History of Atmospheric Science from Satellites

Lorraine Remer
UMBC

1. Long introduction
    - what is in the atmosphere
    - why do I care about the atmosphere
    - how do we measure atmospheric parameters
    - the concept of remote sensing
    - why size and wavelength matter
    - gaseous absorption
    - temperature profiles

2. The very beginning of satellite Earth observations belong to atmospheric science (1960 – 1964)

3. Weather satellite era (1964 – 2000)

4. The EOS era (2000 – 2022)

5. Links in the chain

Atmospheric Science

atmosphere

What is in the atmosphere?

Gases:

Nitrogen
Oxygen
Water vapor
Trace gases
(greenhouse gases)

Clouds:

Suspended water particles (liquid or ice)

Precipitation

Falling water particles (liquid or ice)

Aerosols:

Suspended non-water particles (liquid or solid)

Atmospheric Science

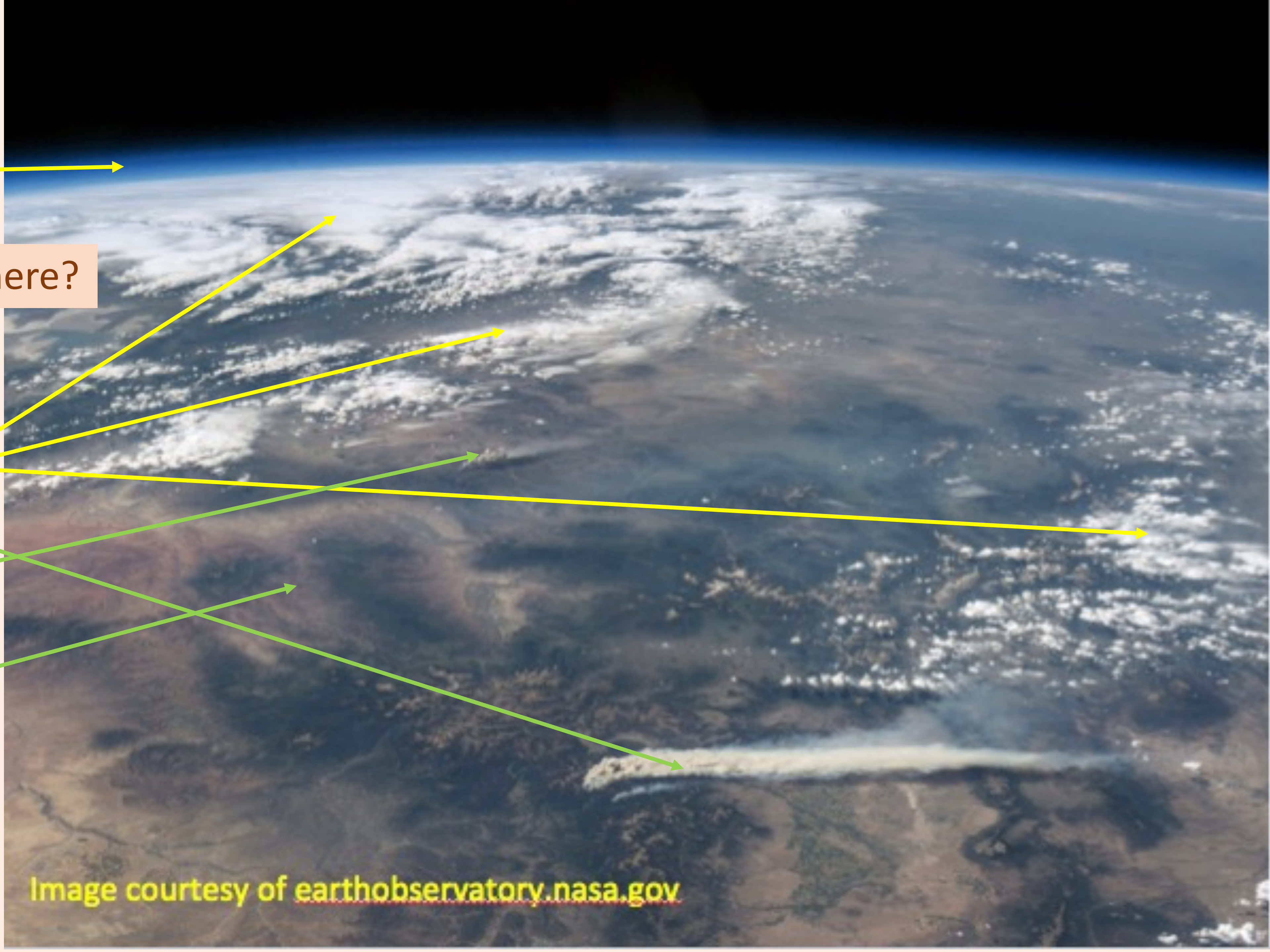
What is in the atmosphere?

gases

clouds

Smoke aerosol

Dust aerosol?



Why should I care about….?

