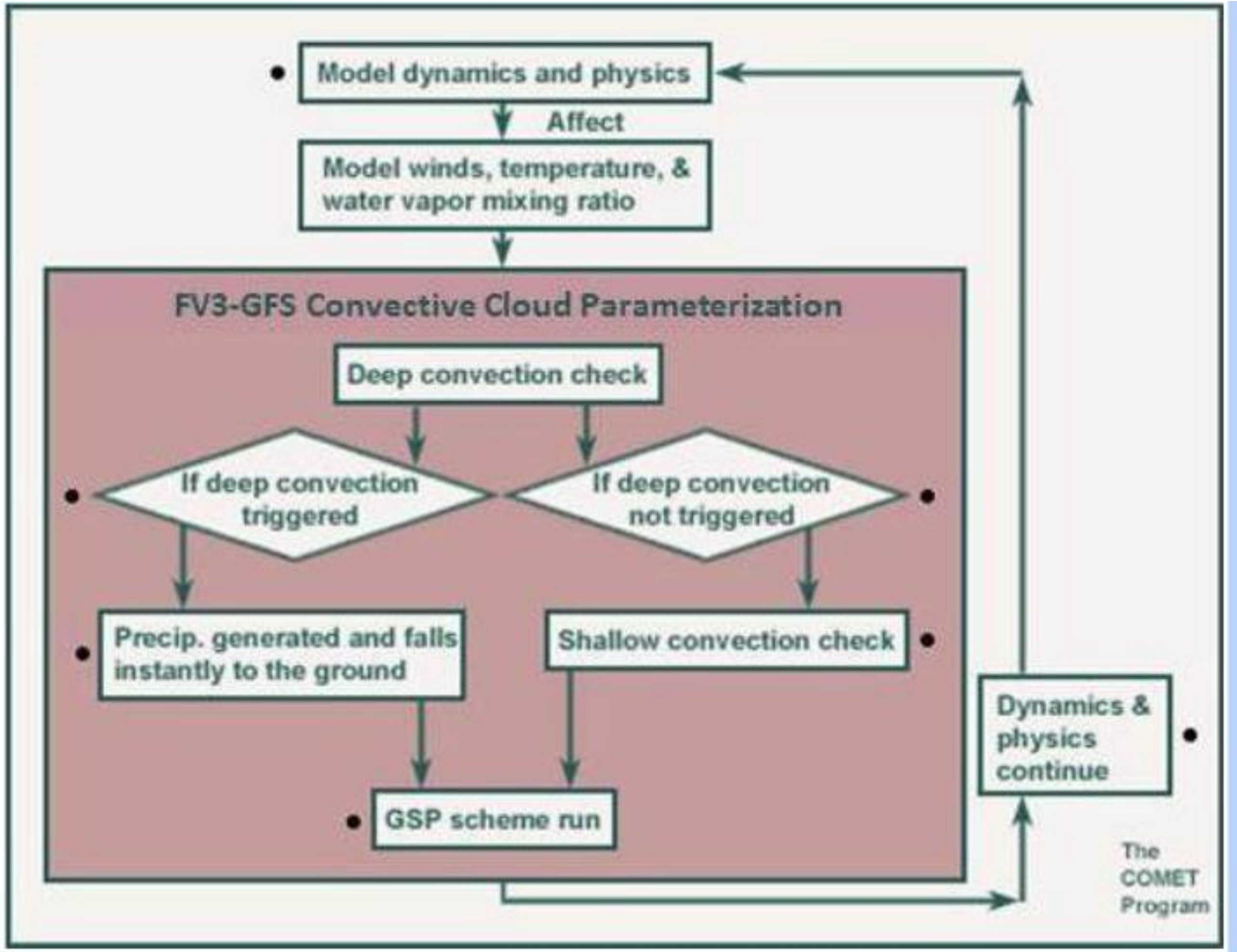
- Improvements in model physics:
  1) new scheme to parameterize both stationary and non-stationary gravity waves that are not explicitly resolved by the model
  2) new scale-aware turbulent kinetic energy based moist eddy-diffusivity mass-flux vertical turbulence mixing scheme to better represent the planetary boundary layer processes
  3) updating the RRTMG radiation package to improve solar radiation absorption by water clouds and the cloud overlapping algorithm



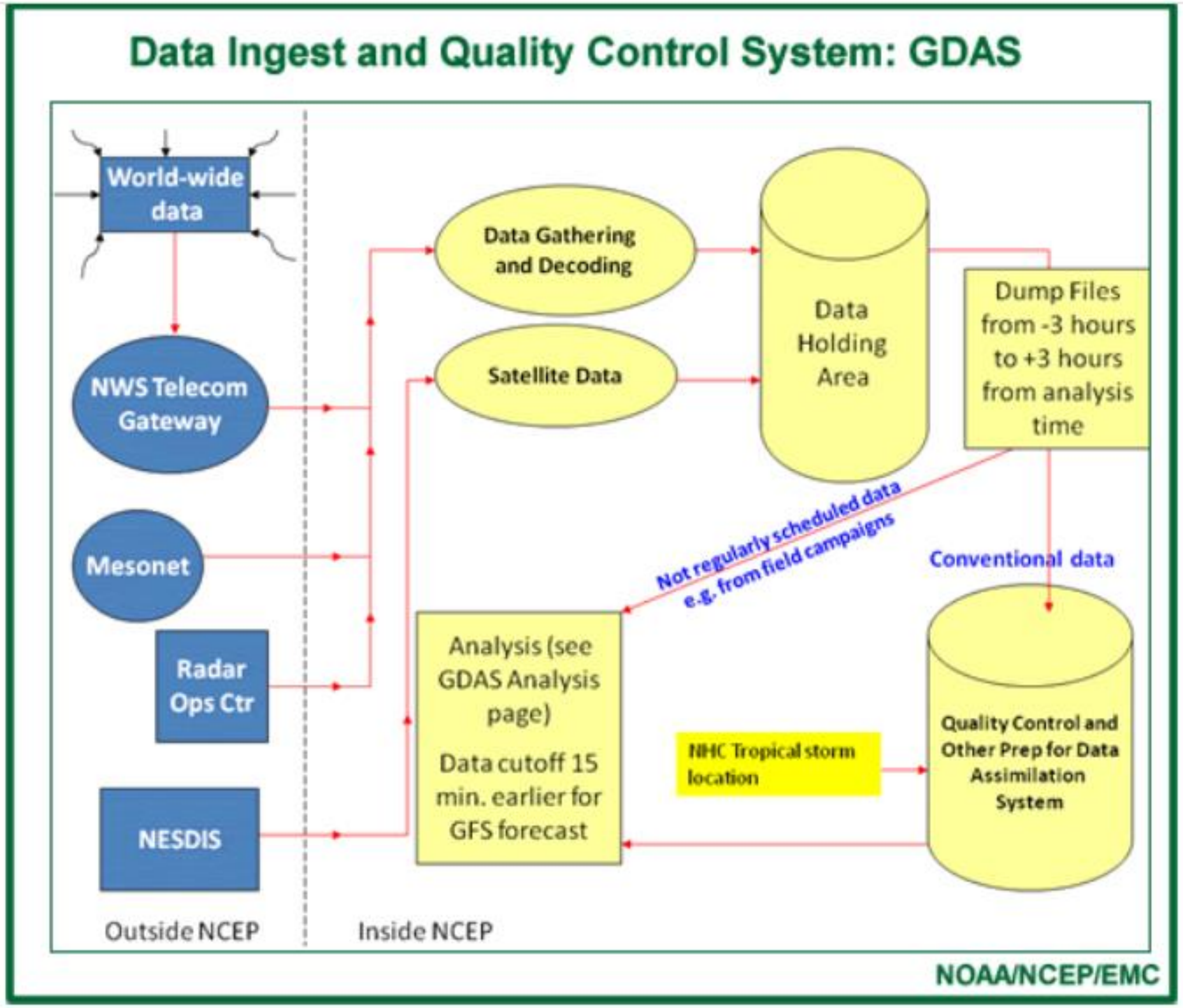
Microphysics Parameterization



Convective Parameterization



GFS Initialization



02

Ensemble Forecasting

Ensemble Forecasting

- It is a method in numerical weather prediction that consists of running a model several times to generate a set of forecasts and evaluate the range of different potential solutions.

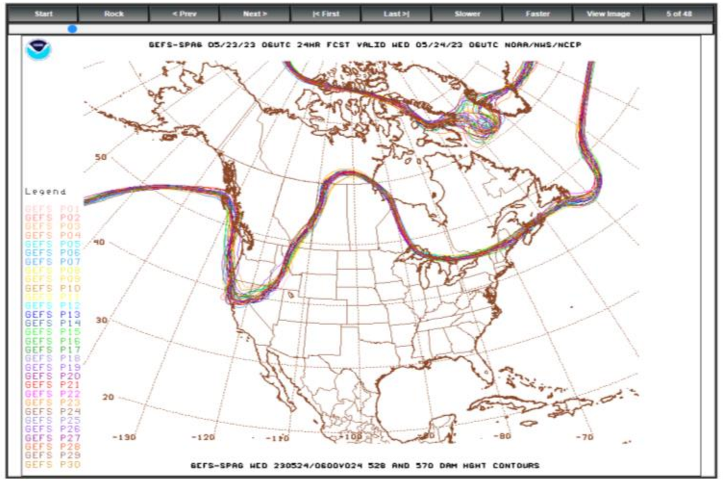
- Multiple simulations are used to address two sources of uncertainty. Errors introduced by:
  1) imperfect initial conditions
  2) imperfections on the solution of model equations

- Due to computational capacity constrains, ensembles are usually run at lower resolitions that the single “deterministic” model run.

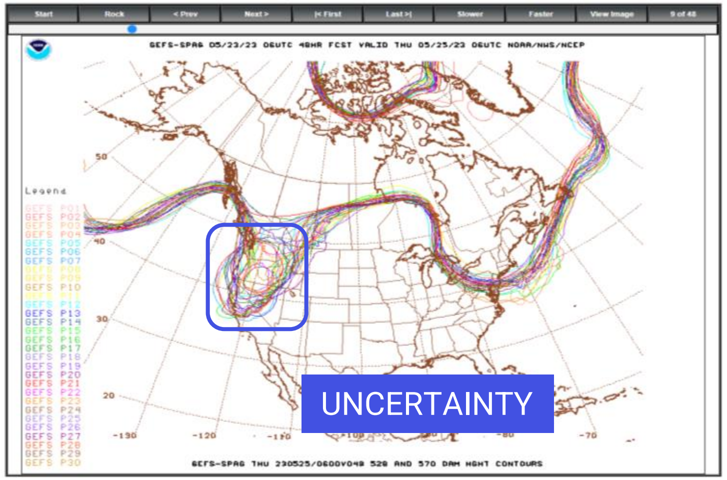
Ensemble Forecasting Examples

- Example of the solution of the 5700m geopotential heights resolved by the 30 members of the GFS Model Ensemble (GEFS).
- Note how the forecast degrades with time in some locations (blue). This indicates that model confidence on the solution on these locations is lower than in locations where the contours match better by hour 72.

F24



F48



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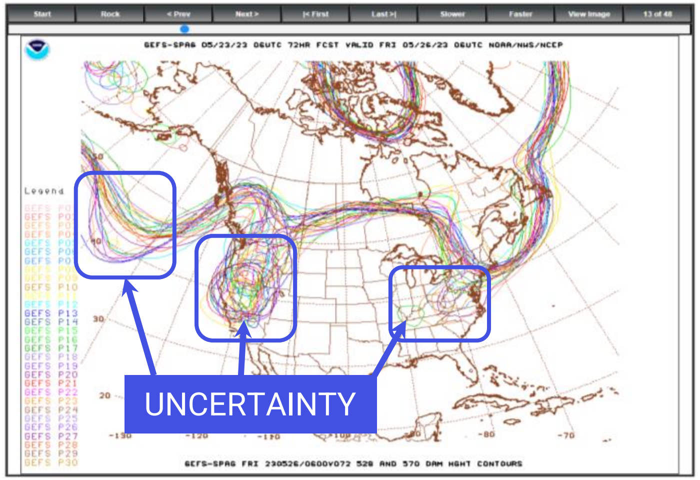


Single-Model Ensemble

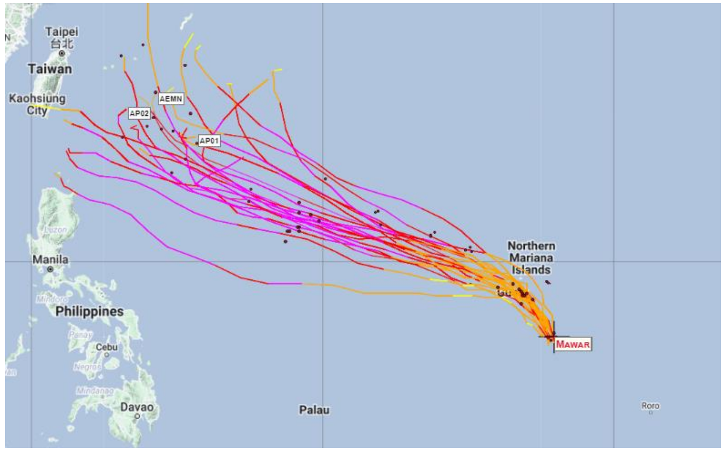
- Several modeling Global Modeling systems run ensembles. E.g.: GFS, ECMWF,

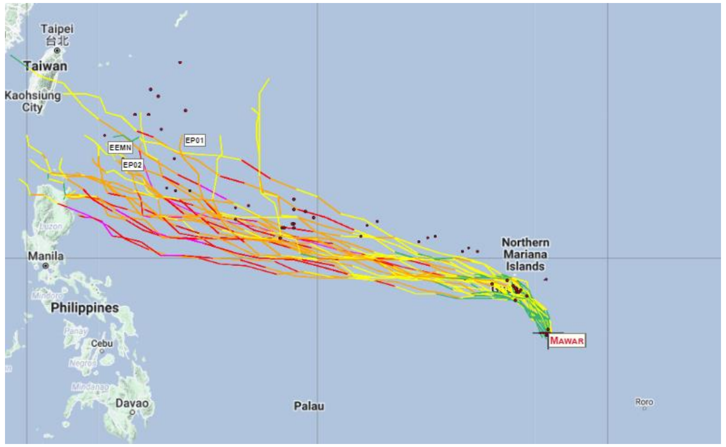
Global Ensemble Forecast System (GEFS)

- Operational since 1992
- Resolution: ~25km
- Ensemble Size: 31 members
- Forecasts up to 16 days

ECMWF Forecast System Emsembles (ECENS)

- Resolution: ~36km
- Ensemble Size: 51 members

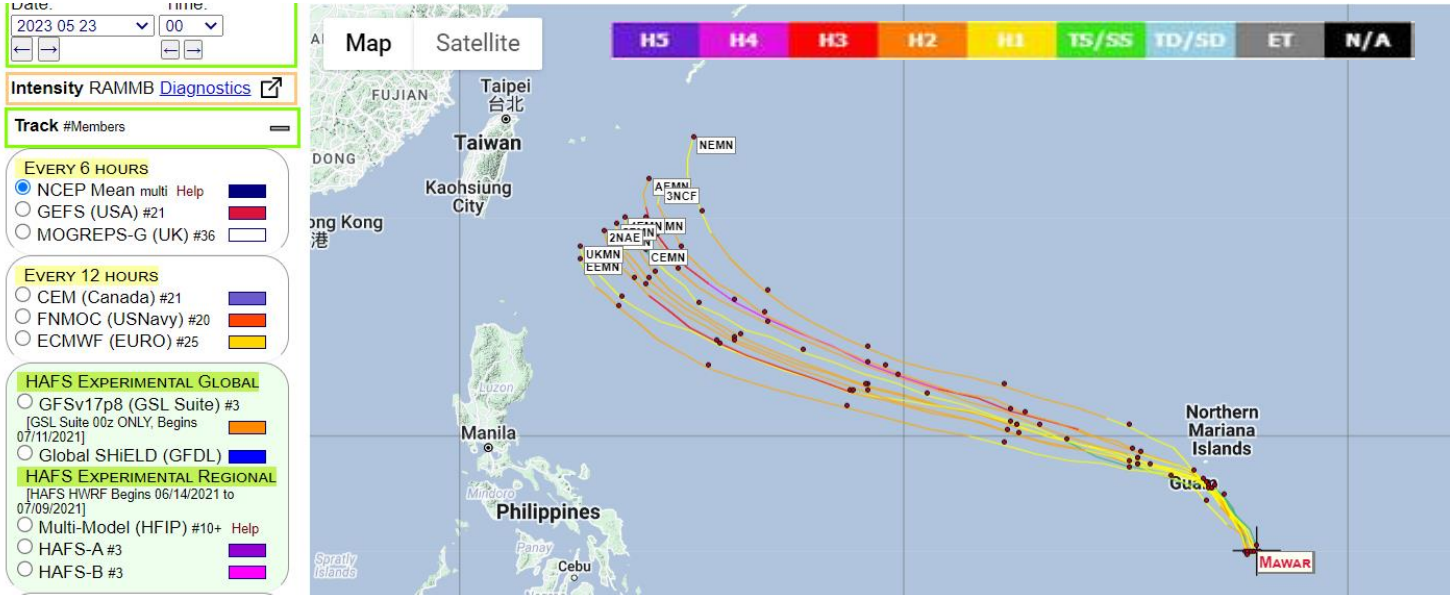




Multi-Model Ensembles

- Consists of considering solutions from different models.
- Tends to be more accurate than the ensemble from a single model, as it captures the impacts of different physics and even methods of initialization that influence model biases.
- “Superensemble”: When biases of the models are considered.

Example of a multi-model ensemble for Tropical Cyclone Mawar. Colors indicate



Importance of considering several models

Models contain their own biases: From differences in data initialization, from methods to resolve the equations of motion and from parameterization of small scale processes.

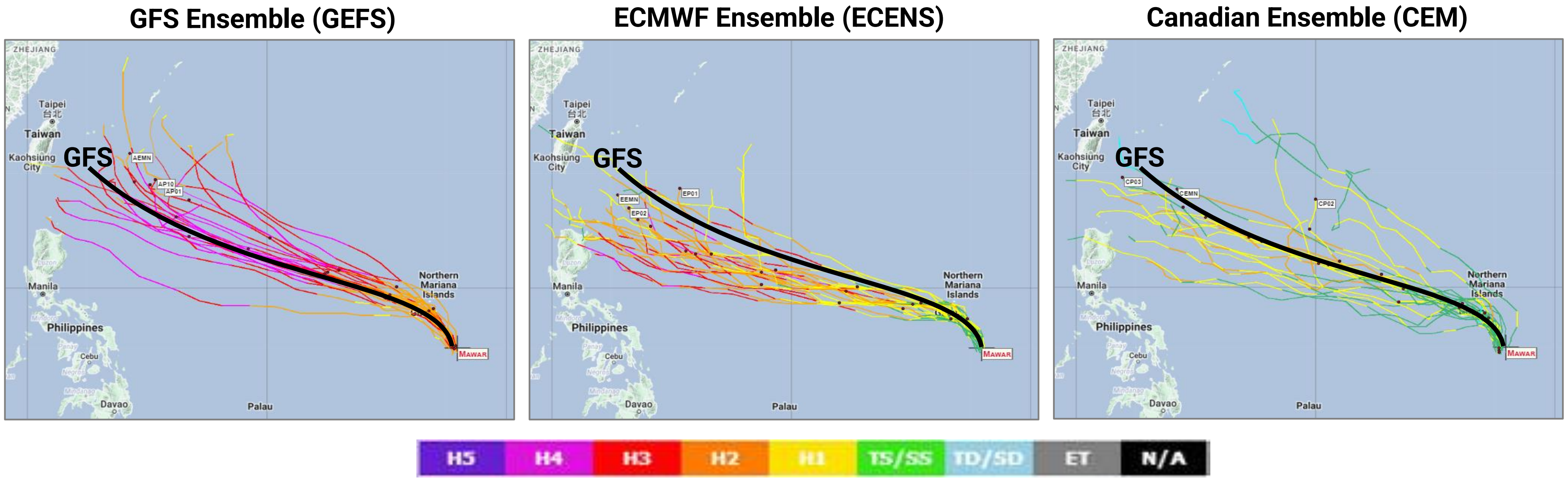
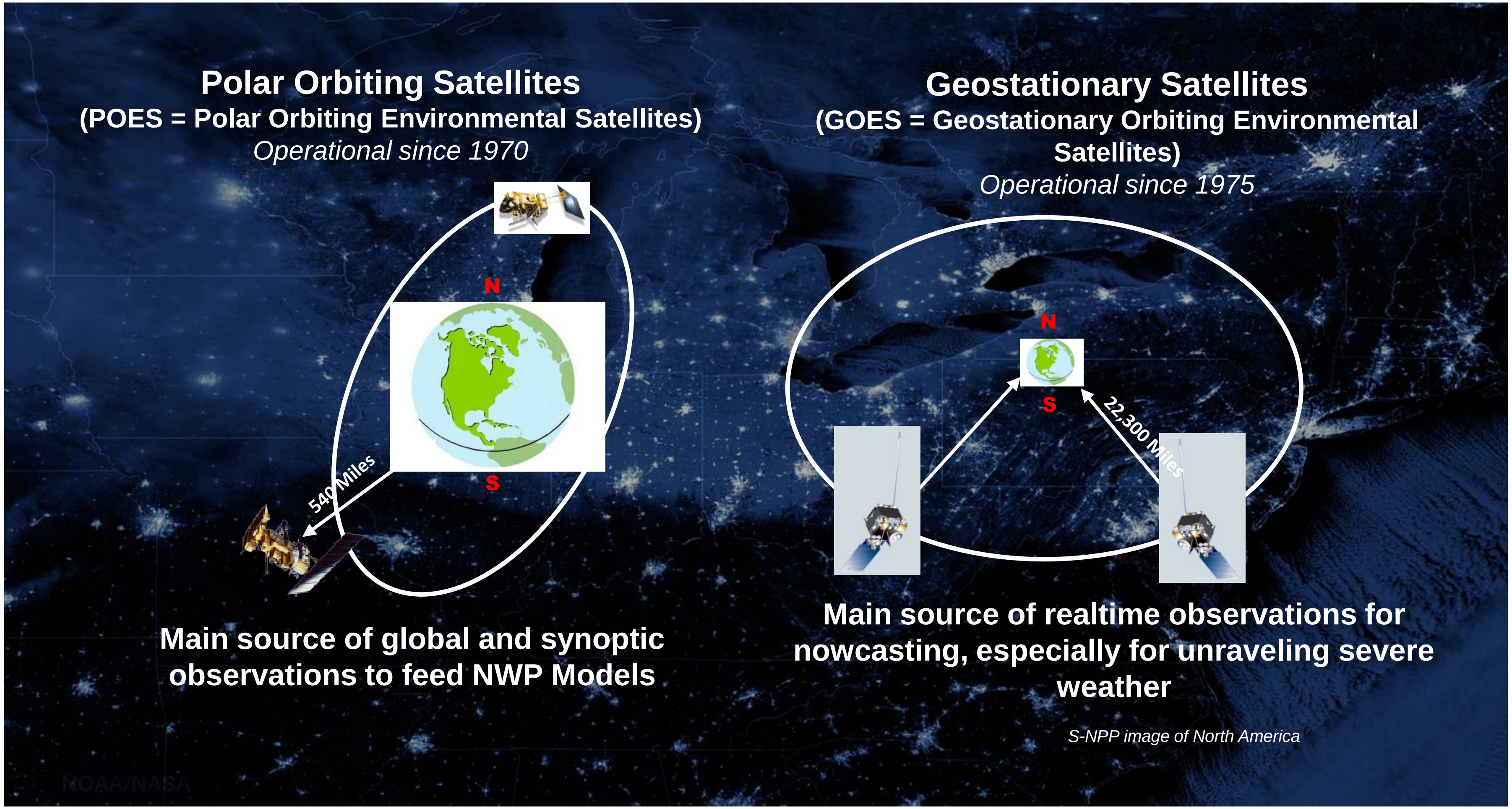


Figure: GFS, ECMWF and CMC ensemble members for the track and intensity fo Tropical Cyclone Mawar (western Pacific, May 2023). Although there is spread, the GFS members are consistently much stronger than the other models (Cat 4). The ECMWF leans further south and is weaker (Cat 1-Cat 3). The CMC leans towards GFS trajectory bit it is much weaker as well. Seems like initialization of intensity was very different in the GFS compared with the other two models.

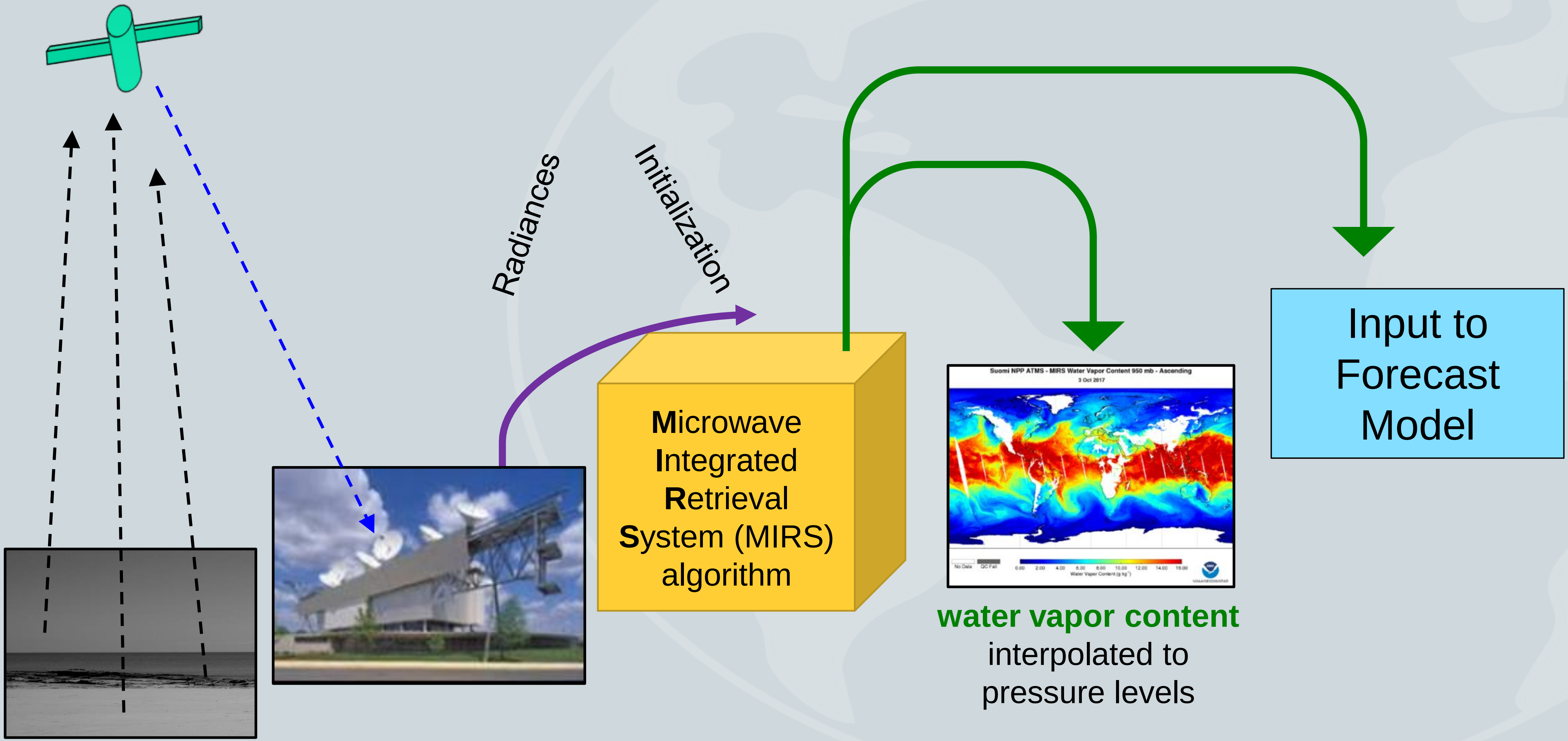
03

Introduction to Satellite Meteorology

Satélites Polares y Geoestacionarios Operacionales de la NOAA para el Tiempo – JPSS y Series GOES-R



Measured Radiance to Display Information and Model Input



Solar vs Earth emission Spectra

Ideal diagram (black body assumption) for radiation emitted by the sun and earth, based on their temperatures:

- Radiación Solar: pico alrededor de los 0,5 µm
- Radiación terrestre: pico alrededor de los 10 µm

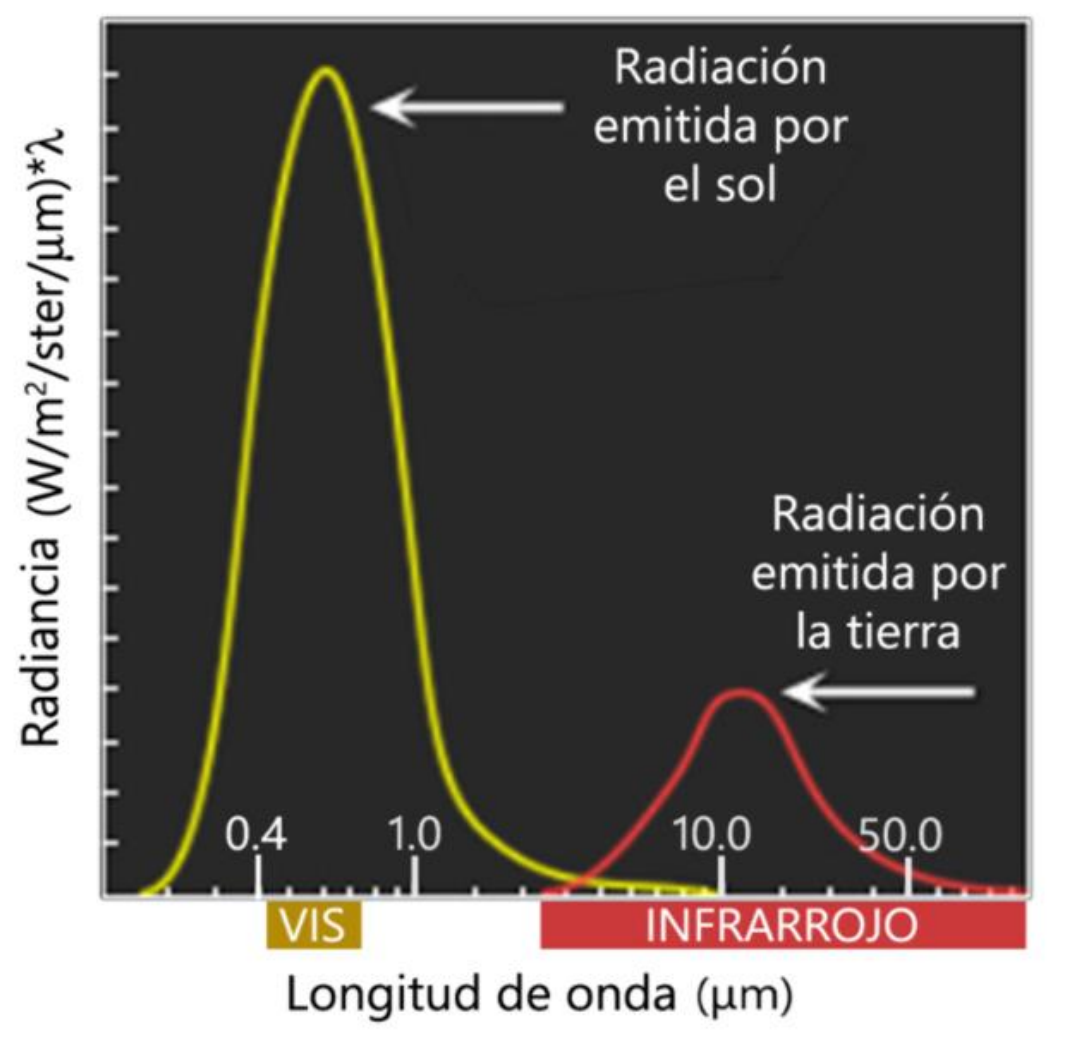


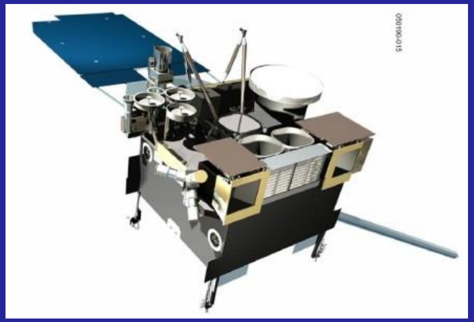
Diagram from COMET Forecaster's Multimedia Library: Satellite Meteorology: Remote sensing Using the New Goes Image

M.E.Pestaina-Jeffers
CIMH, Barbados

Measuring Limitations

The design of satellite sensors and sampling resolution depend upon several factors:

- Horizontal detail (image generators)
- Vertical detail (sounders)
- Earth-satellite distance
  - (36.000 km vs. 850 km)
- Power of the lens and resolution
- Size of the sensor and satellite

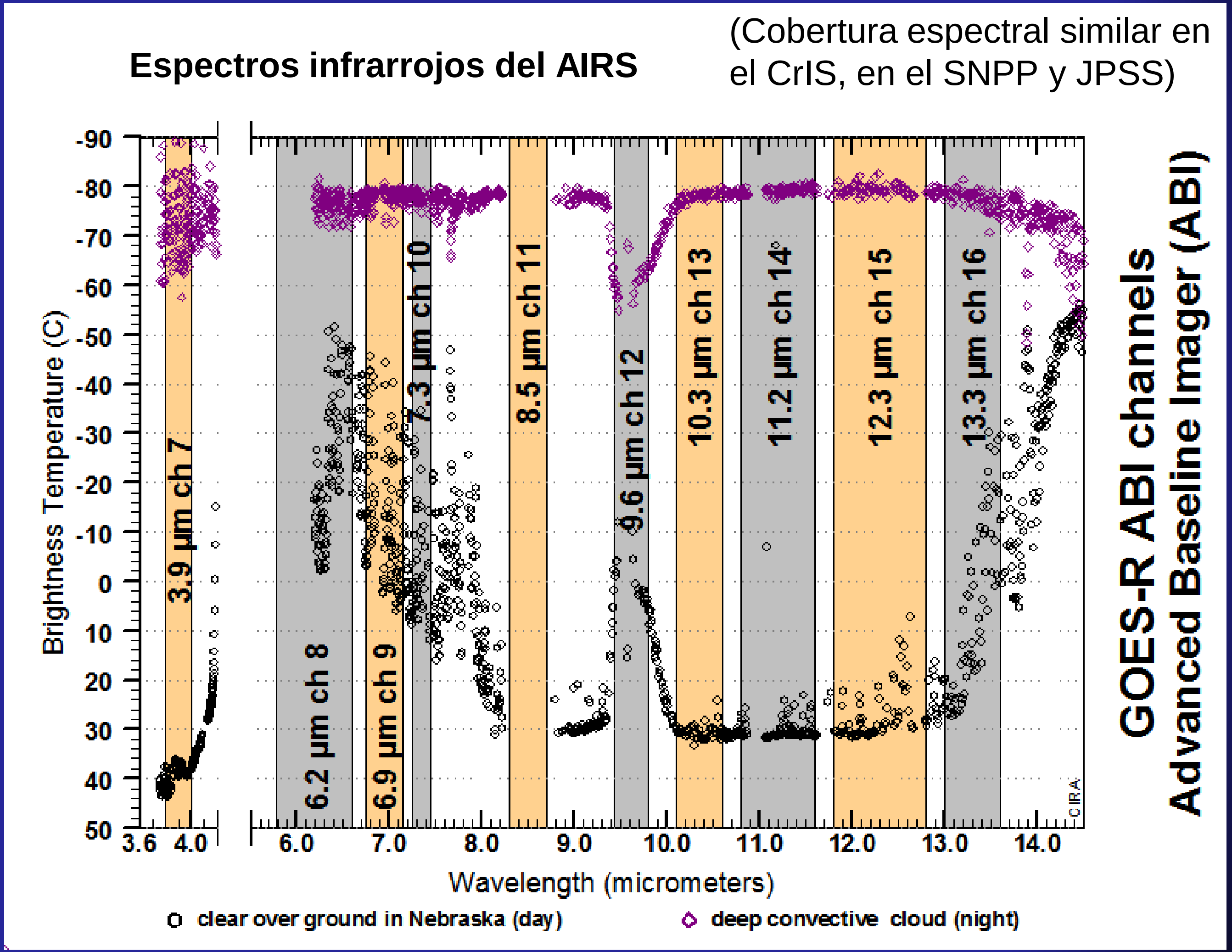


$$,$$$,$$$,$$$'s

Spectral Resolution types

- **High Resolution**– very large number of fine bands, each measuring very specific wavelengths.

