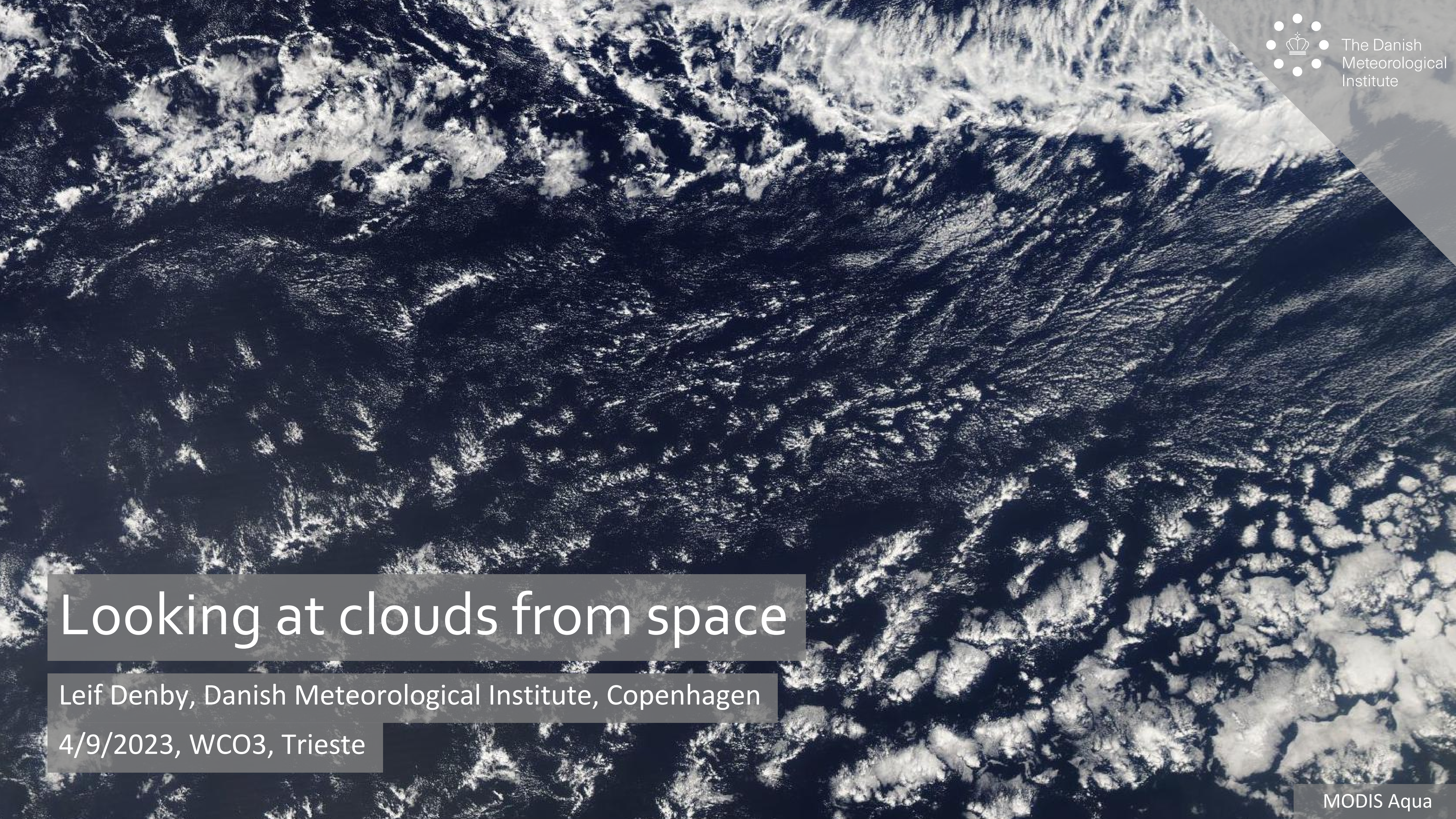


Looking at clouds from space

Leif Denby, Danish Meteorological Institute, Copenhagen

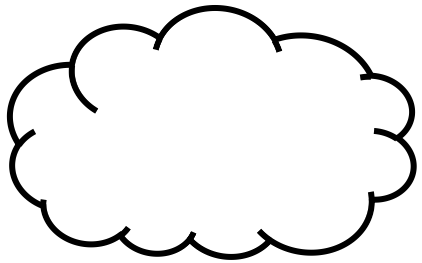
4/9/2023, WCO3, Trieste

MODIS Aqua

The Danish Meteorological Institute

Looking at clouds from space

- What do clouds look like from space?
- How do we observe them? What do the instruments measure?



- I wil focus on passive remote sensing - i.e. only receiving, no sending of signals
  - Synthetic Aperture Radar (SAR) for example sends and receives radiation

Looking at clouds from space

Remote sensing from satellites is all about *electromagnetic radiation*

But where does the radiation come from?

- What we observe is either *emmitted* or *scattered/reflected*
- But the source is where it was *emmitted*

Emmision of radiation

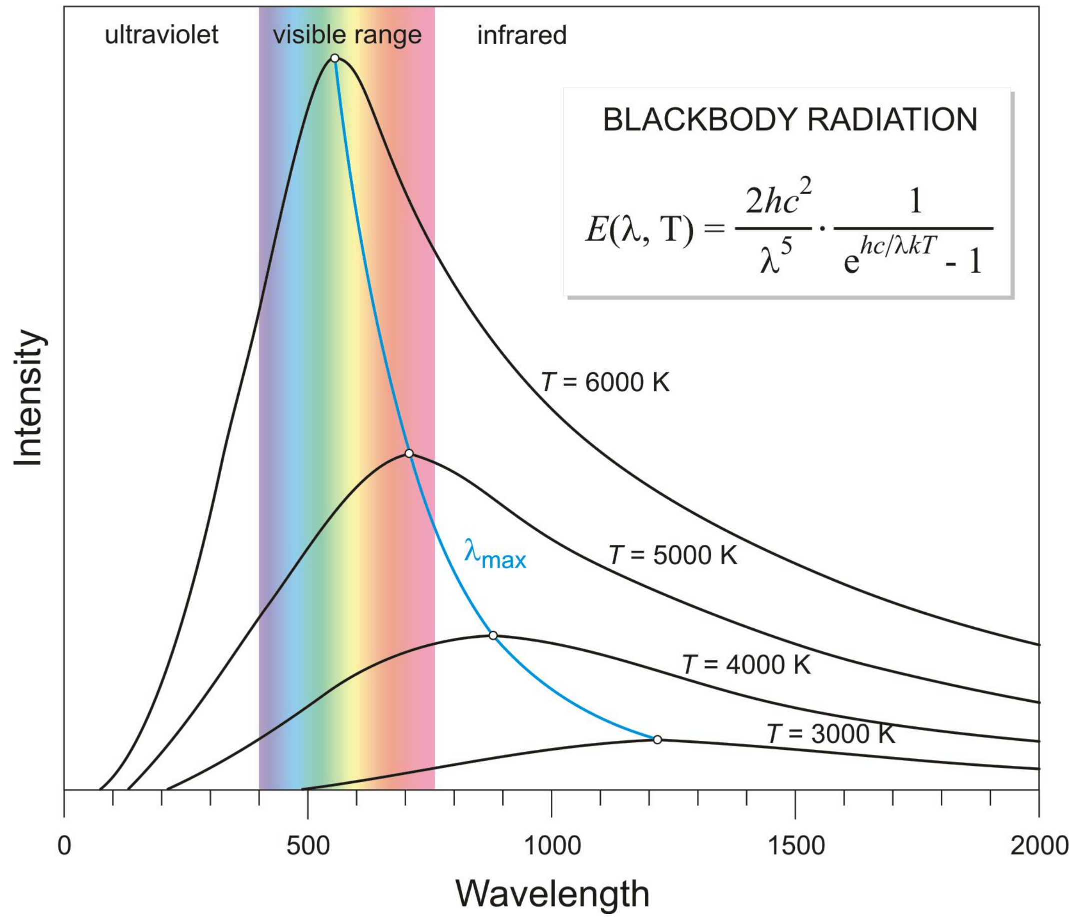
<u>Key fact 1</u>:

All matter with temperature above 0K radiate eletromagnectic waves and wavelength of emmision depends on temperature

- The warmer the object the shorter the wavelength

$T_{sun,surface}$ ~ 7000K

T_{candle} ~ 1900K



Emmision of radiation, Sun vs Earth

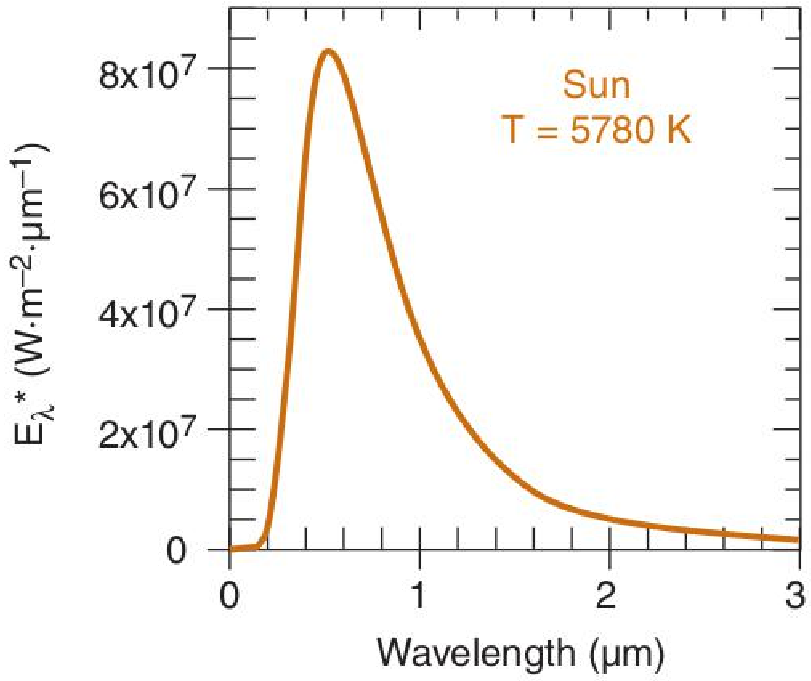


Figure 2.8
Planck radiant exitance, E_λ, from a blackbody approximately the same temperature as the sun.*