Gases

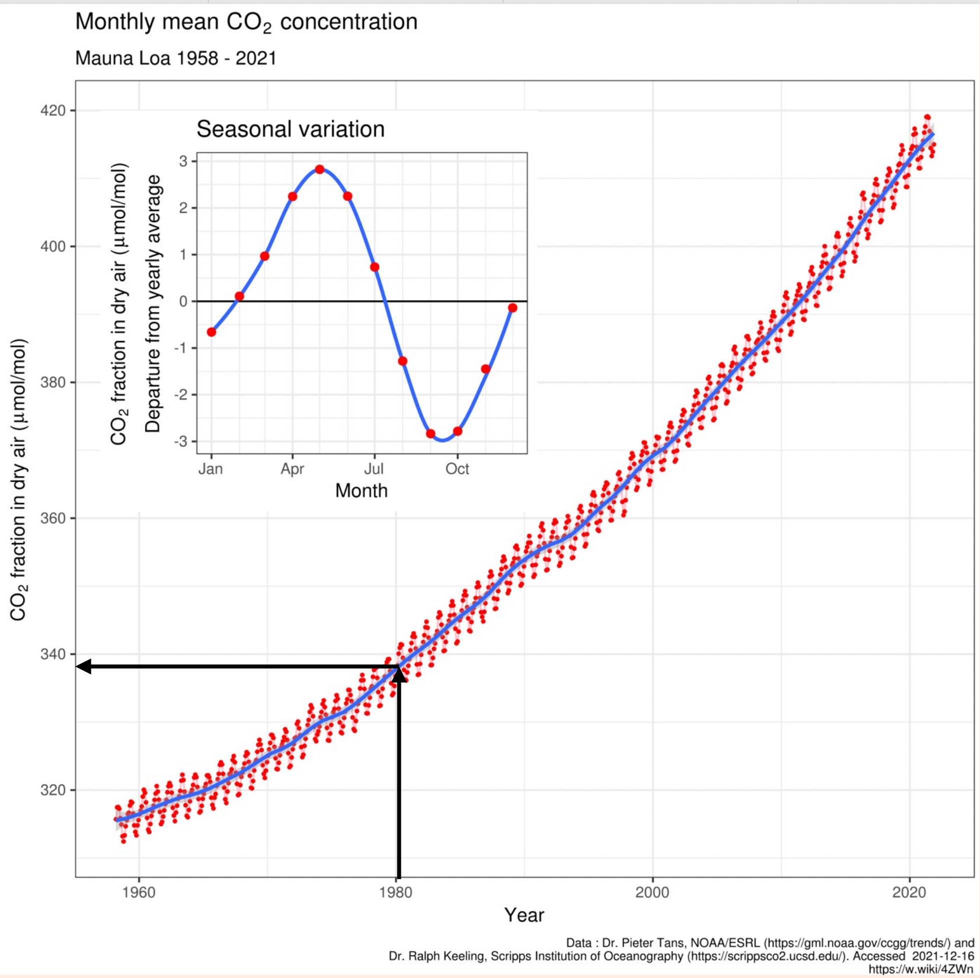
Clouds

Precipitation

Aerosols

Measuring atmospheric parameters

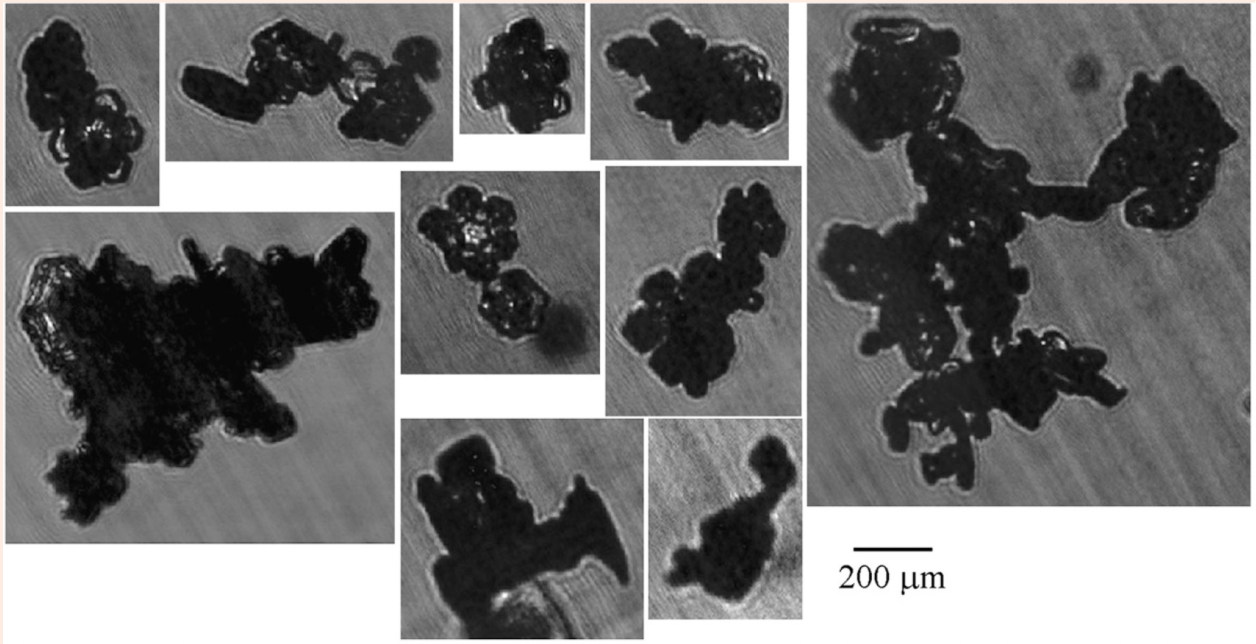
In situ gas measurements



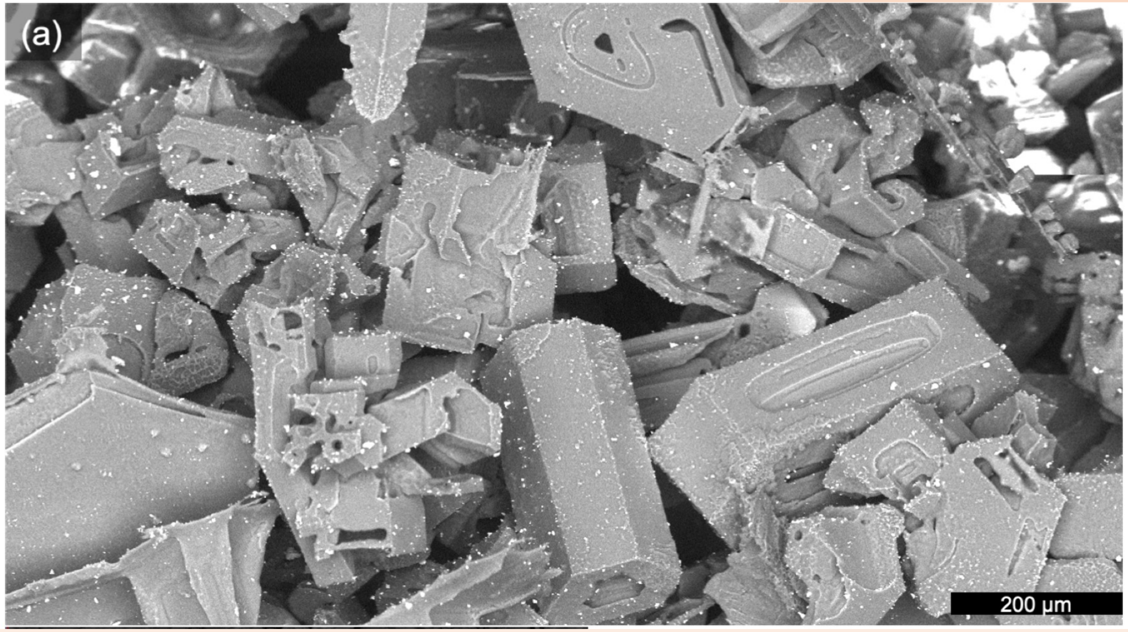
Measuring atmospheric parameters

In situ cloud measurements

Magee et al. 2021

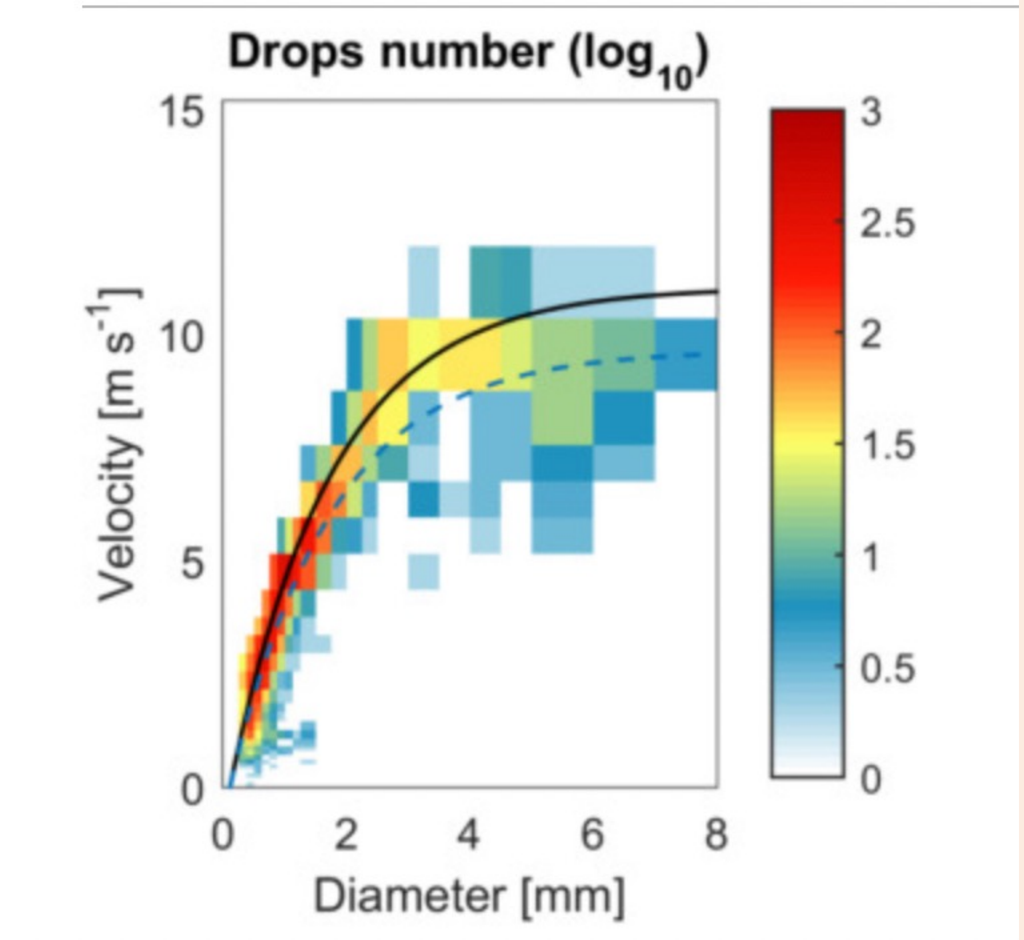


Schmitt and Heymsfield 2010



Measuring atmospheric parameters

In situ precipitation measurements

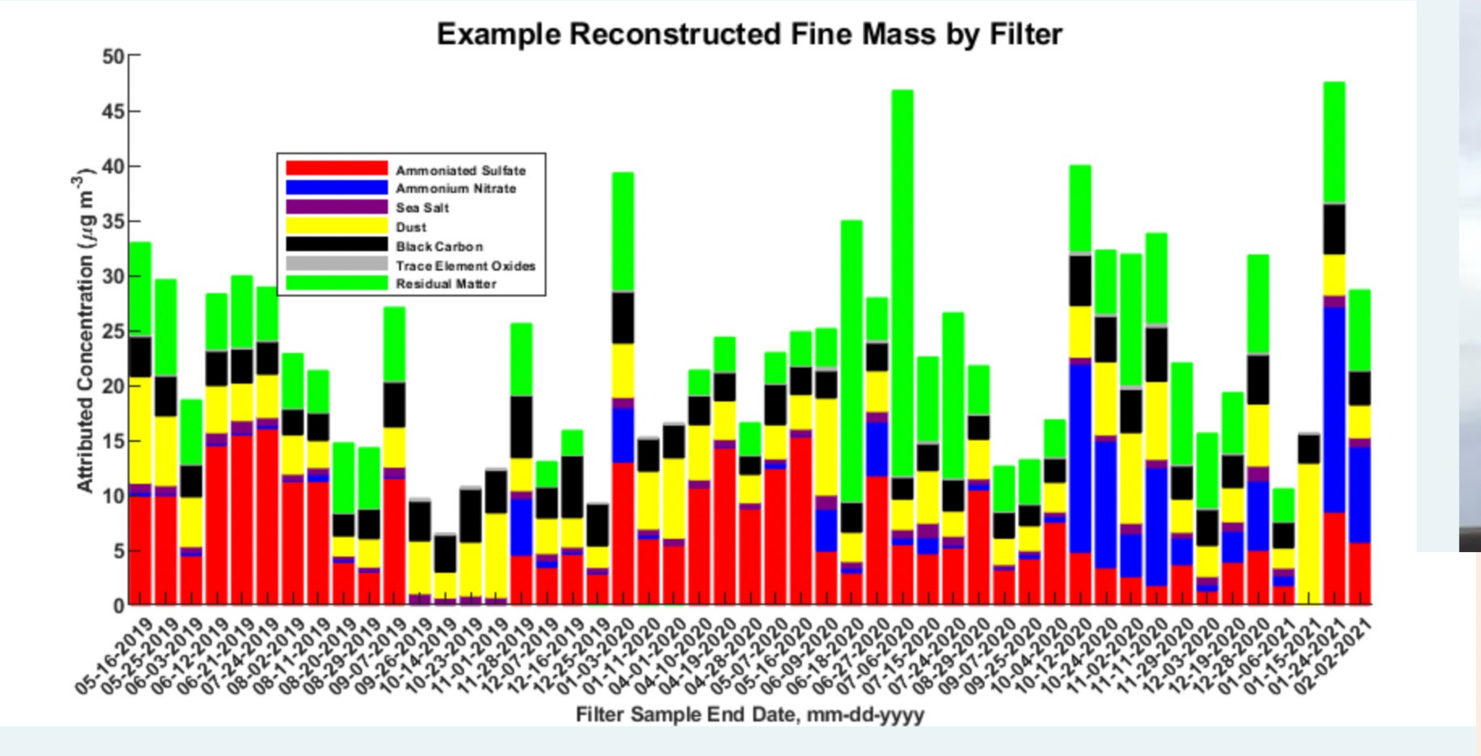


disdrometer

Valdivia et al. 2020

Measuring atmospheric parameters