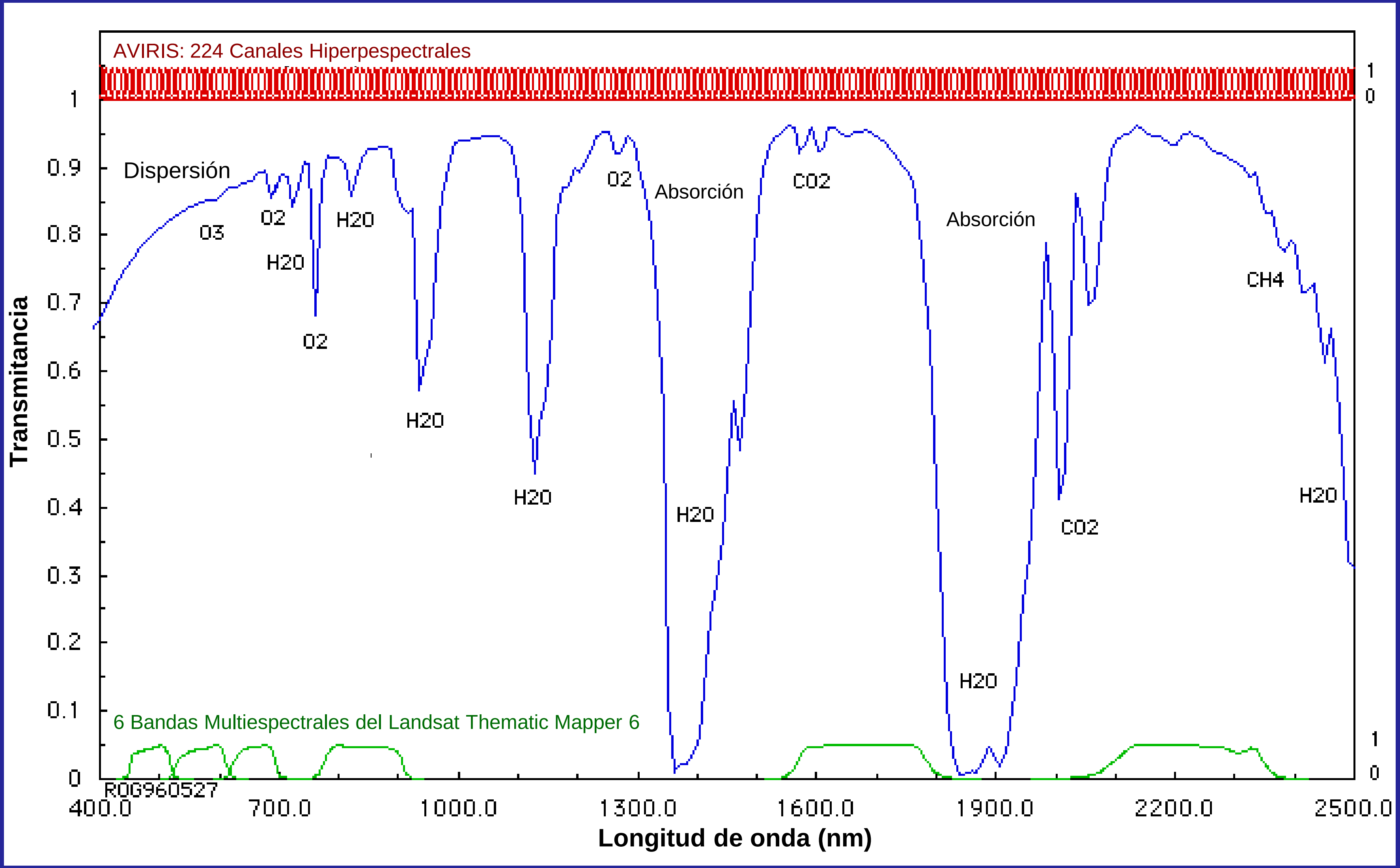
- **Multispectral** – smaller number of broader bands, averaging over a range of wavelengths.



Visible and Near-IR Spectra

0.4-2.5 μm

Visible and Near IR Spectra



Aspects that help us to interpret satellite imagery

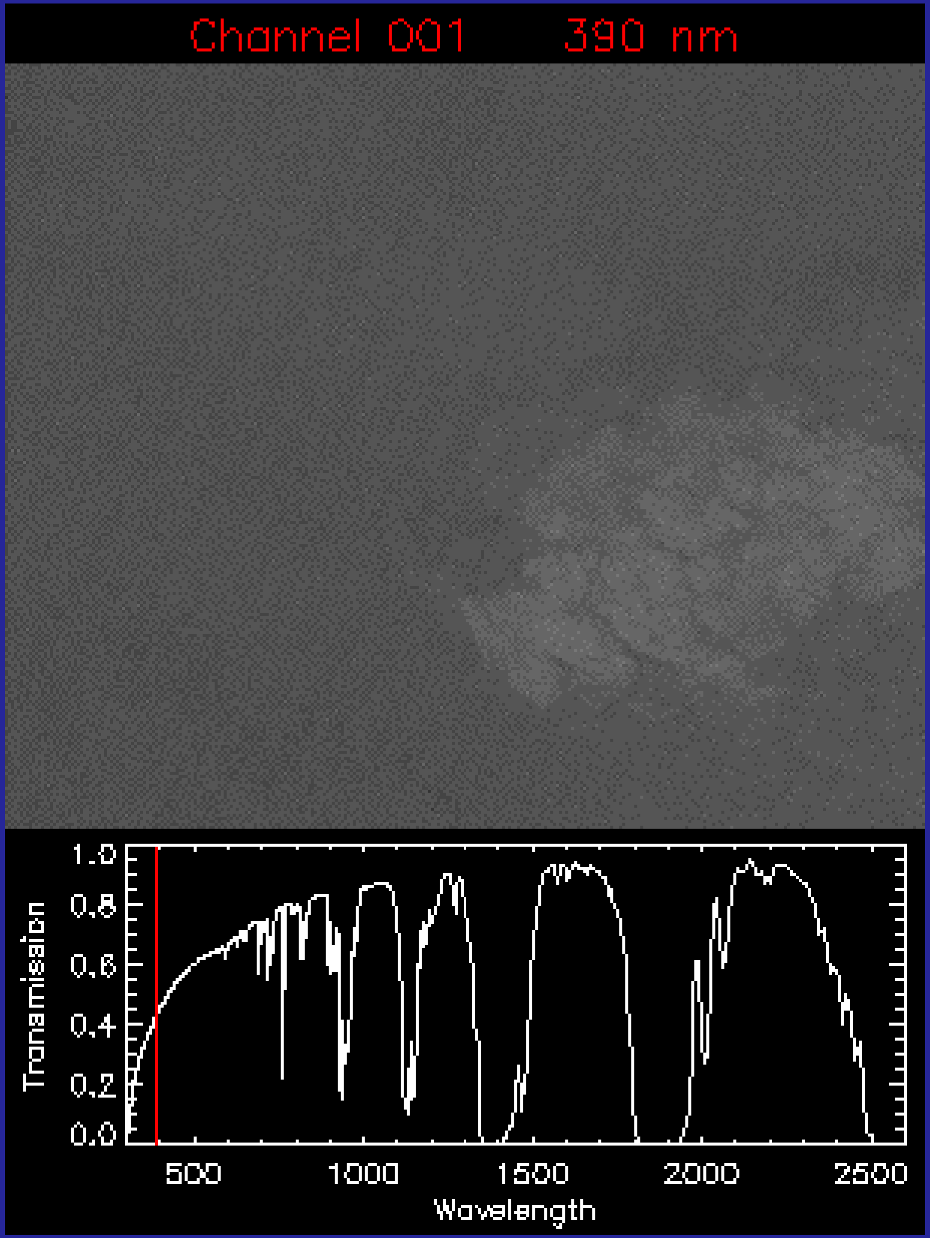
- Reflectance (Vis/Near IR) and brightness temperature (IR)
- Texture
- Context
- Single image vs. animation
- Single channel vs channel combination (RGB composites)

True color RGB measured from a plane with the sensor AVIRIS (multispectral), showing areas of fires and hotspots

Imagen AVIRIS

Linden CA

20-Ago-1992
224 Bandas espectrales
0,4 – 2,5 mm
Pixel: 20m x 20m
Escena:
10km x 10km



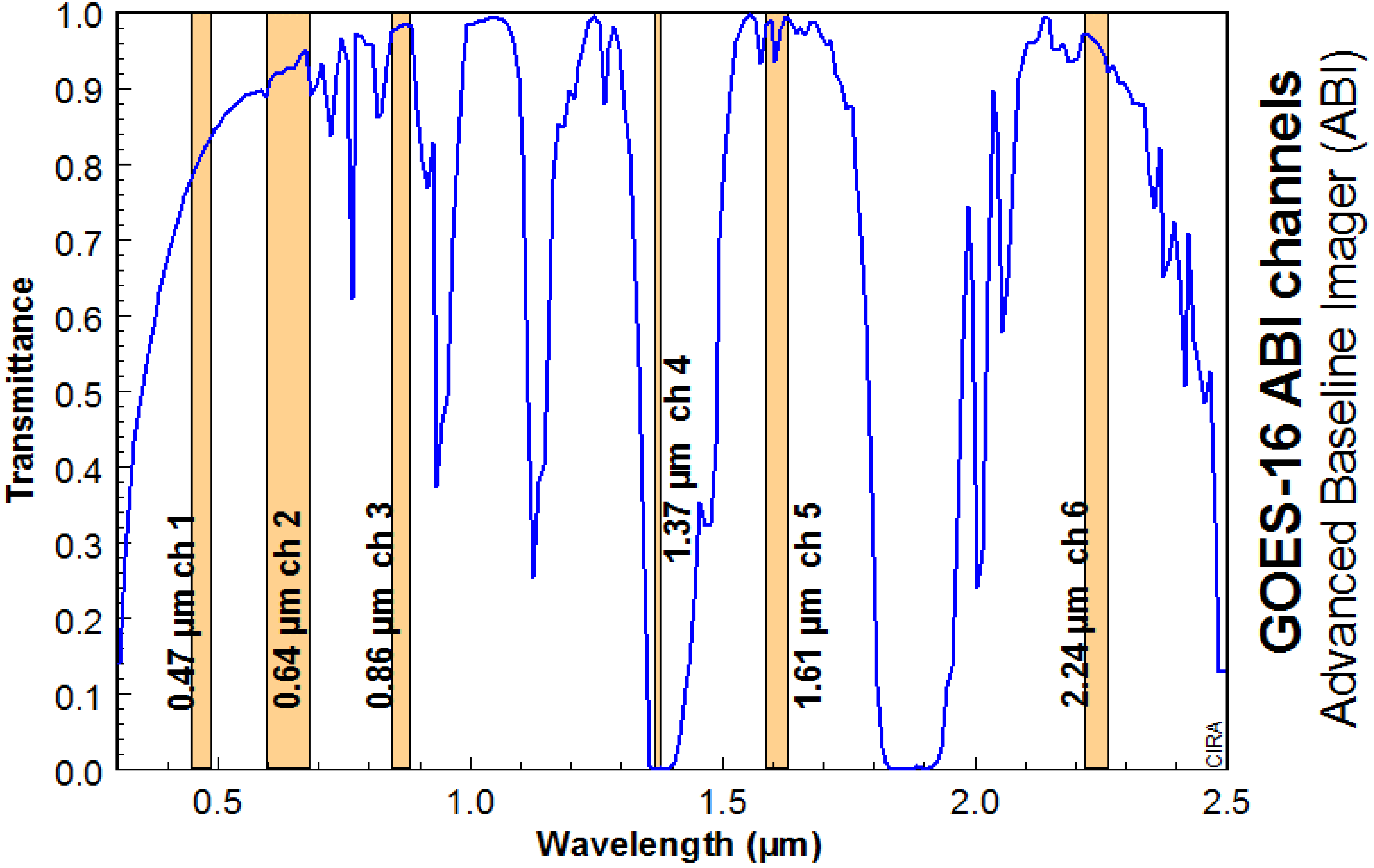
390 nm (0,39 µm) – 2500 nm (2,50 µm)

This animation reveals the high spectral resolution of AVIRIS, and shows what we can see at different wavelengths.

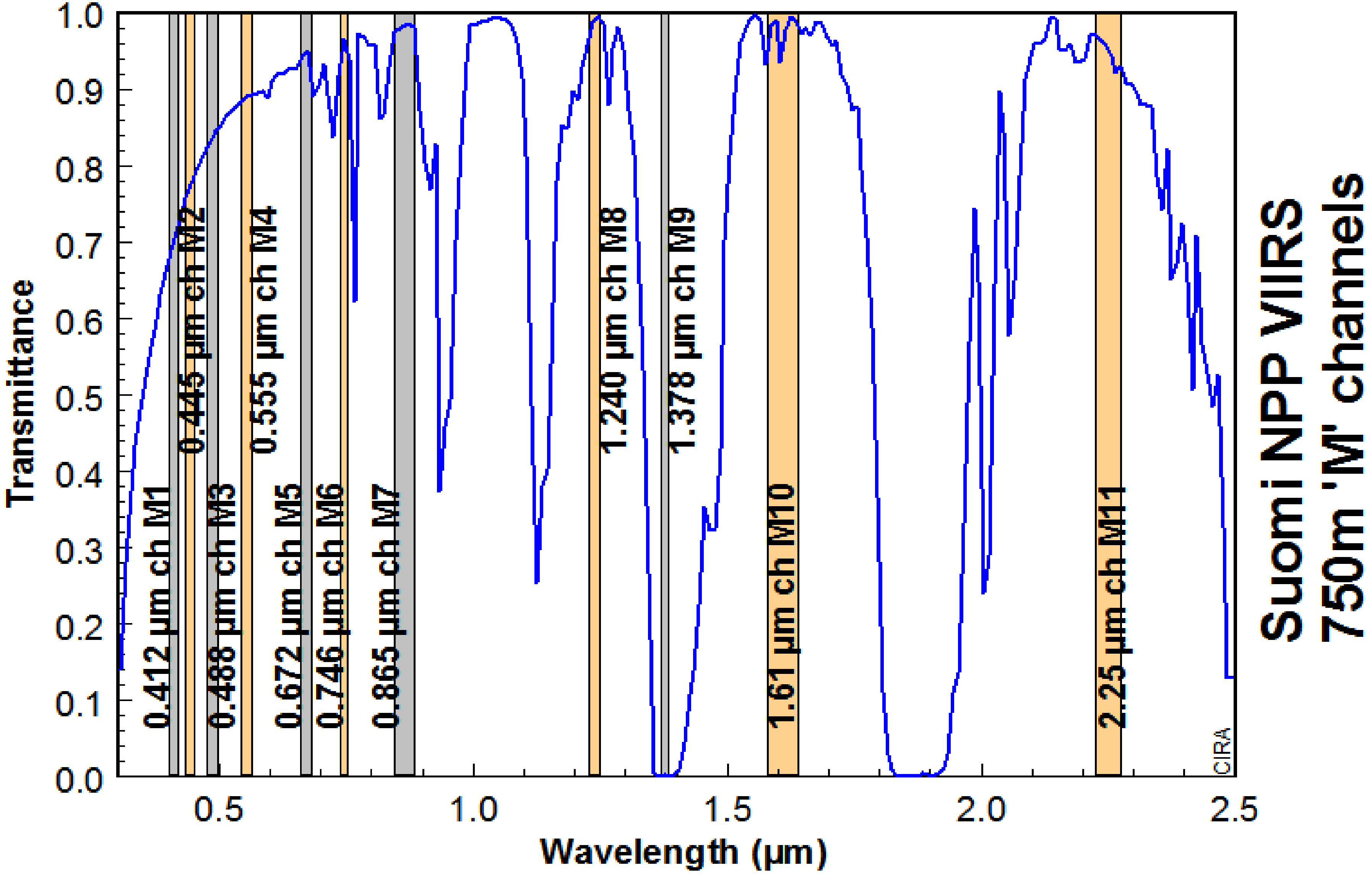
Imagen AVIRIS - Linden CA
20-ago-1992
224 Bandas espectrales: 0,4 – 2,5 um
Pixel: 20mx20m
Scene: 10kmx10km

Animation:
Dr. Mike Griffin
MIT Lincoln Laboratory

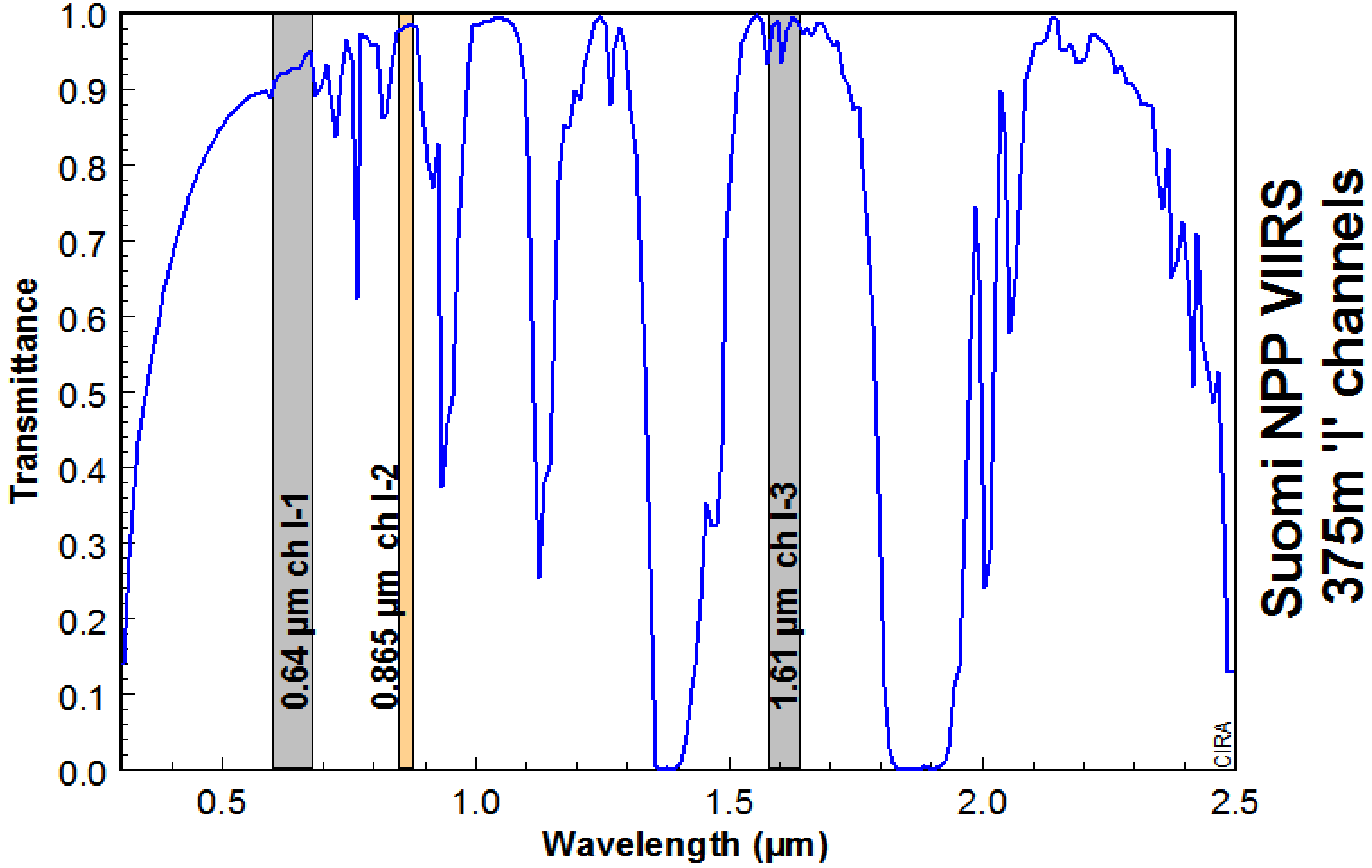
Visible to Near Infrared



Visible to Near Infrared

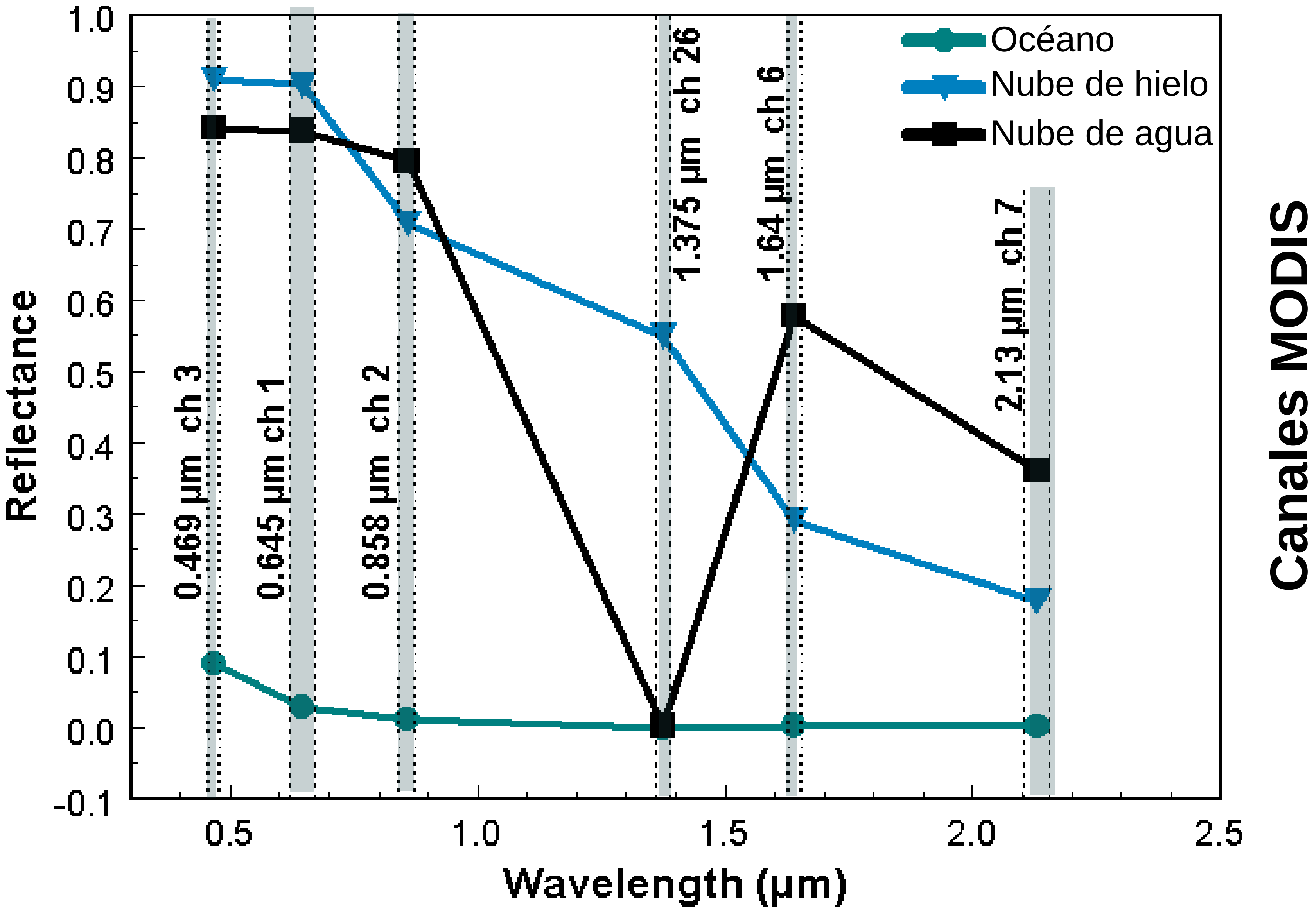


Visible to Near Infrared

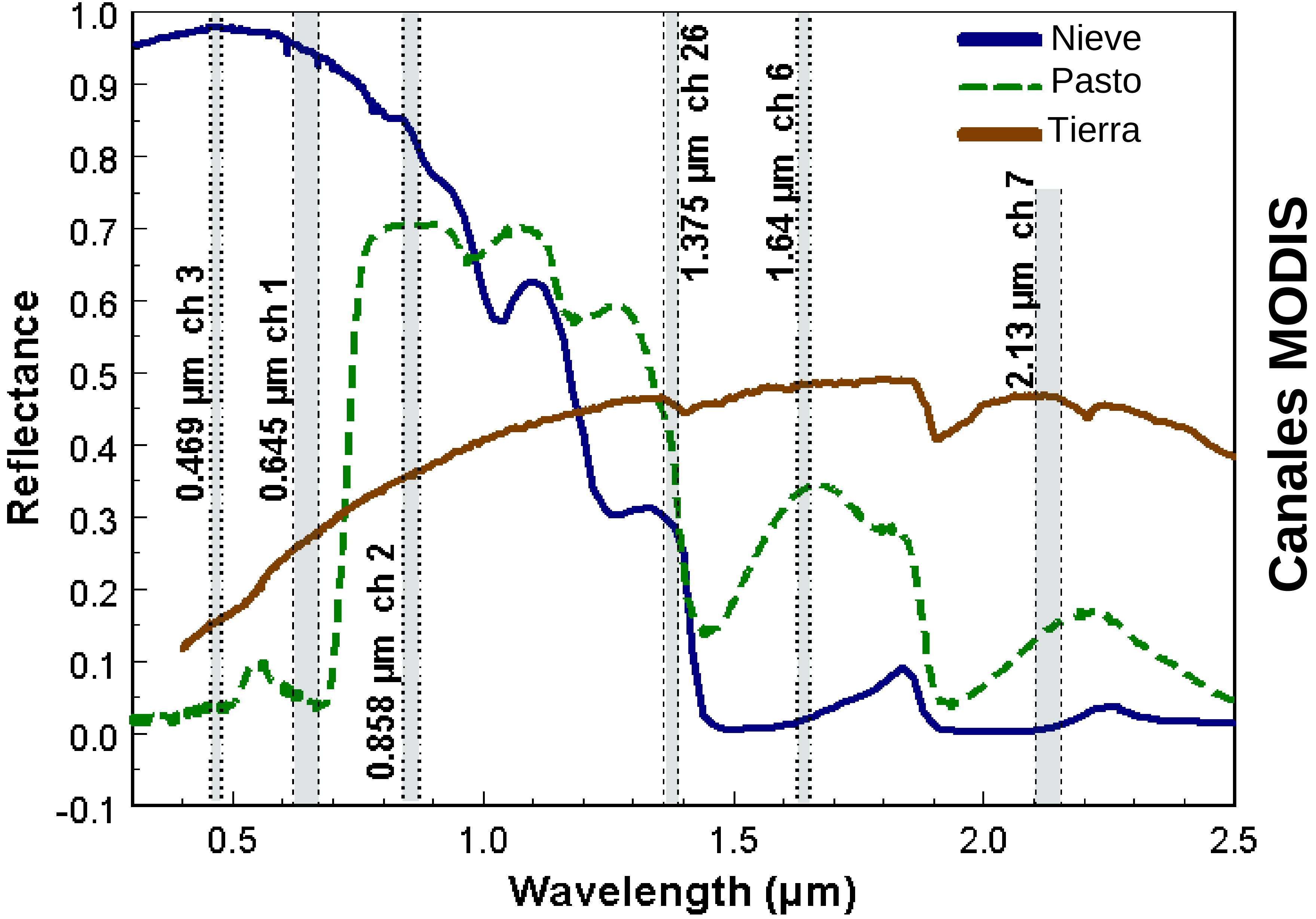


Reflectance of different surfaces in VIS and NIR Spectra

Visible to Near Infrared



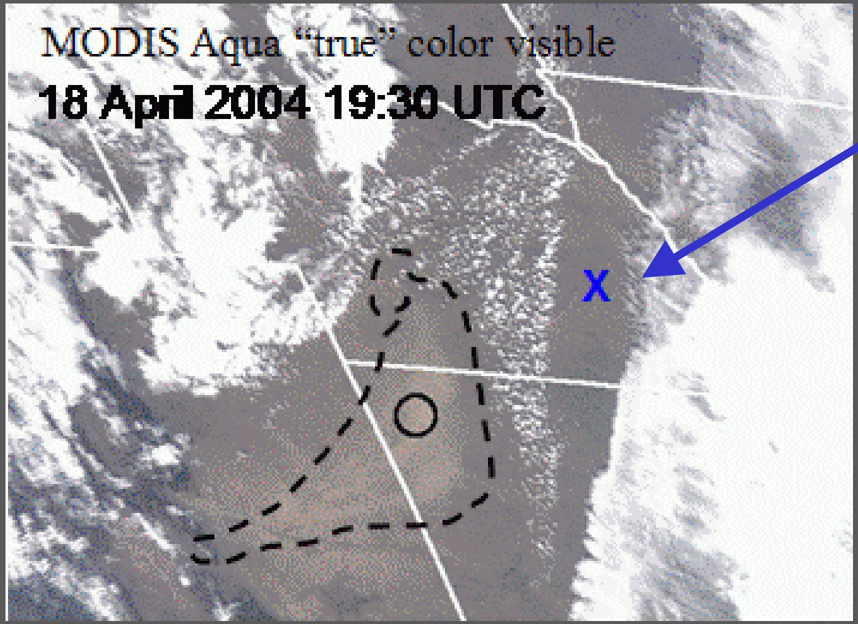
Visible to Near Infrared



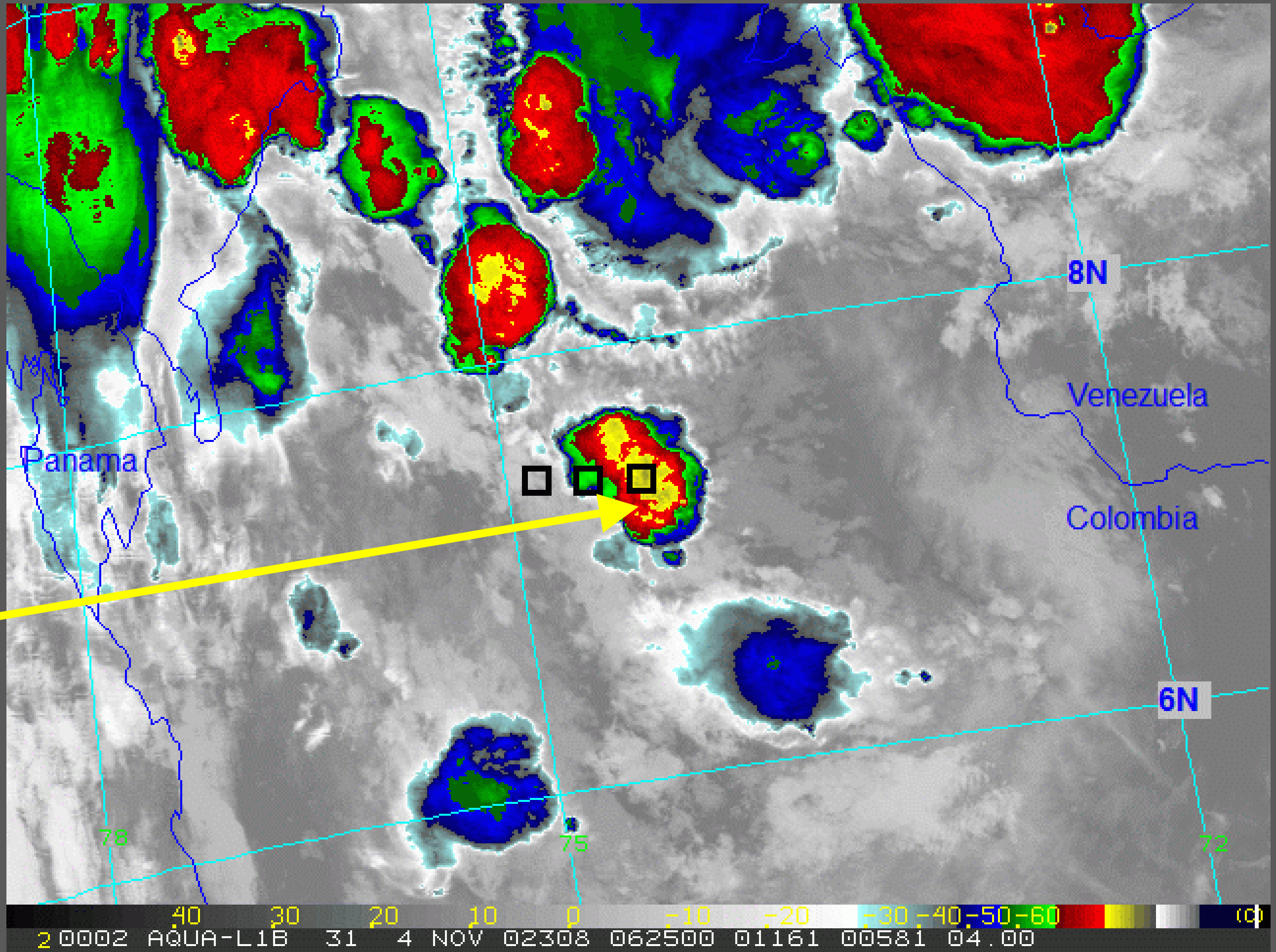
Infrared Spectra (IR)

Measurements of radiation emitted by earth features (not solar radiation reflection)

Clear Skies vs Convective Clouds



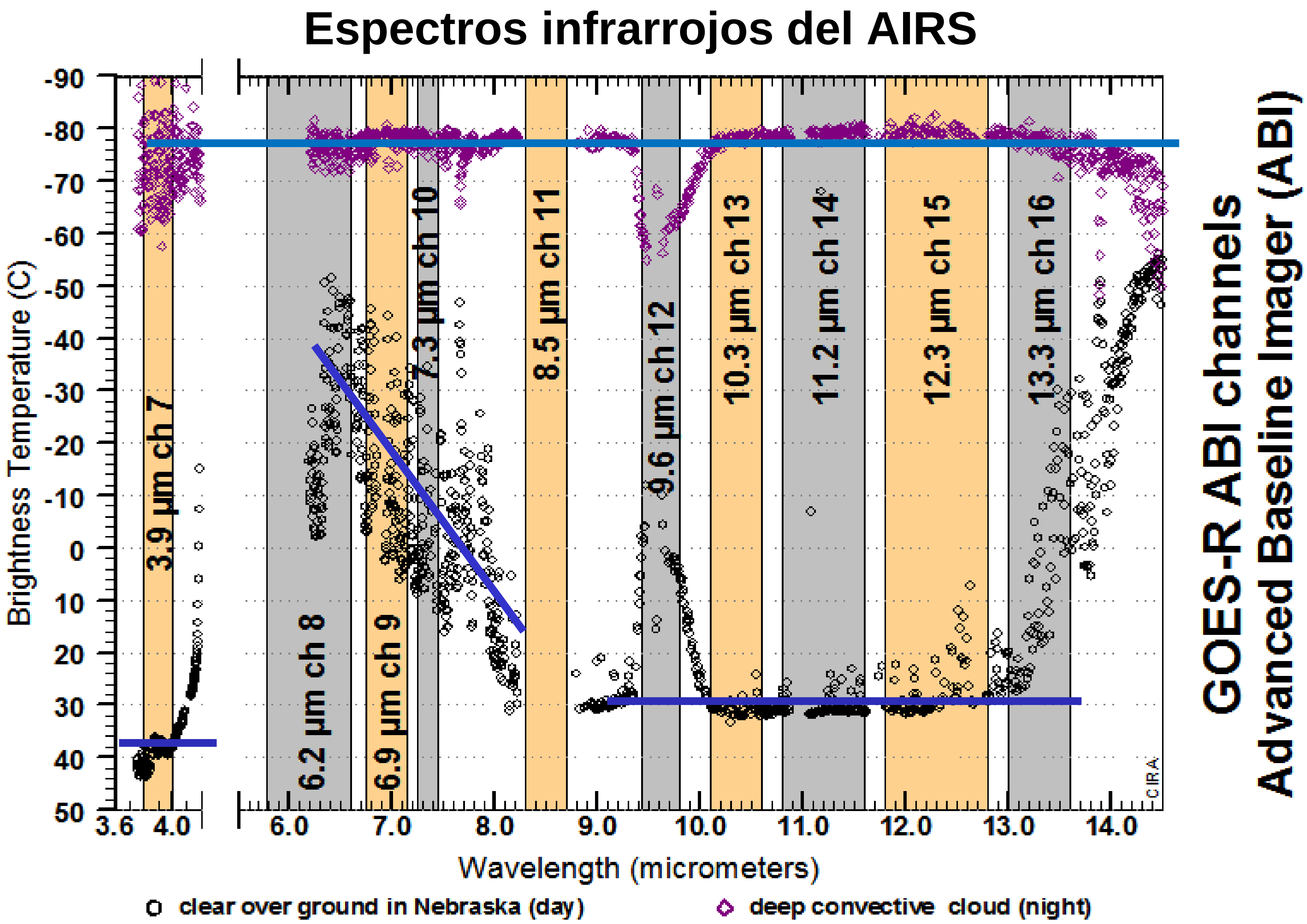
Warm soil in a clear sky day



Cold top of a convective cloud at night

Brightness Temperature Spectra

launch 2016

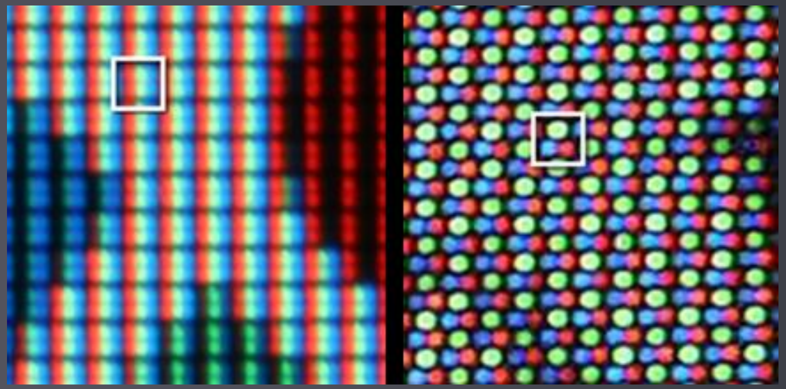


04

Red-Green-Blue (RGB) Composites

Red-Green-Blue (RGB) Compositing

- RGB is the color mode used in electronic monitors
- The RGB technique combines light in shades of red, green and blue to generate visual effects that look like other colors.
- It is additive