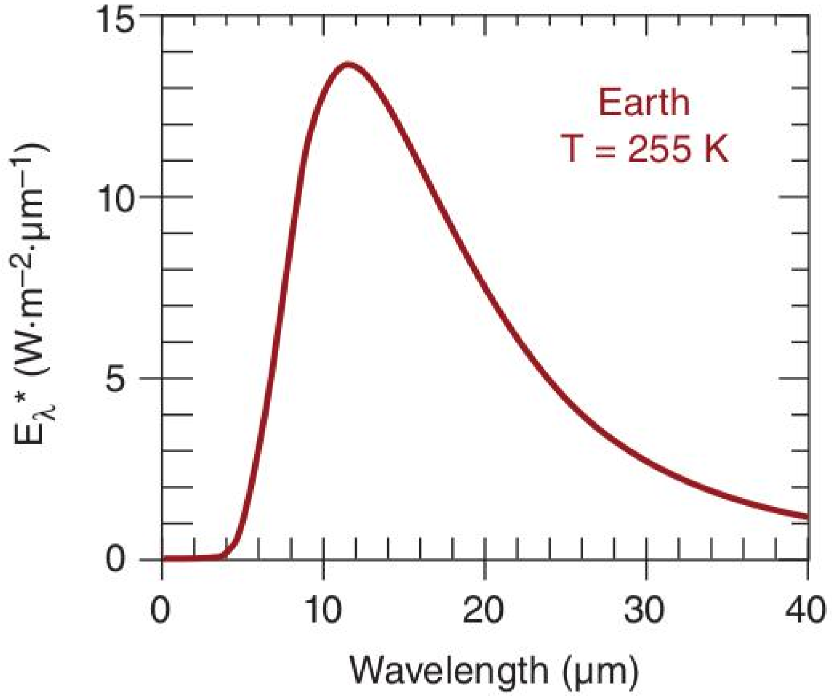
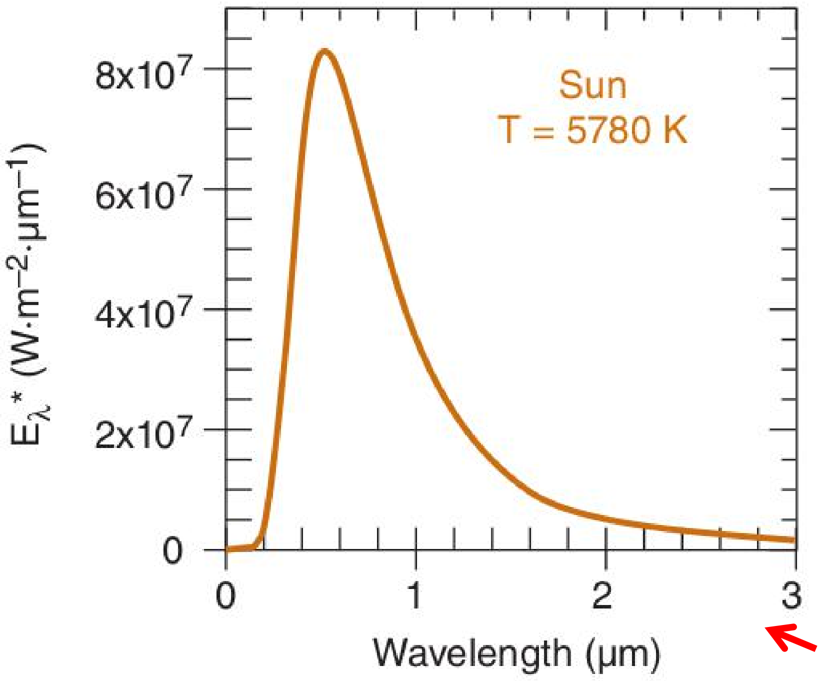


Figure 2.9
Planck radiant exitance, E_λ, from a blackbody approximately the same temperature as the Earth.*

Figures from hereon from the excellent Practical Meteorology (Stull 2018)

Emmision of radiation, Sun vs Earth

Radiation per solid angle



Note wavelength difference

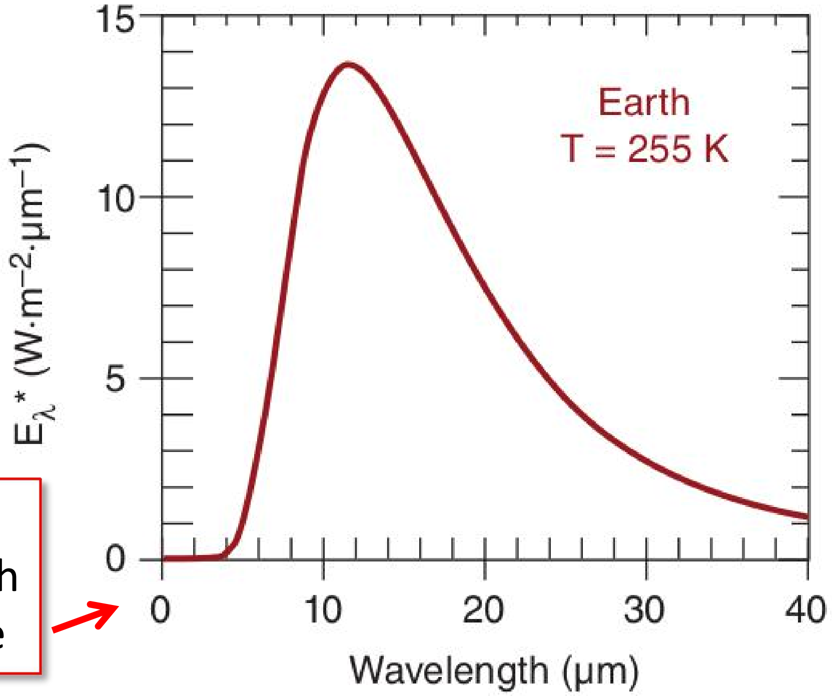


Figure 2.8
Planck radiant exitance, E_λ^*, from a blackbody approximately the same temperature as the sun.

Figure 2.9
Planck radiant exitance, E_λ^*, from a blackbody approximately the same temperature as the Earth.

Emmision of radiation, Sun vs Earth

At top-of-atmosphere (TOA) we're quite far from the Sun :)

- What is the relative radiance per unit area here?

Emmision of radiation, Sun vs Earth

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- What is the relative radiance per unit area here?

Key fact 2:

At top-of-atmosphere the incoming solar radiation ("short-wave") and the outgoing radiation from Earth ("long-wave") are nearly perfectly separated (!)

- This means the frequency tells us whether the radiation originated from the Sun or not.

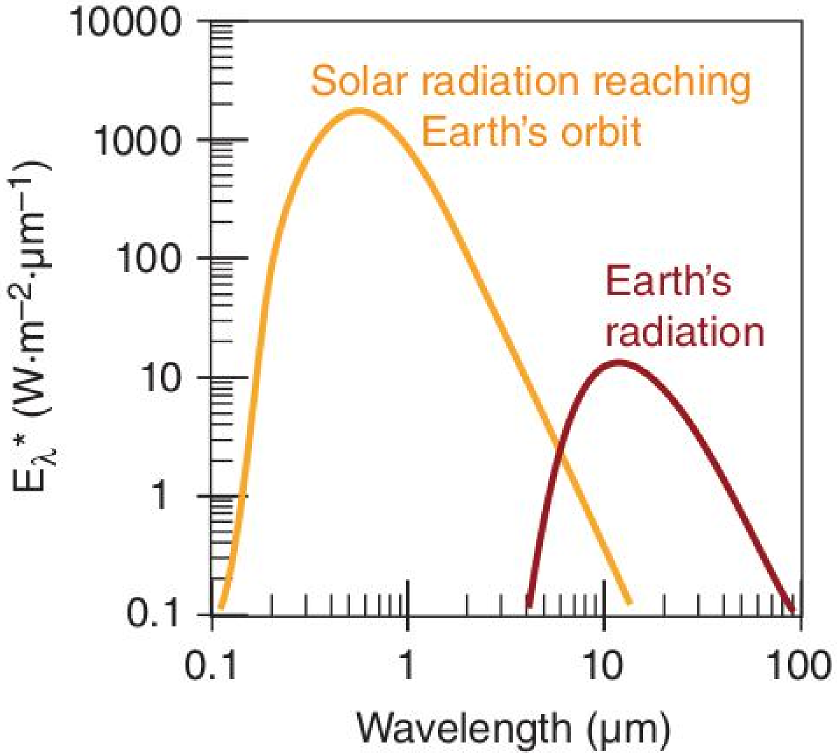

Figure 2.10
Blackbody radiance E reaching top of Earth's atmosphere from the sun and radiance of terrestrial radiation leaving the top of the atmosphere, plotted on a log-log graph.*

Emmision of radiation, Sun vs Earth

At top-of-atmosphere (TOA) we're quite far from the Sun :)