In situ aerosol measurements



SPARTAN network, Beijing station.
Randall Martin, PI. AirPhoton instruments.
Disclosure Remer is an owner of AirPhoton.

Measuring aerosol

How much aerosol in that smoke plume?


2
INCHES
3
In Situ measurements
(Danny Bickford, age 9)

" You know,
at night, at a campfire, when I shine my flashlight on the smoke…"

D'Niel Speedone, age 9

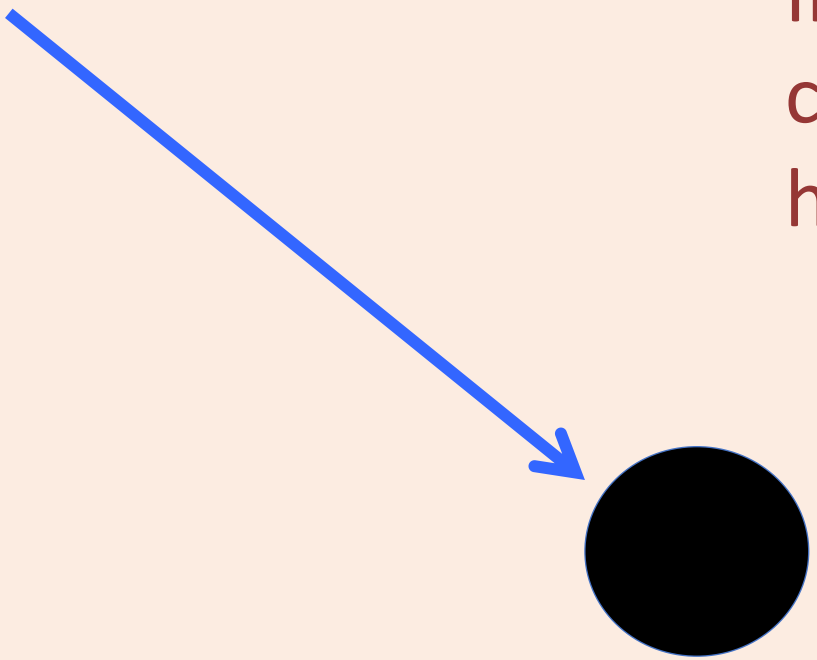
Remote sensing is the measurement made without sampling the substance. Generally, it uses the interaction of the substance with light or sound.