Acercamiento a un monitor. Fuente: https://designmanagementlucerne.wordpress.com/

Red 0%	+	Green 0%	+	Blue 0%	=	0		Black or no color (no one contributes)
Red 100%	+	Green 100%	+	Blue 100%	=	300		White or brightest color (everyone contributes)

Generating a grayscale in RGBs

Brightness means more information

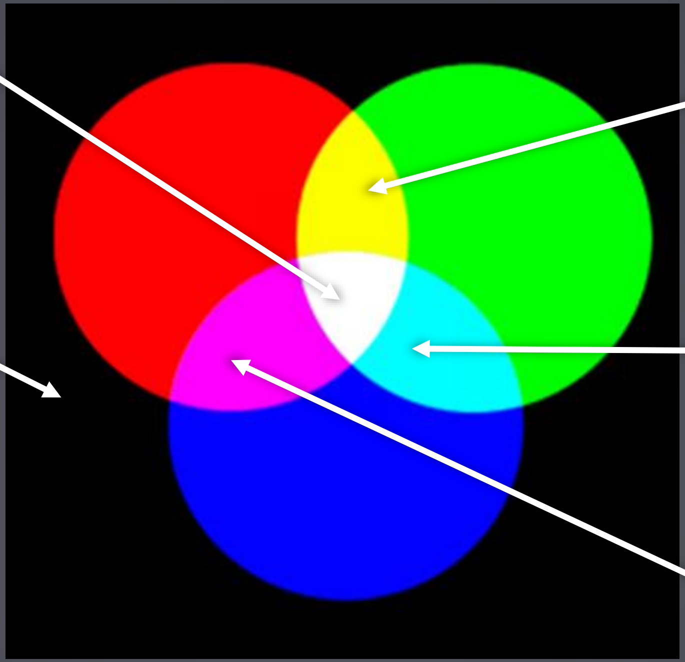
To attain a grayscale, we need equal contributions of R, G and B:

Rojo 100%	+	Verde 100%	+	Azul 100%	= 300		**White** Large equal contributions
Rojo 67%	+	Verde 67%	+	Azul 67%	= 200		**Light gray** Moderate equal contributions
Rojo 33%	+	Verde 33%	+	Azul 33%	= 100		**Dark gray** Low equal contributions
Rojo 0%	+	Verde 0%	+	Azul 0%	= 0		**Black (no color)** No one contributes

Different mixes produce different colors

White: All RGB contributing 100%

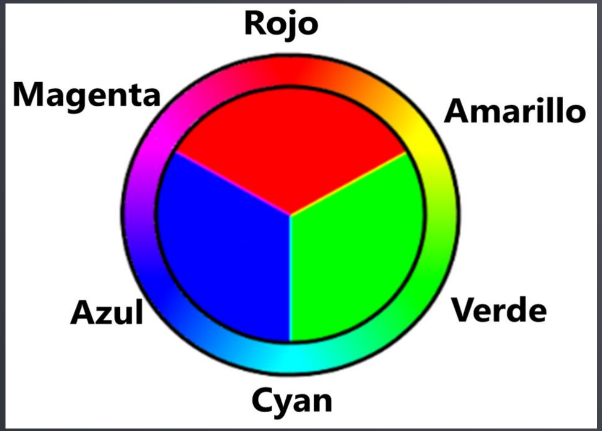
Black: All RGB contributing 0%



Red and Green only produce yellow
R G B

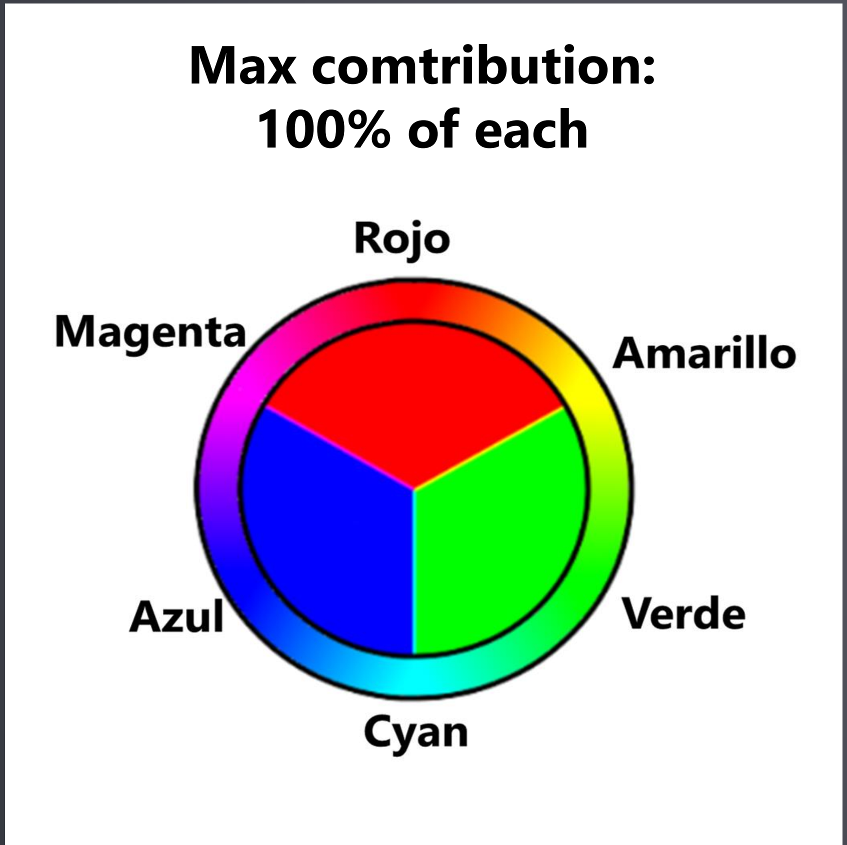
Green and blue only produce cyan
R G B

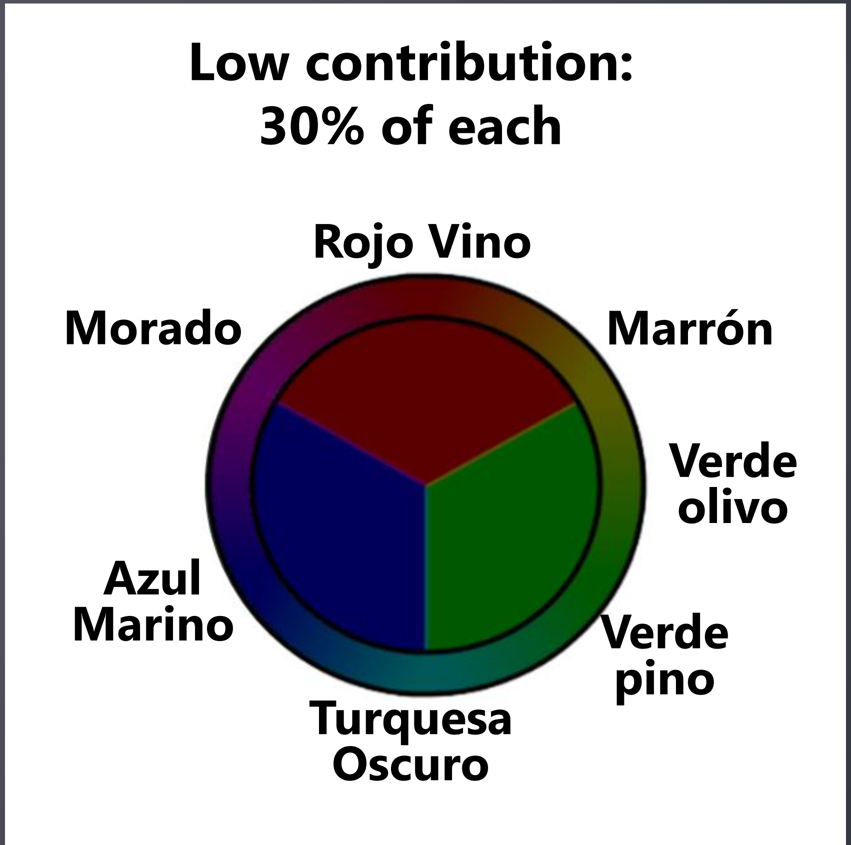
Red and blue only produce magenta
R G B



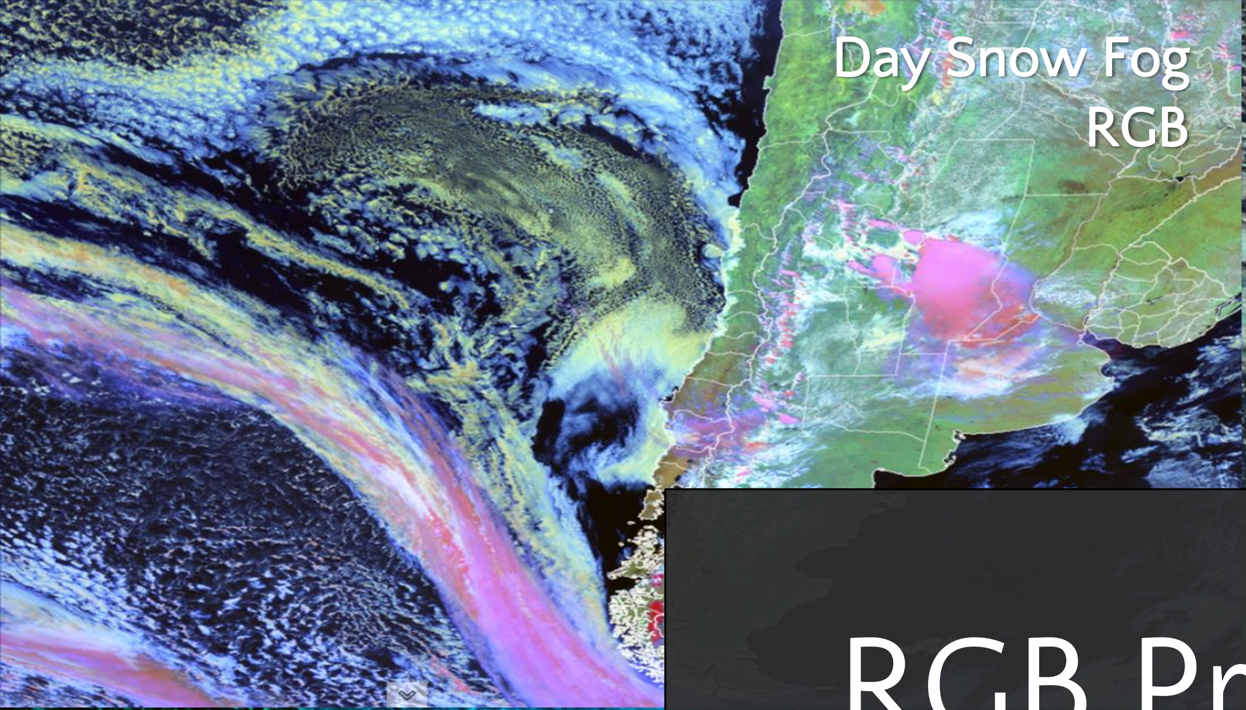
We can attain many more colors just by playing with the proportions of red, green and blue

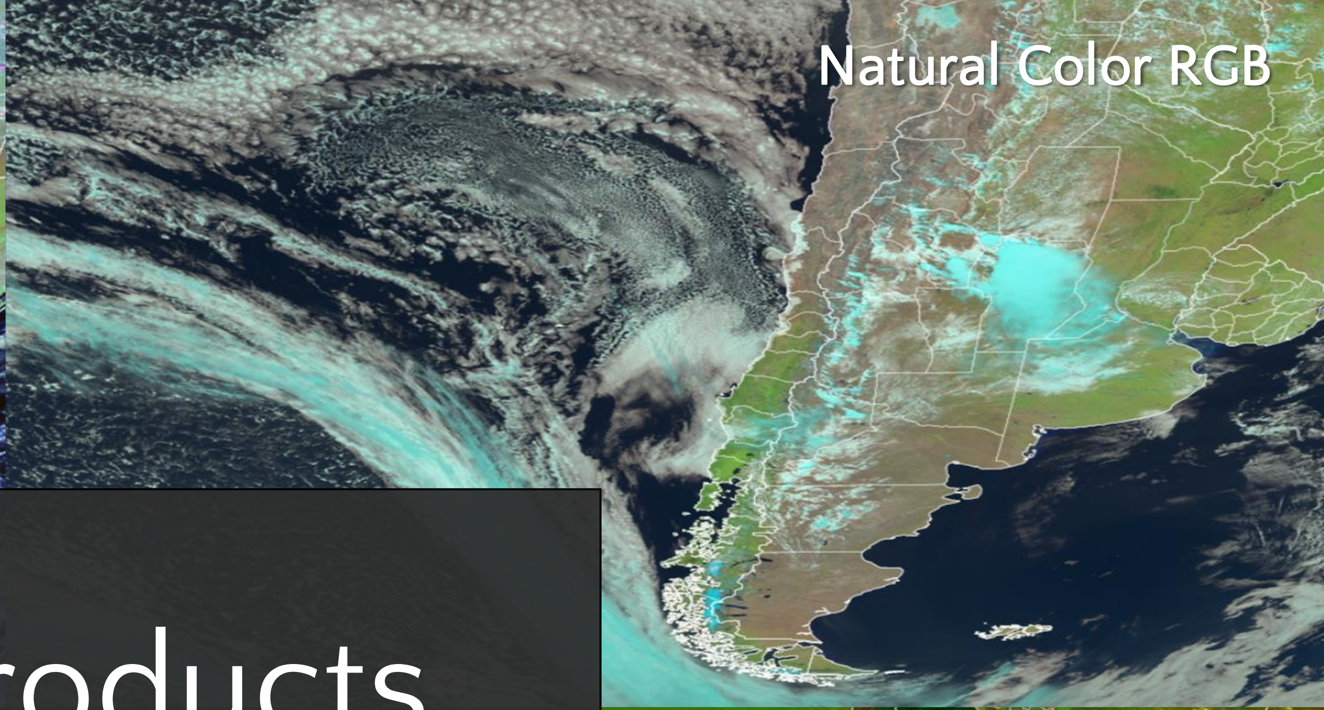
The intensity (amount of contribution) of red, green and blue affect the brightness of the final color

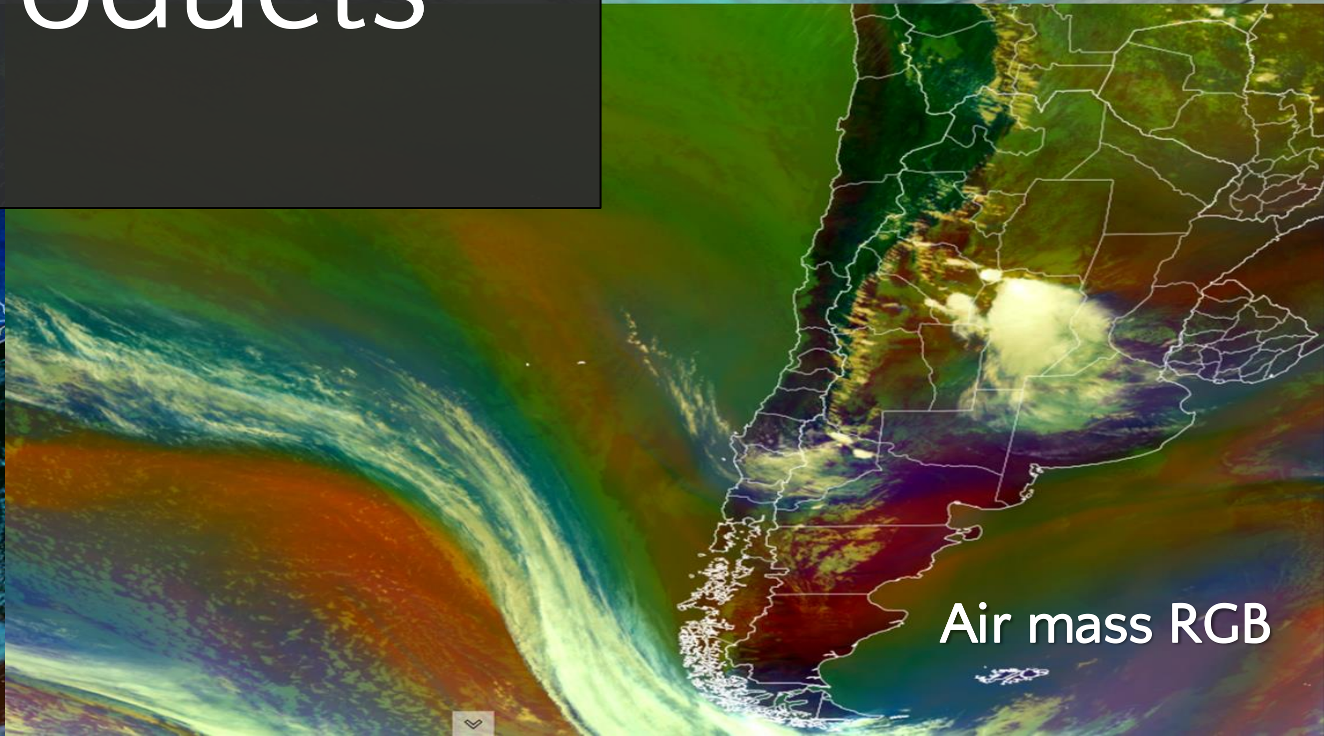




RGB Products

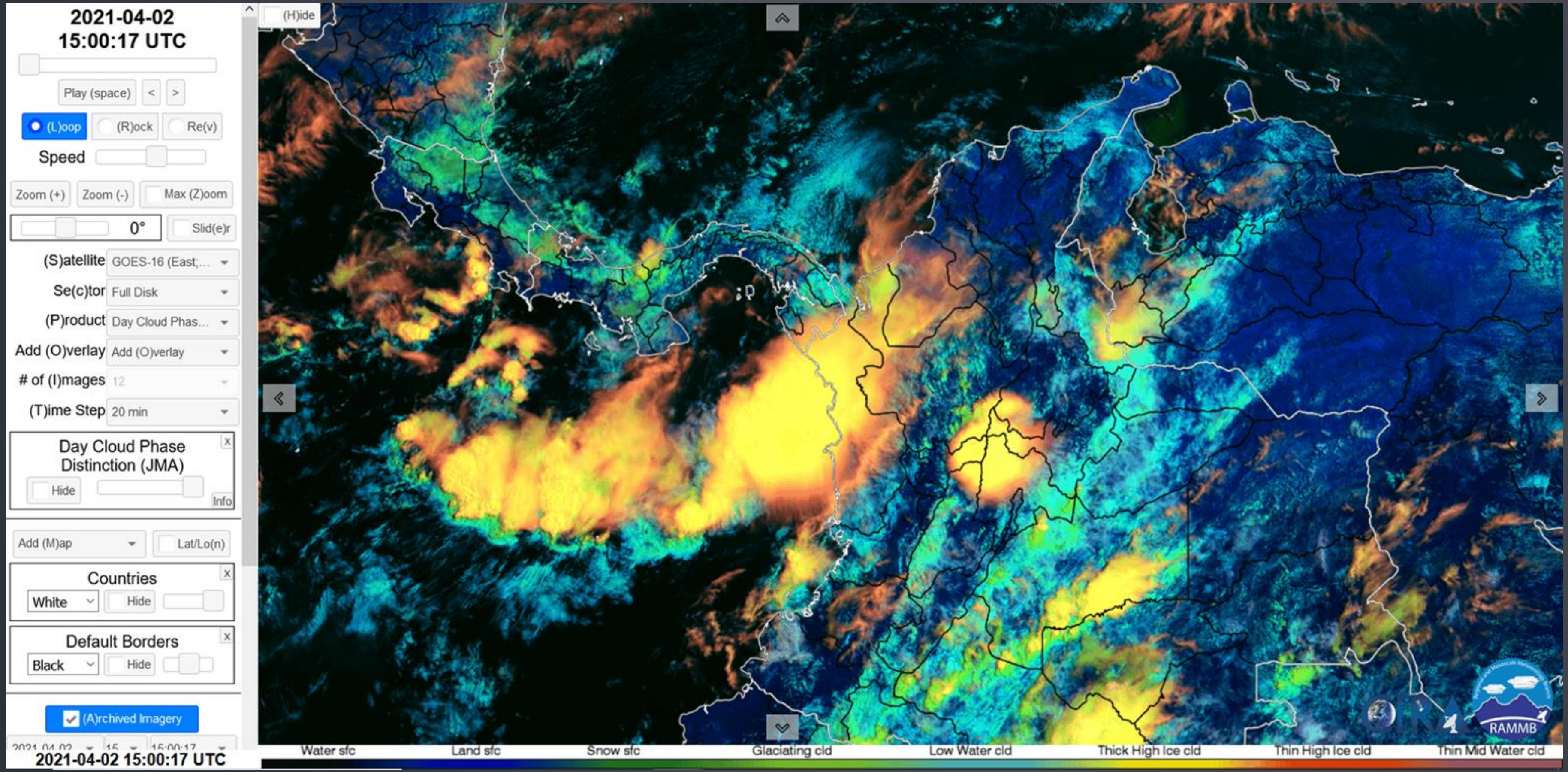


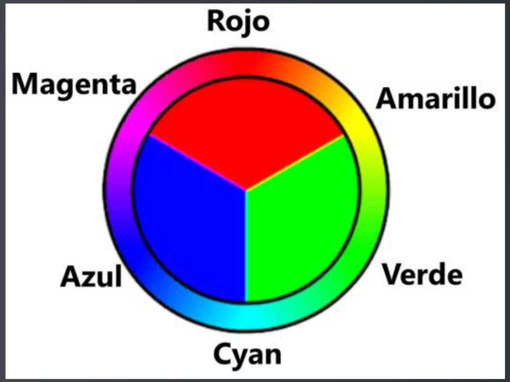




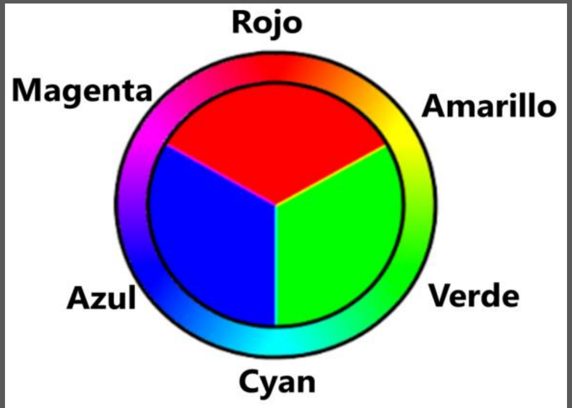
Interpreting an RGB

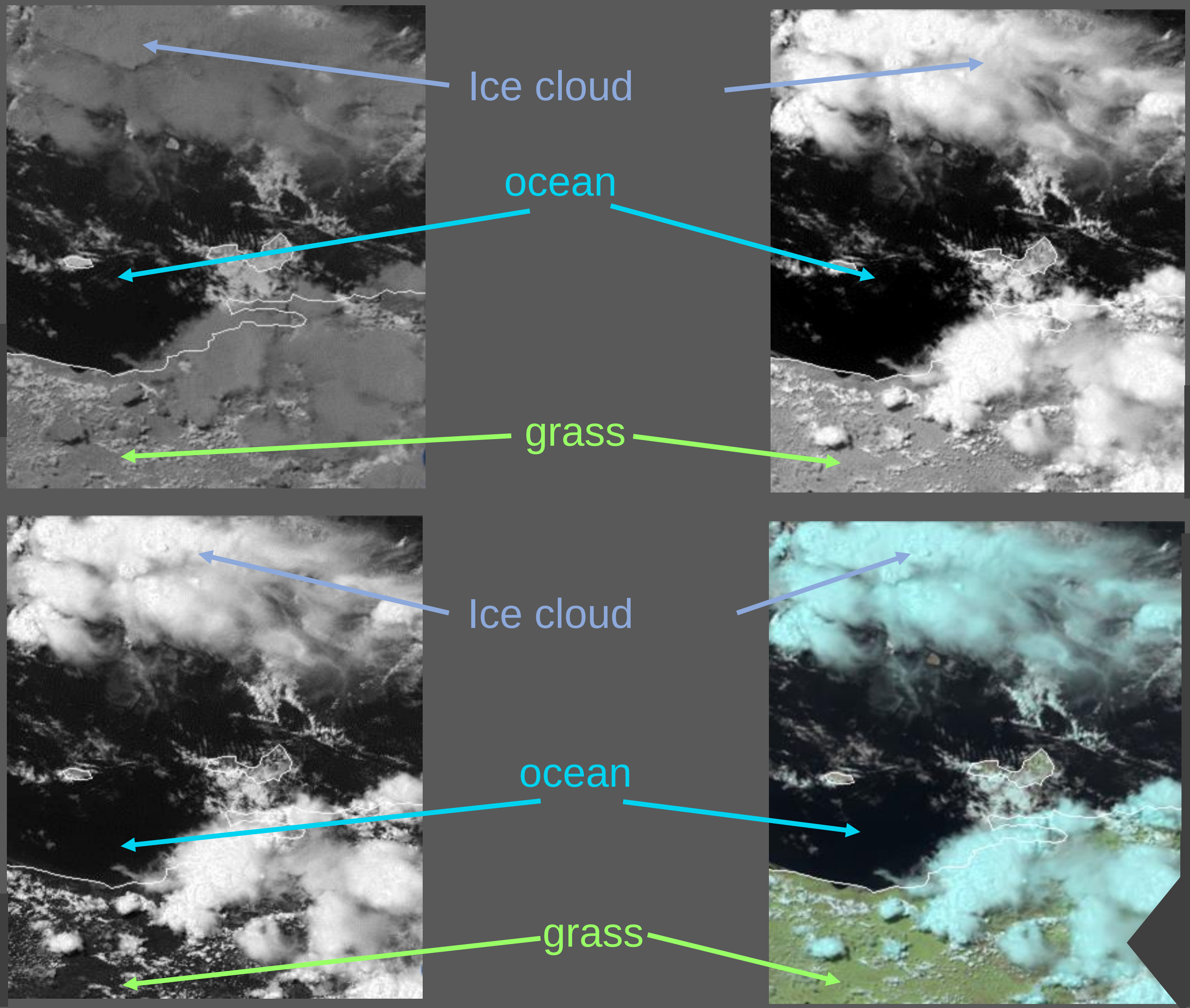
Different colors mean different things.
Context, texture, movement and other aspects give more information.





Natural Color RGB





1,6 µm
(NIR)

0,84 µm
NIR

0,64 µm
Red visible

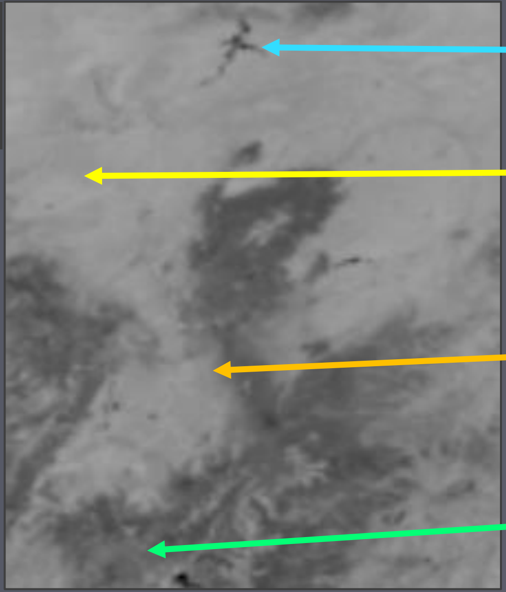
RGB EUMETSAT
Natural Color

RGB NOAA
Day-land-cloud

R:
R:1.6
G: 0.84
B: 0.64

Natural color RGB, again

1,6 µm
IR cercano

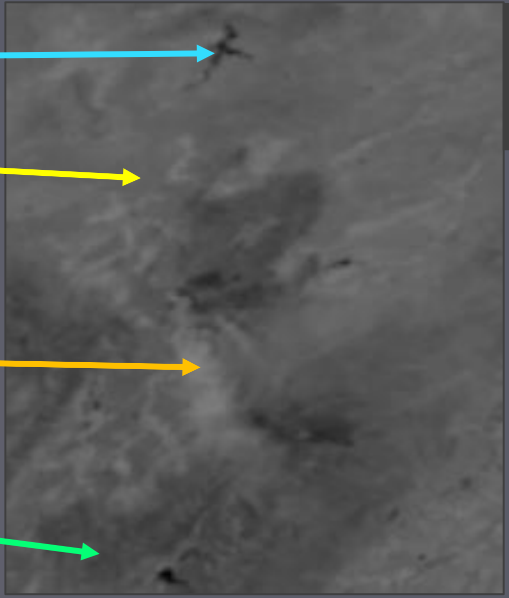


water

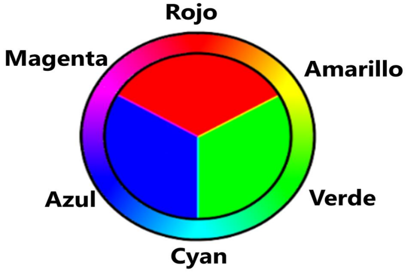
Dry pastures

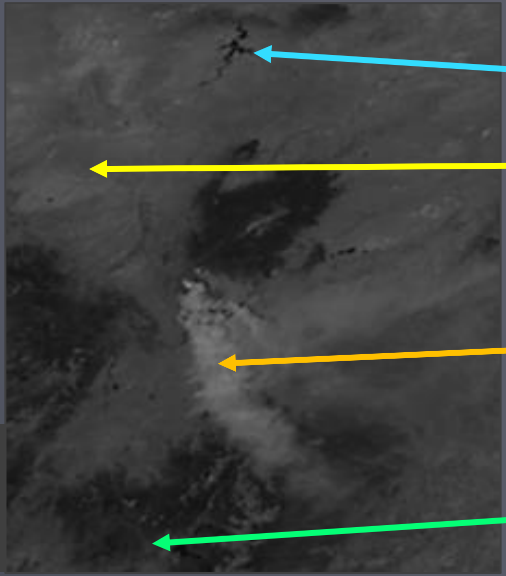
Smoke and ice cloud?

forest



0,84 µm
IR cercano





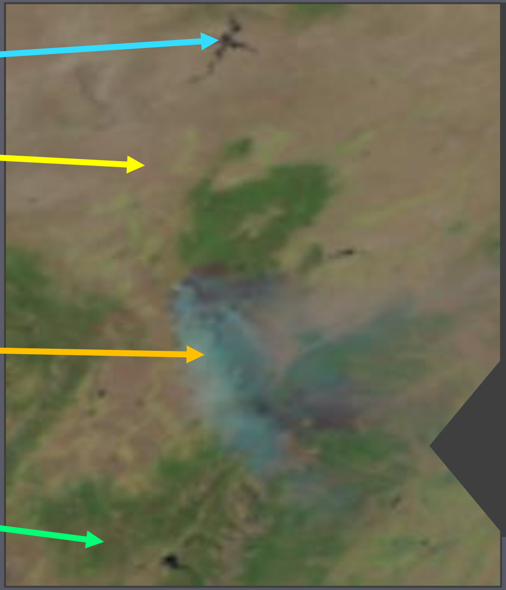
0,64 µm
VIS “Rojo”

water

Dry pastures

Smoke and ice cloud?