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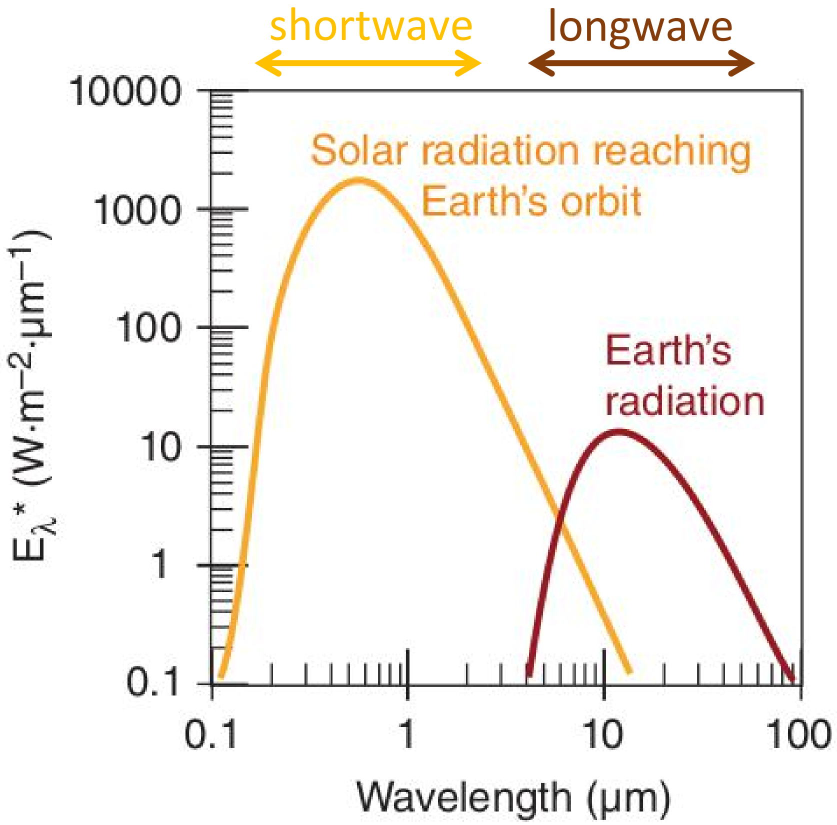

Figure 2.10
Blackbody radiance E reaching top of Earth's atmosphere from the sun and radiance of terrestrial radiation leaving the top of the atmosphere, plotted on a log-log graph.*

Satellite observation frequency-bands

Table 8-2. Advanced Baseline Imager (ABI) channels/bands on USA GOES-16 weather satellite. WV = water vapor. IR = infrared.
• Popular old GOES-15 channels for visible, WV & IR.

Channel #	Nickname of the Spectral Band	Center Wavelength (µm)	Wavelength Range (µm)
1	visible blue	0.47	0.45 - 0.49
2•	visible red	0.64	0.59 - 0.69
3	"veggie"	0.865	0.846 - 0.885
4	cirrus	1.378	1.371 - 1.386
5	snow/ice	1.61	1.58 - 1.64
6	cloud-particle size	2.25	2.225 - 2.275
7	shortwave IR window	3.90	3.80 - 4.00
8•	high troposphere WV	6.19	5.77 - 6.6
9	mid-troposphere WV	6.95	6.75 - 7.15
10	low-troposphere WV	7.34	7.24 - 7.44
11	cloud-top phase	8.5	8.3 - 8.7
12	ozone	9.61	9.42 - 9.8
13•	surface & cloud IR	10.35	10.1 - 10.6
14	longwave IR window	11.2	10.8 - 11.6
15	dirty-window IR	12.3	11.8 - 12.8
16	carbon dioxide	13.3	13.0 - 13.6

Table 8-3. Imager channels on European MSG-3 (Meteosat-10) weather satellite. VIS = visible. NIR = near infrared. IR = infrared. WV = water vapor.

Channel #	Name	Center Wavelength (µm)	Wavelength Range (µm)
1	VIS 0.6 (visible orange)	0.635	0.56 - 0.71
2	VIS 0.8 (deep red)	0.81	0.74 - 0.88
3	NIR 1.6 (near IR)	1.64	1.50 - 1.78
4	IR 3.9	3.90	3.48 - 4.36
5	WV 6.2 (water vapor: high trop.)	6.25	5.35 - 7.15
6	WV 7.3 (water vapor: mid-trop.)	7.35	6.85 - 7.85
7	IR 8.7	8.70	8.30 - 9.10
8	IR 9.7 (ozone)	9.66	9.38 - 9.94
9	IR 10.8	10.80	9.80 - 11.8
10	IR 12.0	12.00	11.0 - 13.0
11	IR 13.4 (high-troposphere)	13.40	12.4 - 14.4
12	HRV (high-resolution visible)	broad-band	0.4 - 1.1

- Satellites measure radiation within discrete frequency intervals (frequency-bands)
- Why is this?
- How are these bands picked?

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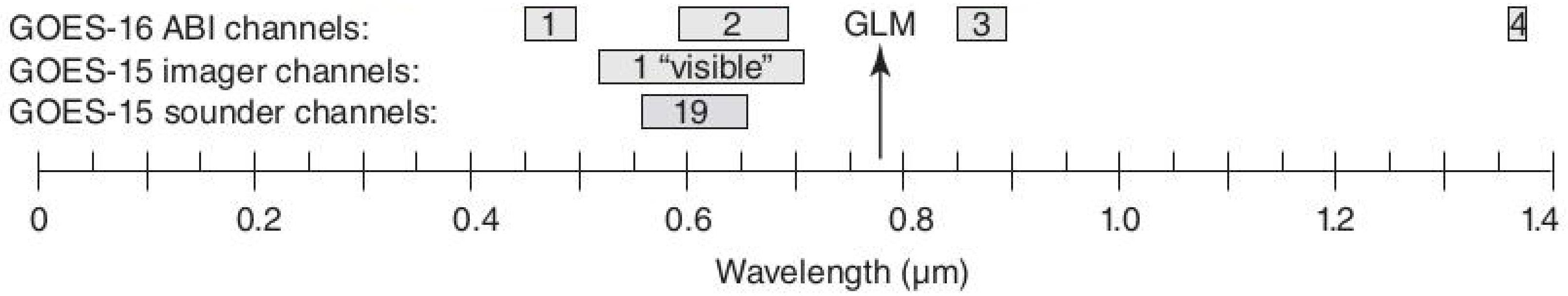
- Satellites measure radiation within discrete frequency intervals (frequency-bands)
- Why is this?
- How are these bands picked?
  - Key fact 3:
    Different things in the atmosphere absorb radiation to a different degree dependent on frequency

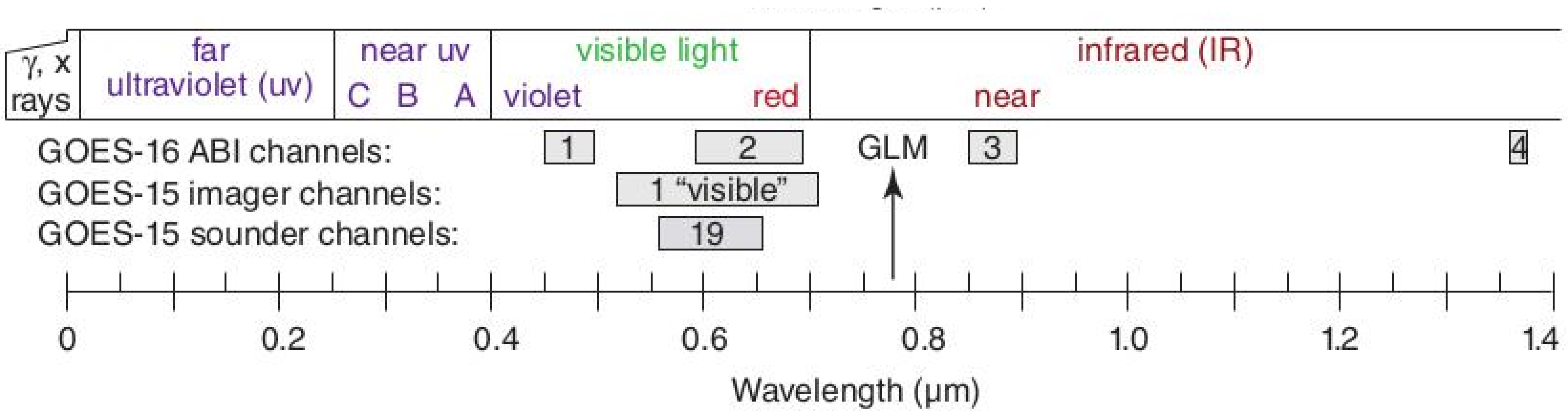
“short-wave” frequency range

- The first three channels of GOES-16 sit in the “short-wave” range
- This radiation is primarily reflected sun light