We are seeing here incident light (flashlight) Scattered back to the sensor (camera or eyes). The more smoke the more light scattered.

Suspended particles in the atmosphere both scatter and absorb light.

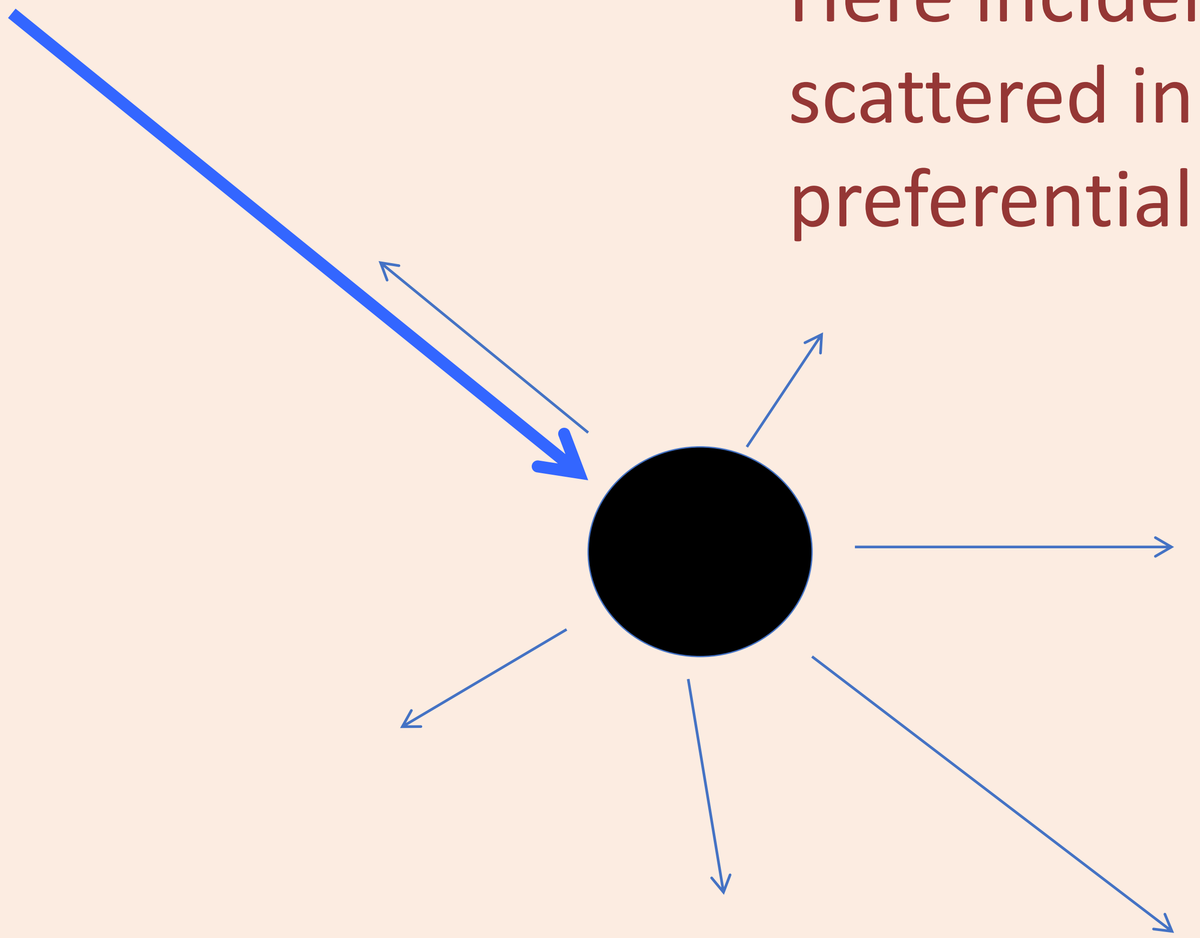
Difference between white and black smoke is the relative amount of how much light is scattered versus absorbed by the particles

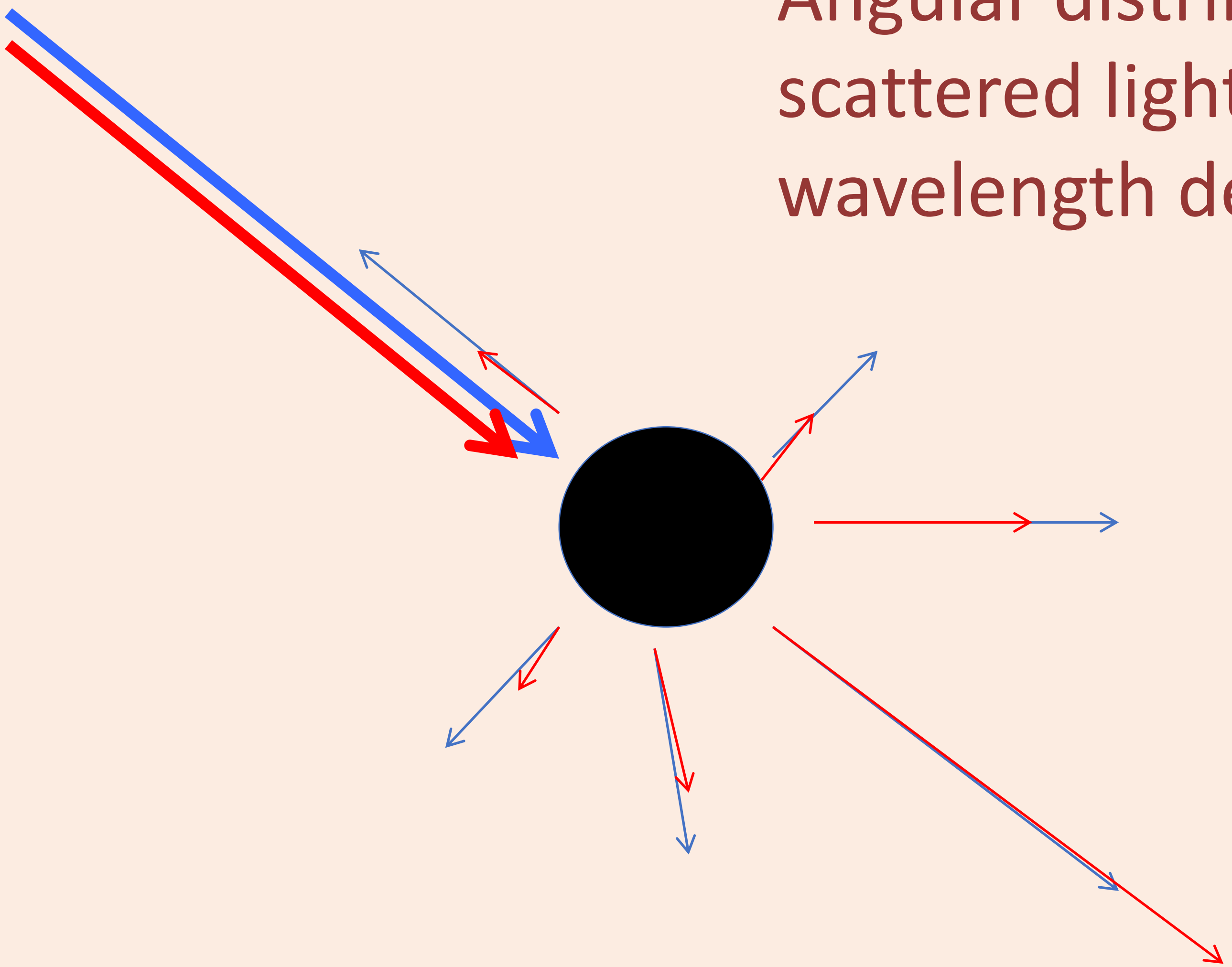
"Particles" denotes anything from molecules to aerosols to cloud droplets to precipitation