Forest

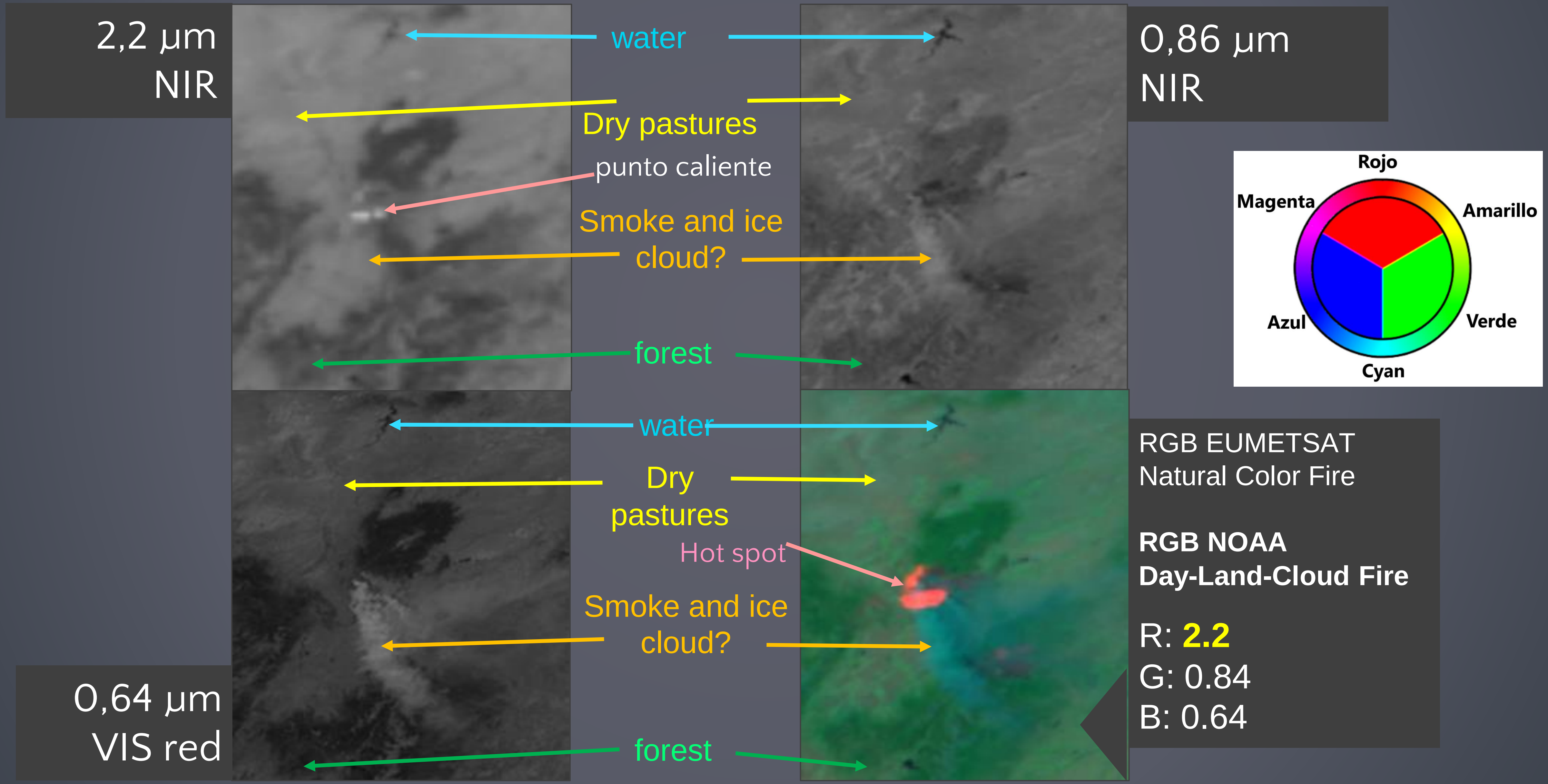


RGB EUMETSAT
Natural Color

RGB NOAA
Day-land-cloud

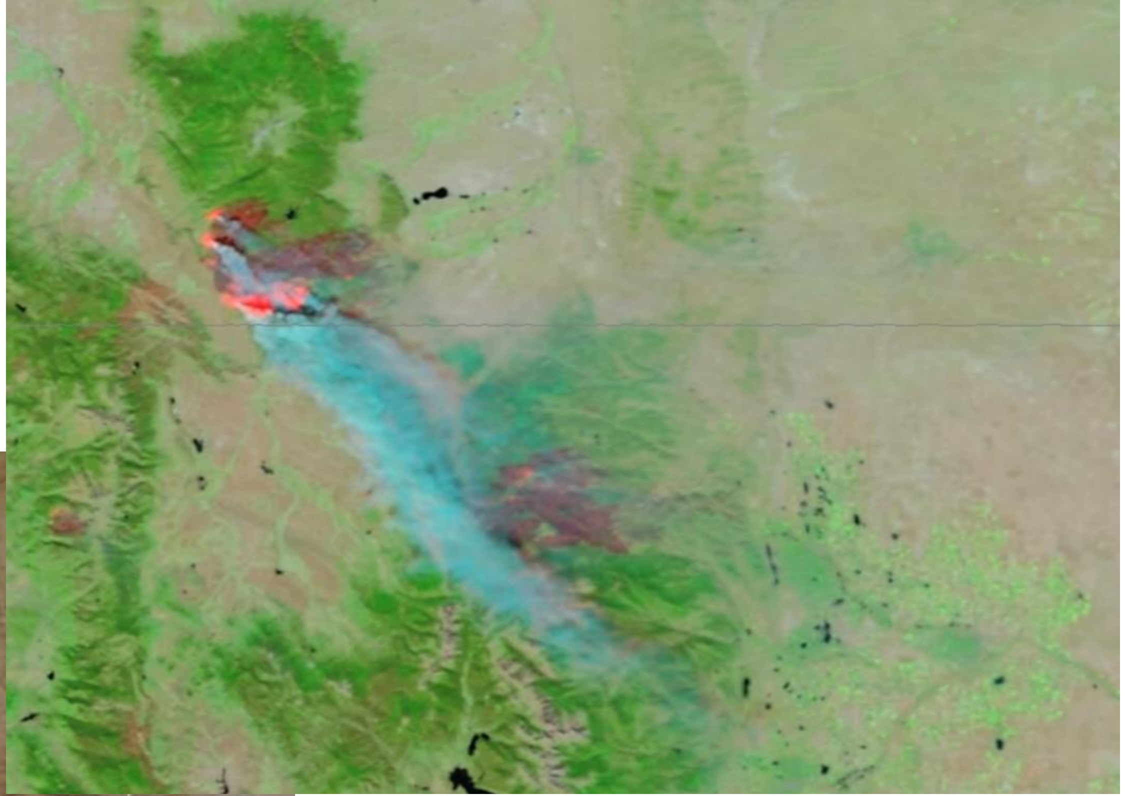
R: 1.6
G: 0.84
B: 0.64

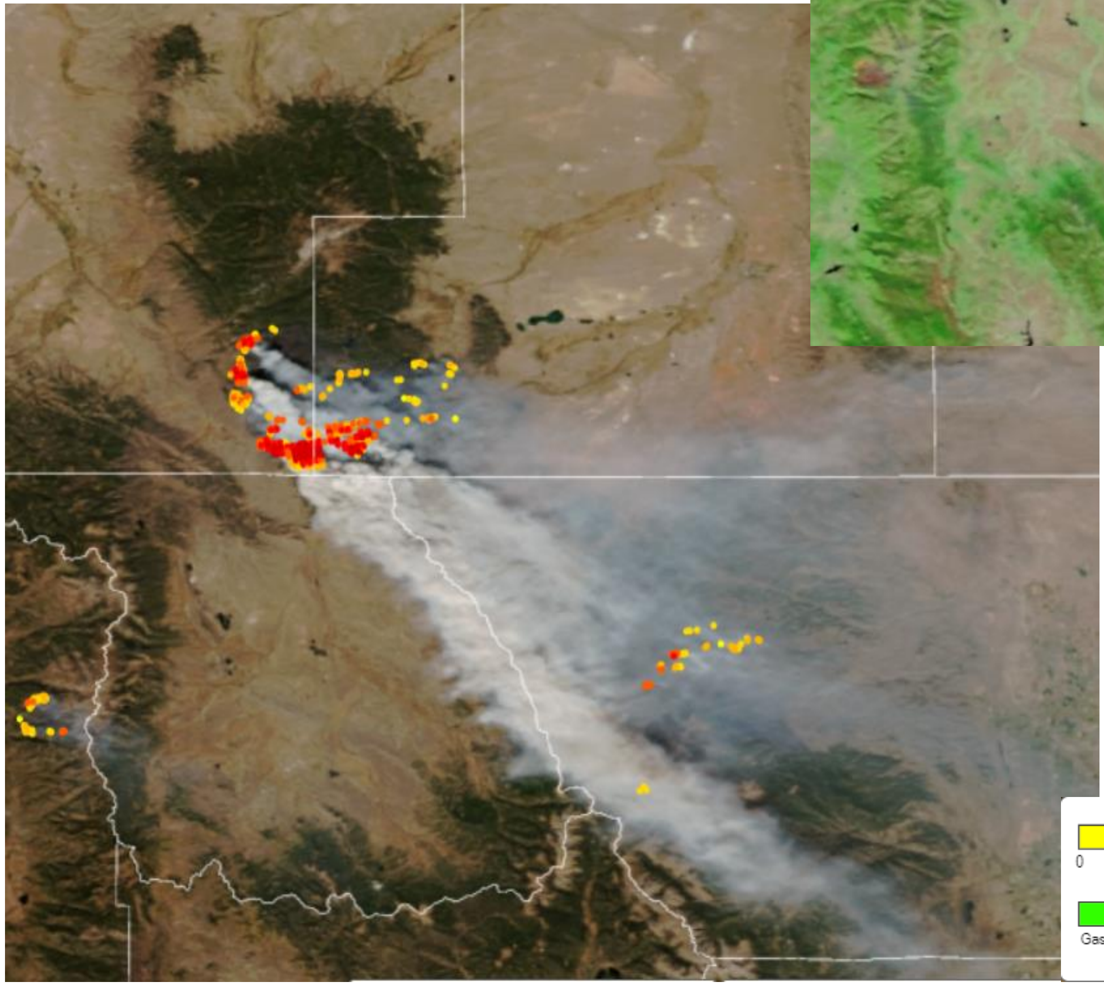
Natural color fire (band 1.6 replaced with 2.2)



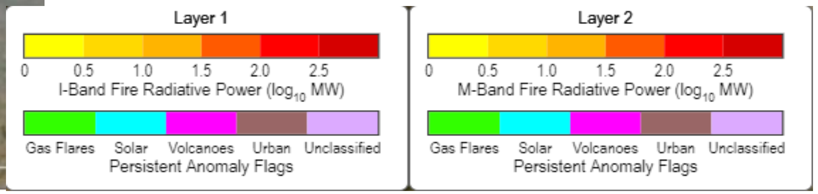
Day land cloud fire RGB using VIIRS (polar satelites)>>>

30 sep 2020
~20:15 UTC



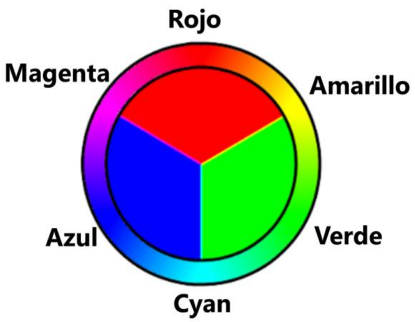


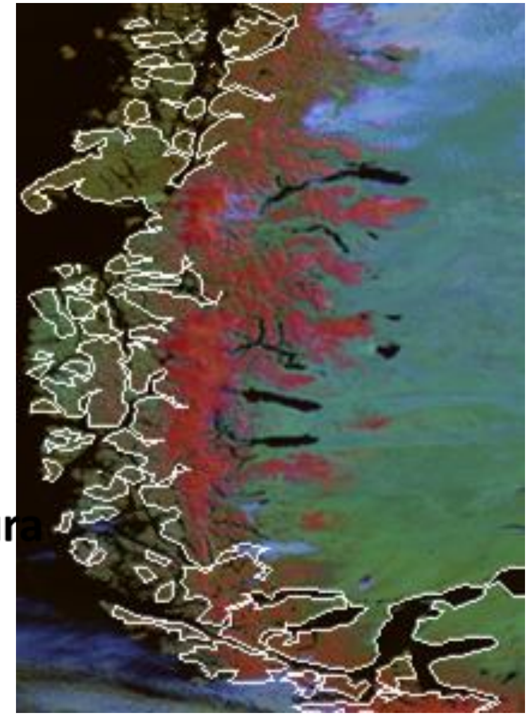
<<< True Color RGB, overlaid to Fire Radiative power, bands I and M. *Fuente JSTAR Mapper: https://www.star.nesdis.noaa.gov/jpss/mapper/*



RGB Day-Snow-Fog

Who is R, G and B?



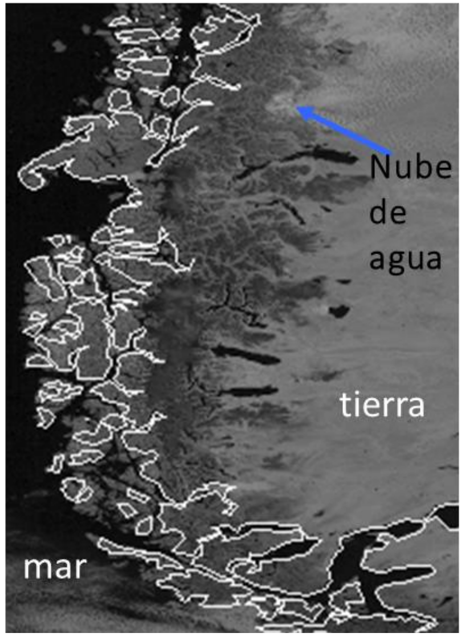


“RGB Nieve-niebla en el día”

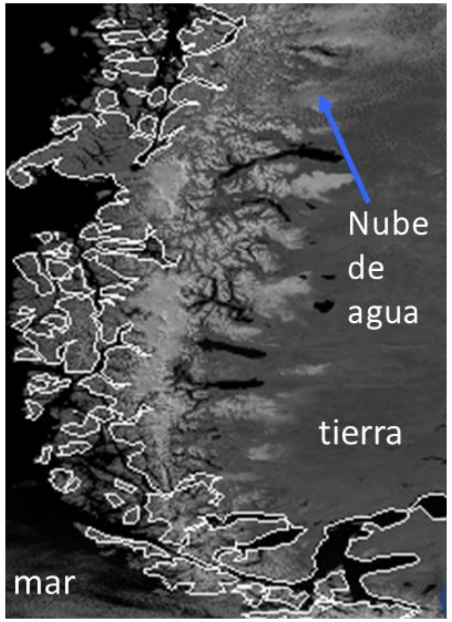
R:
G:
B:

* Un poco diferente de EUMETSAT y JMA

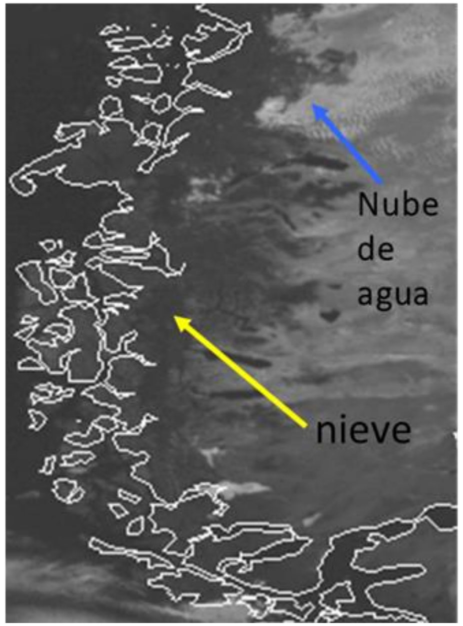
1.6 µm, IR cercano



0.86 µm, IR cercano

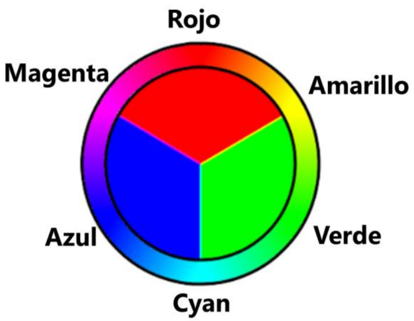


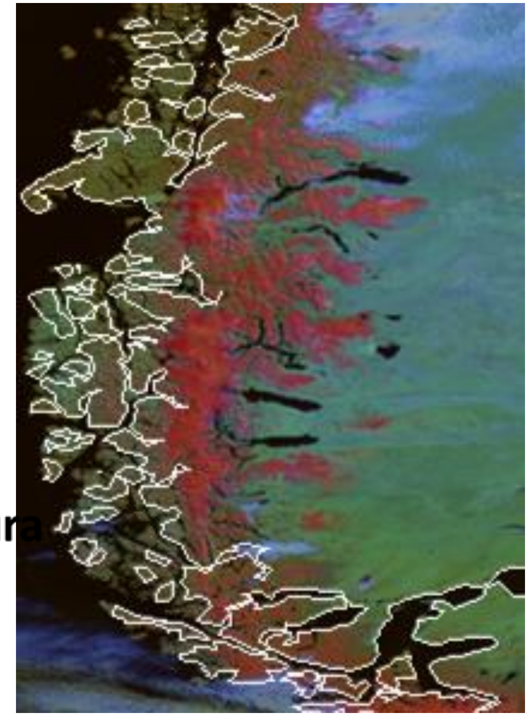
Diferencia de Temperatura de Brillo de 3.9-10.3µm



RGB Day-Snow-Fog

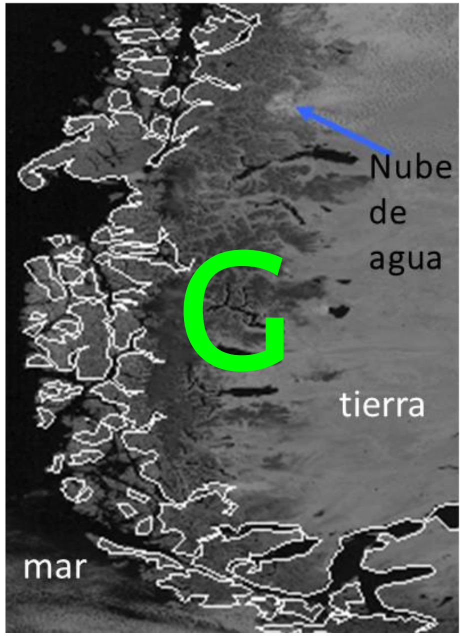
Quién es R, G y B?



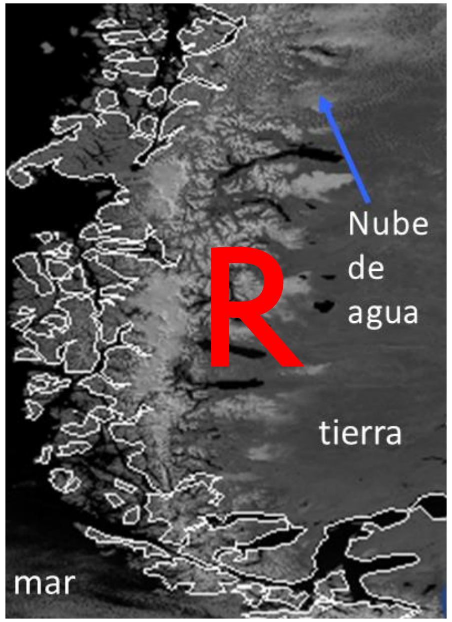


“RGB Nieve-niebla en el día”

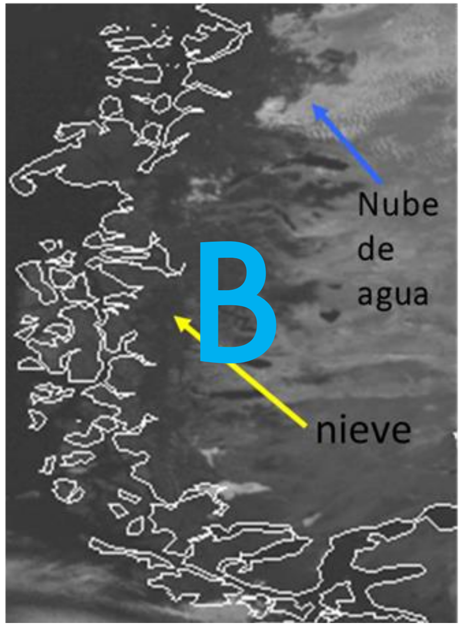
1.6 µm, IR cercano



0.86 µm, IR cercano



Diferencia de Temperatura de Brillo de 3.9-10.3µm



R: 0.86 µm
G: 1.61 µm
B: BTD 3.9-10.3

* Un poco diferente de EUMETSAT y JMA

Some RGBs what work during daytime and both day and night

Reflexión — Emisión (Infrarrojas)

Spectrum	Visible		Near IR				SW IR	Water Vapor			SO2	O3	Long Wave IR			CO2
Band ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Central Wavelength	.47	.64	.86	1.3	1.6	2.2	3.9	6.2	6.9	7.3	8.5	9.6	10.3	11.2	12.2	13.3
RGBs THAT ONLY WORK WITH DAYLIGHT																
Day Convection or Severe Storm		■			■		■	■		■			■			
Day Cloud Phase Distinction		■			■								■			
Day Cloud Phase Distinction CPTEC		■			■	■										
Day Microphysics			■				R						■			
Day land cloud or Natural Colors		■	■			■										
Day Snow Fog			■		■		■						■			
GeoColor Day	■	■	■													
RGBs THAT ONLY WORK WITHOUT DAYLIGHT																
Night Microphysics							■						■		■	
Night Fog and Geocolor Night							■						■			

RGBs that work all day

- Since they do not rely on solar reflexion

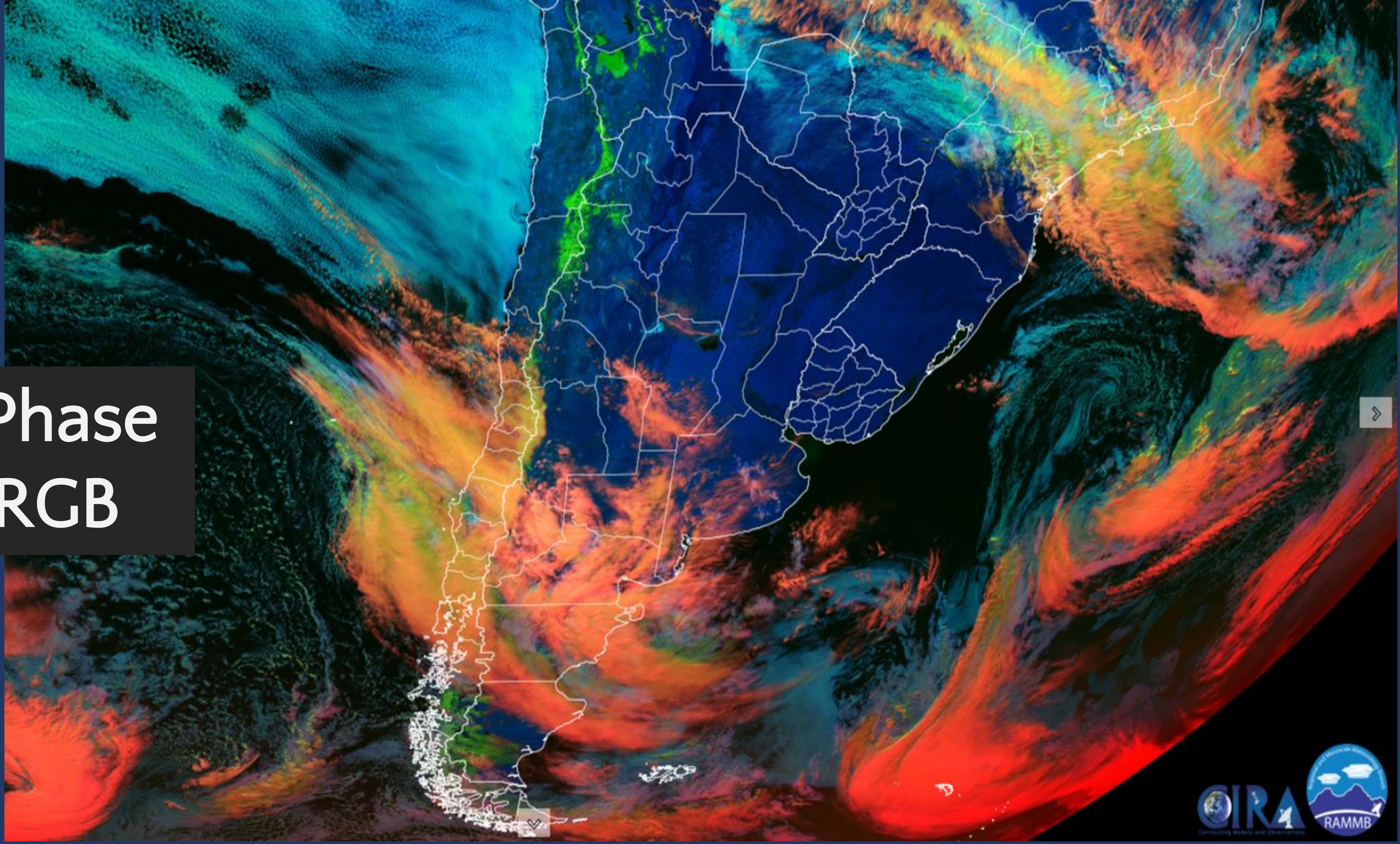
Reflexión | Emisión (Infrarrojas)

Spectrum	Visible		Near IR				SW IR	Water Vapor			SO2	O3	Long Wave IR			CO2
Band ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Central Wavelength	.47	.64	.86	1.3	1.6	2.2	3.9	6.2	6.9	7.3	8.5	9.6	10.3	11.2	12.2	13.3
Air Mass								■		■		■	■			
Differential Water Vapor								■		■						
Dust											■		■	■	■	
Ash											■		■	■	■	
SO2									■	■	■		■			

05

Satellite detection of weather systems with emphasis in convection

Day Cloud Phase Distinction RGB



Guía Rápida:
http://rammb.cira.colostate.edu/training/rmtc/docs/QuickGuides/QuickGuide_DayCloudPhaseDistinctionRGB_es.pdf

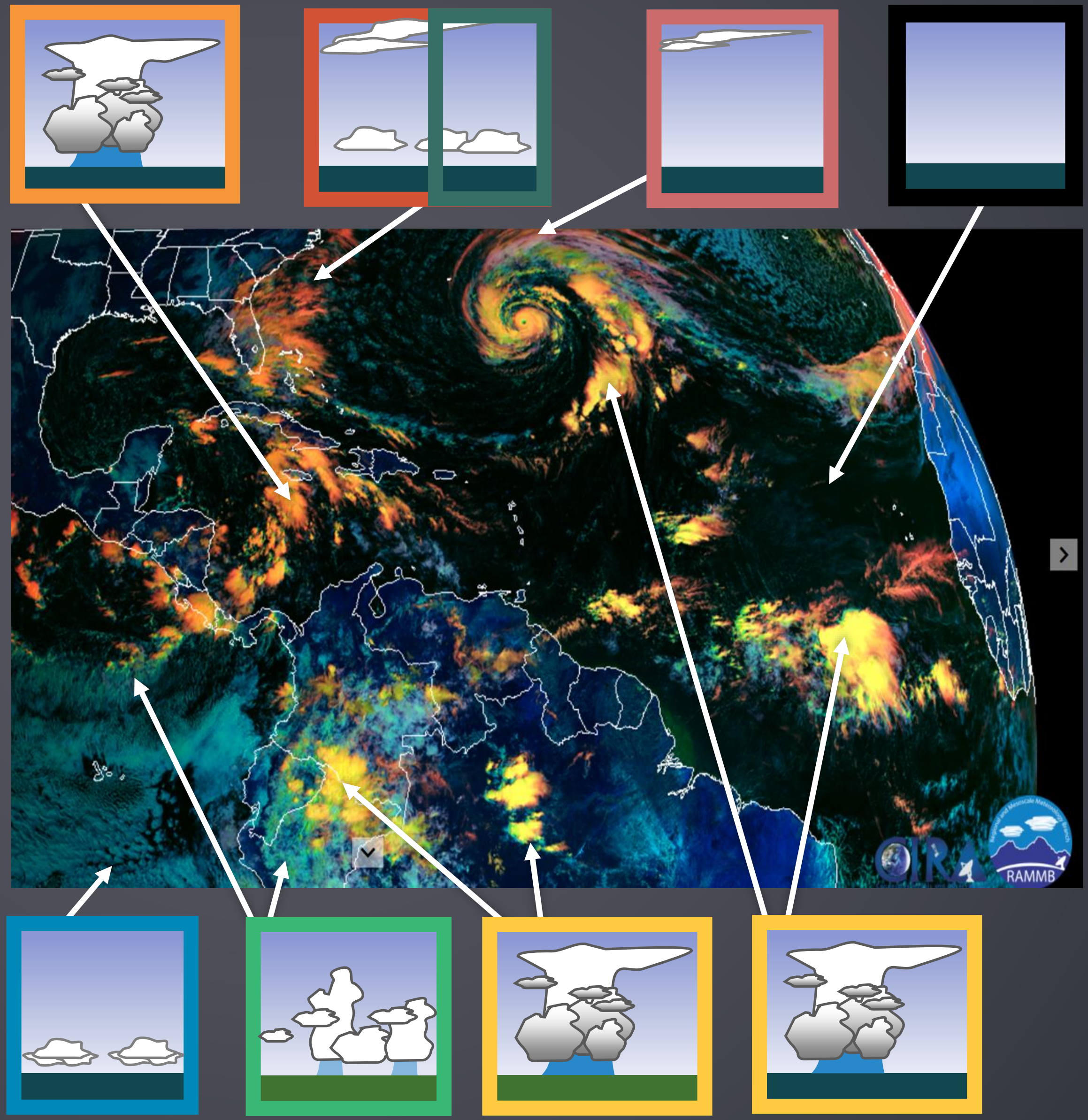
Day Cloud Phase Distinction RGB

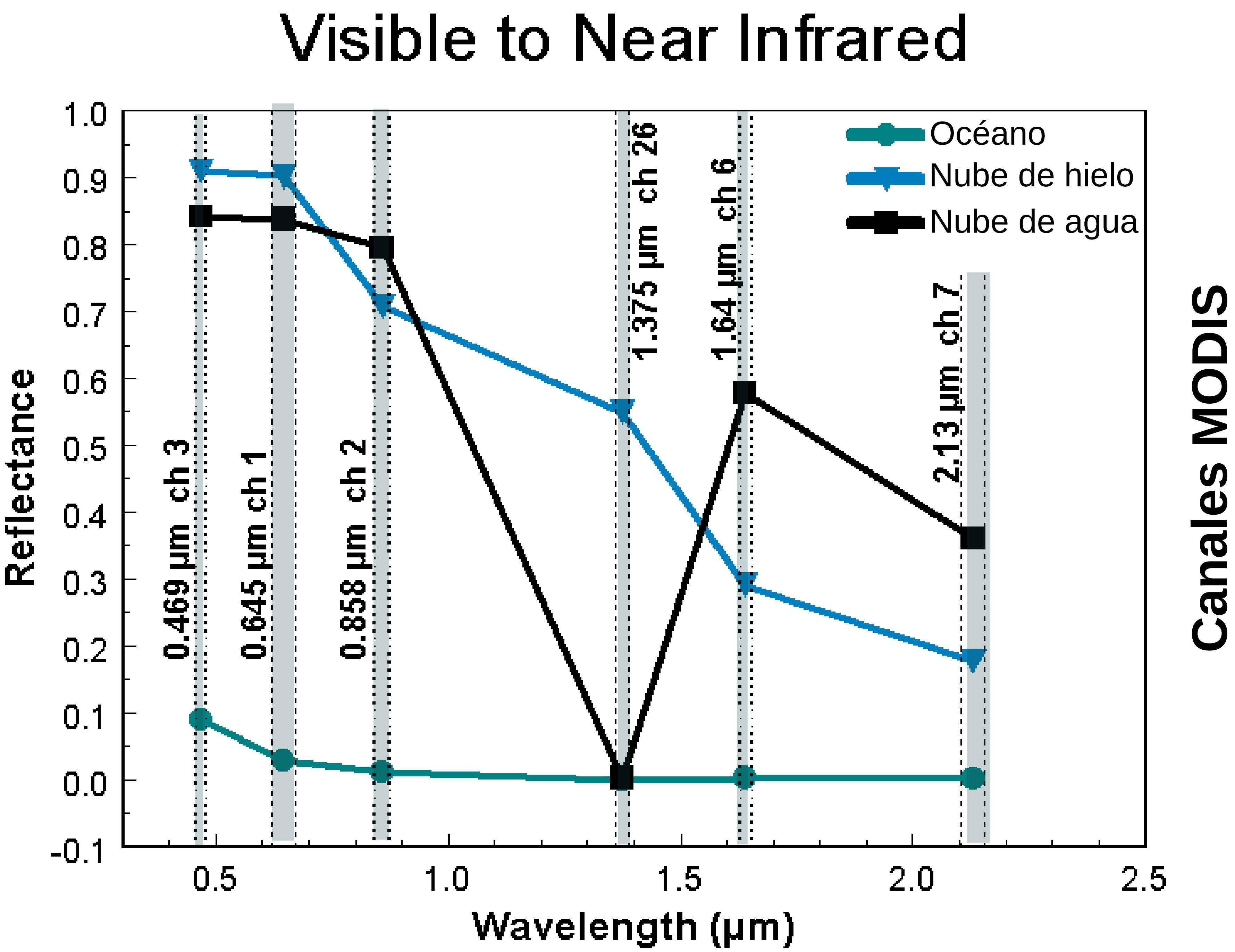
Objective

Distinguish between liquid vs ice in clouds with applications to severe weather, glaciation, heavy rainfall and evaluation of convective initiation.

R: 10.3um (atmospheric window in the long wave IR), great estimation of cloud top temperatures. Captures cold clouds (deep convection).

- G, B: They use two reflective channels, one of which highlights the presence of ice.