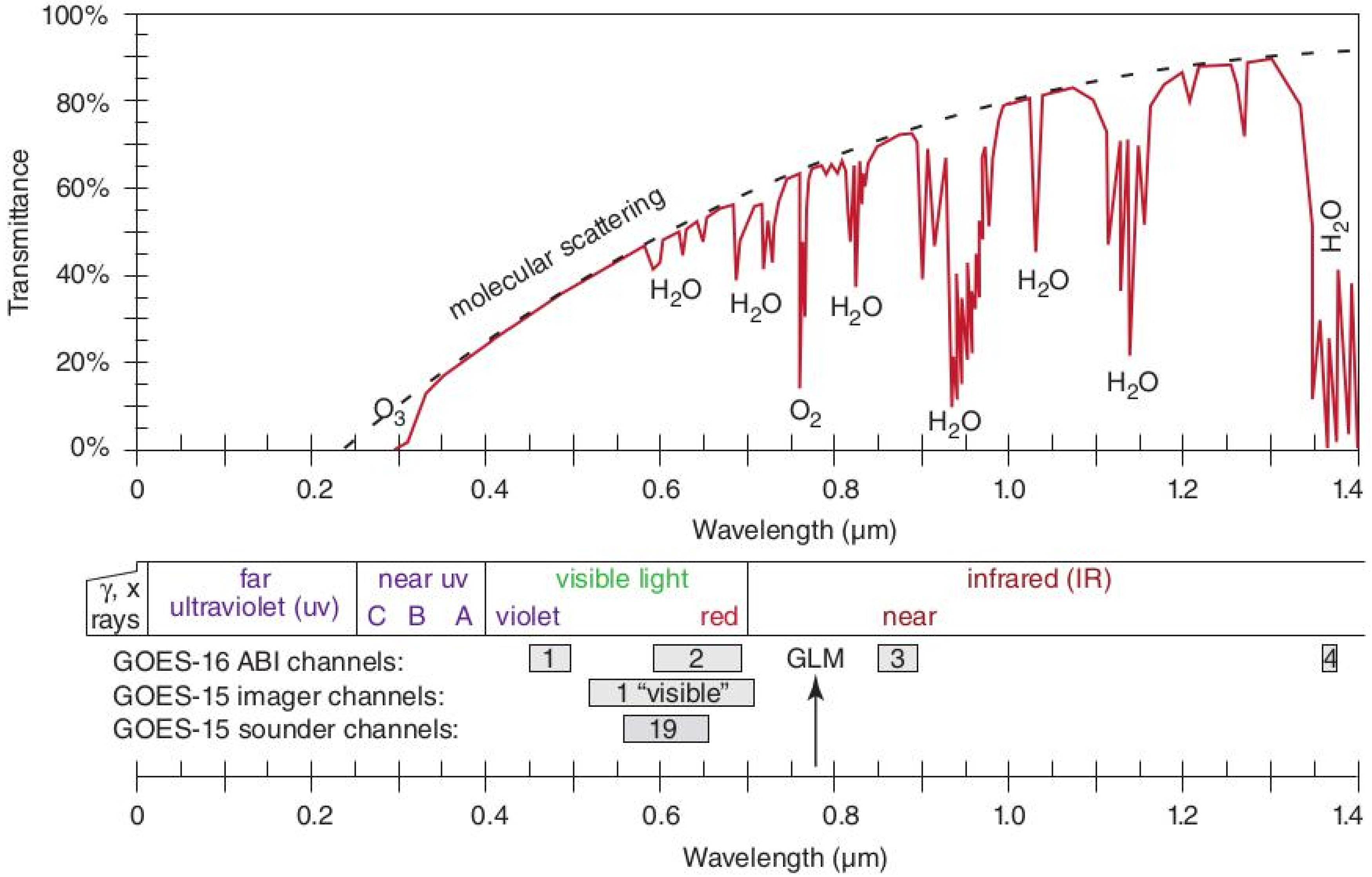


“short-wave” frequency range

- The first three channels of GOES-16 sit in the “short-wave” range
- This radiation is primarily reflected sun light
- From these observations we can reconstruct what you would see from space (with the three red, green and blue sensitive cones in your eye)

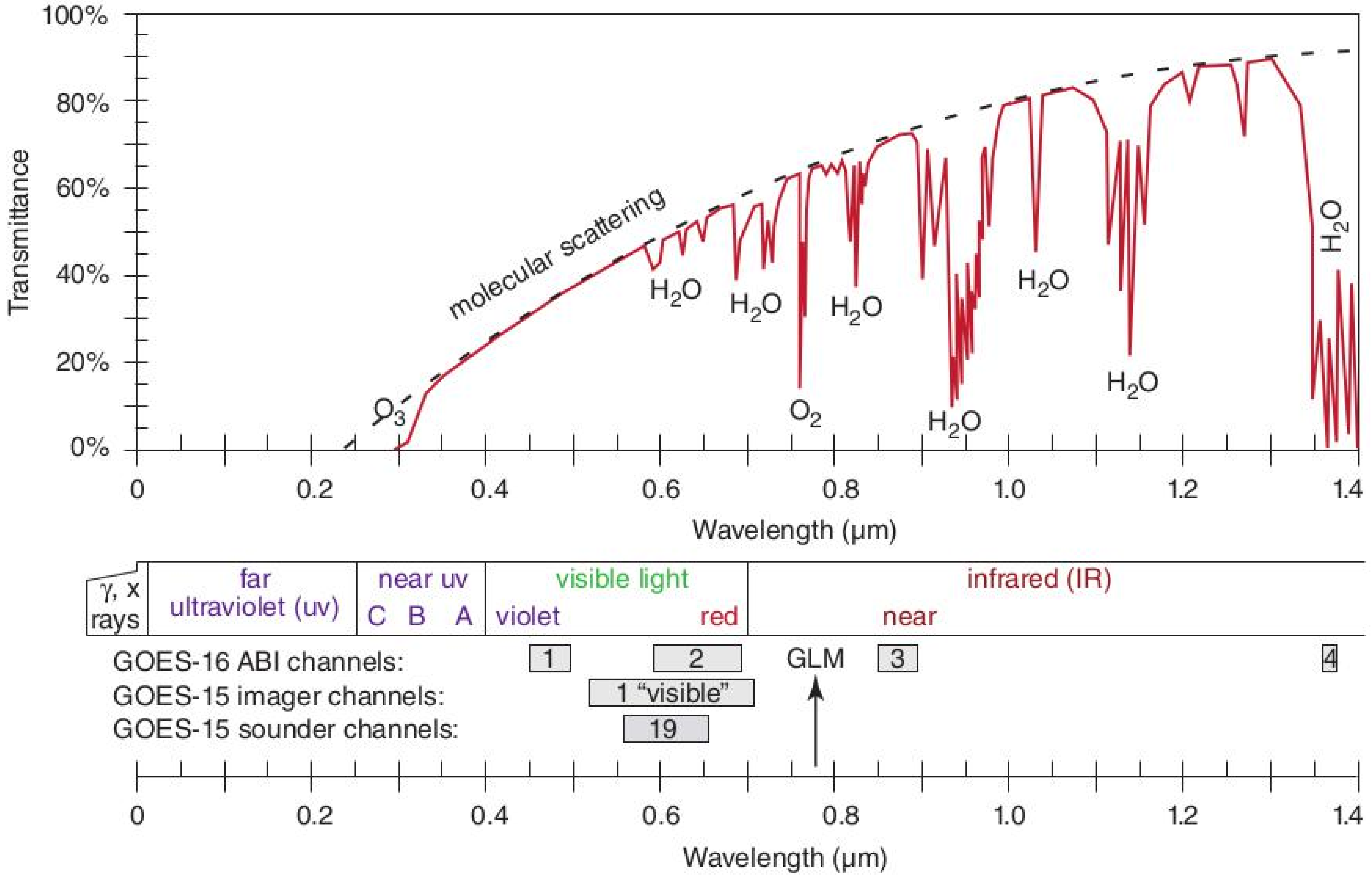


“short-wave” frequency range



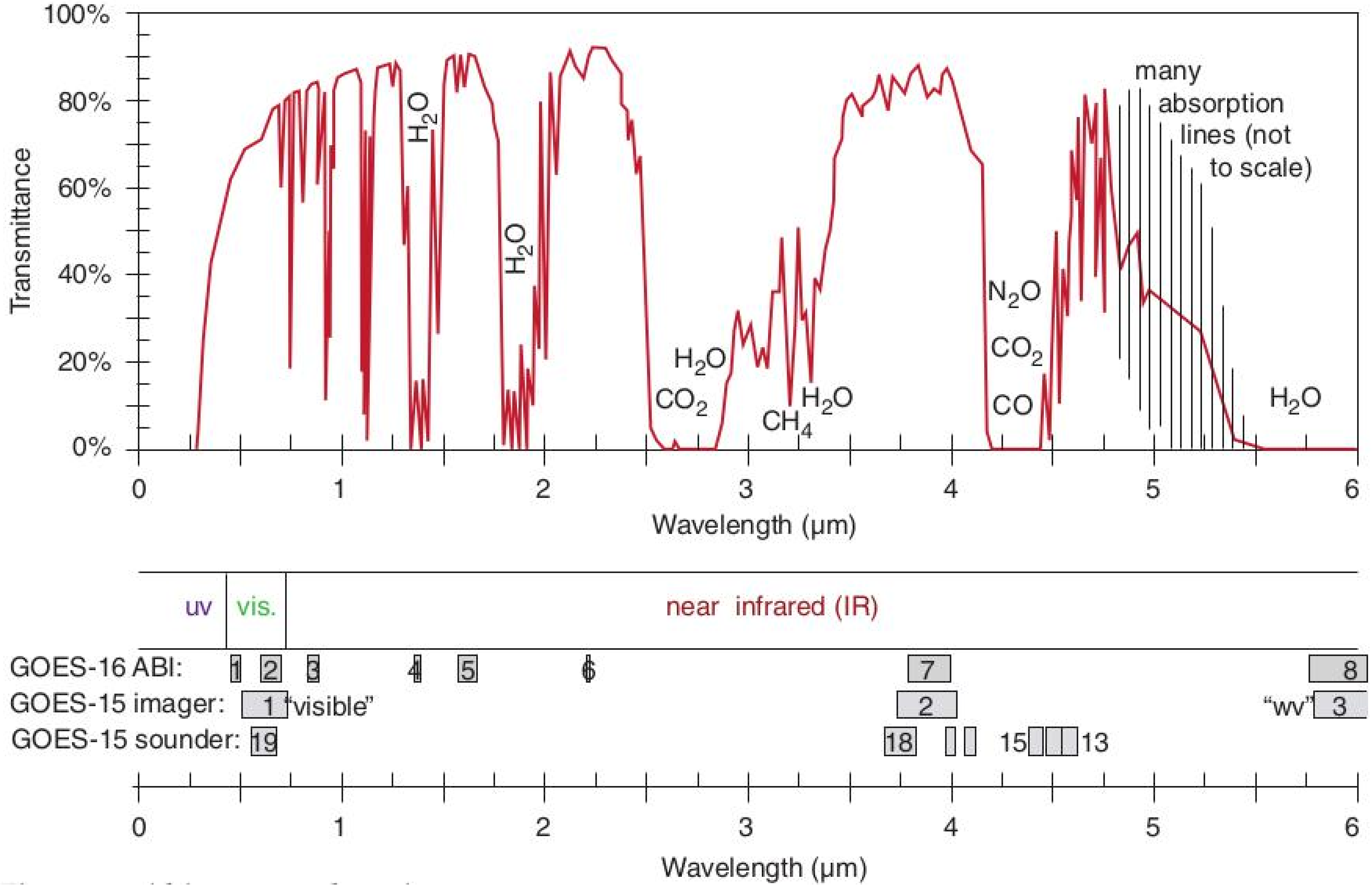
- Above the UV range the atmosphere lets a smoothly increasing amount of radiation through (no spectral lines)

“short-wave” frequency range



- Above the UV range the atmosphere lets a smoothly increasing amount of radiation through (no spectral lines)
- Above this wavelength different molecules absorb because of excited modes of motion (rotation, vibration, etc)