Incident light is completely absorbed here

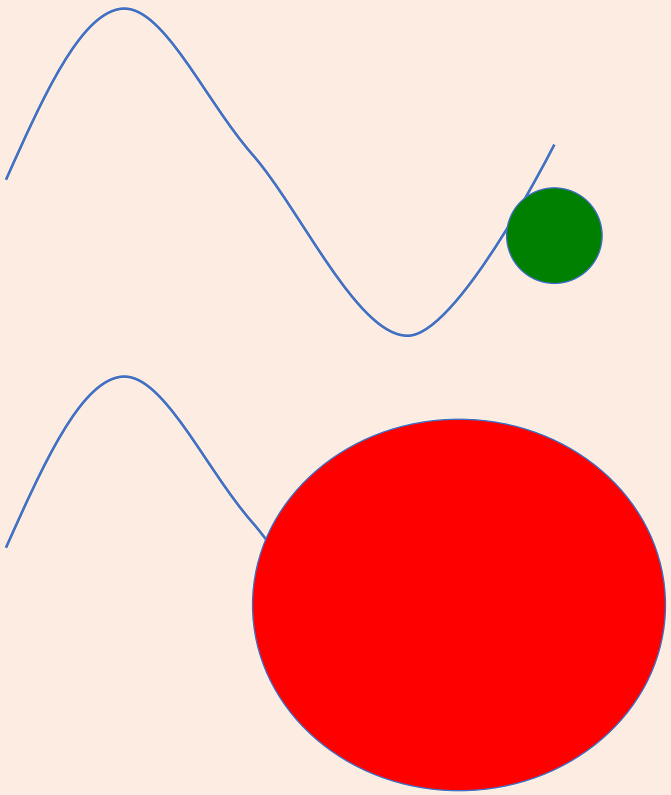
Here incident light is scattered in preferential directions