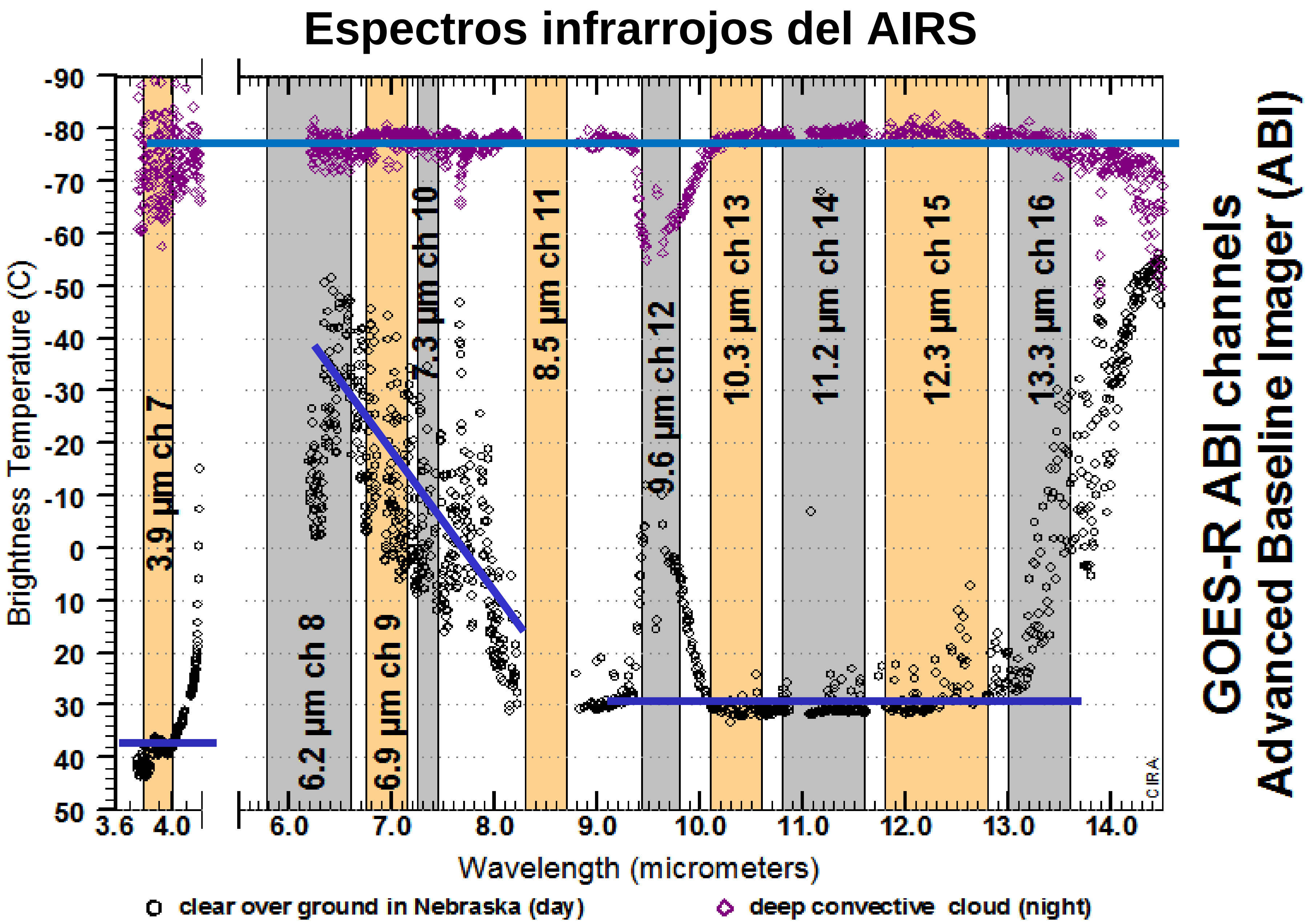




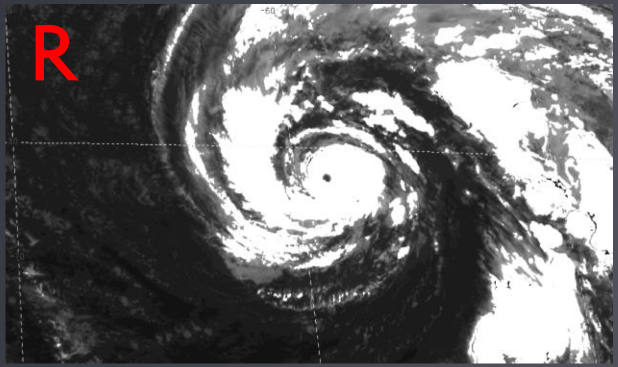
Visible to Near Infrared
Reflectance
Wavelength (μm)
Océano
Nube de hielo
Nube de agua
0.469 μm ch 3
0.645 μm ch 1
0.858 μm ch 2
1.375 μm ch 26
1.64 μm ch 6
2.13 μm ch 7
Canales MODIS
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0.5
1.0
1.5
2.0
2.5

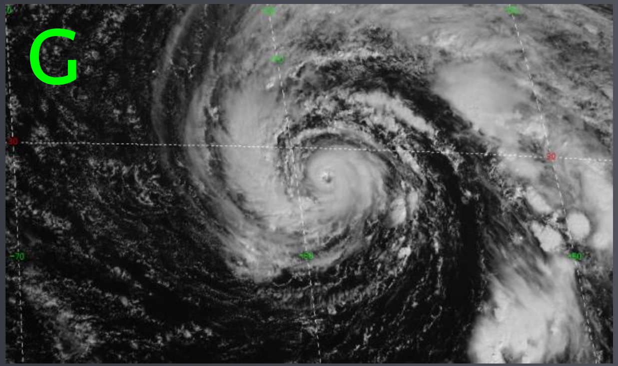
Brightness Temperature Spectra

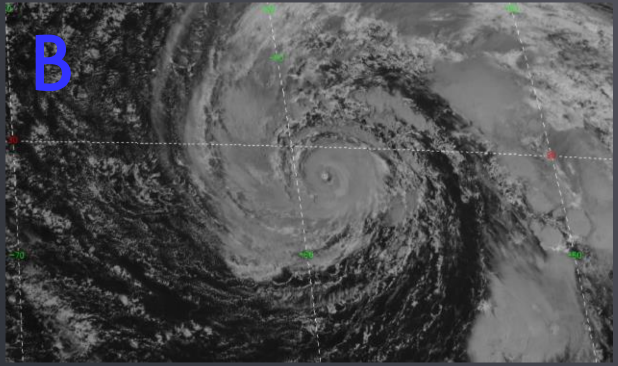
launch 2016



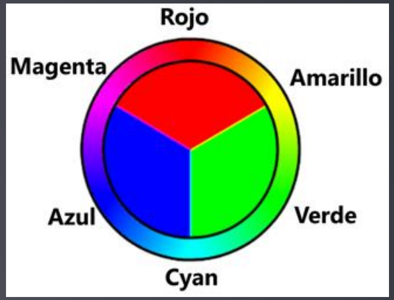
Day Cloud Phase Distinction RGB

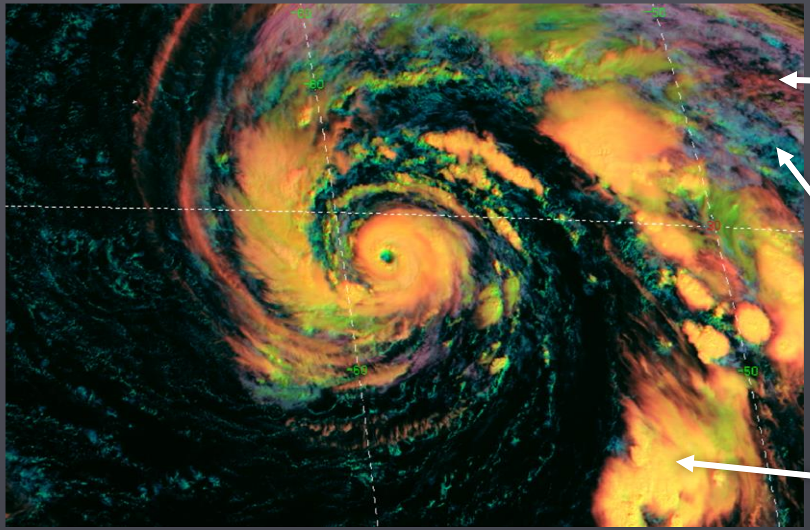






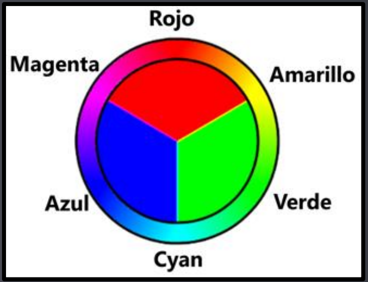
Color	Long de onda (µm) [Banda]	Mín a máx Gamma
R- rojo	10.3 [13]	7.5 a -53.5°C 1
G- verde	0.64 [2]	0 a 78 % albedo 1
B- azul	1.6 [5]	1 a 59 % albedo 1

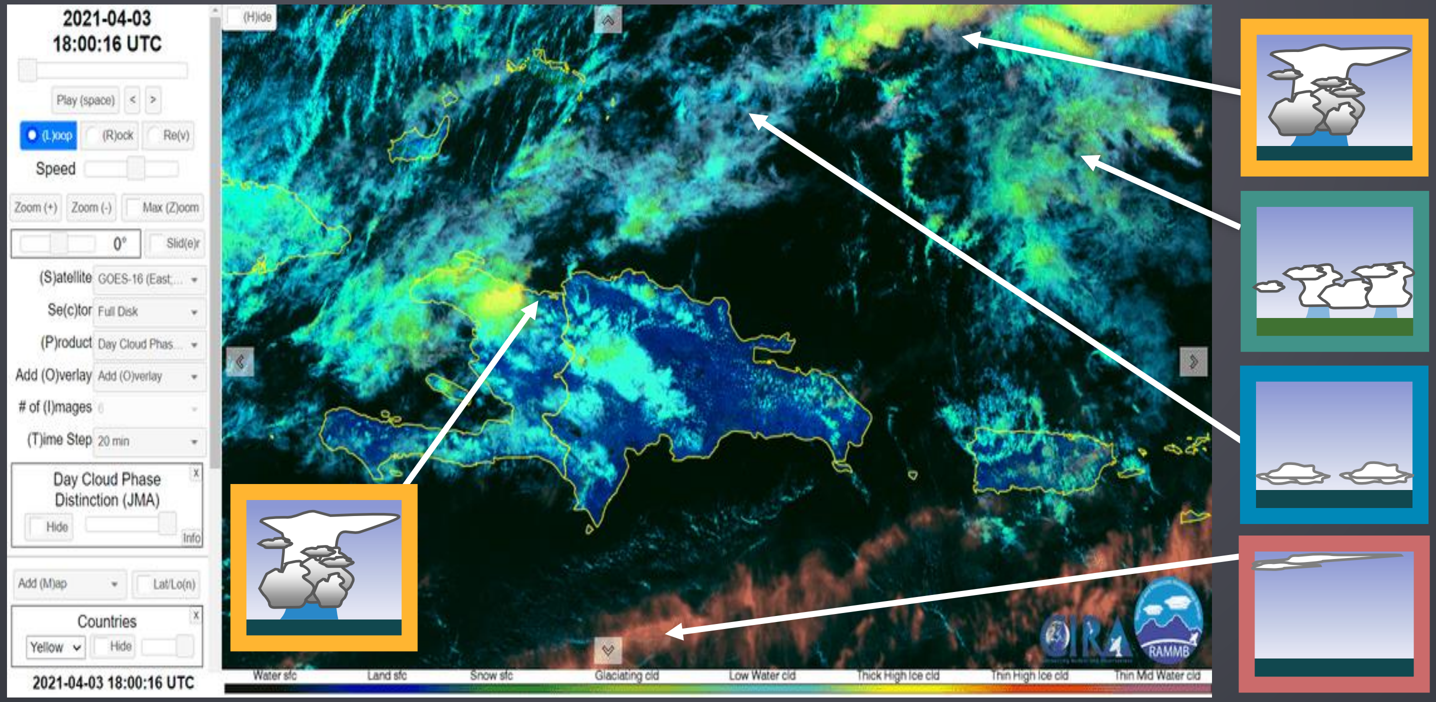




RGB de Distinción de Fase de Nube de Día

Color	Long de onda (µm) [Banda]	Mín a máx Gamma	Se relaciona físicamente con…	Aporte pequeño a píxeles indica…	Aporte grande a píxeles indica…
R- rojo	10.3 [13]	7.5 a -53.5°C 1	Temperatura de la superficie o el tope de la nube	Caliente: tierra (estacional), océano	Frío: suelo (invierno), nieve, nubes altas
G- verde	0.64 [2]	0 a 78 % albedo 1	Reflectancia de las nubes y superficies	Agua, vegetación, suelo, océano	Nube, nieve, arena blanca
B- azul	1.6 [5]	1 a 59 % albedo 1	Reflectancia, fase de las partículas	Partículas de hielo, océano	Partículas de agua, superficie del suelo

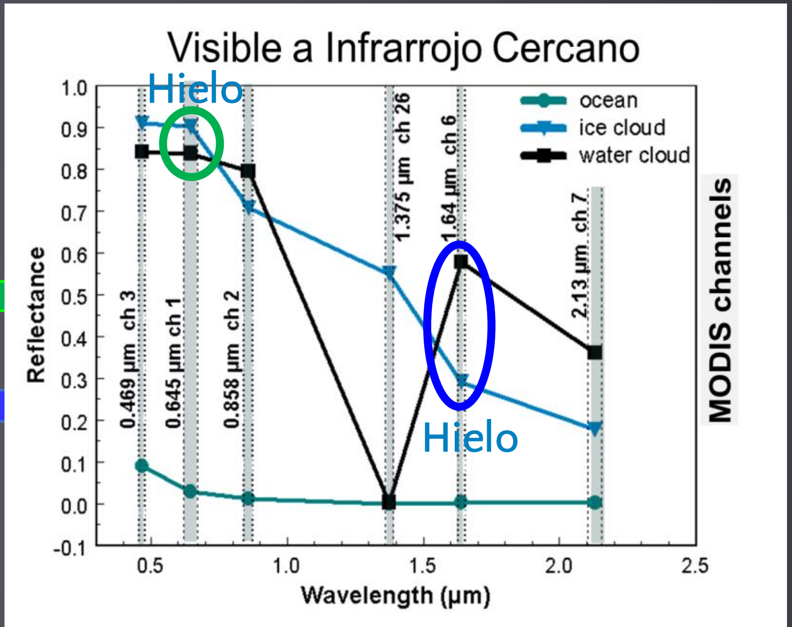


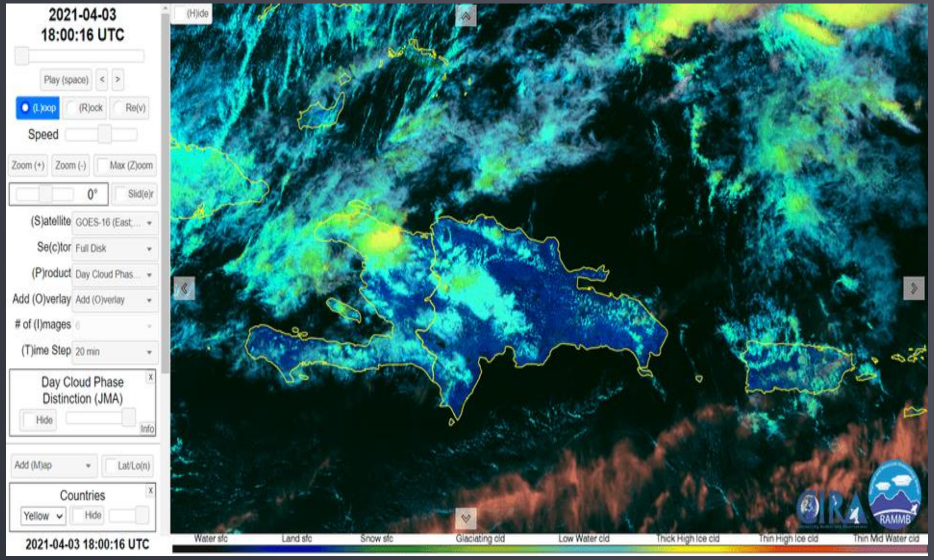


Differentiation of ice vs water in clouds

Color	Long de onda (µm) [Banda]	Mín a máx Gamma
R- rojo	10.3 [13]	7.5 a -53.5°C 1
G- verde	0.64 [2]	0 a 78 % albedo 1
B- azul	1.6 [5]	1 a 59 % albedo 1

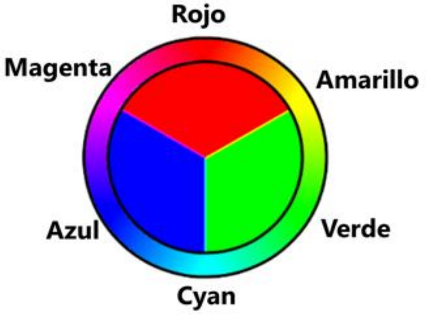
Rojo = Nubes frías (hielo)

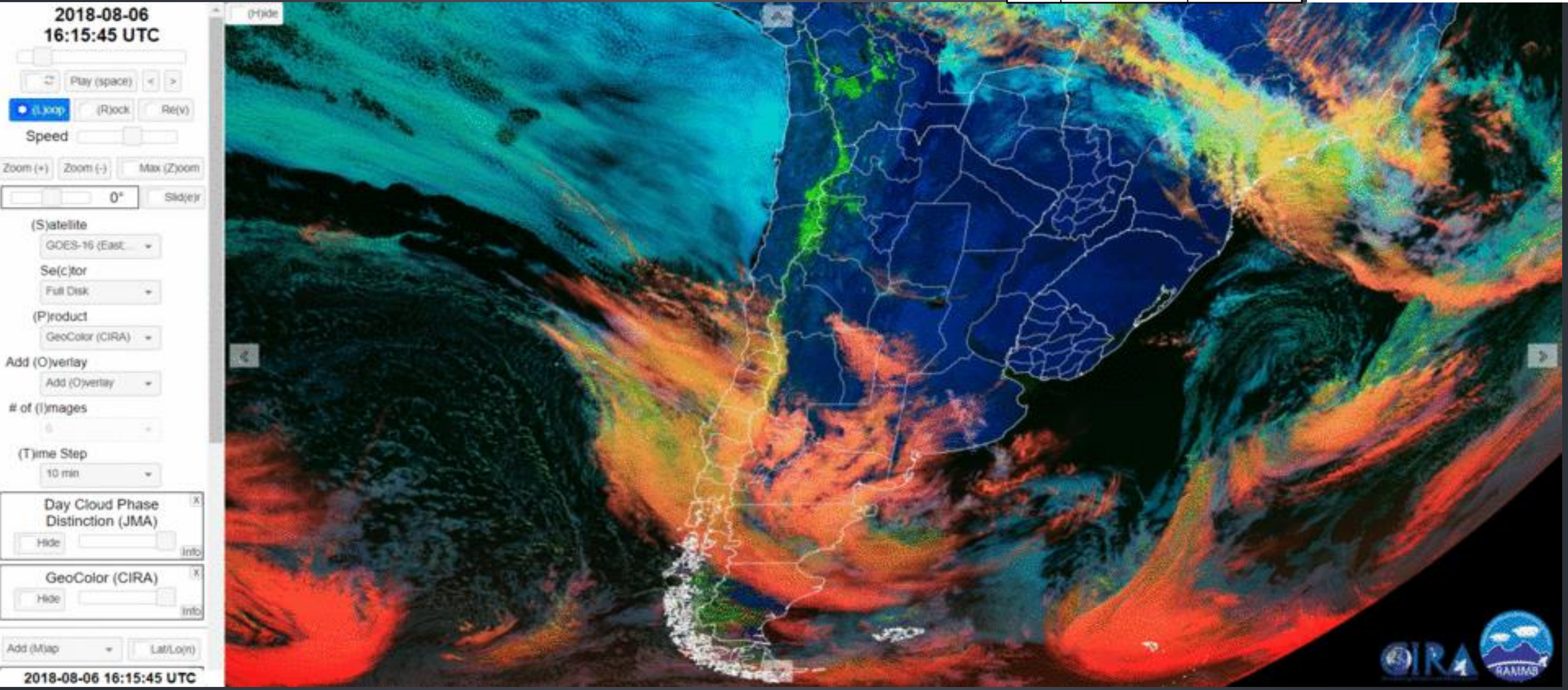




Exercise: Evaluate Cloud Types

Color	Long de onda (µm) [Banda]	Mín a máx Gamma
R-rojo	10.3 [13]	7.5 a -53.5°C 1
G-verde	0.64 [2]	0 a 78 % albedo 1
B-azul	1.6 [5]	1 a 59 % albedo 1

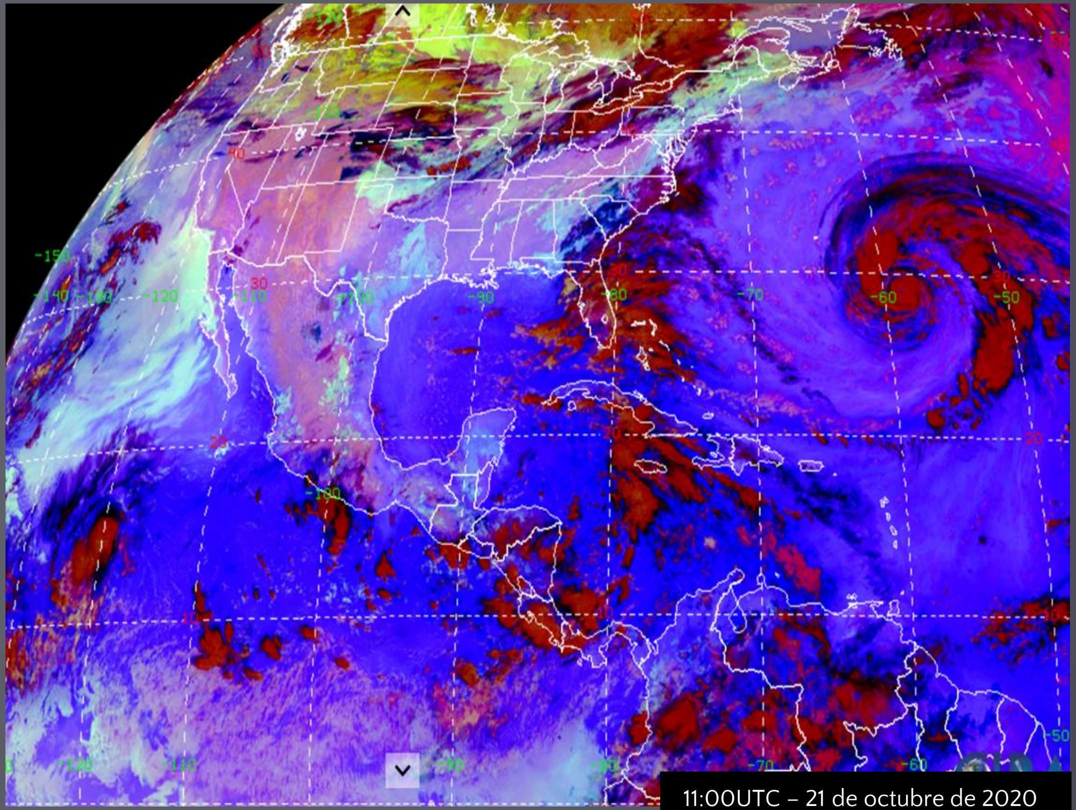




Nighttime Microphysics RGB

Objective

- Improve the detection of cloud types and processes during night, especially for the detection of low clouds and fog
- 10.3 – 3.9 um difference helps to detect water vs ice clouds, highlighting low clouds in cyan/white.
- Note that all channels used are IR, so they work all night long: 3.9, 10.3 and 12.3um



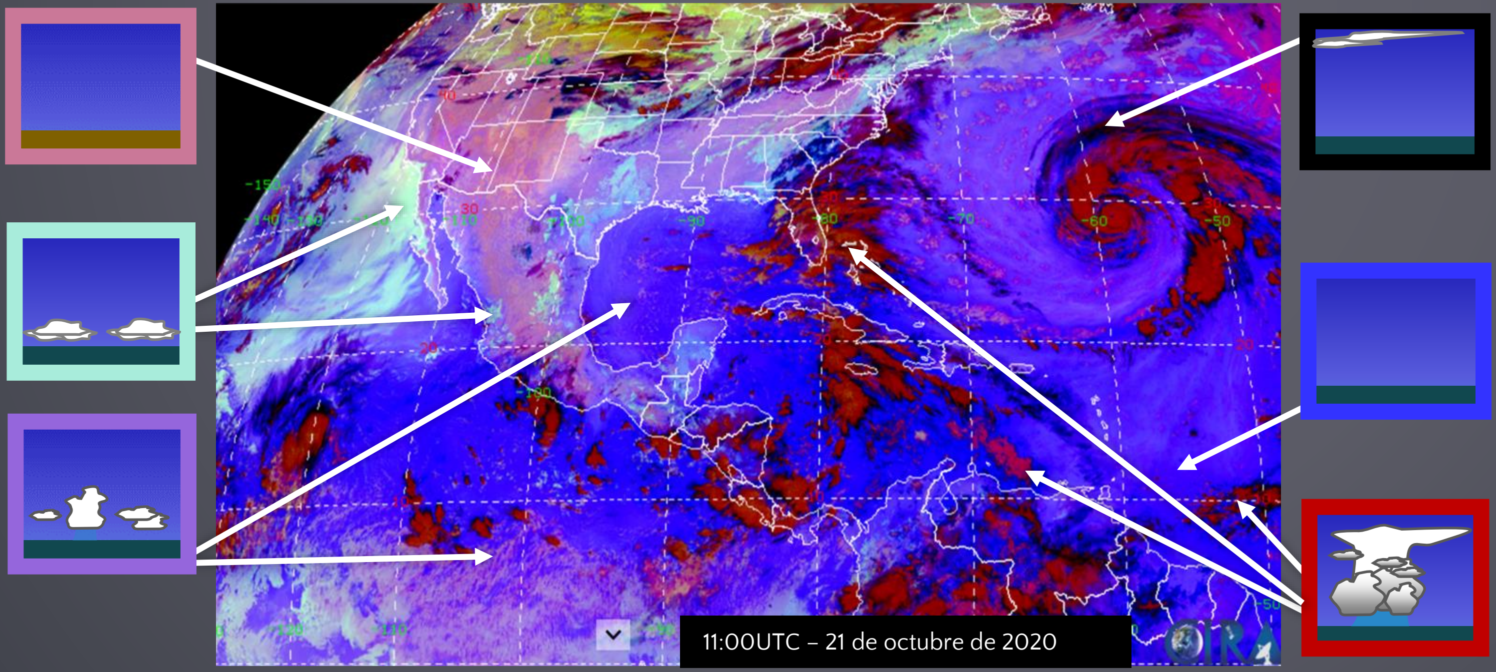
11:00UTC – 21 de octubre de 2020

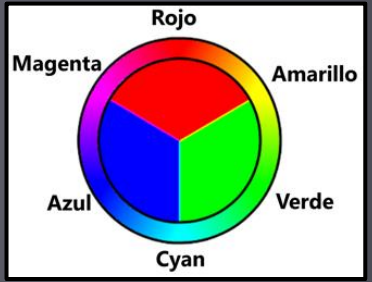
Nighttime Microphysics RGB

Fórmula del producto RGB Microfísica Nocturna

(**Nota:** las nubes opacas constituyen la mejor aplicación. Las nubes semitransparentes sienten la influencia de las superficies subyacentes.)

Color	Banda / Resta de bandas (µm)	Rango (mín. – máx.)	Se relaciona físicamente con...	Aporte pequeño a píxeles indica...	Aporte grande a píxeles indica...
R - rojo	12.3-10.3	-6.7 a 2.6 °C	Profundidad óptica	Nubes delgadas	Nubes gruesas
G - verde	10.3-3.9	-3.1 a 5.2 °C	Fase y tamaño de las partículas	Partículas de hielo; superficie (sin nubes)	Nubes de agua con partículas pequeñas
B - azul	10.3	-29.6 a 19.5 °C	Temp. de la superficie	Superficies frías	Superficies cálidas



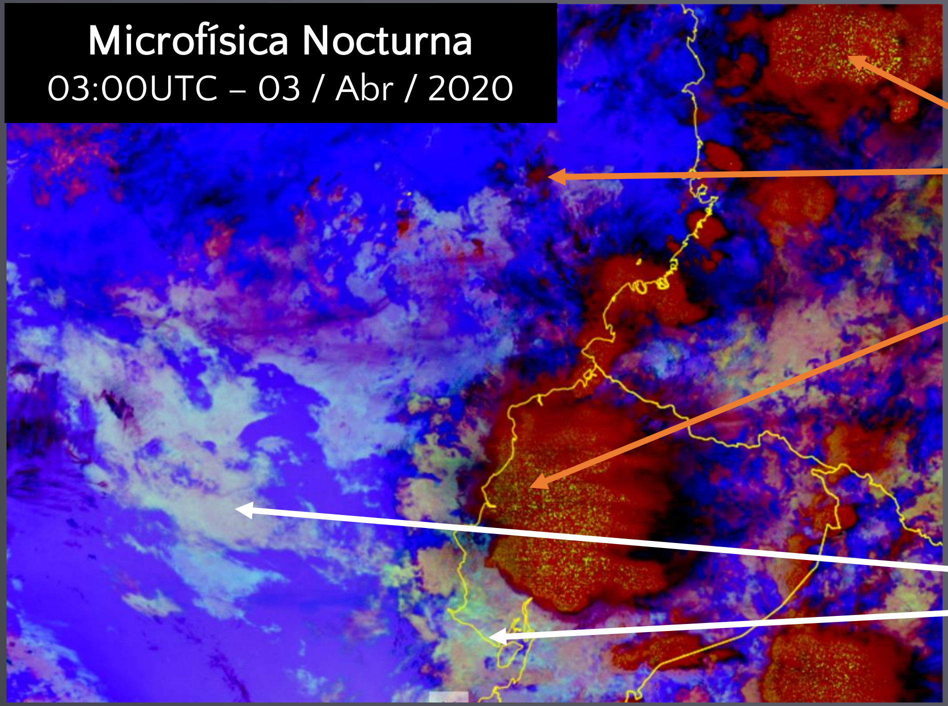


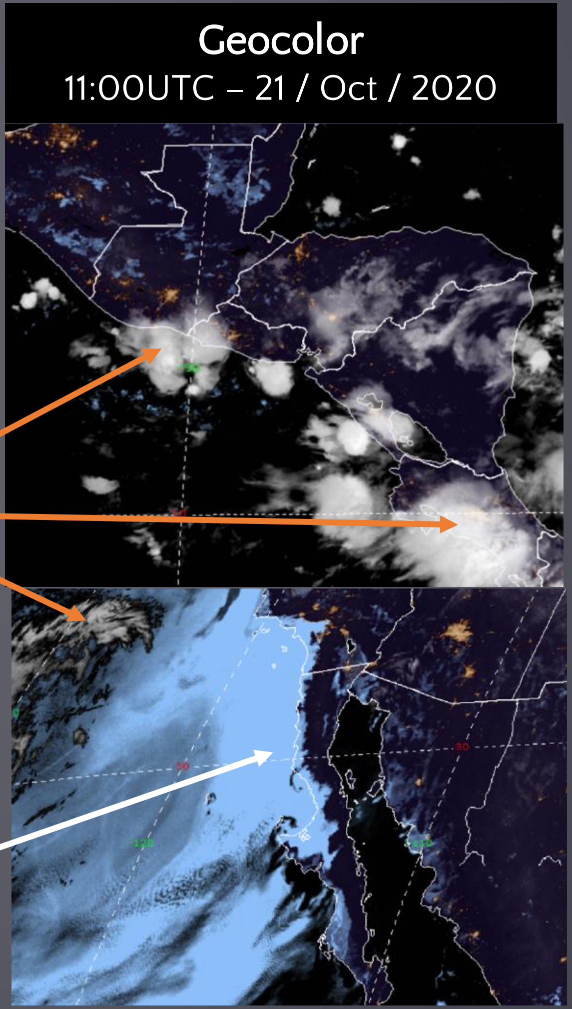
Ice vs water clouds

(3.9 - 10.3um Difference)

Liquid vs ice clouds produce different radiative signals at 3.9 and 10.3um, so differentiating them allows to determine the type of cloud.

This difference is used in the Geocolor and in the Nighttime Microphysics RGB





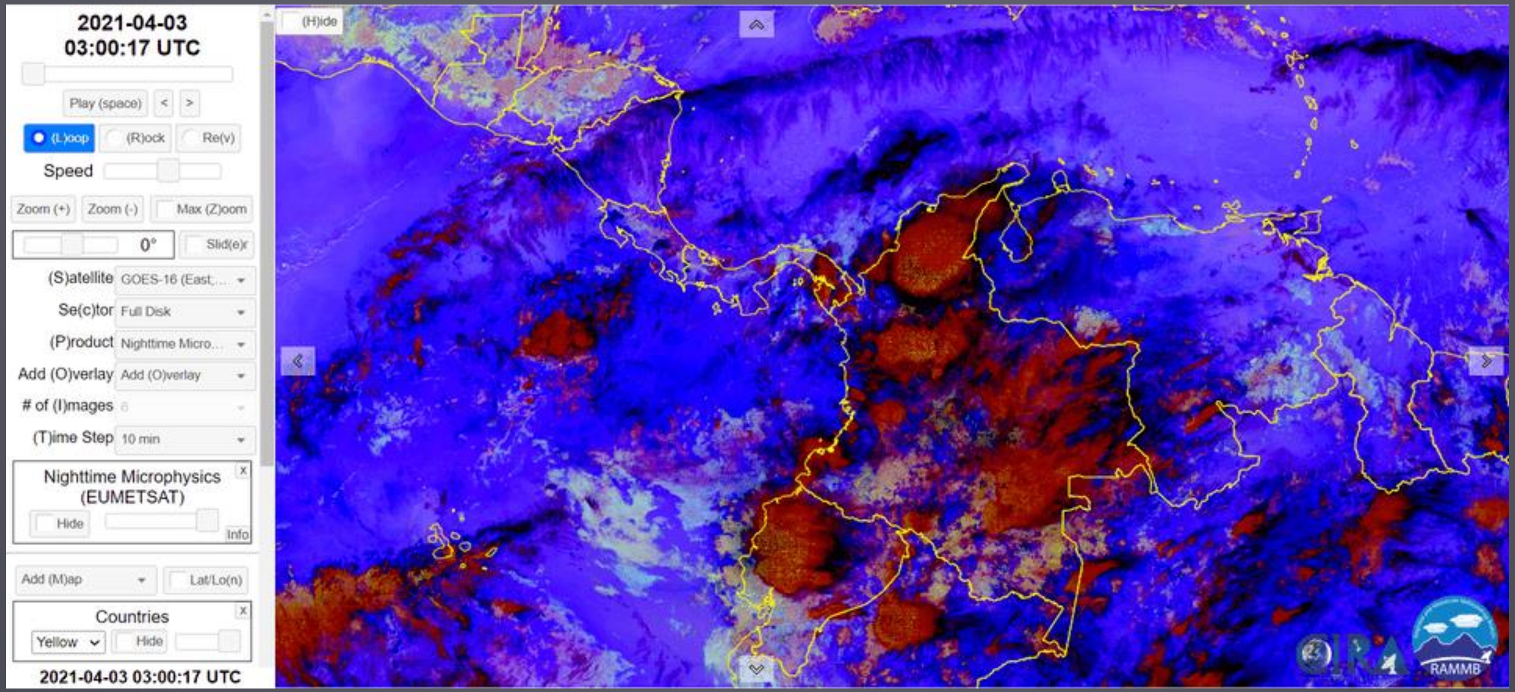
Nighttime Microphysics RGB

Color	Banda / Resta de bandas (µm)	Rango (mín. – máx.)	Se relaciona físicamente con...
R - rojo	12.3-10.3	-6.7 a 2.6 °C	Profundidad óptica
G - verde	10.3-3.9	-3.1 a 5.2 °C	Fase y tamaño de las partículas
B - azul	10.3	-29.6 a 19.5 °C	Temp. de la superficie

Nubes gruesas
Nubes delgadas

Nubes de agua
Nubes de hielo

Cálido
Frio



06

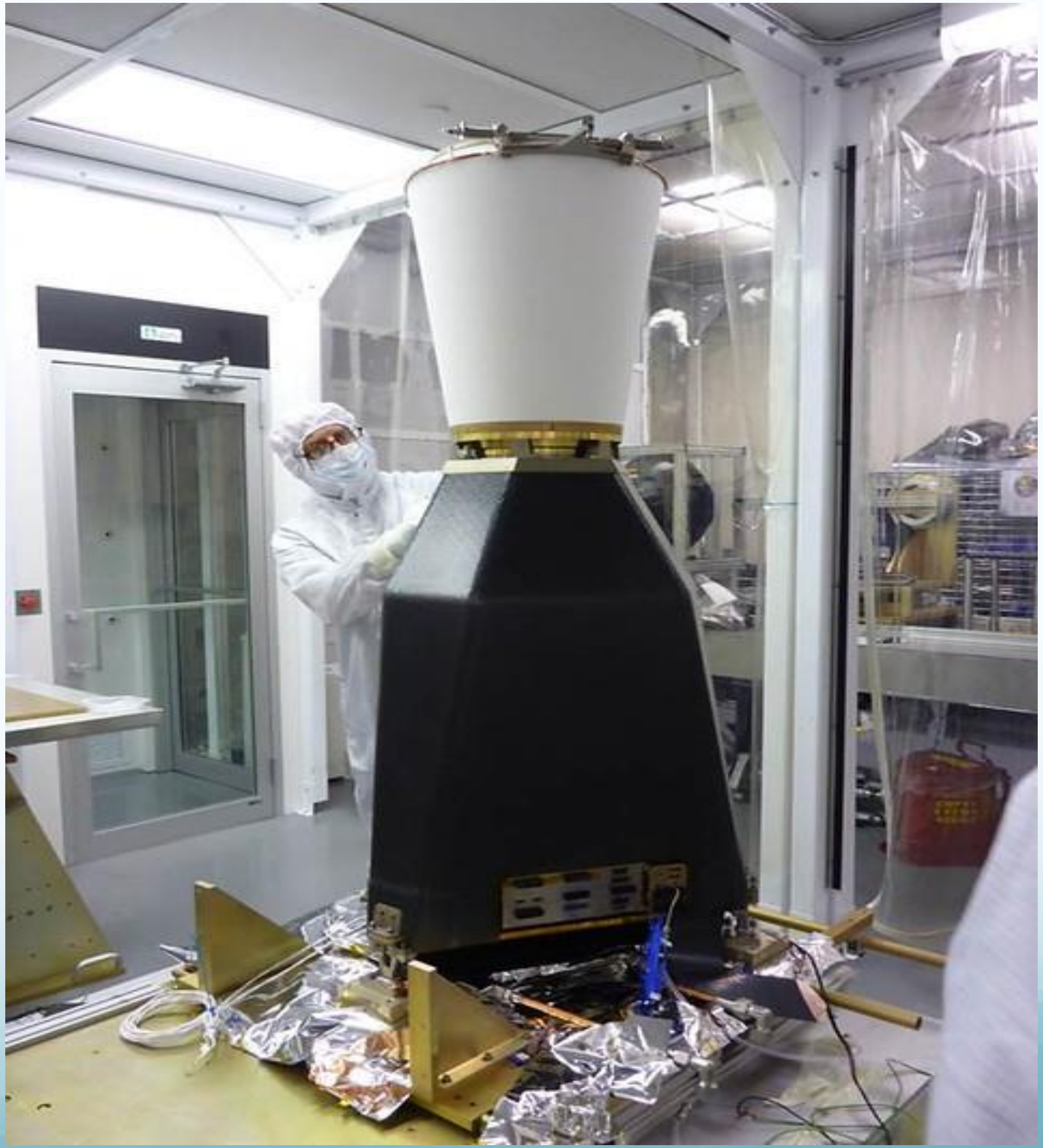
Geostationary Lightning Mapper (GLM)

Based on material prepared by
Dr. Jonathan Wynn Smith (UMD/ESSIC/CISESS)
Dr. Scott Rudlosky (NOAA/NESDIS/STAR)

ICAO

Geostationary Lightning Mapper (GLM) Training Outline

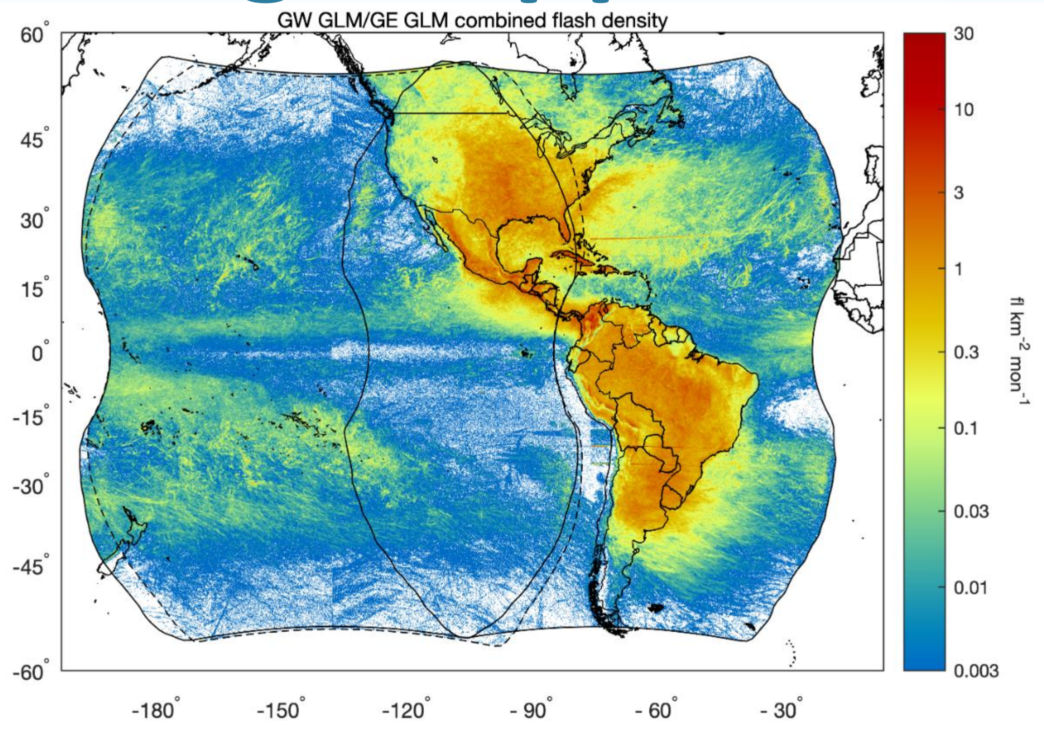
- What is Geostationary Lightning Mapper (GLM)?
- GLM Status
- GLM Level 2 Products
- GLM Gridded Products
  - Flash Extent Density
  - Average Flash Area
  - Minimum Flash Area
  - Total Optical Energy
- Where can we find GLM imagery?