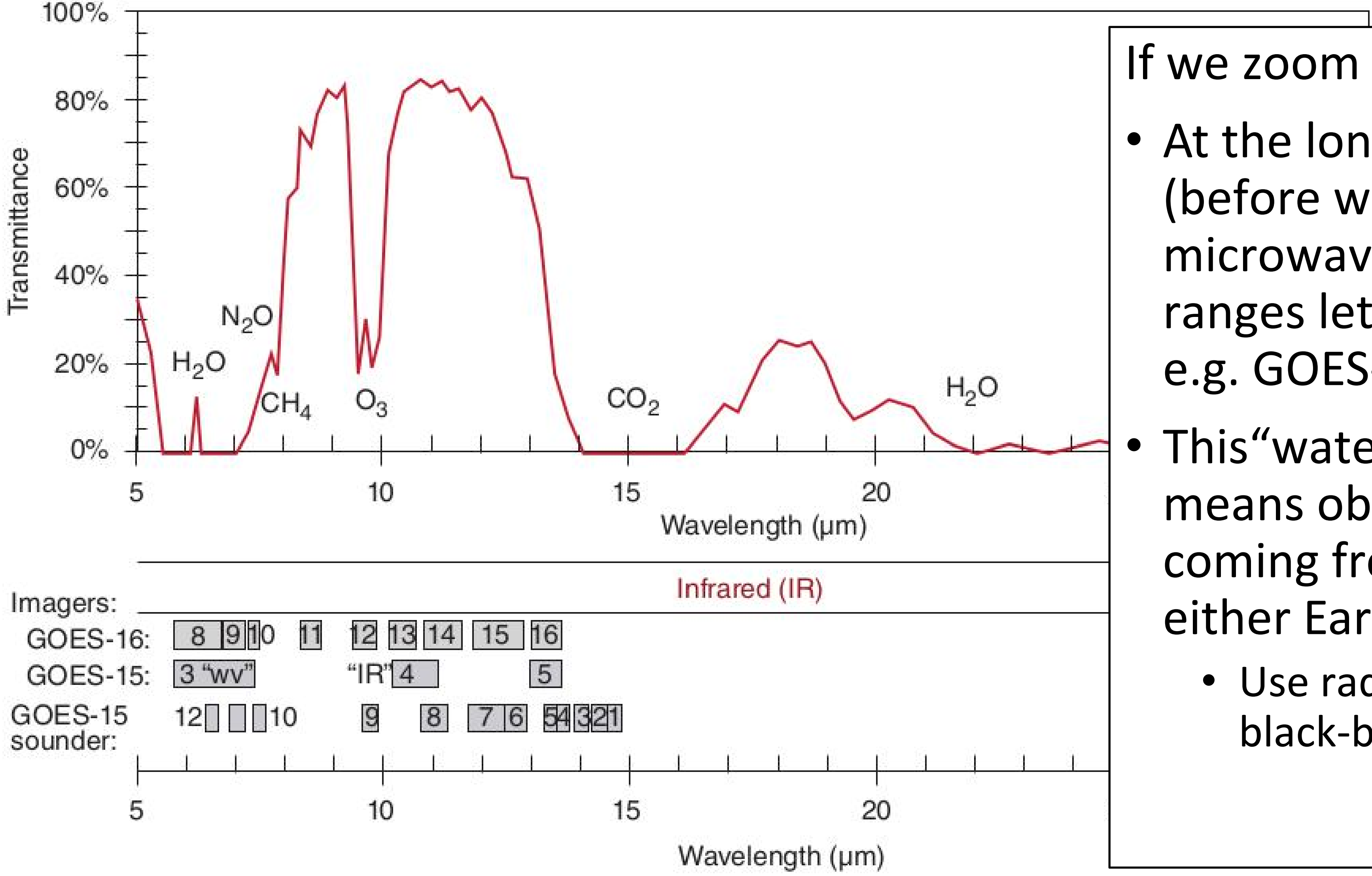
near-infrared, shortest “long-wave”



If we zoom out:

- At longer wavelengths (source of radiation is now Earth) there are many frequency ranges where radiation is blocked by the atmosphere (!)
  - We can use the presense/absence of radiation to infer the concentration of species

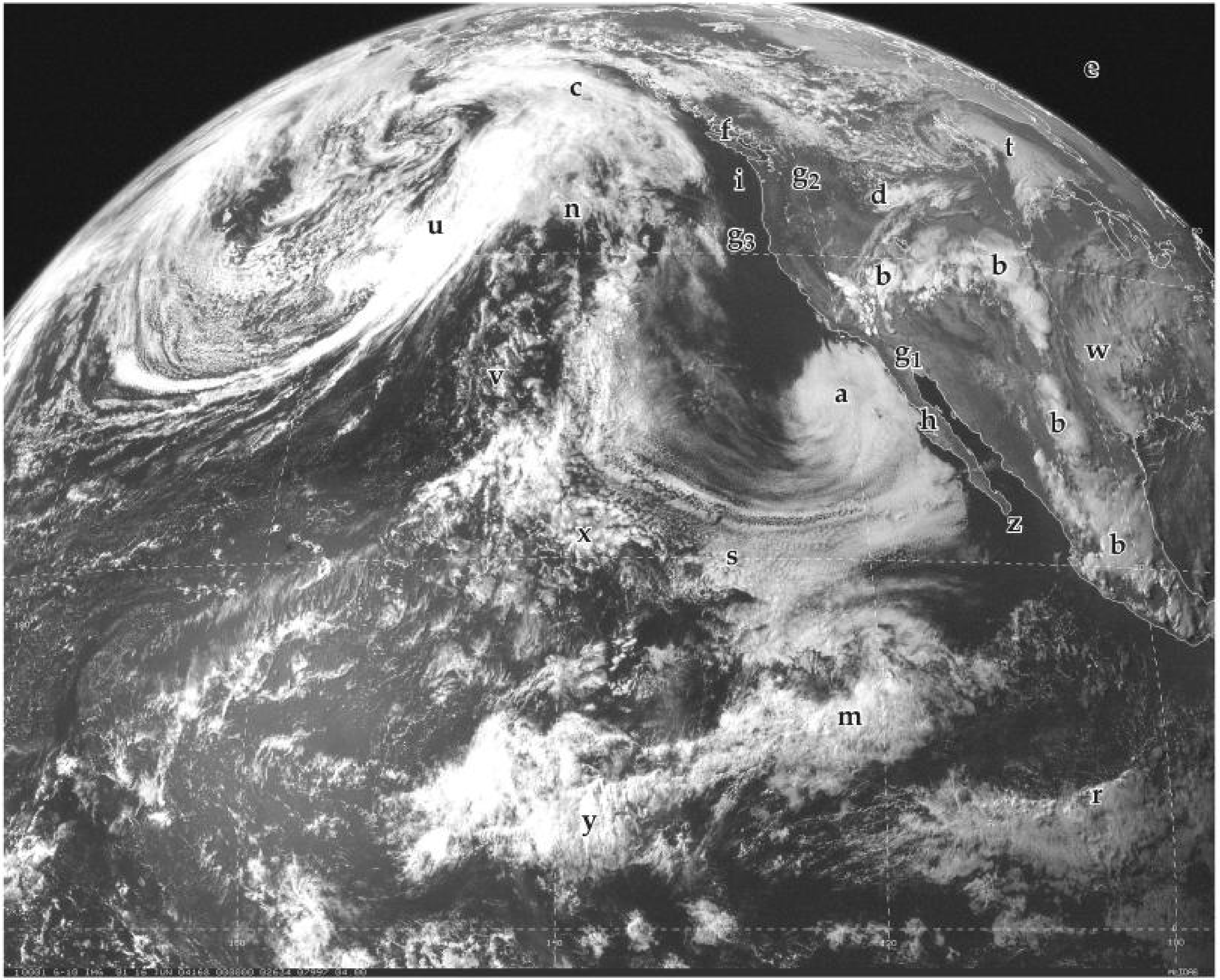
longer "long-wave"



If we zoom out:

- At the longest wavelengths (before we reach (far infrared and microwaves) some frequency ranges let through radiation again, e.g. GOES-16 channel 13
- This"water-vapour window" means observed radiation is coming from radiating body (e.g. either Earth's surface or clouds)
  - Use radiation intensity to estimate black-body radiation temperature