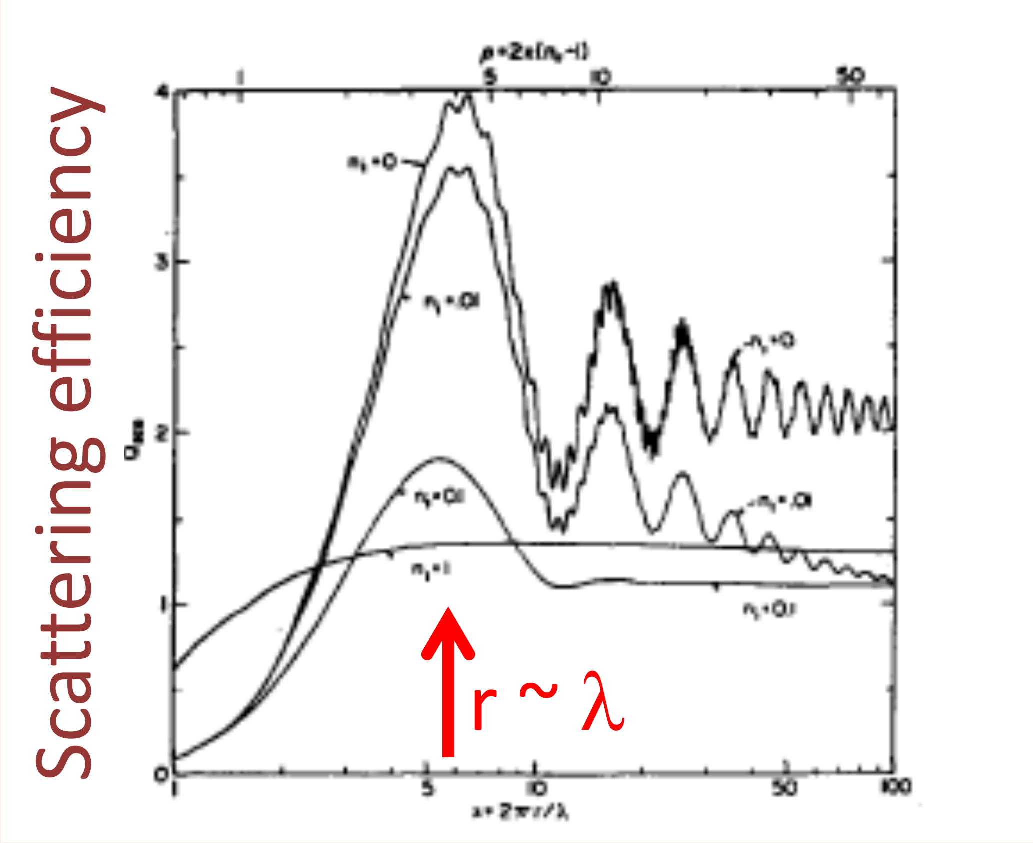




Angular distribution of scattered light is wavelength dependent

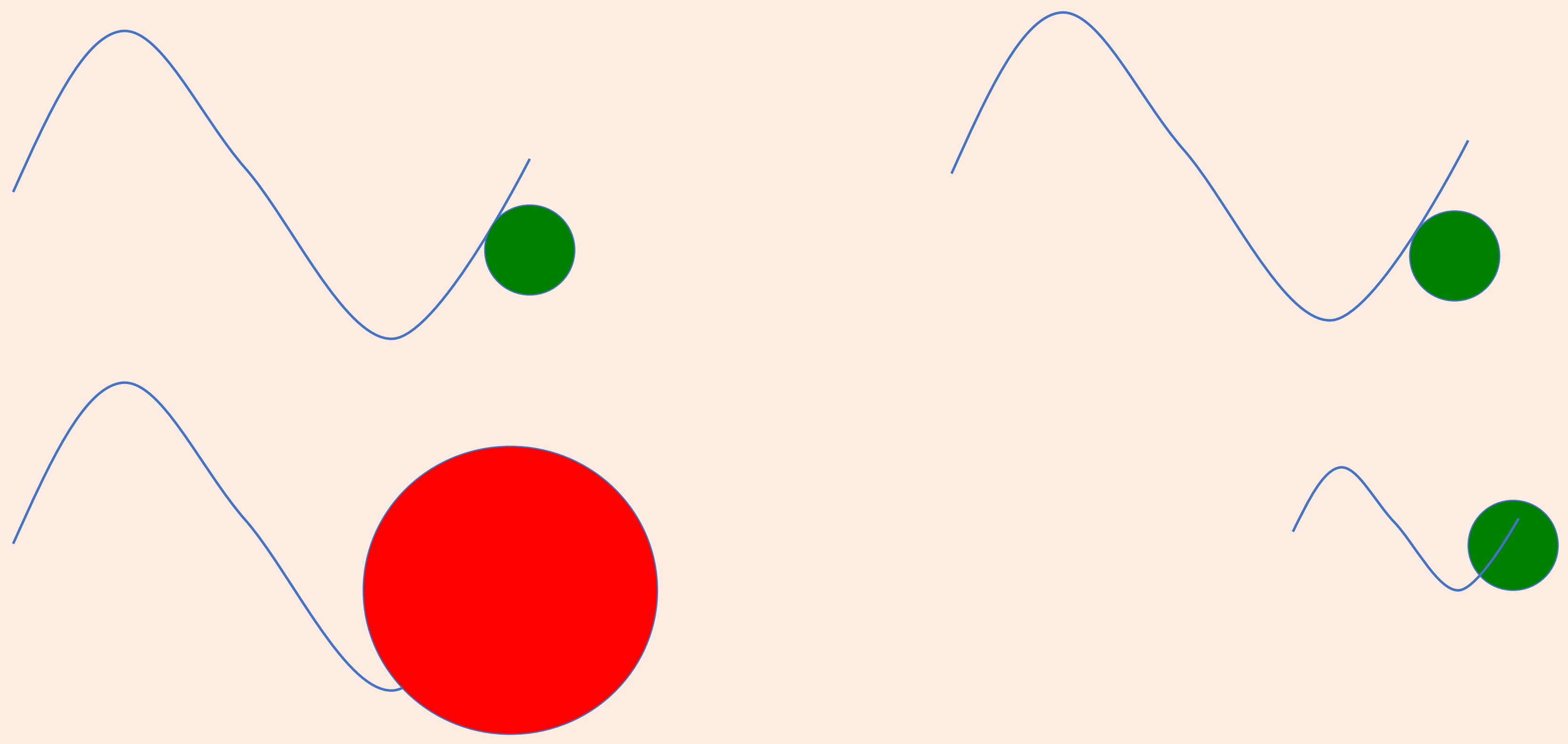
When radiation interacts with a particle, scattering depends on relative sizes of particle radius and radiation wavelength

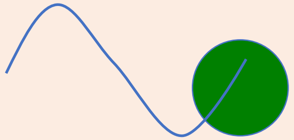




$2\pi r/\lambda$

Same size wavelength with different size particles is analogous to same size particles with different size wavelengths