GLM Pre-Launch

Geostationary Lightning Mapper

- **GLM on GOES-16/-17 is a narrow-band, near infrared (777.4 nm) imager that detects brightness changes at 500 frames/sec relative to a continuously updating background image**
- **Spatial resolution 8 km nadir / 14 km edge**
- **Provides continuous total lightning measurements to 54° N/S**
- **Observes total lightning – both intra-cloud and cloud-to-ground lightning, does not natively distinguish between them**
- **Instrument undergoing extended calibration and validation**
- **Filters remove non-lightning events, leaving only those most likely to be lightning**



Rudlosky and Virts (2020, MWR, Under review)

Performance Requirements
Detection efficiency > 70%, averaged over 24 hours within the full GLM domain
Flash false alarm rate shall be less than 5%, averaged over 24 hours
Navigation error within ~1/2 pixel or ~4 km

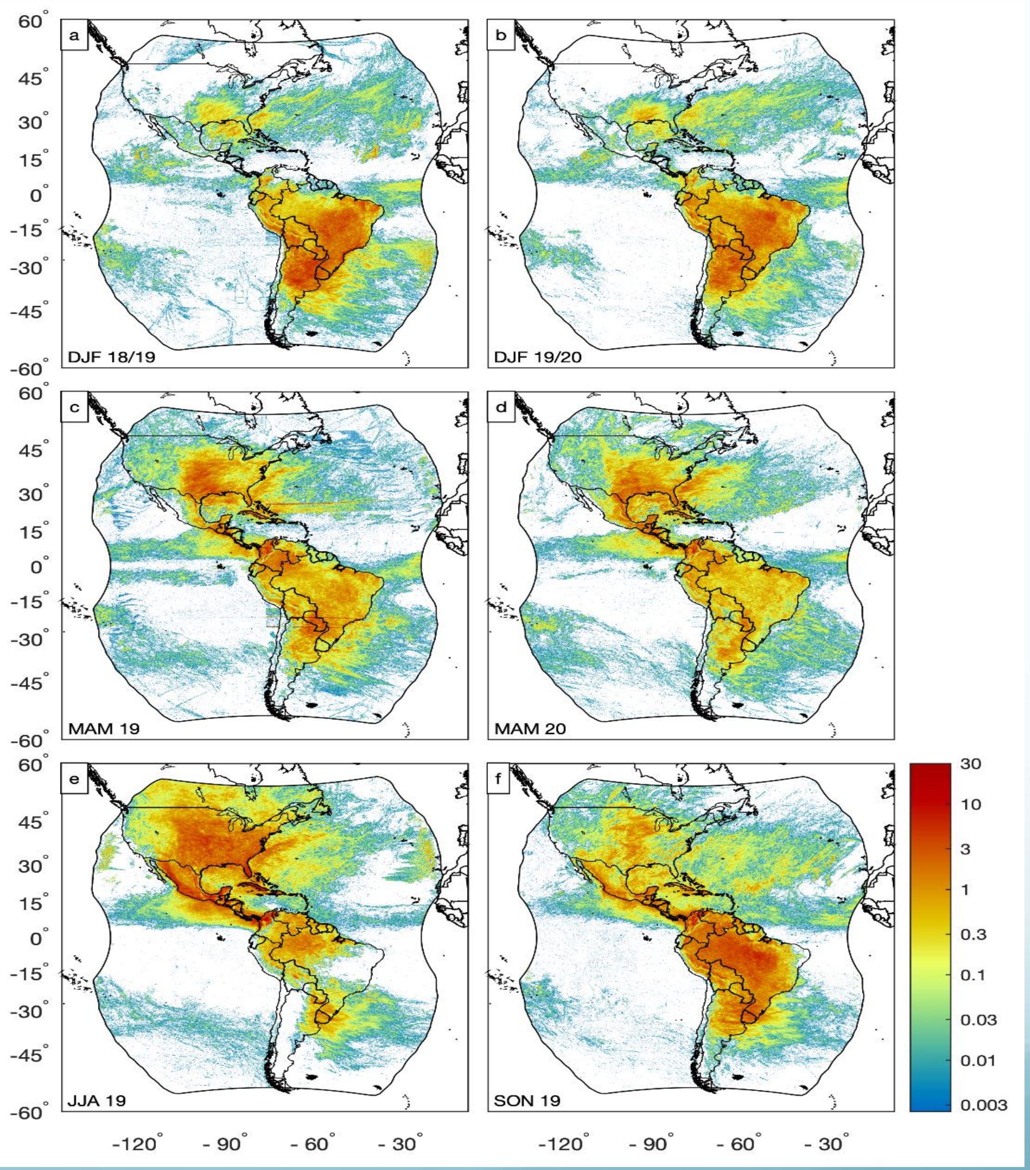
Seasonal Flash Densities Detected by GLM

- GLM flash densities
- Units: flash count per square kilometers per month
- Flash rate activity subsides over Costa Rica in December, January, February (DJF)
  - 0.01-1 flashes per square kilometers per month
- Flash rate activity peaks over Costa Rica in September, October, November (SON)
  - > 1 flashes per square kilometers per month
- March, April, May (MAM)
- June, July, August (JJA)

DJF 2018-19 | DJF 2019-20

MAM 2019 | MAM 2020

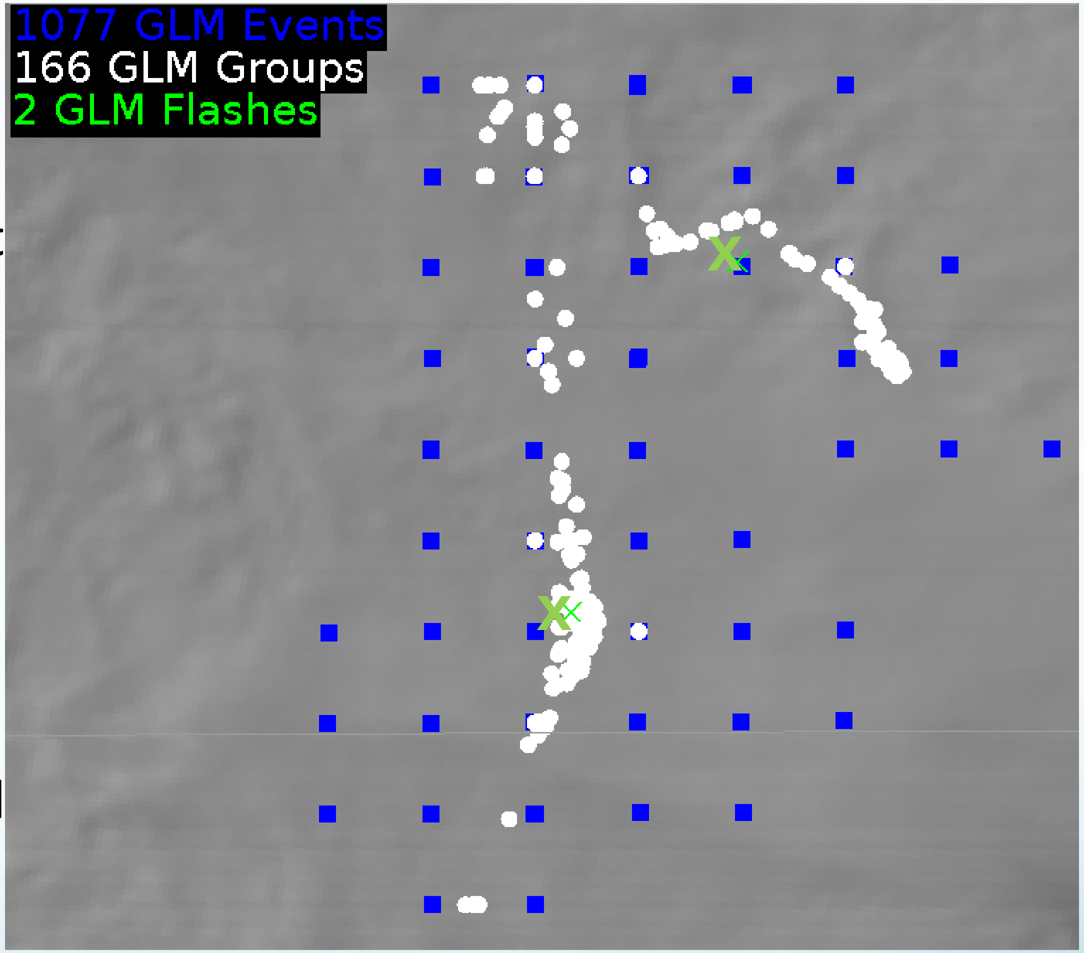
JJA 2019 | SON 2019



Rudlosky and Virts (2020, MWR, Under review)

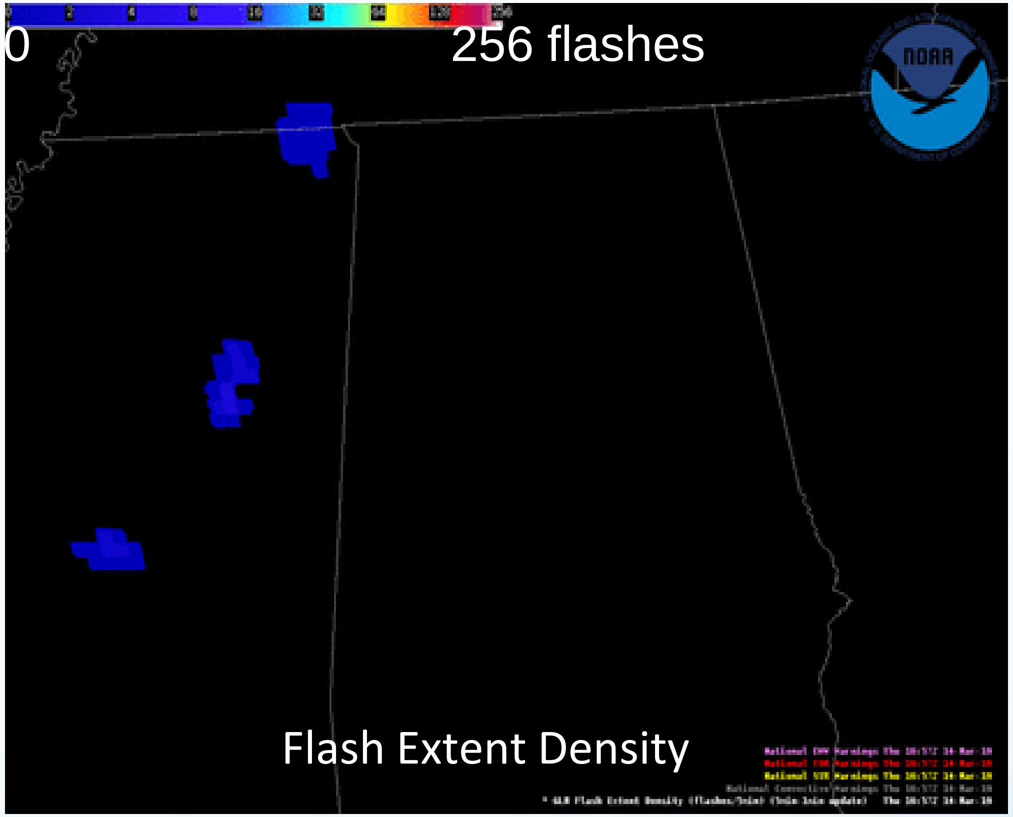
GLM Level 2 Definitions

- **<u>Event</u>:** occurrence of a single pixel exceeding the detection threshold during any one ~2 ms frame
  - To ensure the event is lightning lightning and not noise the first event in a flash is disregarded
  - No recursive pixel processing
- **<u>Group</u>:** one or more simultaneous GLM events observed in adjacent (neighboring/diagonal) pixels
- **<u>Flash</u>:** one or more sequential groups separated by less than 330 ms and 16.5 km
- **GLM flash rates are most closely tied to updraft and storm evolution, and GLM Event locations best depict the spatial extent**



GLM Gridded Products

- **GLM Level 2 data (events, groups, and flashes) are produced as point on a latitude/longitude grid, resulting in a loss of information concerning the spatial extent**
- **Gridded GLM products restore and disseminate the spatial footprint information while reducing file size**
- **Gridded GLM products involve re-navigating the GLM event latitude/longitude to the 2×2 km Advanced Baseline Imager fixed grid**
- **The broad spatial coverage and rapid temporal updates suggest the gridded GLM products will provide great value to broadcast meteorologists**
- **Gridded products created by Eric Bruning, Ph.D. of Texas Tech University**

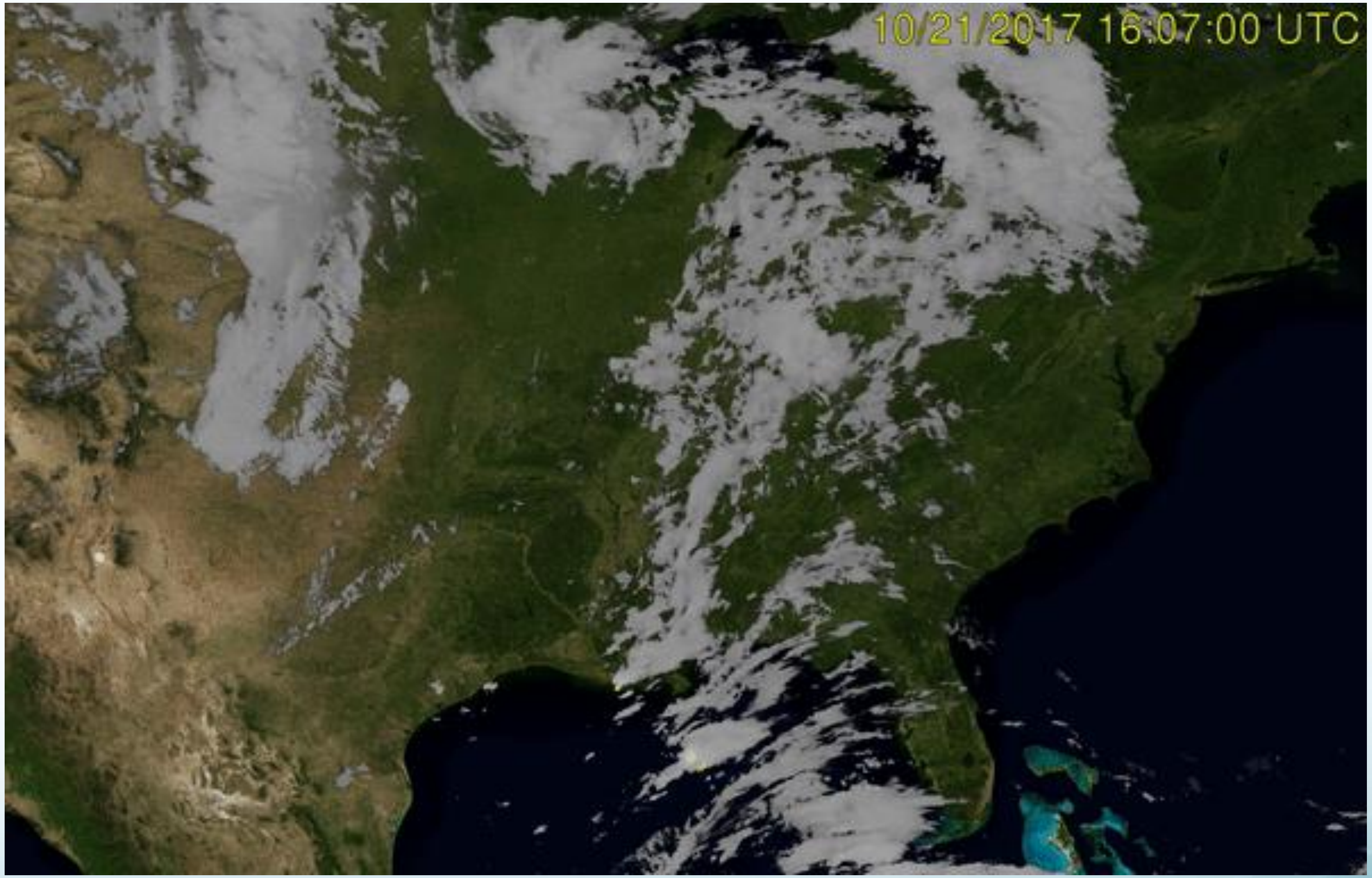


https://github.com/deeplycloudy/glmtools

Further explanation of grid creation: Bruning et al. (2020), Journal of Geophysical Research manuscript - *Meteorological Imagery for the Geostationary Lightning Mapper*

GLM Applications Allows Forecasters To . . .

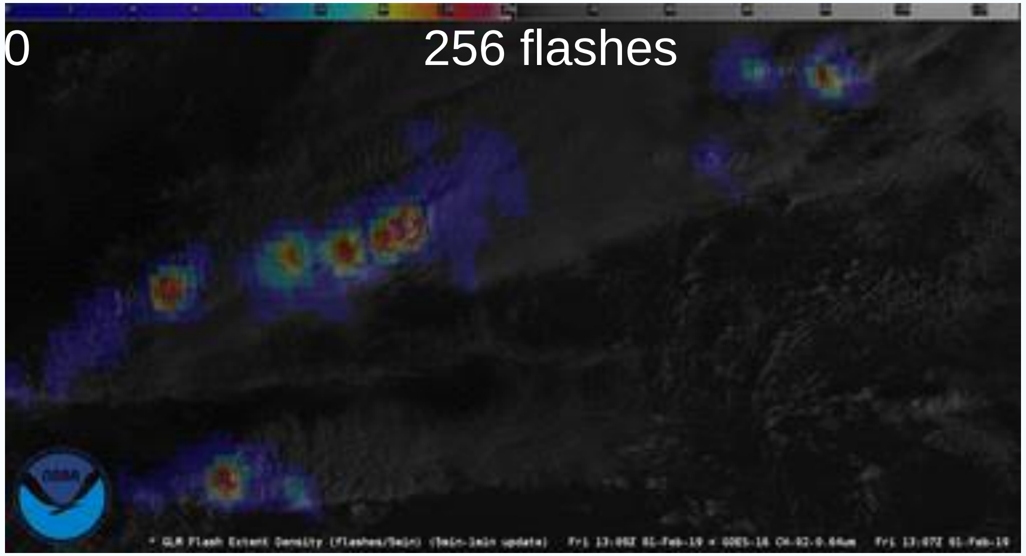
- **Track embedded convection**
- **Identify strengthening and weakening storms**
- **Observe the areal extent and propagation of the flash over time**
- **Monitor convective mode and storm evolution**
- **Characterize storms as they transition offshore**
- **Gain insights into tropical cyclone intensity changes**

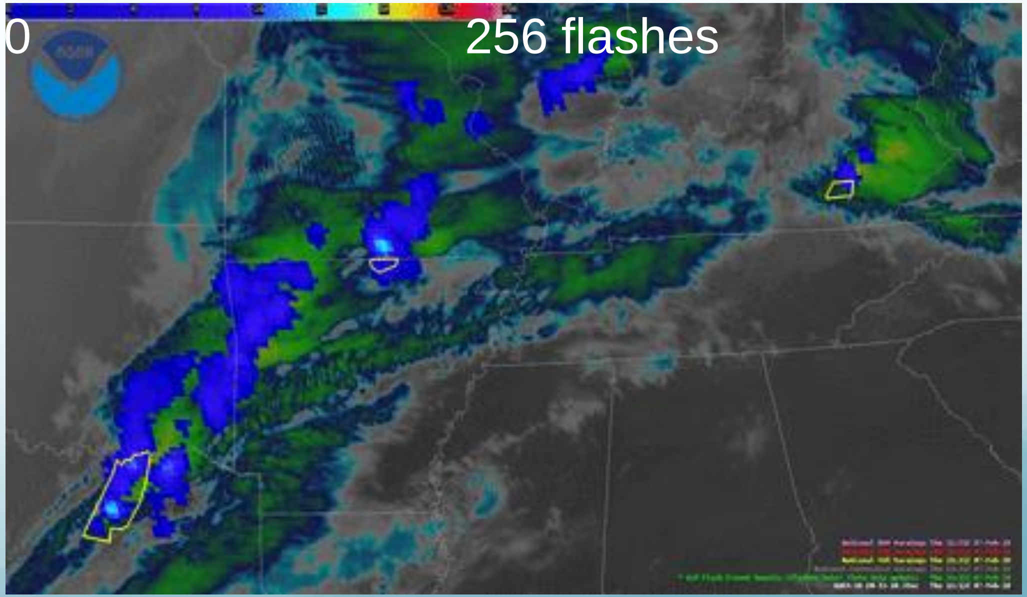


Above: GLM flashes (yellow) over Advanced Baseline Imager infrared imagery for 22 October 2017 for the contiguous United States.

Flash Extent Density

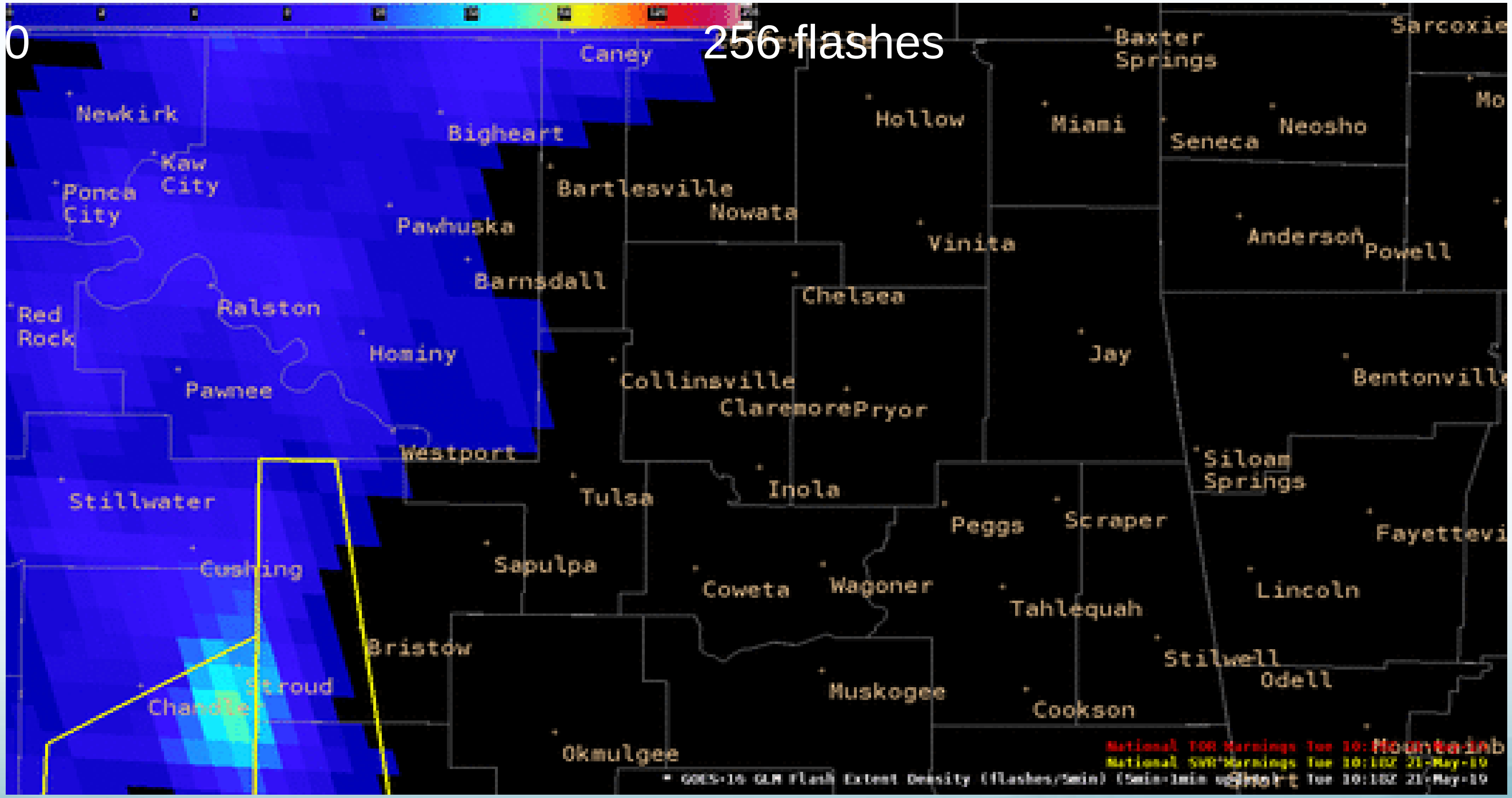
- The number of flashes that occur within a grid cell over a given period of time
- Many years of research and operational demonstrations have shown the Flash Extent Density to be the preferred total lightning product
- Flash Extent Density best portrays the quantity of GLM flashes and the extent of GLM events
- More frequent lightning indicates robust thunderstorm charging which occurs with strong and persistent updrafts
- Lightning trends respond quickly to changing updraft conditions



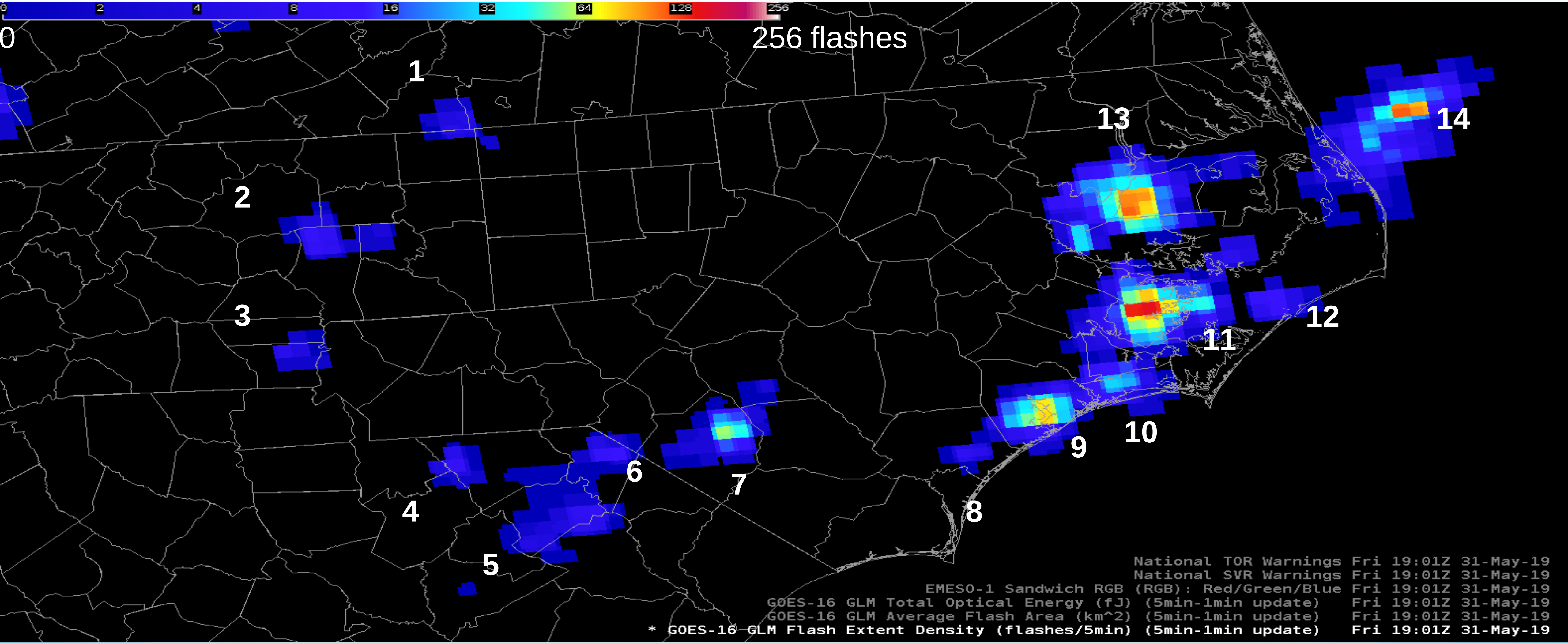


Lightning Trends Indicate Updraft Evolution

- **Sudden shift in the total lightning frequency and the location of maximum intensity coincide with the storm becoming tornadic**

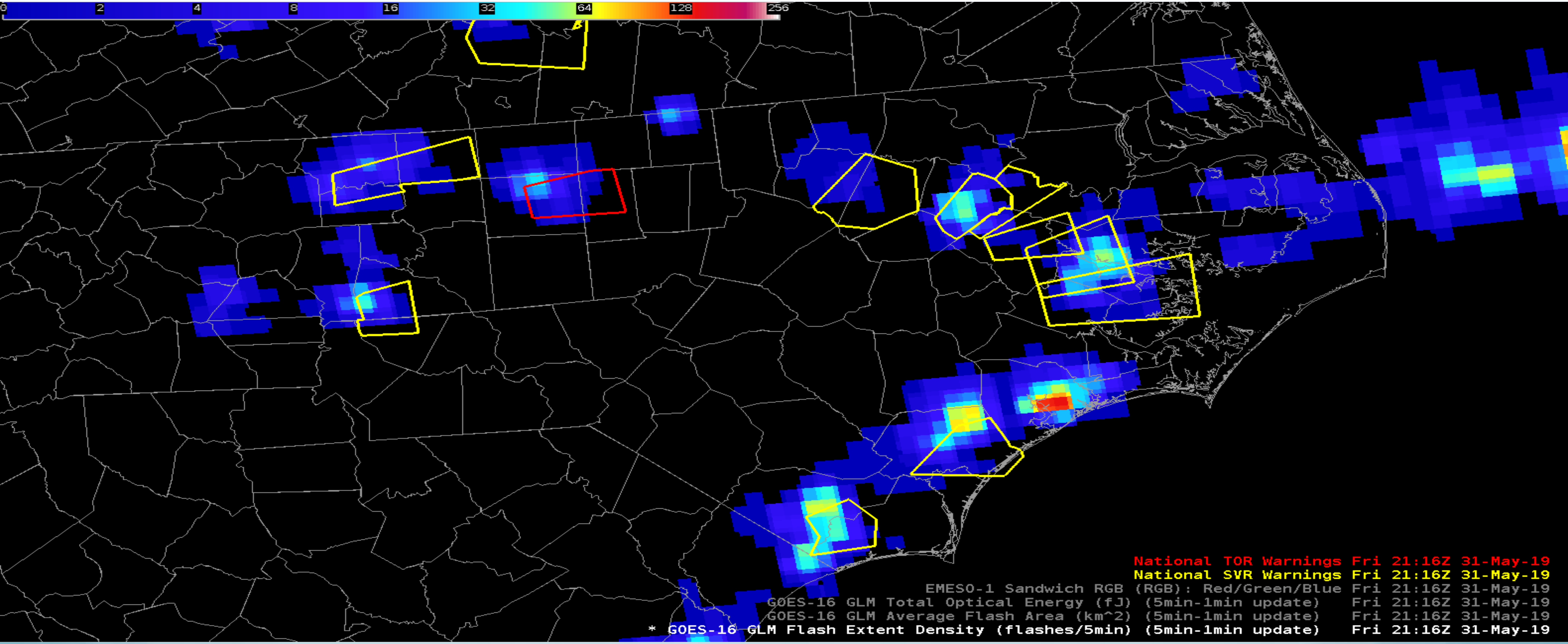


Diagnosing Storm Severity



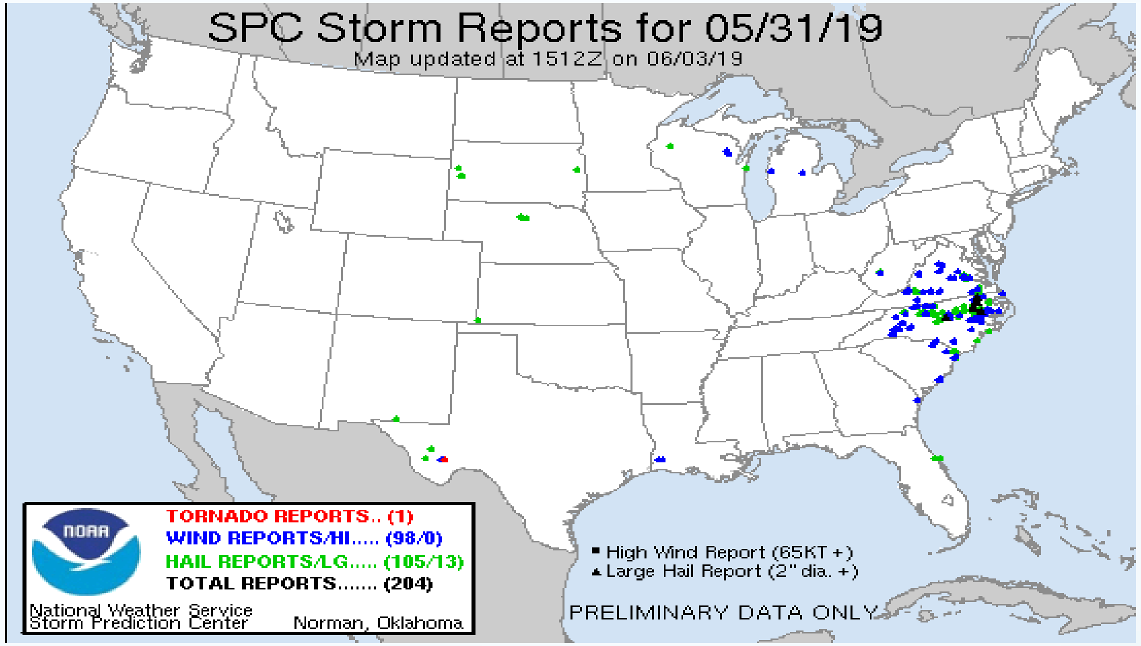
- Which storms might you put extra attention on at this point?
- Which of the 14 cells will become severe (will be severe thunderstorm or tornado warned)?