Visible frequency example

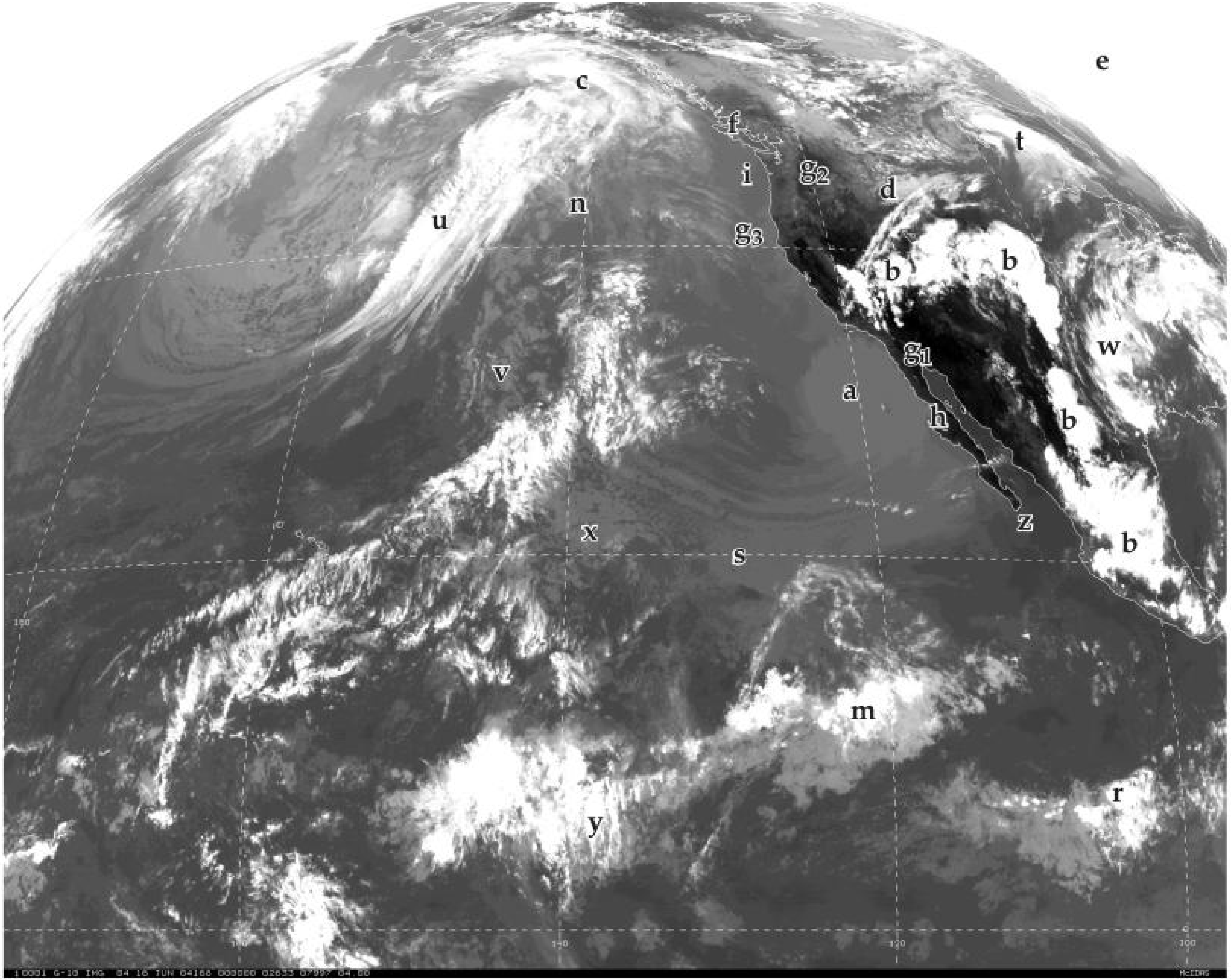


(channel 2, 0.64um, "red")

- Shows what you would see with your eye from space
- Reflection of the Sun's incoming radiation

Space Science & Engineering Center, Univ. of Wisconsin-Madison.
Valid time: 00UTC on 16 June 2004.

Infrared frequency example

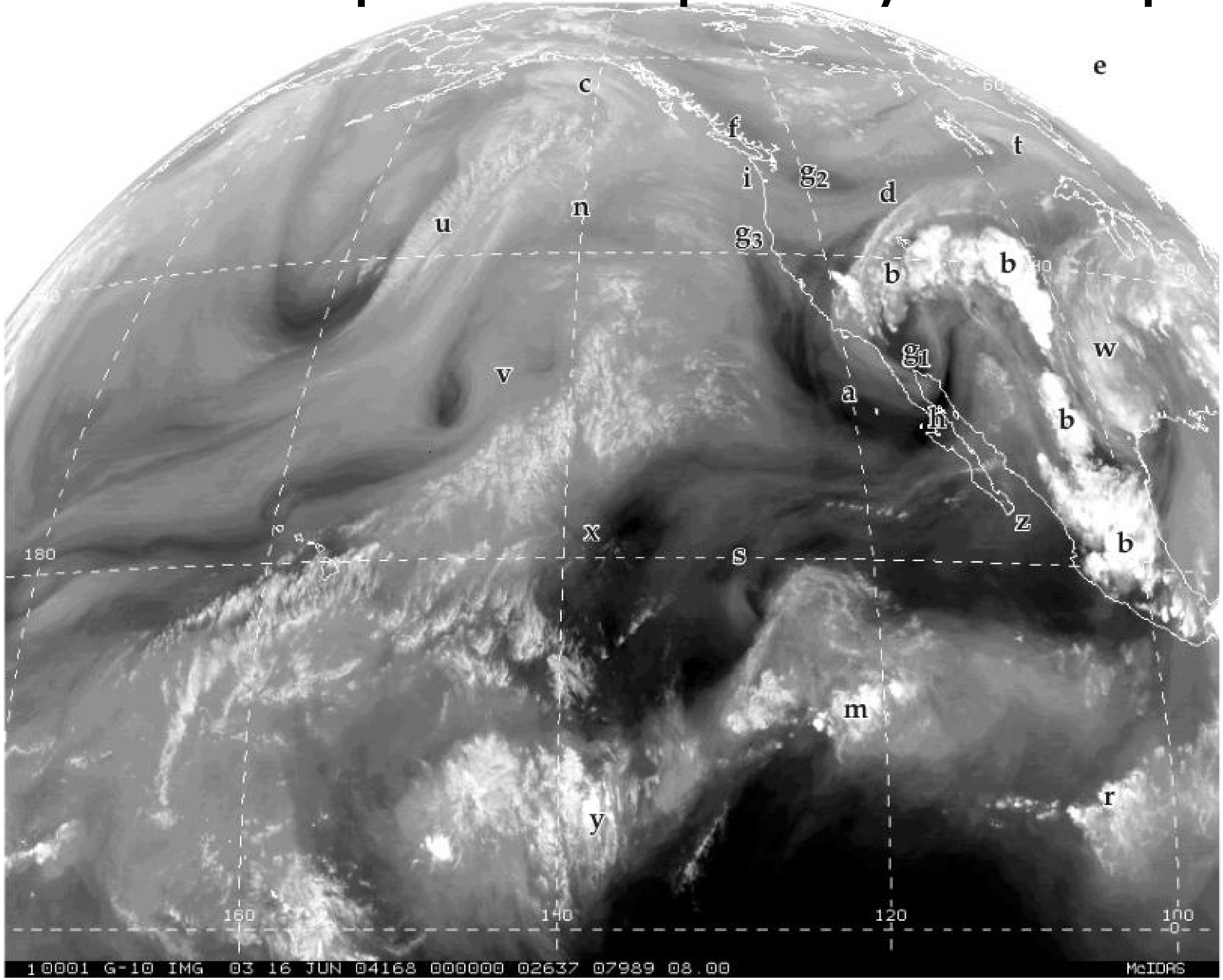


(channel 13, 10.35um, "surface & cloud IR")

- In tranmission "window" so we can see through the atmosphere, to the surface or highest cloud-top
  - Can infer temperature of radiating body (black-body temperature)
- NB: These are usually plotted with lowest radiation as we're used to clouds being white

Space Science & Engineering Center, Univ. of Wisconsin-Madison.
Valid time: 00UTC on 16 June 2004.