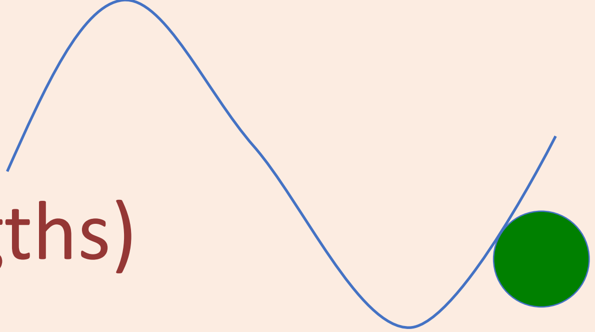


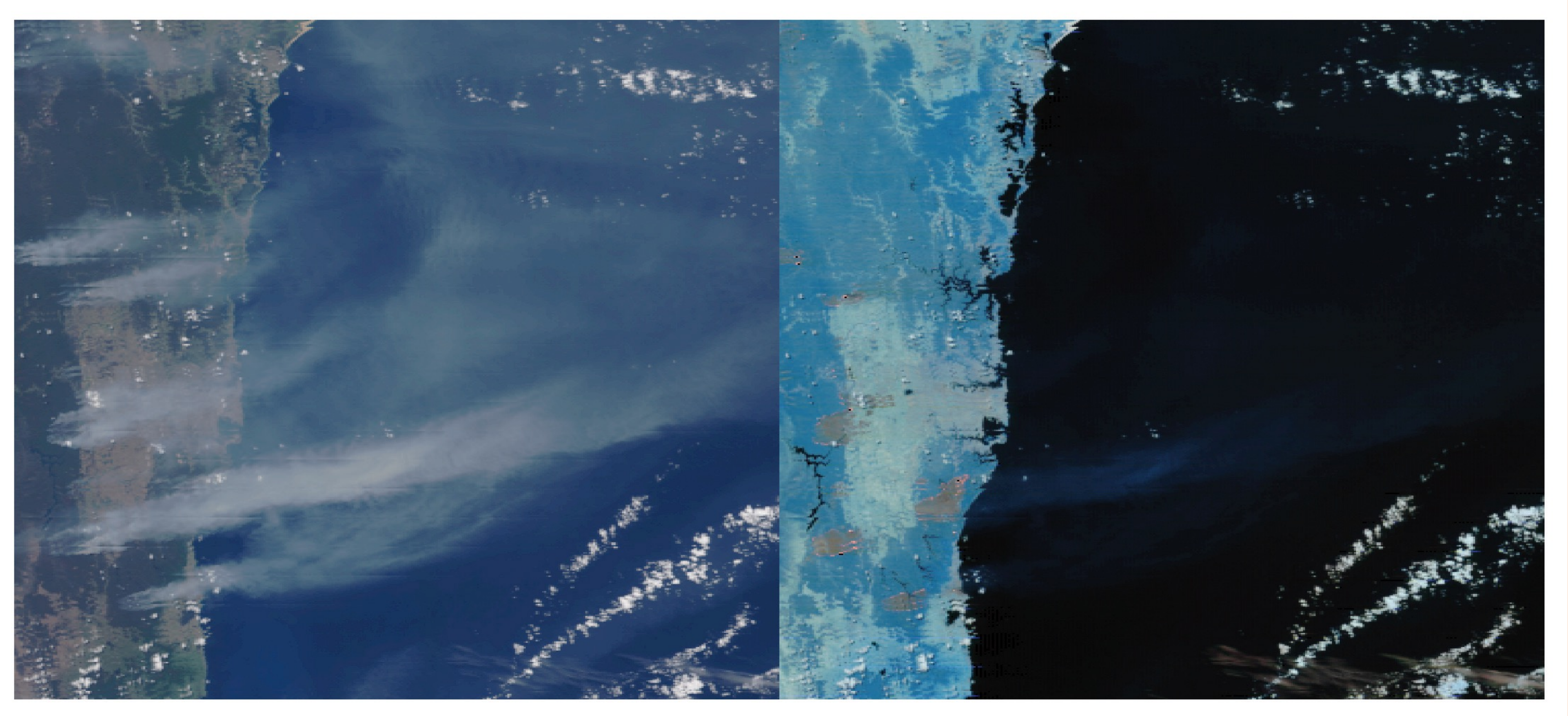
Visible wavelengths

$2\pi r/\lambda \sim 1$

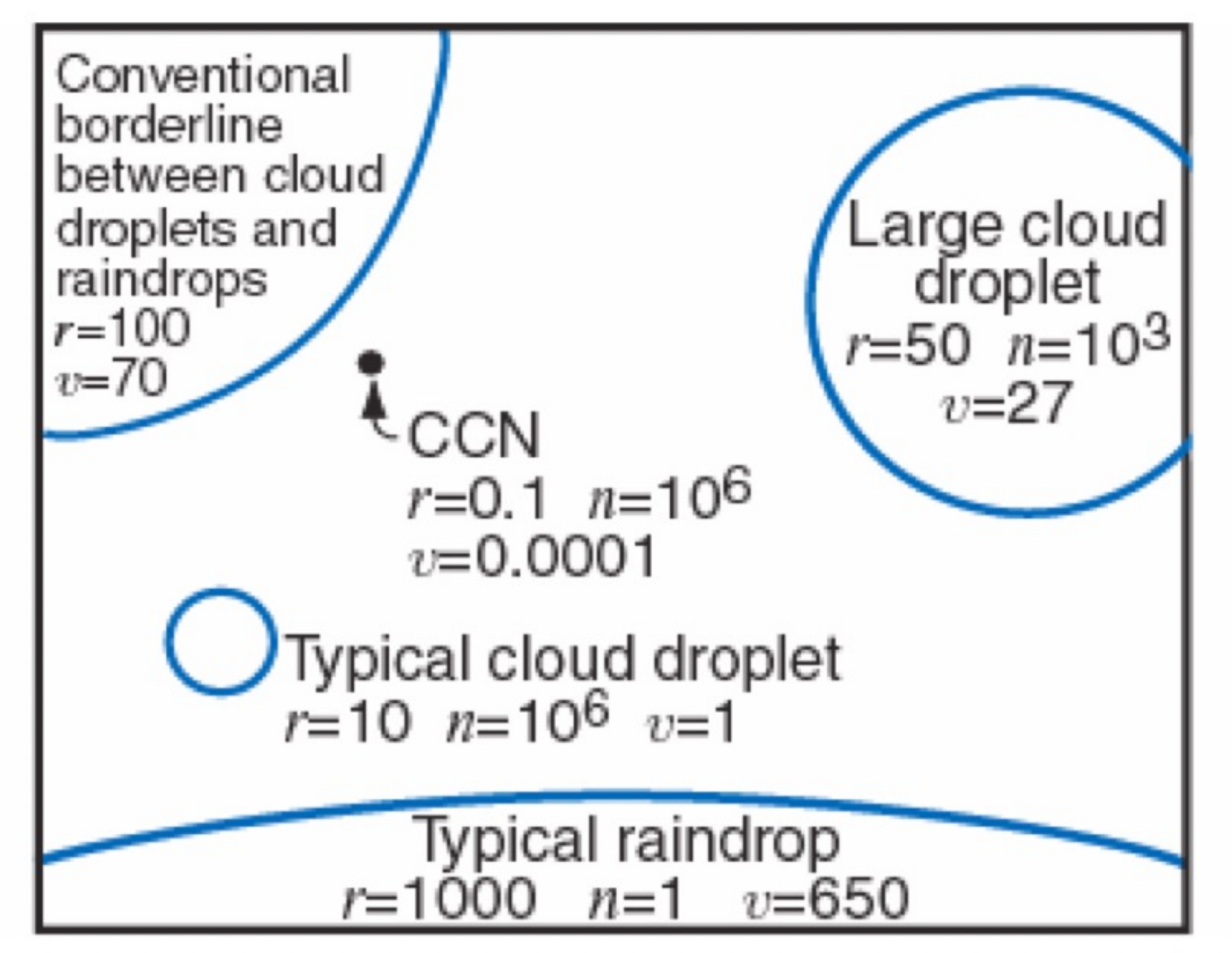
SWIR
(longer wavelengths)

$2\pi r/\lambda < 1$





CCN = cloud condensation nuclei (aerosol)

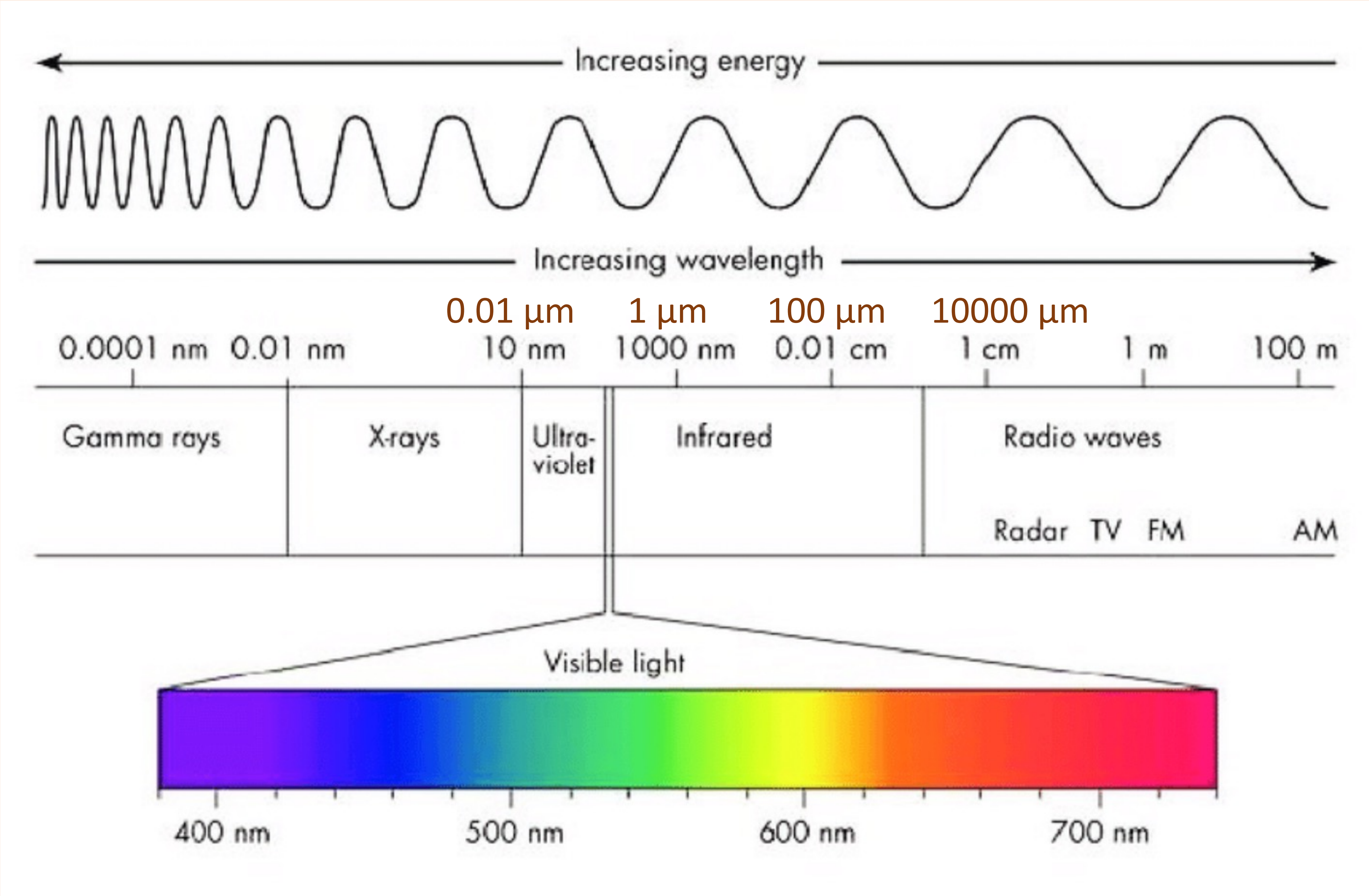


r = radius (µm)