Storm Warnings



Case Synopsis

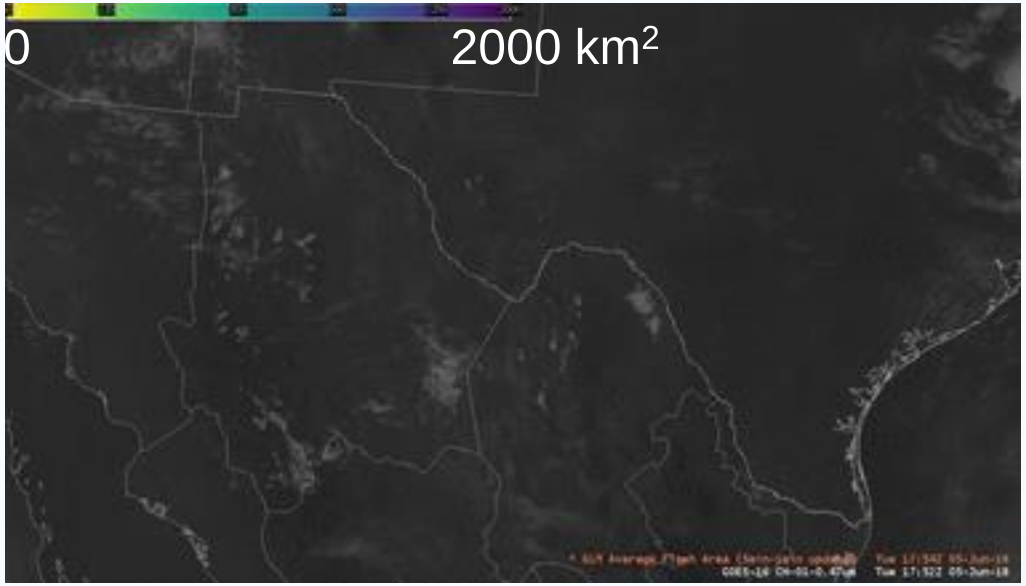
- 9 storms were or became severe
- Vast majority of lightning in the Northeast quadrant at 21 UTC
- Storms 11 and 13 interfere both destructively and constructively
  - Storm outflow interference initially decreases the lightning in both storms
  - Merged storm feature then undergoes strong re-intensification
  - Eventually extends the convective line responsible for most lightning at 21 UTC

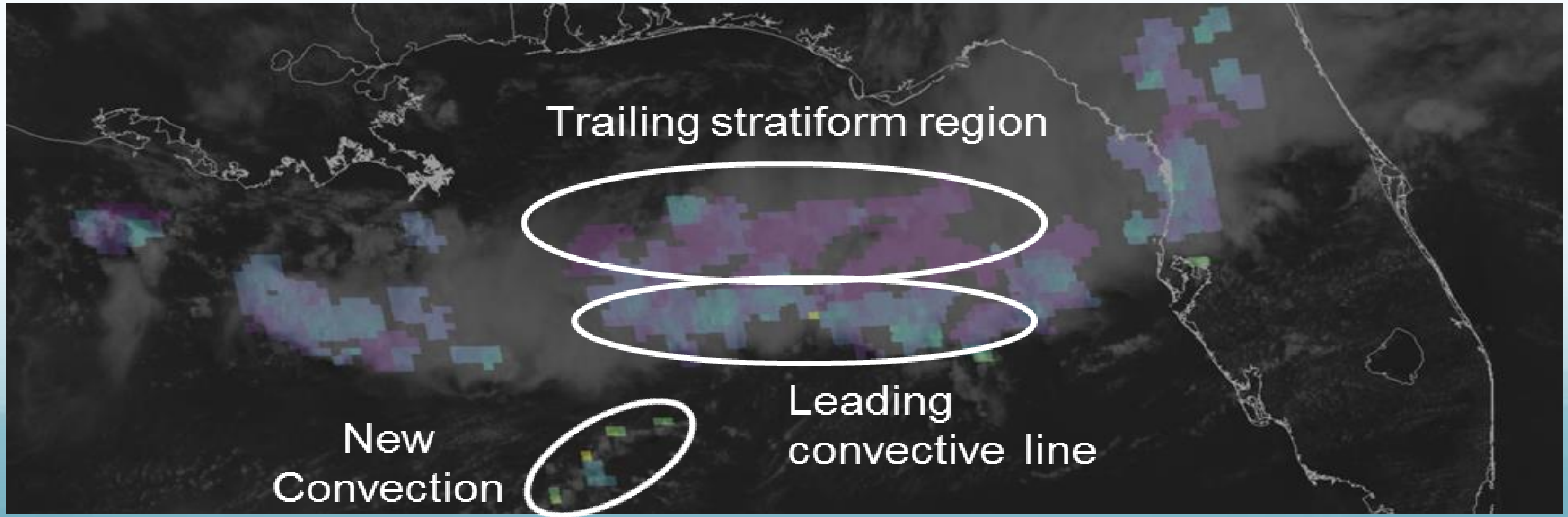


Average Flash Area

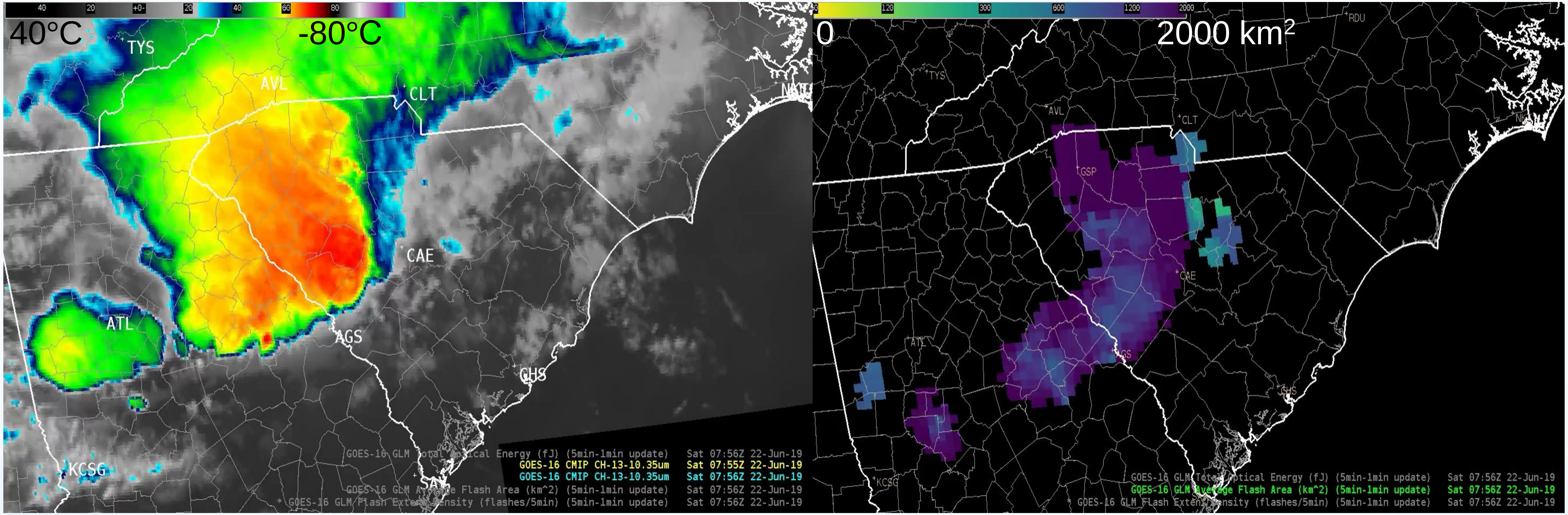
Average Flash Area

- Average area of all GLM flashes spatially coincident with each 2x2 km grid cell during a given time period
- Yellow pixels accentuate the smallest and earliest flashes in cases of both isolated convection and for more linear convective modes
- Larger flashes are most common in the stratiform/anvil regions and decaying storms
- Displacement of stratiform/anvil flashes can be descriptive of convective mode and main severe threat (i.e. tornado/hail, heavy rain)



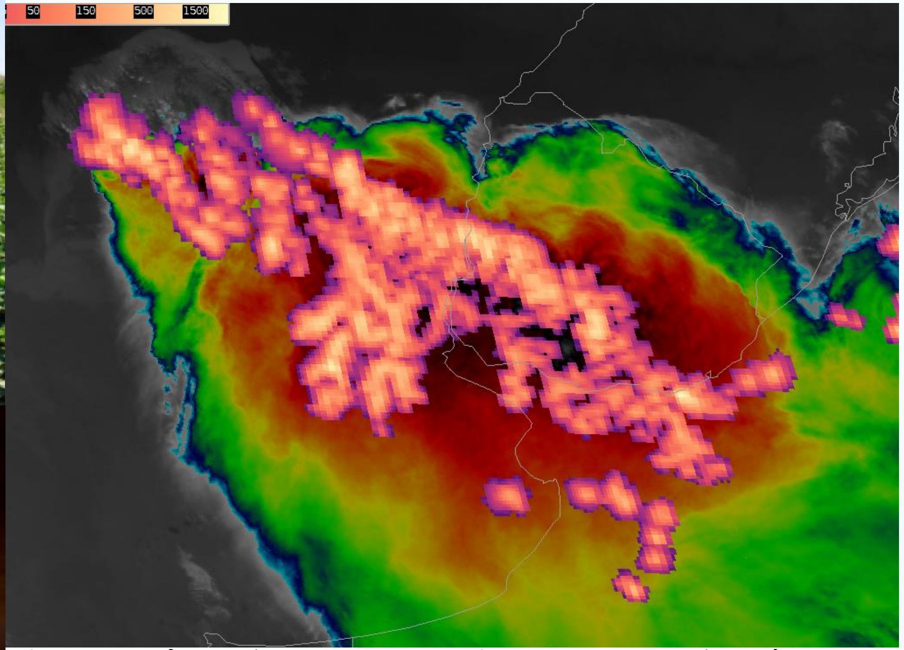


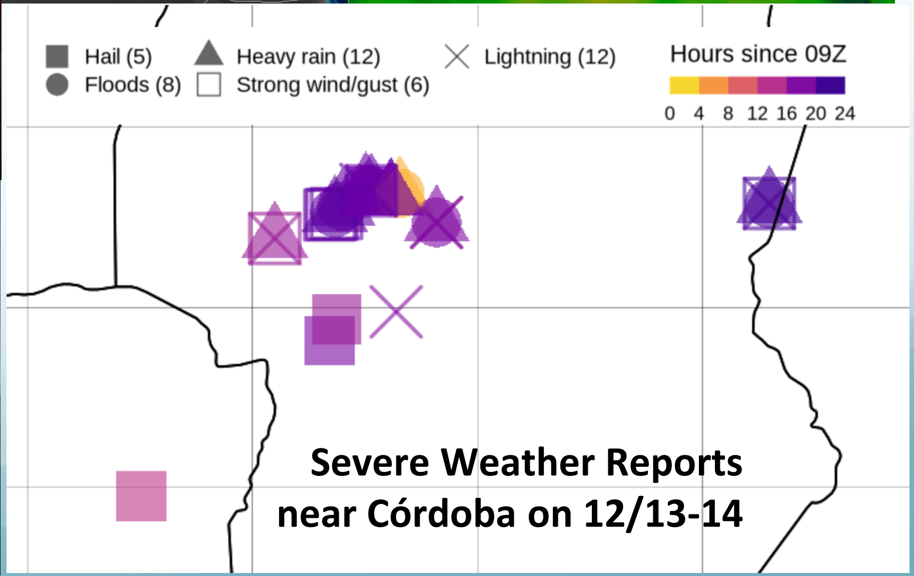
Infrared and Average Flash Area Imagery



- **Weakening mesoscale convective system on morning of 22 June 2019 depicted by IR Image (Channel 13)**
- **Leading line of convection with large flashes (purple) over the stratiform region**
- **Large flashes dominating are emblematic of weakening system**

Large Hail/Flooding Event over Central Argentina 13-14 December 2018





How big are the largest GLM flashes during the Mesoscale Convective System phase (i.e., on 14 December 2018)?

A. **1000-2000 km^2**

B. **2000-3000 km^2**

C. **3000-5000 km^2**

D. **5000-10000 km^2**

E. **Greater than 10000 km^2**

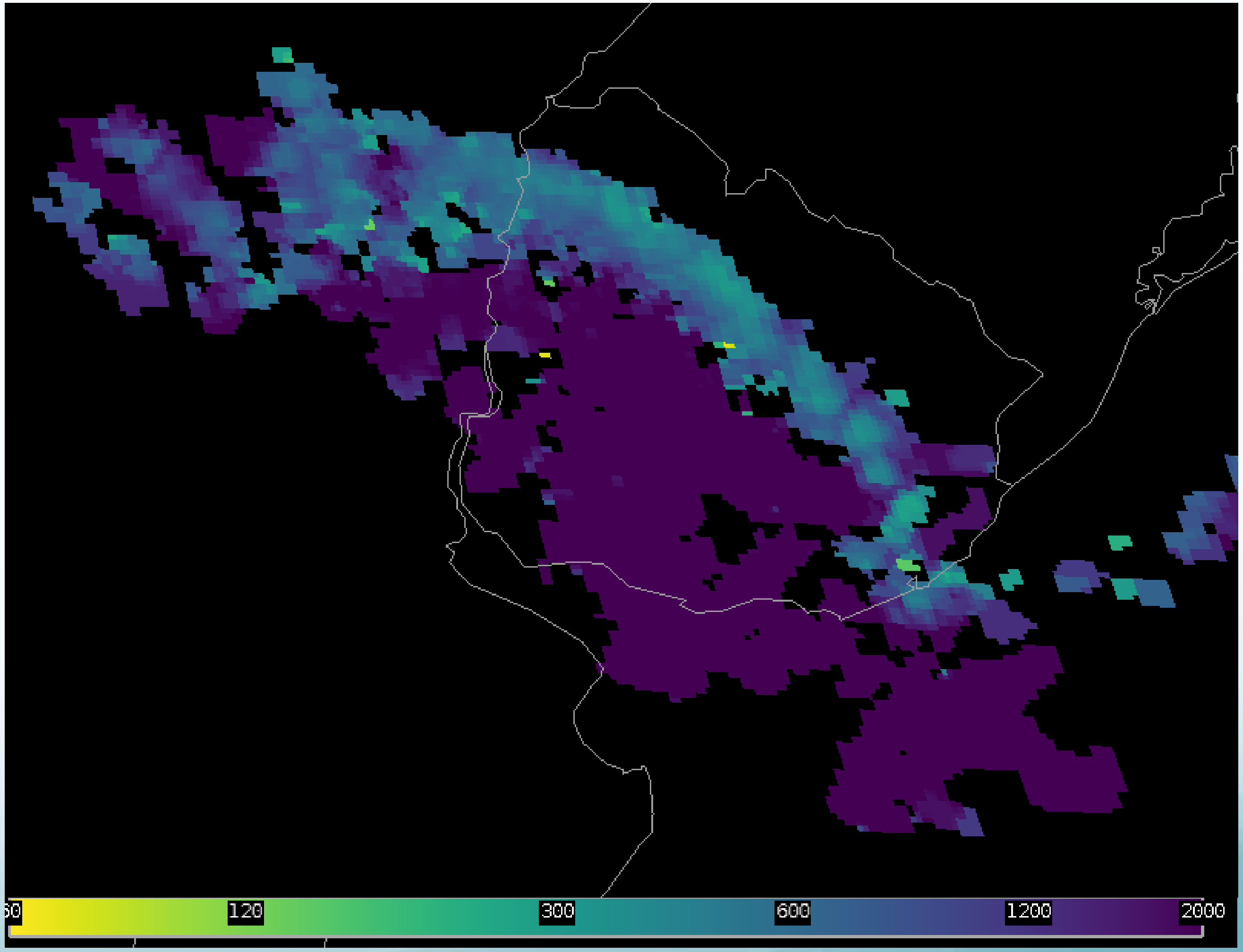
Purple regions indicate Average Flash Area > 1500 km^2

Hints:

San Jose, Costa Rica: 45 km^2

Costa Rica: 51100 km^2

Uruguay: 176215 km^2

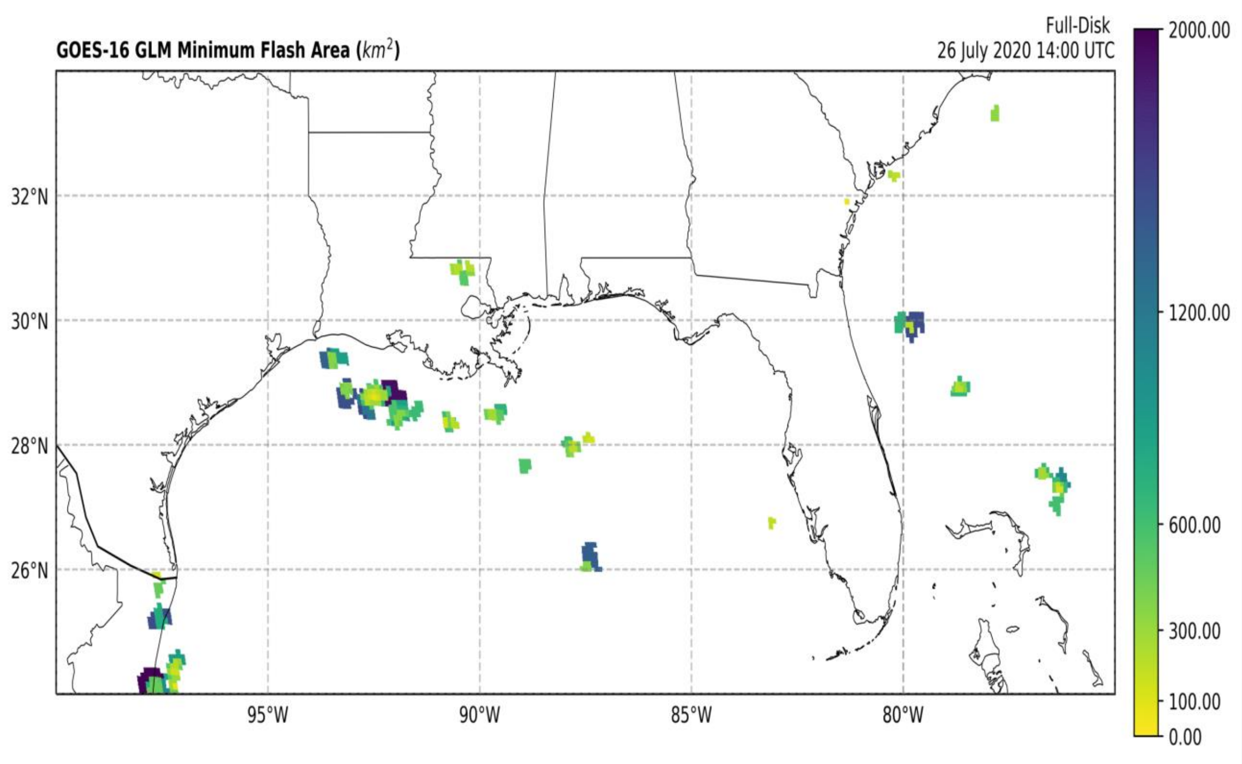


0

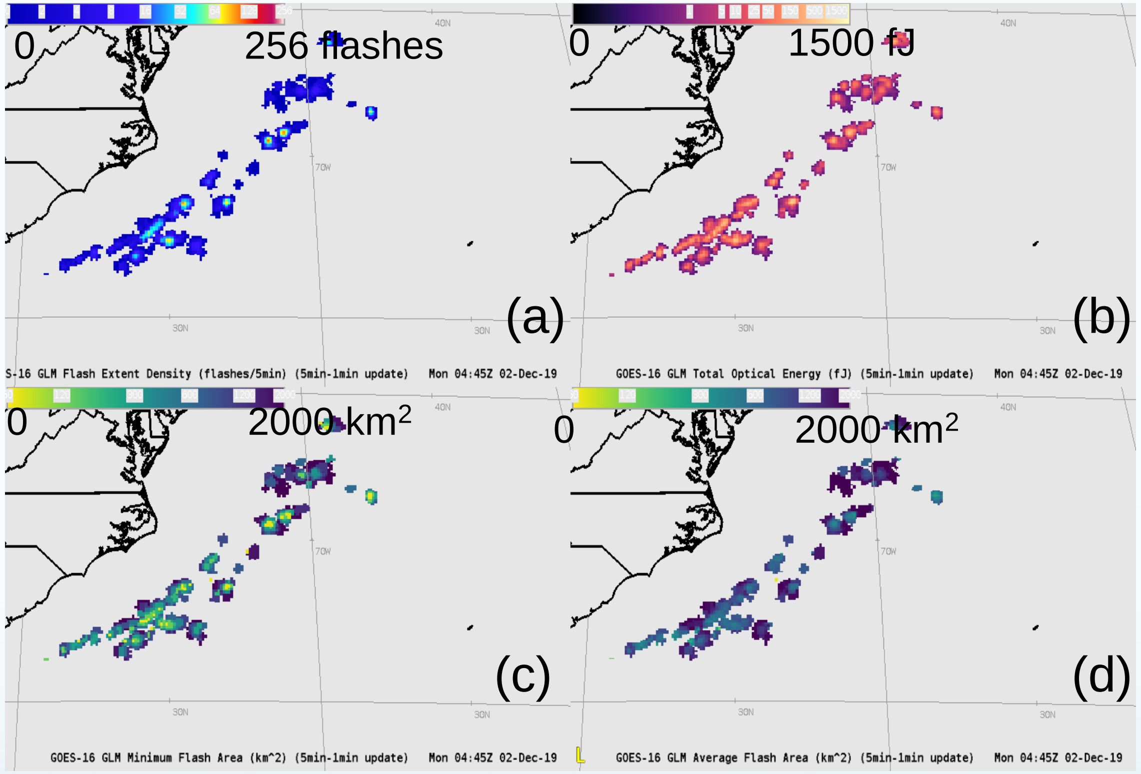
2000 km^2

Minimum Flash Area

- **Minimum area of all GLM flashes spatially coincident with each 2x2 km grid cell over a specified time period**
- **Improved identification of smaller flashes**
- **Forecasters use it to determine convective initiation**



Average Flash Area vs Minimum Flash Area

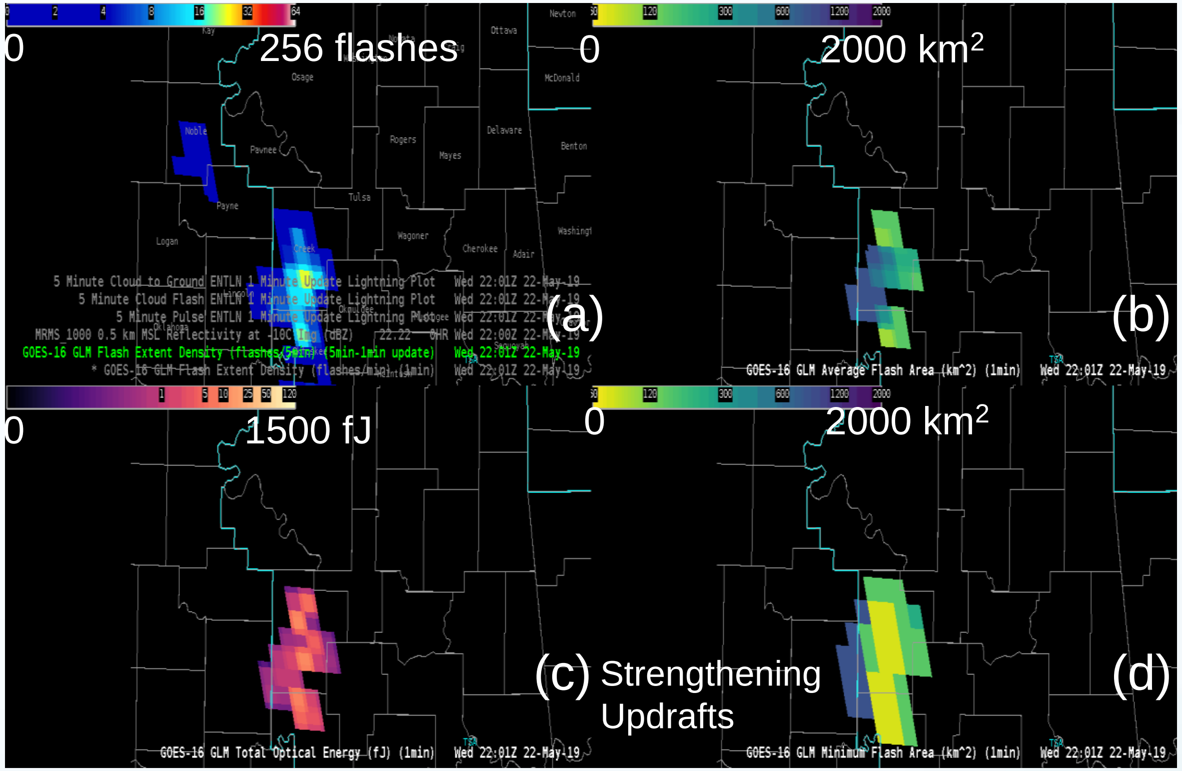


Above: a. Flash extent density, b. total optical energy, **c. minimum flash area**, d. average flash area

Average Flash Area vs Minimum Flash Area

- **22 May 2019 Hazardous Weather Testbed Blog**

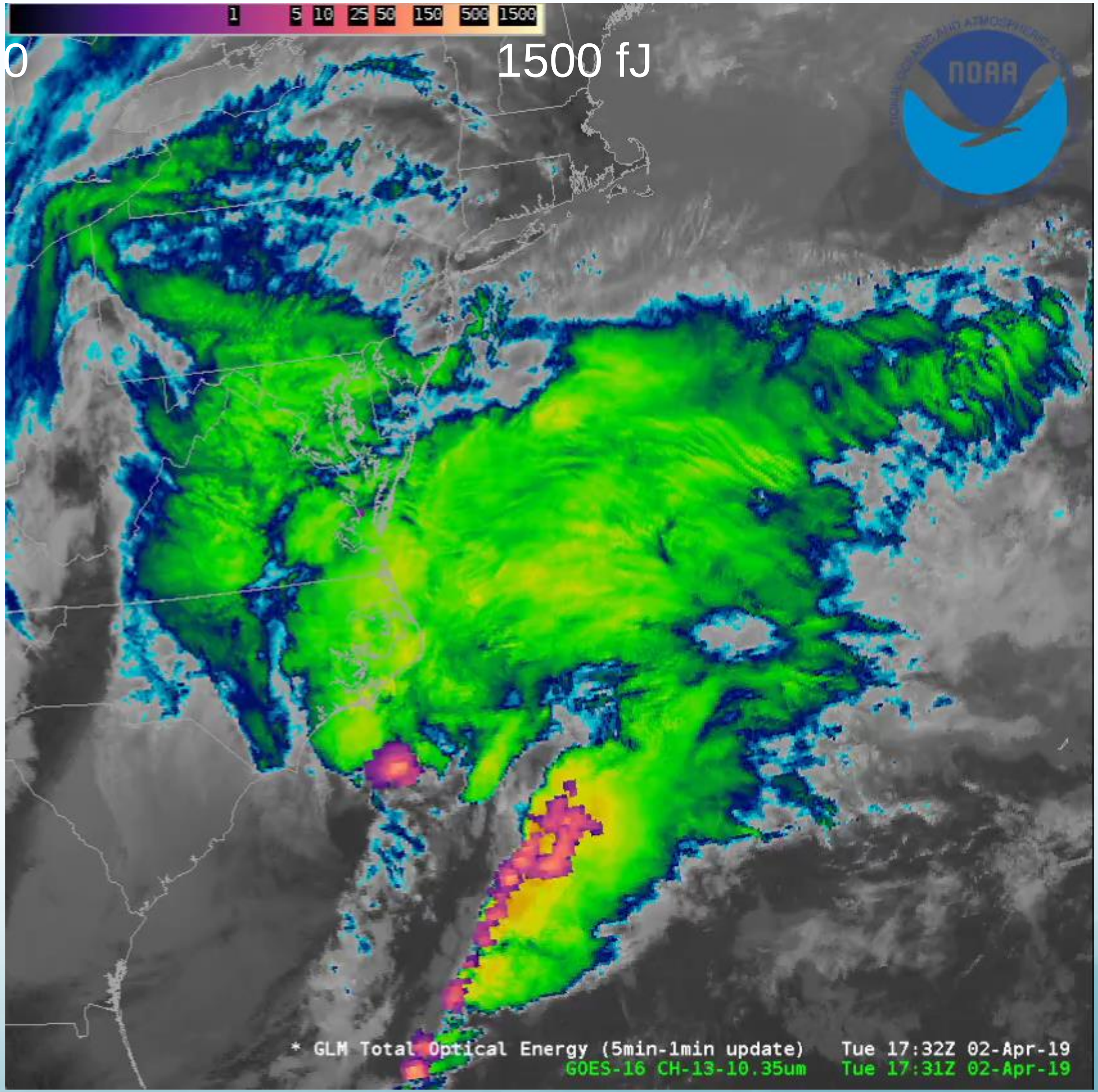
"A loop of GLM products, particularly the Flash Extent Density and the Minimum Flash (top left and bottom right, respectively), appear to have depicted strengthening updrafts in the Tulsa area. In particular, notice the uptick in Flash Extent Density going from Creek to Osage Counties, as well as the area over northwestern Rogers County. The increases in FED coincided with low areas of Minimum Flash Area."



Above: a. Flash extent density, b. average flash area, c. total optical energy, d. minimum flash area

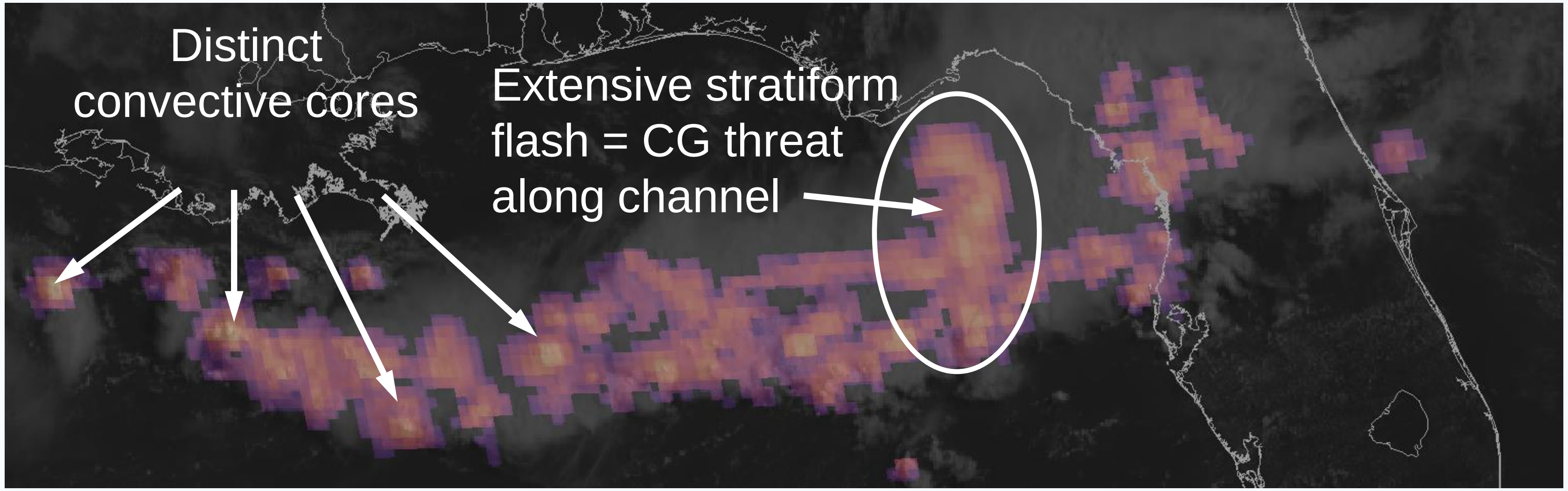
Total Optical Energy

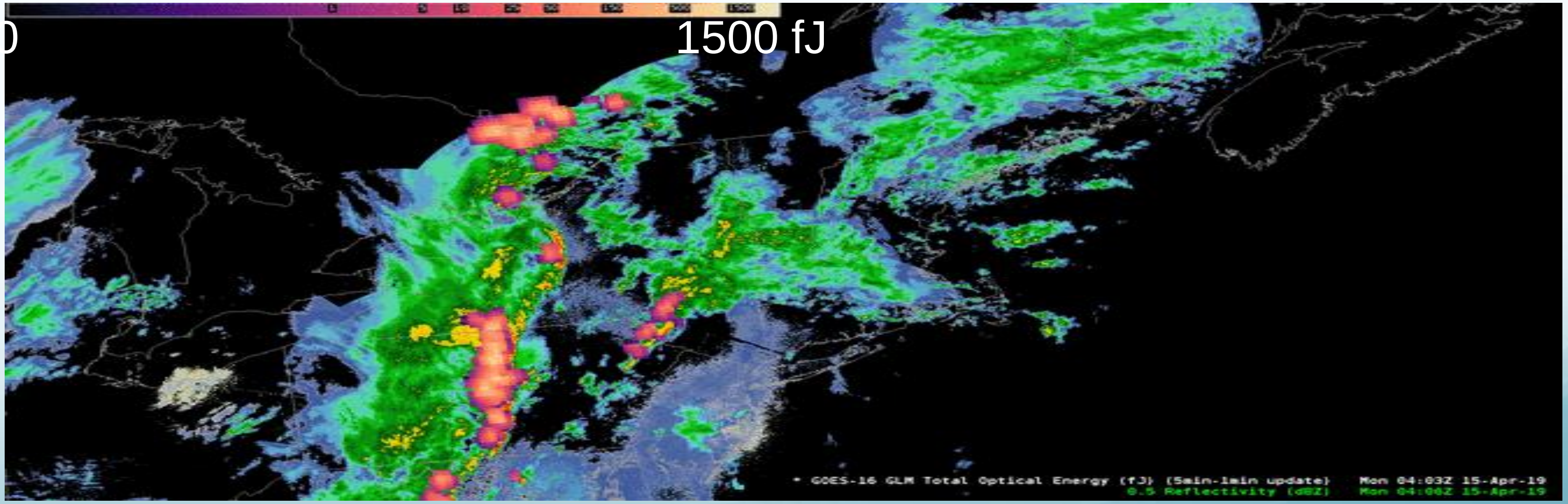
- Sum of all optical energy observed within each grid cell during a specified time period
- Units of femtojoules (10^{-15} J) ranging from decimal values for the dimmest flashes to thousands for regions with frequent, bright flashes
- A fundamental measurement from an optical sensor, portrays an intuitive relationship between lightning optical emissions, frequency, and intensity



Bright regions in the Total Optical Energy indicate…

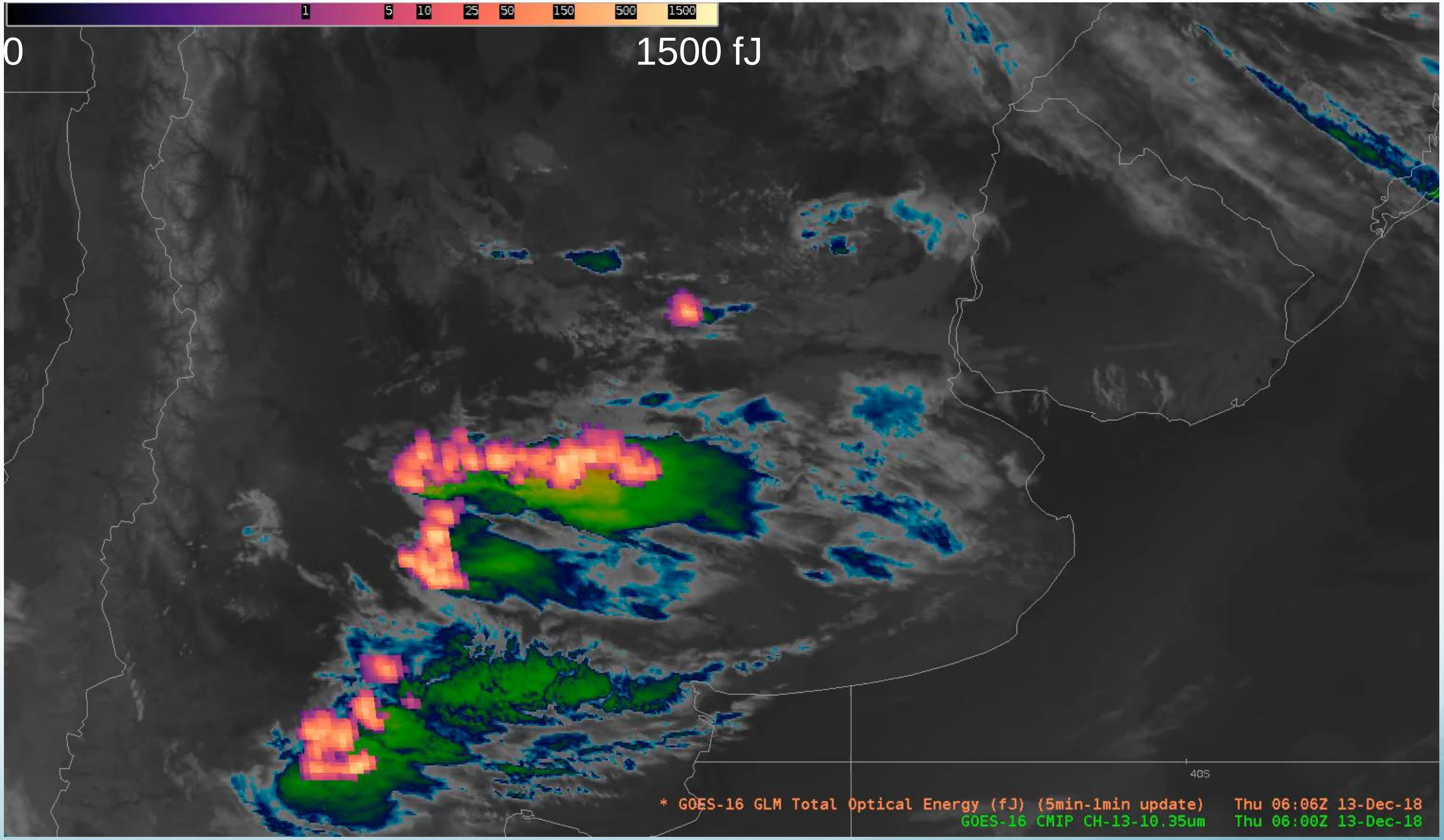
- **Most energetic convective cores (strengthening / weakening convection)**
- **Depicts individual cells propagating along/through convective lines**
- **Lightning channels within extensive flashes**





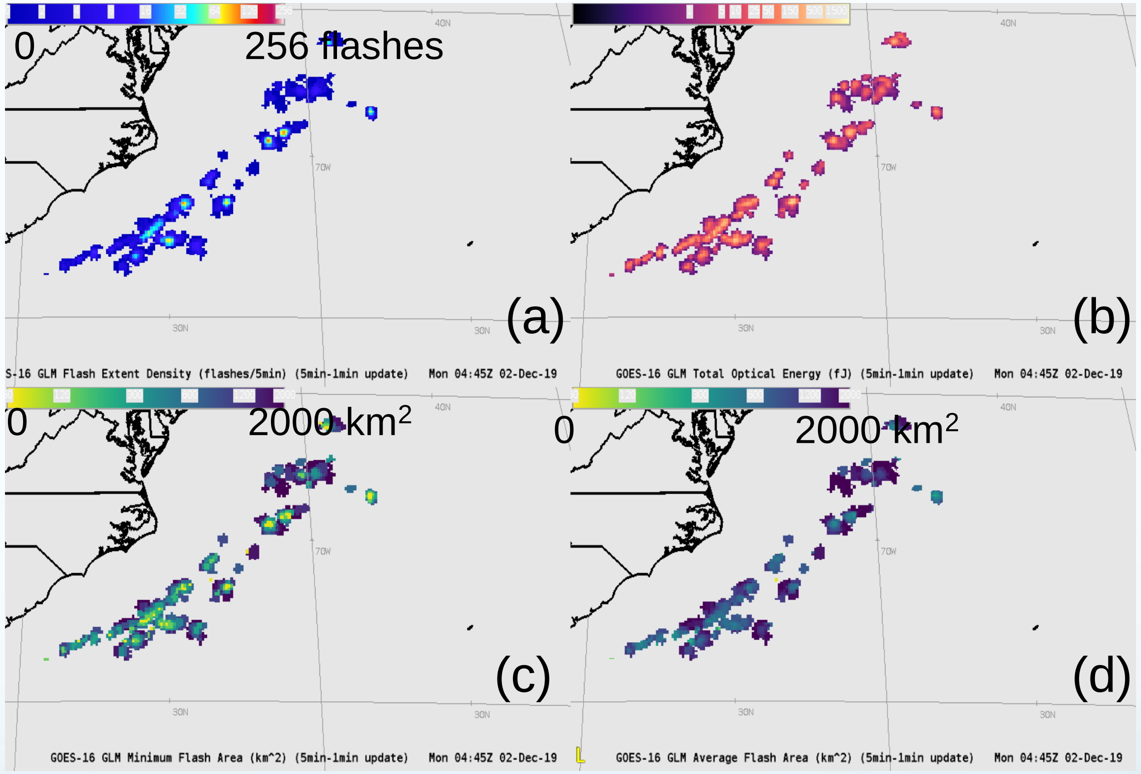
GLM Total Optical Energy and Advanced Baseline Imager Infrared Imagery

- **Total Optical Energy directly represents the optical observations**
- **Identify strengthening and weakening storms**
- **Analyze the cloud-to-ground lightning threat**



Which gridded GLM products are you interested in exploring for nowcasting applications?