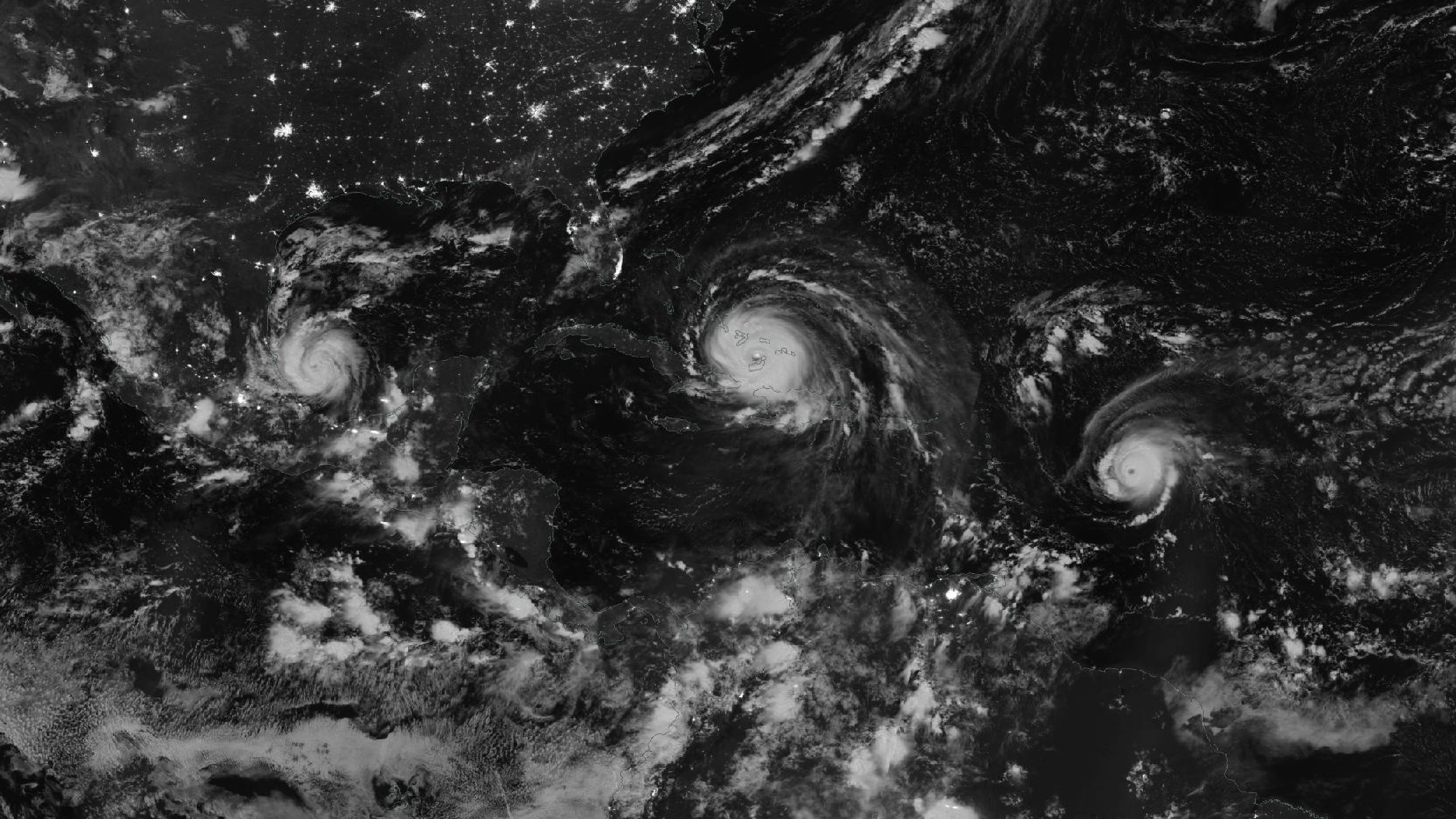
Water-vapour frequency example

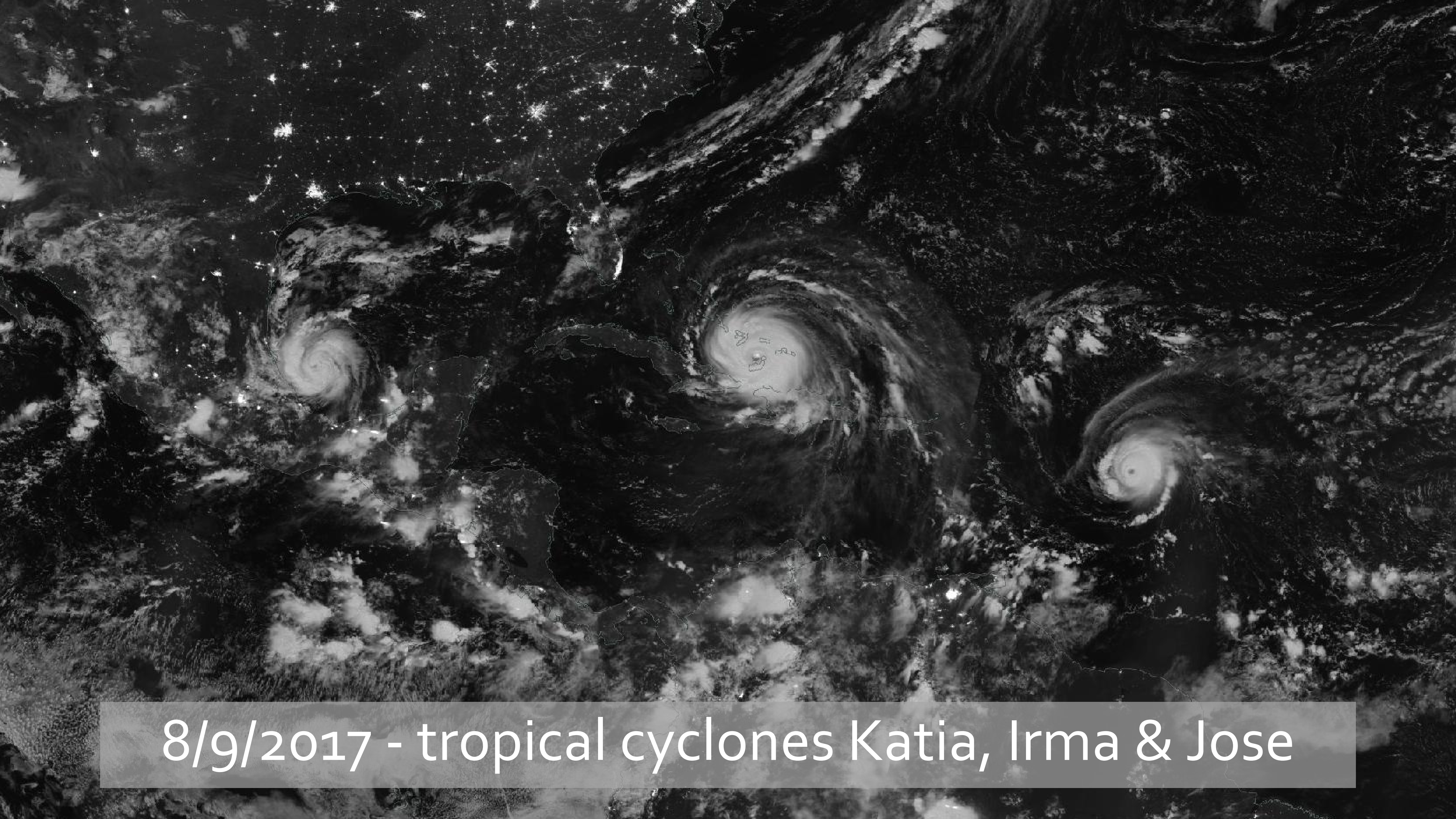


(channel 8, 6.19um, "high troposphere water vapour")

- Not in water-vapour window
- With low concentrations of water vapour see radiation from warm surface
- Higher water vapour concentration blocks radiation and re-radiates at lower temperature

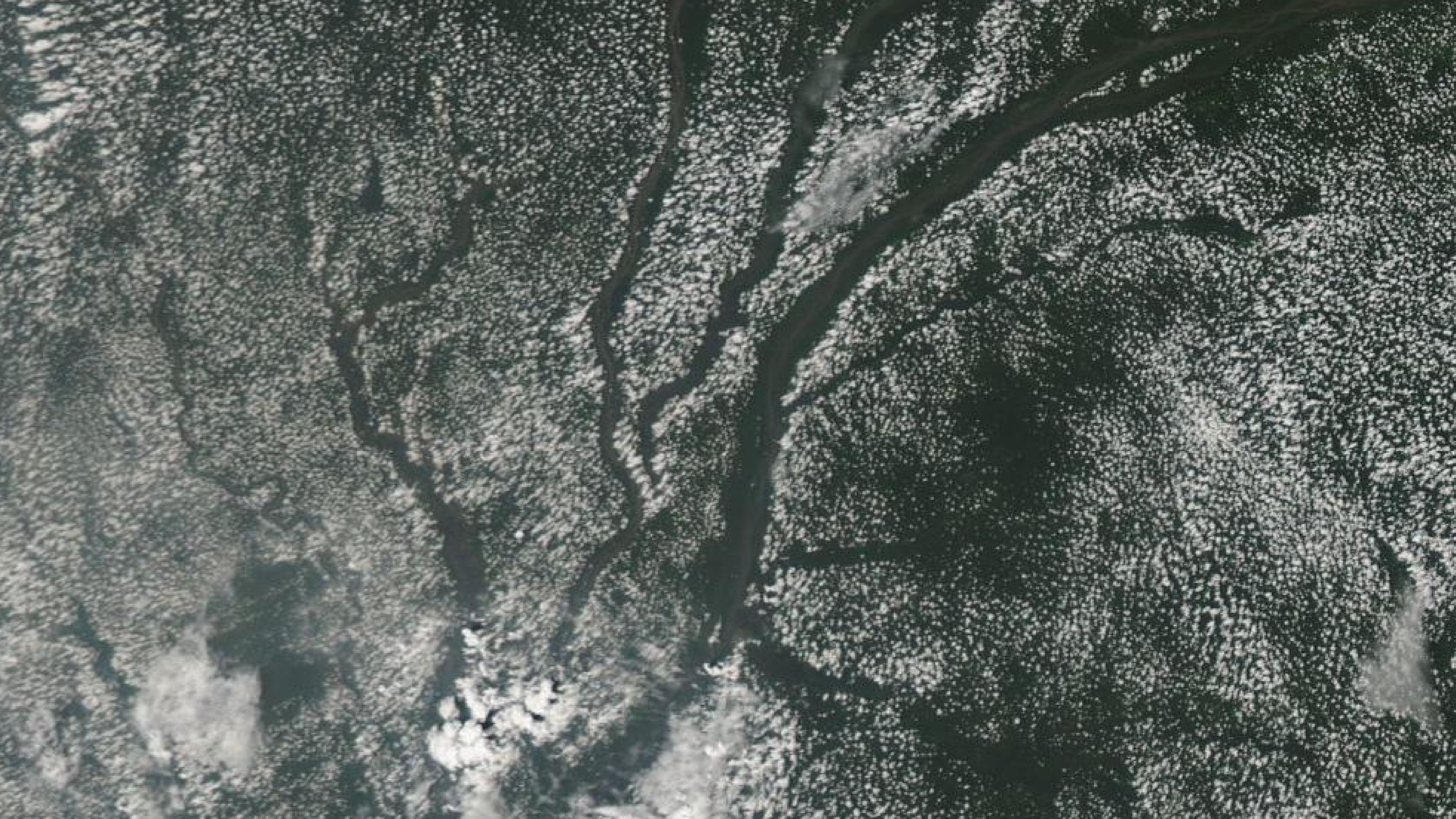
Space Science & Engineering Center, Univ. of Wisconsin-Madison.
Valid time: 00UTC on 16 June 2004.





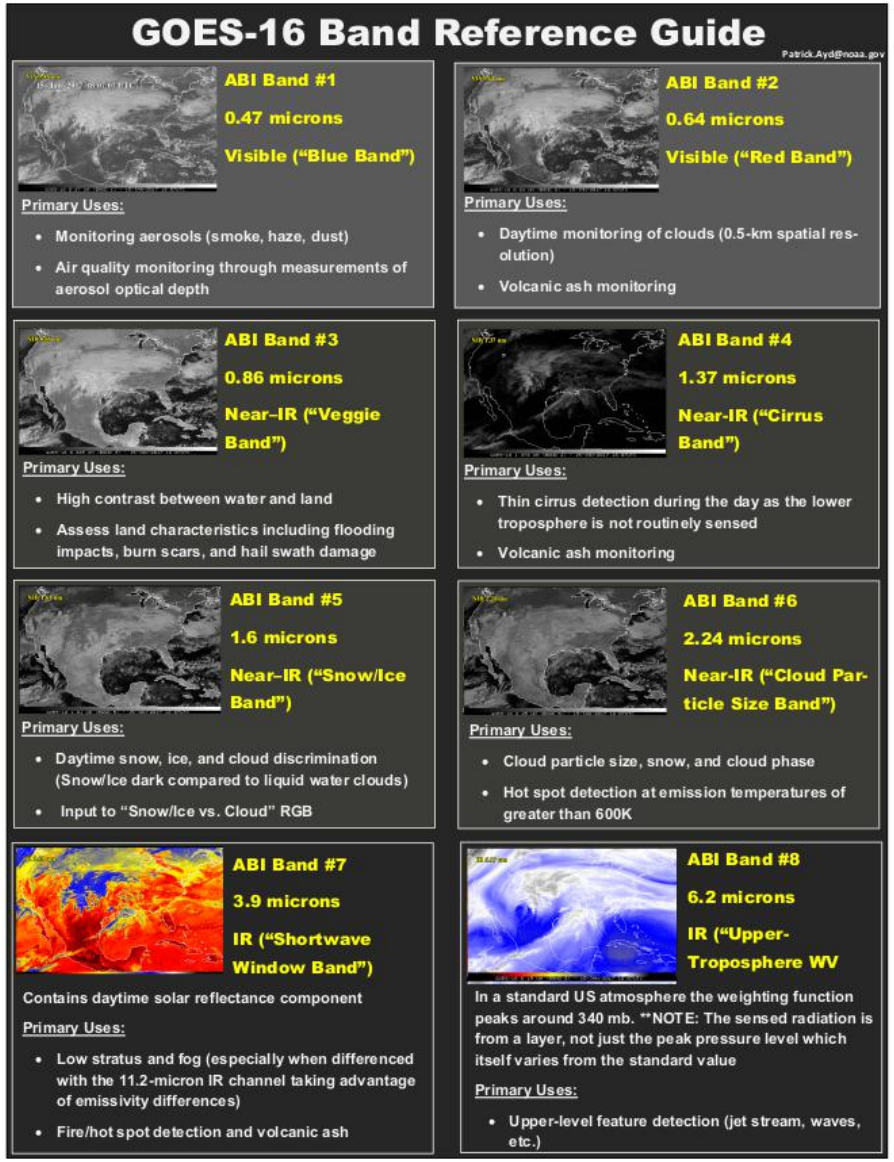
8/9/2017 - tropical cyclones Katia, Irma & Jose

11/5/2019 - California Stato-Cumulus



23/12/2019 - Cumulus in Congo Basin

Specific frequencies address resonances of specific species in the atmosphere



GOES-16 Band Reference Guide

Patrick.Ayd@noaa.gov

ABI Band #1
0.47 microns
Visible ("Blue Band")

Primary Uses:

- Monitoring aerosols (smoke, haze, dust)
- Air quality monitoring through measurements of aerosol optical depth

ABI Band #2
0.64 microns
Visible ("Red Band")

Primary Uses:

- Daytime monitoring of clouds (0.5-km spatial resolution)
- Volcanic ash monitoring

ABI Band #3
0.86 microns
Near-IR ("Veggie Band")

Primary Uses:

- High contrast between water and land
- Assess land characteristics including flooding impacts, burn scars, and hail swath damage

ABI Band #4
1.37 microns
Near-IR ("Cirrus Band")

Primary Uses:

- Thin cirrus detection during the day as the lower troposphere is not routinely sensed
- Volcanic ash monitoring

ABI Band #5
1.6 microns
Near-IR ("Snow/Ice Band")

Primary Uses:

- Daytime snow, ice, and cloud discrimination (Snow/Ice dark compared to liquid water clouds)
- Input to "Snow/Ice vs. Cloud" RGB

ABI Band #6
2.24 microns
Near-IR ("Cloud Particle Size Band")

Primary Uses:

- Cloud particle size, snow, and cloud phase
- Hot spot detection at emission temperatures of greater than 600K

ABI Band #7
3.9 microns
IR ("Shortwave Window Band")

Contains daytime solar reflectance component

Primary Uses:

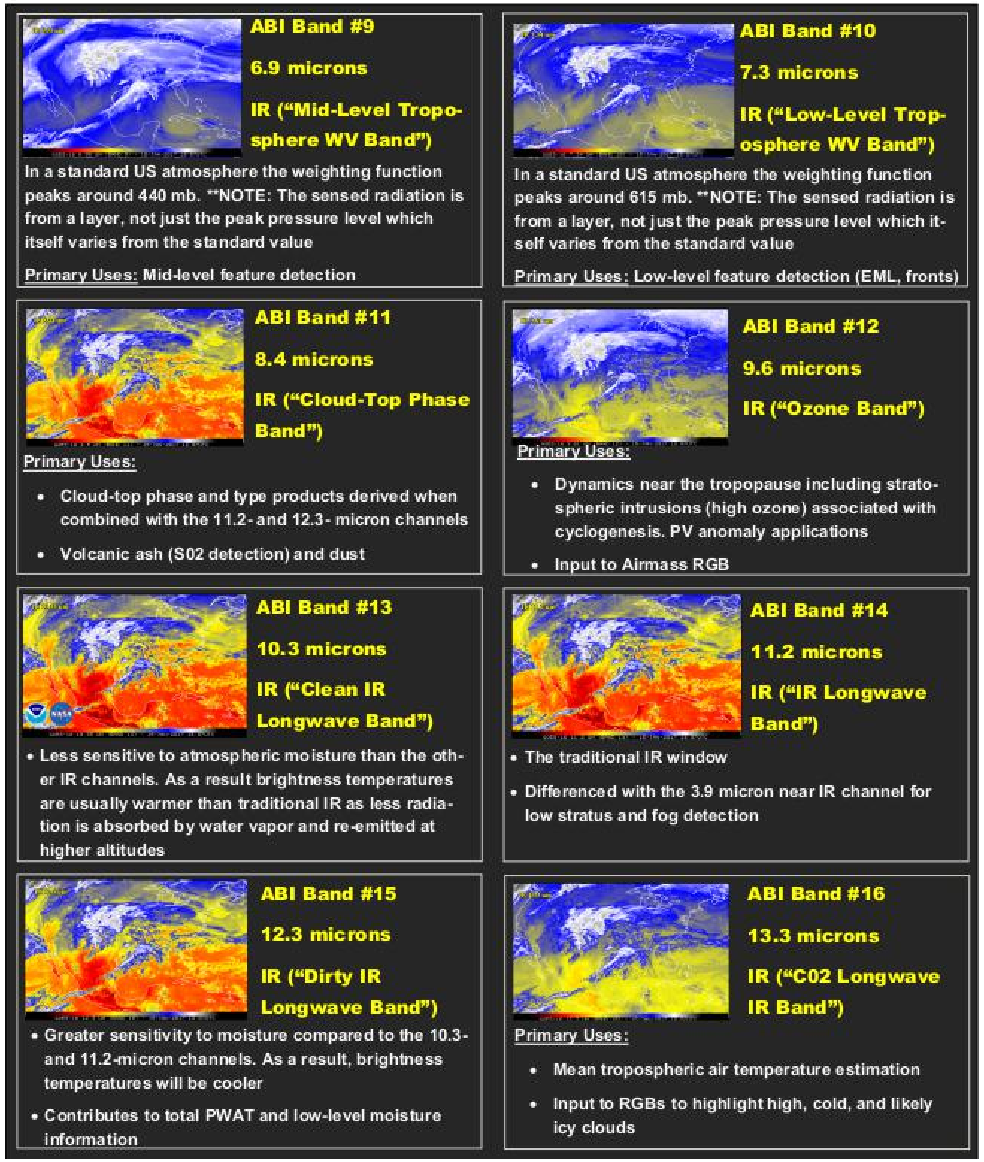
- Low stratus and fog (especially when differenced with the 11.2-micron IR channel taking advantage of emissivity differences)
- Fire/hot spot detection and volcanic ash

ABI Band #8
6.2 microns
IR ("Upper-Troposphere WV

In a standard US atmosphere the weighting function peaks around 340 mb. **NOTE: The sensed radiation is from a layer, not just the peak pressure level which itself varies from the standard value

Primary Uses:

- Upper-level feature detection (jet stream, waves, etc.)



ABI Band #9
6.9 microns
IR ("Mid-Level Troposphere WV Band")

In a standard US atmosphere the weighting function peaks around 440 mb. **NOTE: The sensed radiation is from a layer, not just the peak pressure level which itself varies from the standard value

Primary Uses: Mid-level feature detection

ABI Band #10
7.3 microns
IR ("Low-Level Troposphere WV Band")

In a standard US atmosphere the weighting function peaks around 615 mb. **NOTE: The sensed radiation is from a layer, not just the peak pressure level which itself varies from the standard value

Primary Uses: Low-level feature detection (EML, fronts)

ABI Band #11
8.4 microns
IR ("Cloud-Top Phase Band")

Primary Uses:

- Cloud-top phase and type products derived when combined with the 11.2- and 12.3- micron channels
- Volcanic ash (S02 detection) and dust

ABI Band #12
9.6 microns
IR ("Ozone Band")

Primary Uses:

- Dynamics near the tropopause including stratospheric intrusions (high ozone) associated with cyclogenesis. PV anomaly applications
- Input to Airmass RGB

ABI Band #13
10.3 microns
IR ("Clean IR Longwave Band")

- Less sensitive to atmospheric moisture than the other IR channels. As a result brightness temperatures are usually warmer than traditional IR as less radiation is absorbed by water vapor and re-emitted at higher altitudes

ABI Band #14
11.2 microns
IR ("IR Longwave Band")

- The traditional IR window
- Differenced with the 3.9 micron near IR channel for low stratus and fog detection

ABI Band #15
12.3 microns
IR ("Dirty IR Longwave Band")

- Greater sensitivity to moisture compared to the 10.3- and 11.2-micron channels. As a result, brightness temperatures will be cooler
- Contributes to total PWAT and low-level moisture information

ABI Band #16
13.3 microns
IR ("C02 Longwave IR Band")

Primary Uses:

- Mean tropospheric air temperature estimation
- Input to RGBs to highlight high, cold, and likely icy clouds

Read more in the GOES-16 documentation, there is some great science in there!

Passive remote sensing with satellites

- Frequency-range of visible and infrared neatly split into “short-wave” vs “long-wave”
  - possible because radiation intensity from Sun (short-wave) vs Earth (long-wave) at top-of-atmosphere nearly separate
- “short-wave” visible, measures
  - reflection of solar radiation
  - what we would see with our own eyes
  - only useful during daytime
- “long-wave”, measures
  - radiation from Earth surface, clouds, any physical body
  - in “water-vapour window” we can directly see this body, estimate its temperature
  - outside of “water-vapour window” can for example infer amount of water-vapour as water-vapour absorbs at these frequencies

Time to go find some clouds yourself!

:D

Time to go find some clouds yourself!

:D

See if you can find all these!
(this is a manifold of shallow convective organisation from inside a trianed neural network - I'll say more on Friday)