- **A.** **FED**
- **B.** **AFA**
- **C.** **MFA**
- **D.** **TOE**
- **E.** **FED and MFA**
- **F.** **FED and AFA**
- **G.** **FED and TOE**
- **H.** **FED, AFA, MFA, and TOE**
- **I.** **Different combination**



Above: a. Flash extent density, b. total optical energy, **c. minimum flash area**, d. average flash area

07

Satellite detection of fires, smoke and volcanic eruptions

Fires detection:
Hot Spots and Smoke

FIRES

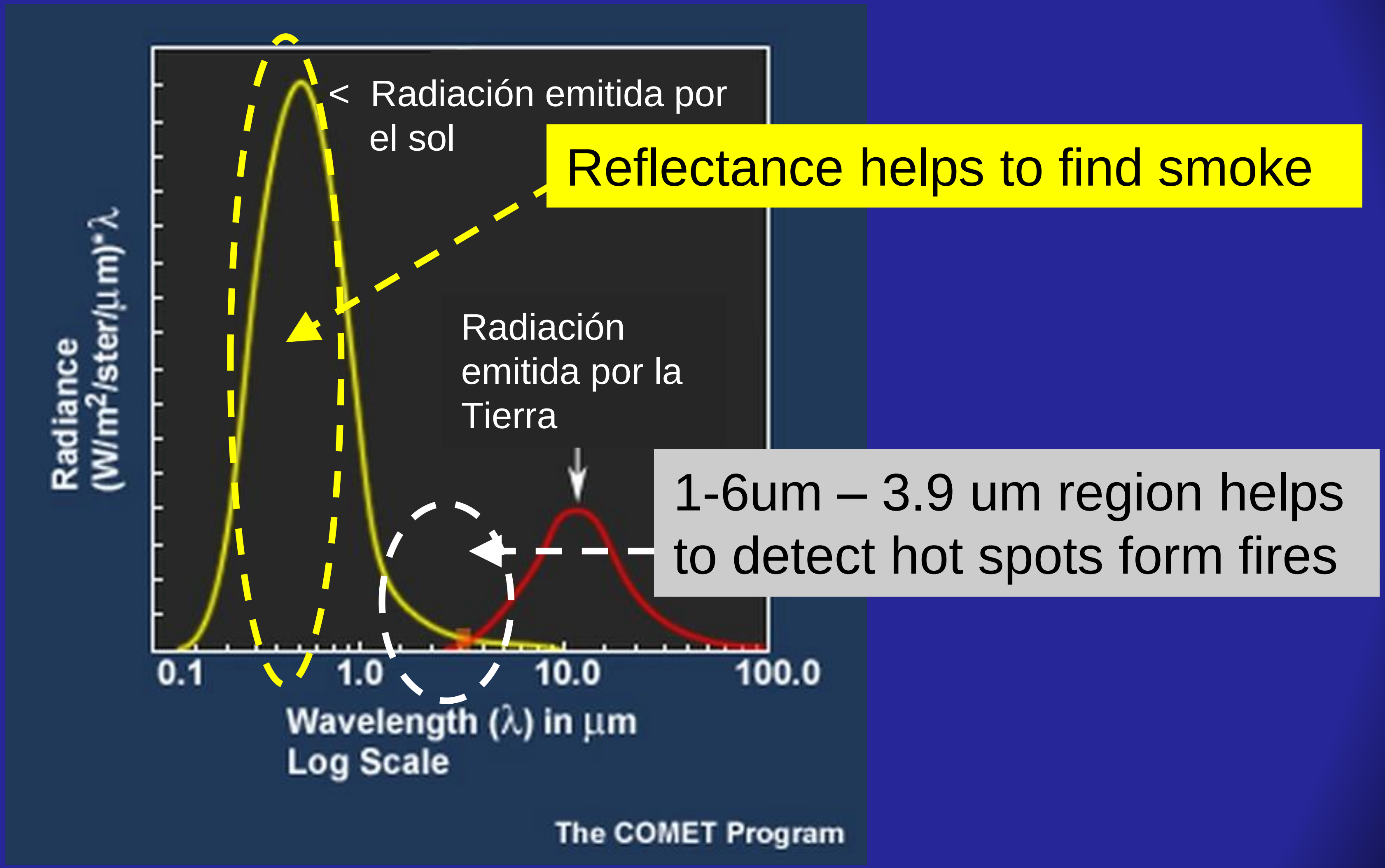
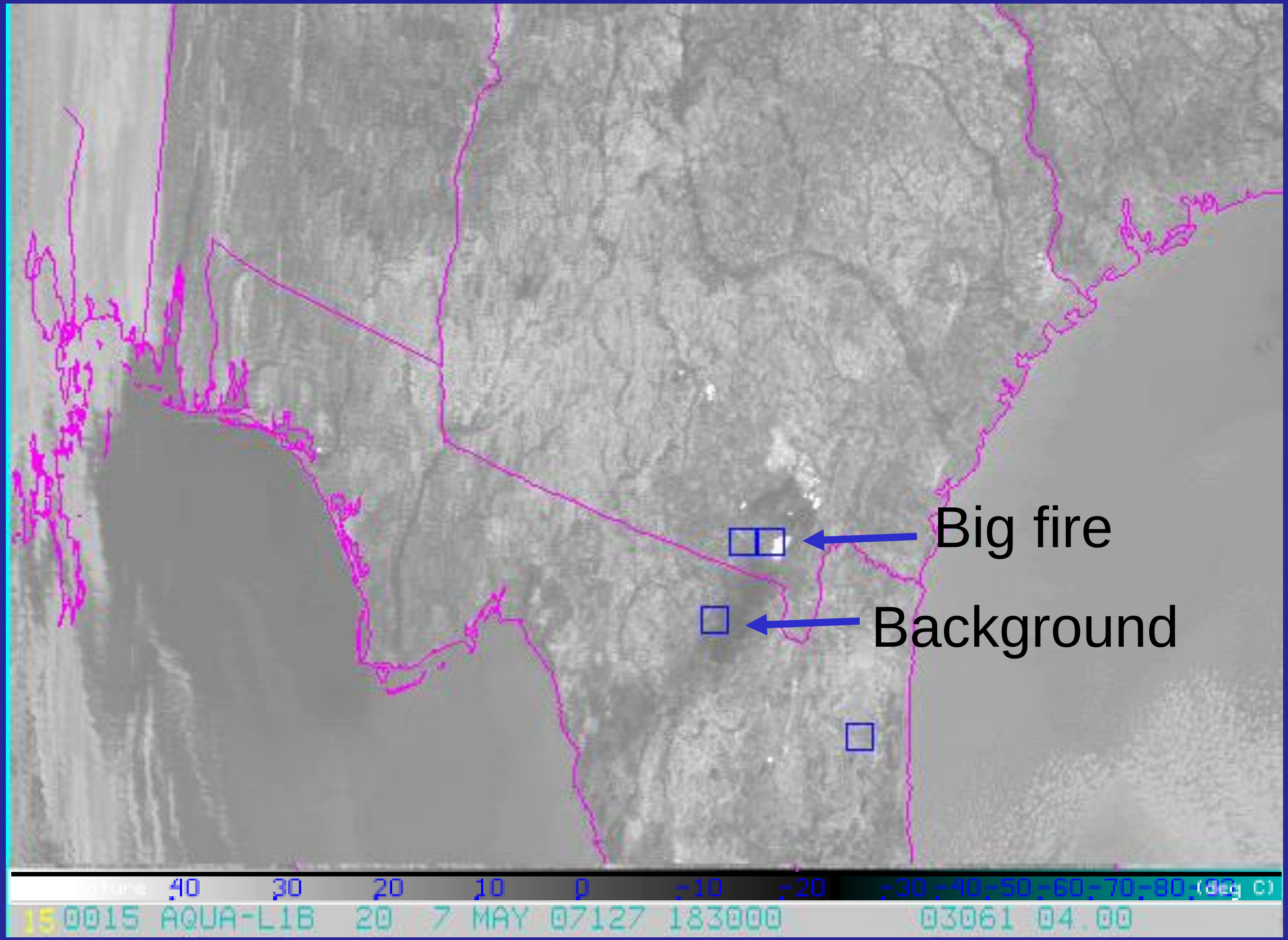


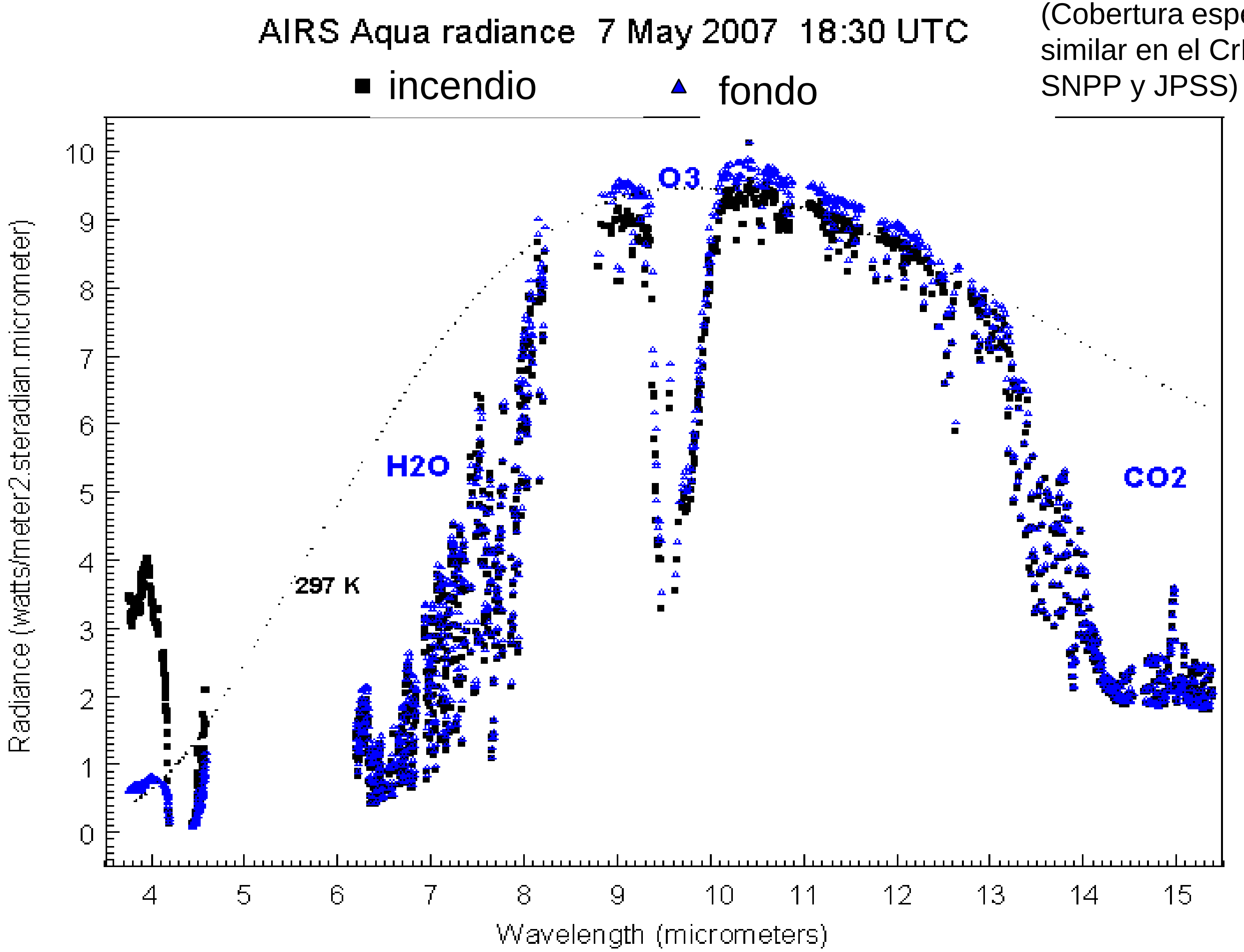
Diagram from COMET Forecaster's Multimedia Library:
Satellite Meteorology: Remote sensing Using the New Goes Image

M.E.Pestaina-Jeffers
CIMH, Barbados



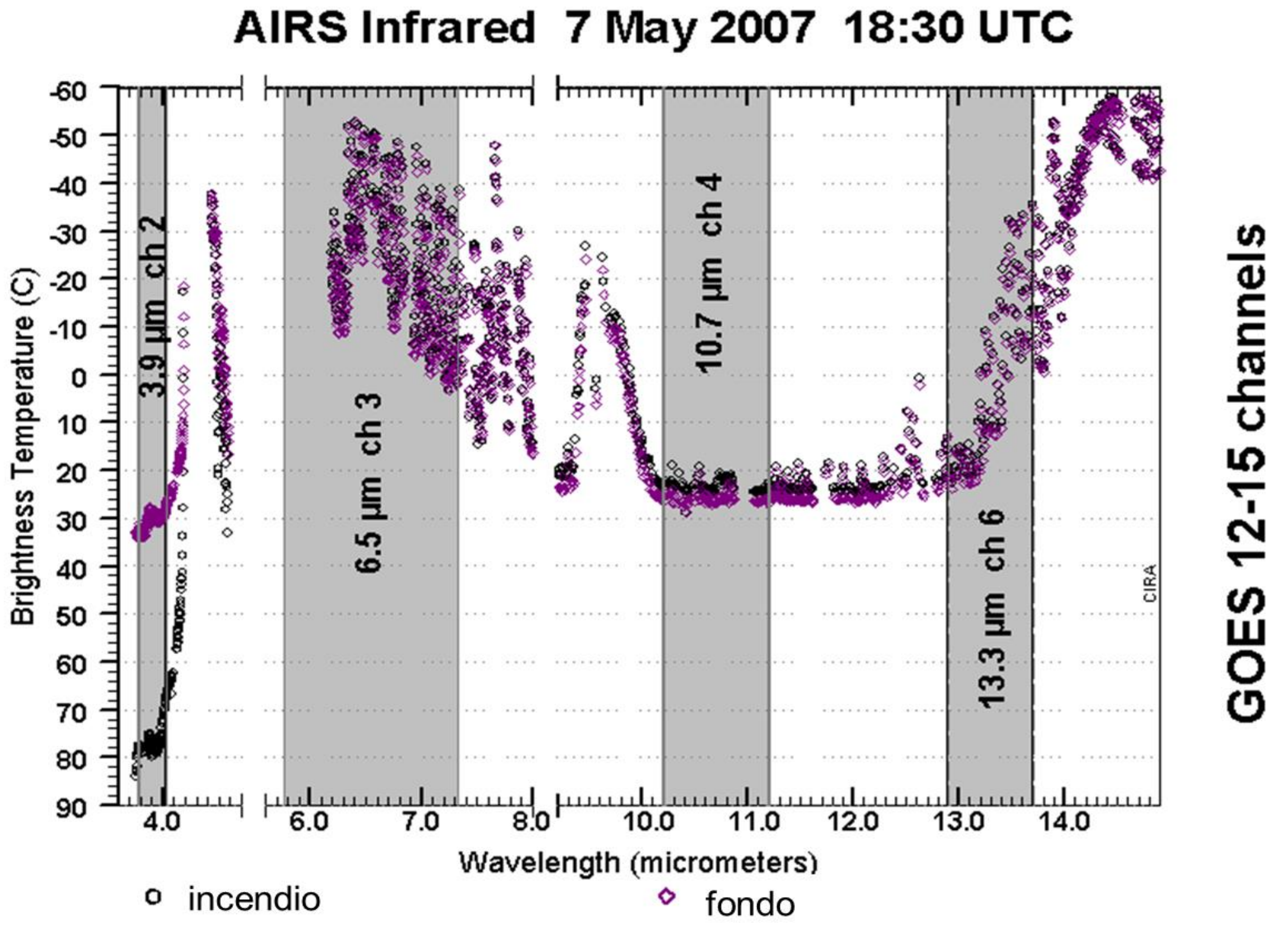
3.9 µm imagery for 7 May 2007   1830 UTC

Radiances: Hot spot (fire) vs background



(Cobertura espectral similar en el CrIS, en el SNPP y JPSS)

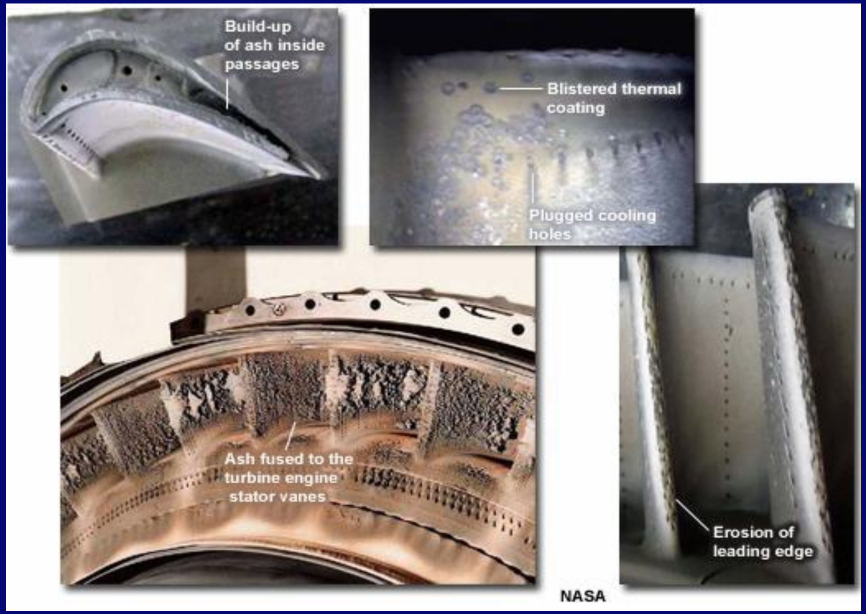
Brightness Temperature: Hot spot (fire) vs background



Satellite Detection of Volcanic Eruptions

Air hazards from volcanic eruptions

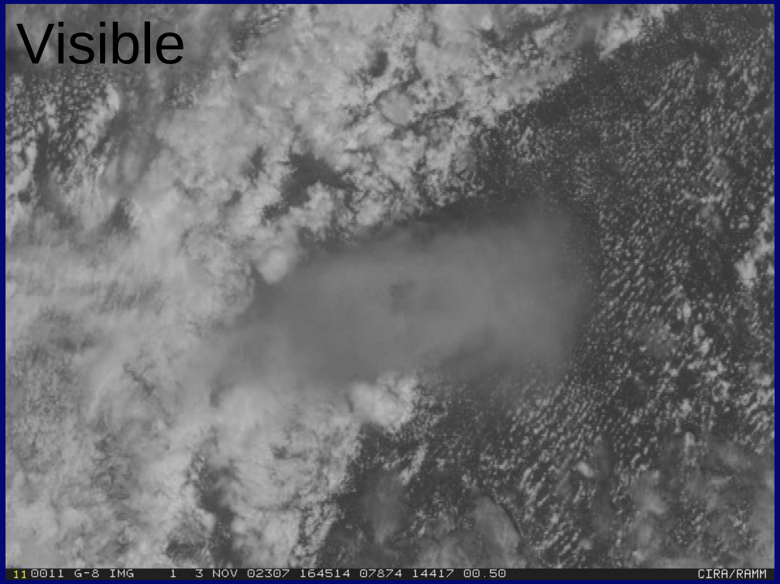
- Planes should not fly through volcanic plumes.
- Ash and sulfates can cause significant damate in aircraft structures, especially in engines:
  - Engines can be lost during flights
  - Windshields can crack
  - Instrumentation can be damaged
- Avoiding volcanic emissions causes important delays and flight operations.
- There are also unknown hazards to health.

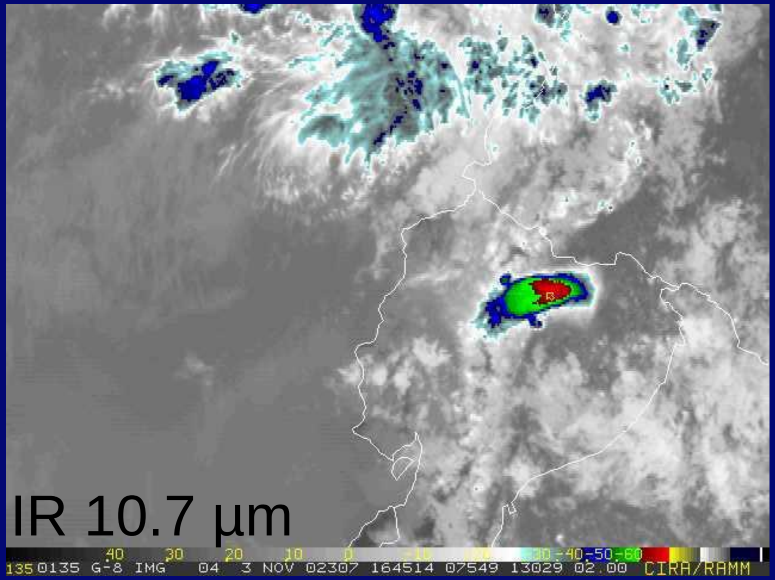


Detecting volcanic emissions

The context is important. Start with evaluating if the signature in the image is unusual (not a common expected meteorological process). In this example:

- The cloud looks darm in visible imagery
- If this is convection, it should not be happening at this time of day and situation
- The cloud is moving in strange and unexpected directions





3 de nov 2002 16:45 UTC Volcán Reventador, Ecuador

Ash (and dust) in the 10.7 – 12.0 um difference

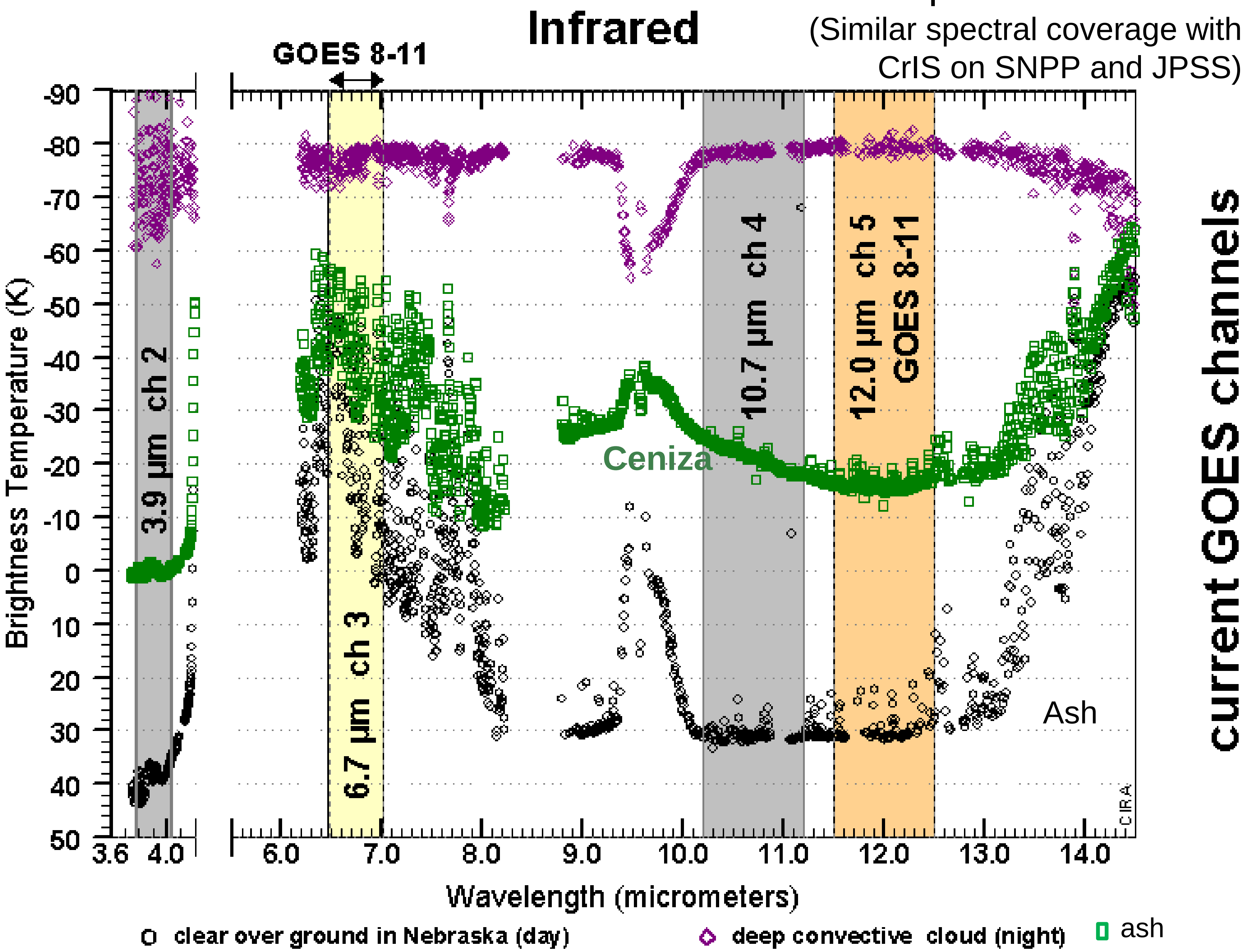
This difference, called “split window”, detects the presence of silicates such as dust and volcanic ash.

$BT_{12um} - BT_{10um} > 0$ … ash and/or dust is present

$BT_{12um} - BT_{10um} \approx 0$ … thick clouds

$BT_{12um} - BT_{10um} < 0$ … thin ice clouds

Spectra from AIRS
(Similar spectral coverage with
CrIS on SNPP and JPSS)



SO_2 Detection: 7.3 y 8.5 µm

The largest absorption of radiation leaving the earth system by SO_2 occurs in the 7.3 - 7.5 µm, and between 8.3 y 9.0 µm but to a lesser extent.

$BT_{6.9um} - BT_{7.3um} > 0$ … SO_2 (generally upper troposphere)

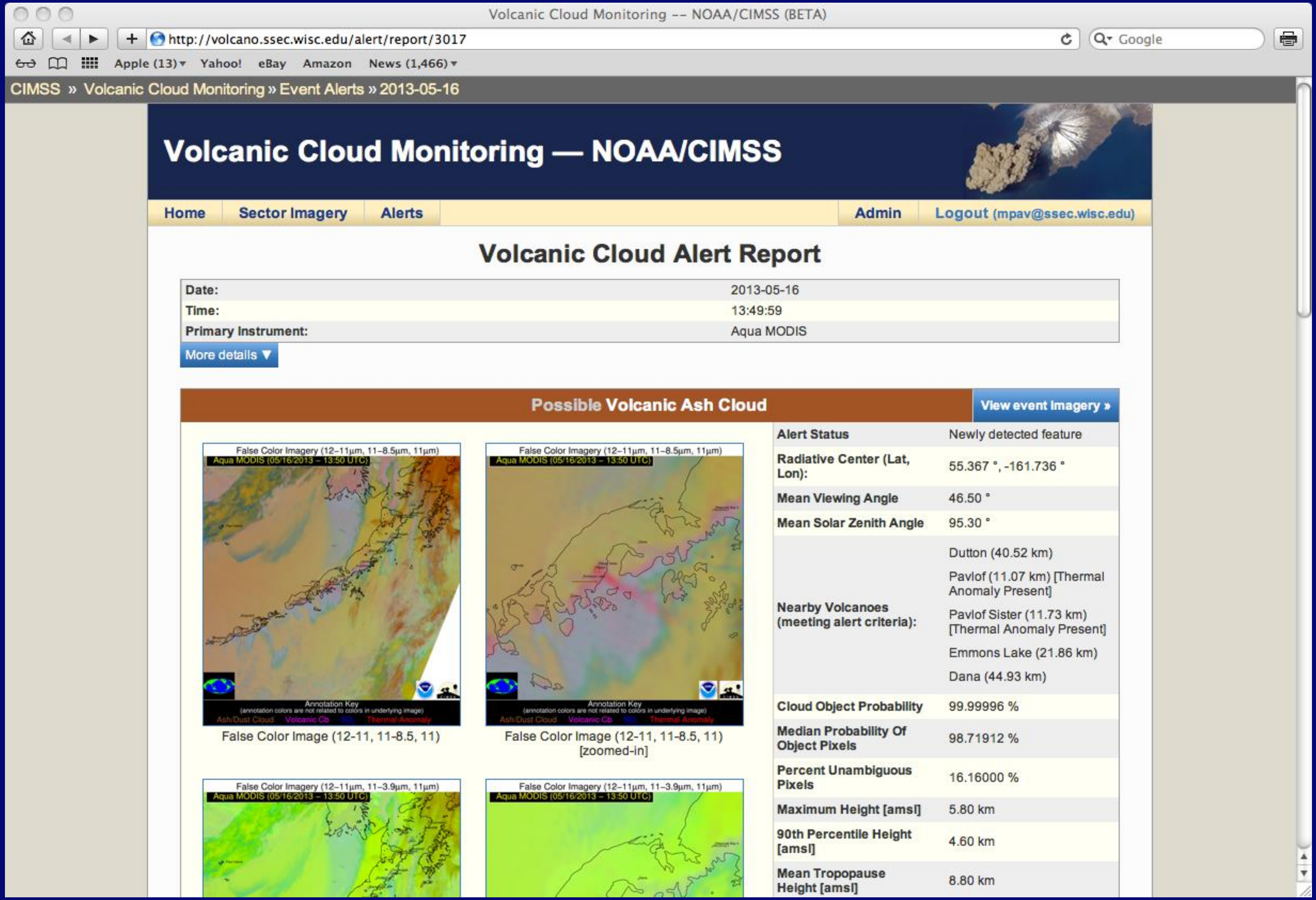
$BT_{6.9um} - BT_{7.3um} \approx 0$ ... Thick clouds

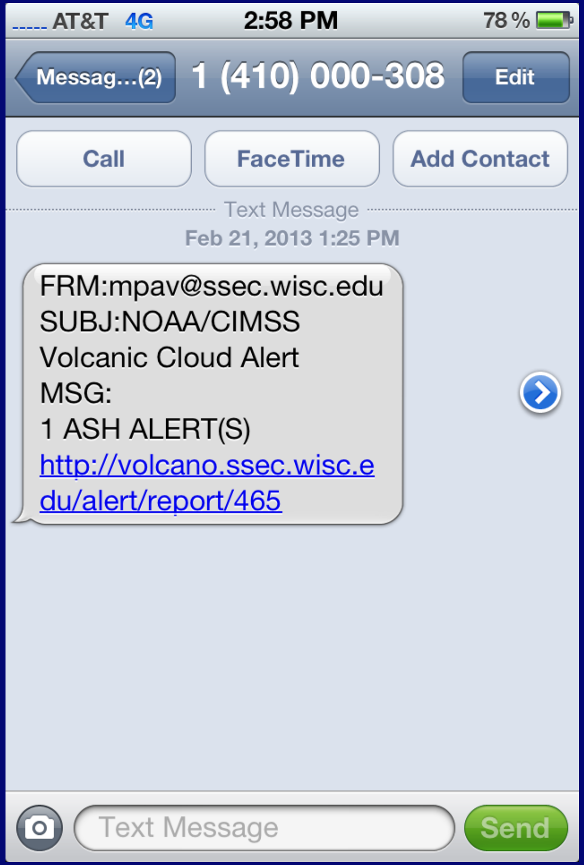
$BT_{6.9um} - BT_{7.3um} < 0$ ... Dry air

$BT_{10.3um} - BT_{8.5um} > 0$ …SO_2

Compare with data extracted from polar orbiting satellites. If Dobson units >2, dangers to aviation are likely.

Warning system for Volcanic Ash





Imágenes del infrarrojo del MODIS y VIIRS se usan para detectar ceniza volcánica

http://volcano.ssec.wisc.edu/

Summary

Volcanic eruptions contain silicates and SO2, but also water vapor, and can be detected from satellite. Yet they can occur in complex environment where background information and clouds complicate with the detection.

- Ash (and dust) detection: BTD 12 - 10 µm > 0

  Also observable by: BTD 10.3 - 8.5 µm > 0

- SO_2 detection: BTD 6.9 - 7.3 µm > 0

  BTD 10 µm - 8.5 µm > 0

  Compare with data extracted from polar orbiting satellites. If Dobson units >2, dangers to aviation are likely.

BTD = Brightness Temperature Difference

Thank You!

ICAO