Wallace and Hobbs, 2006

Limb measurements of the stratosphere

100 nm = 1 µm


Increasing energy
Increasing wavelength
0.01 µm
1 µm
100 µm
10000 µm
0.0001 nm
0.01 nm
10 nm
1000 nm
0.01 cm
1 cm
1 m
100 m
Gamma rays
X-rays
Ultra-
violet
Infrared
Radio waves
Radar
TV
FM
AM
Visible light
400 nm
500 nm
600 nm
700 nm

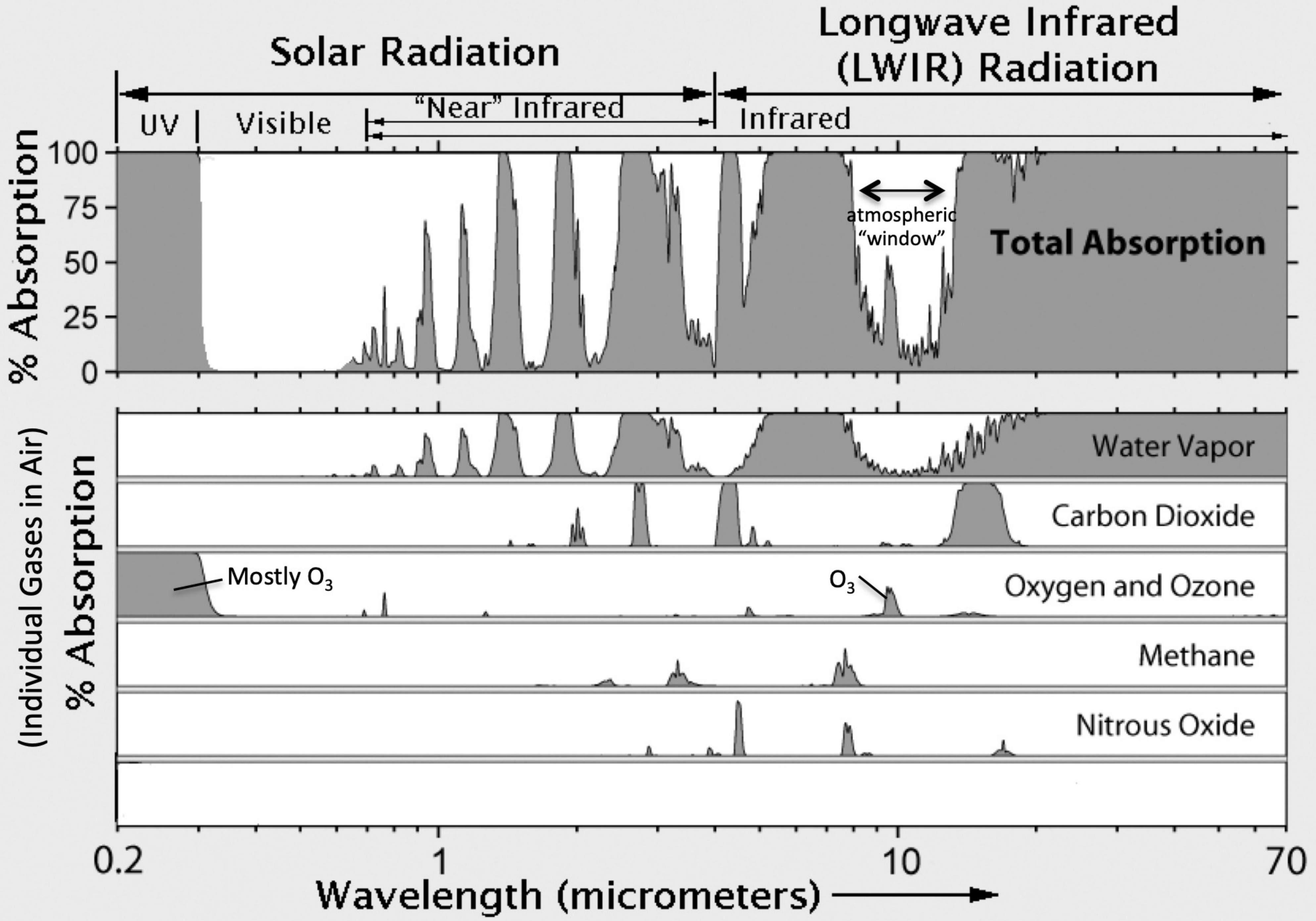
Remote sensing of aerosols: use scattering from UV-visible-SWIR

Remote sensing of clouds: use scattering from visible-SWIR-Thermal infrared

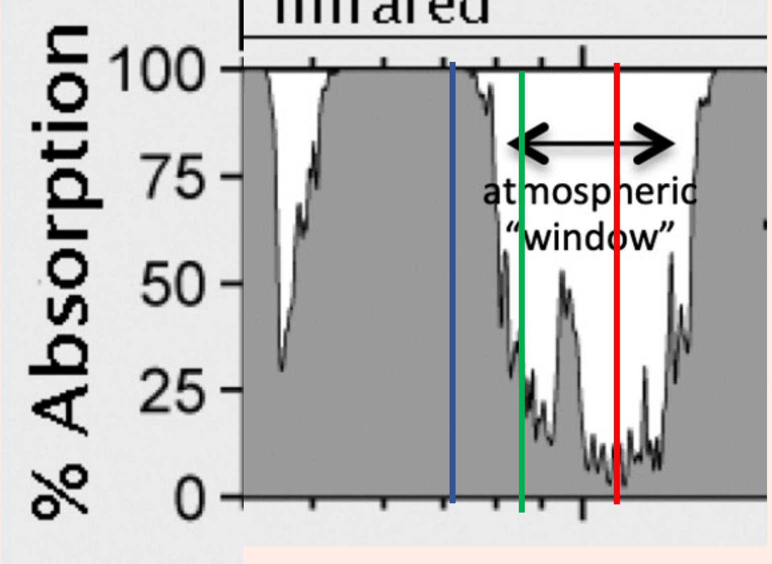
Remote sensing of precipitation: use scattering from radar (can see right through the cloud)

For gases:

Use absorption, not scattering



Temperature profiles:

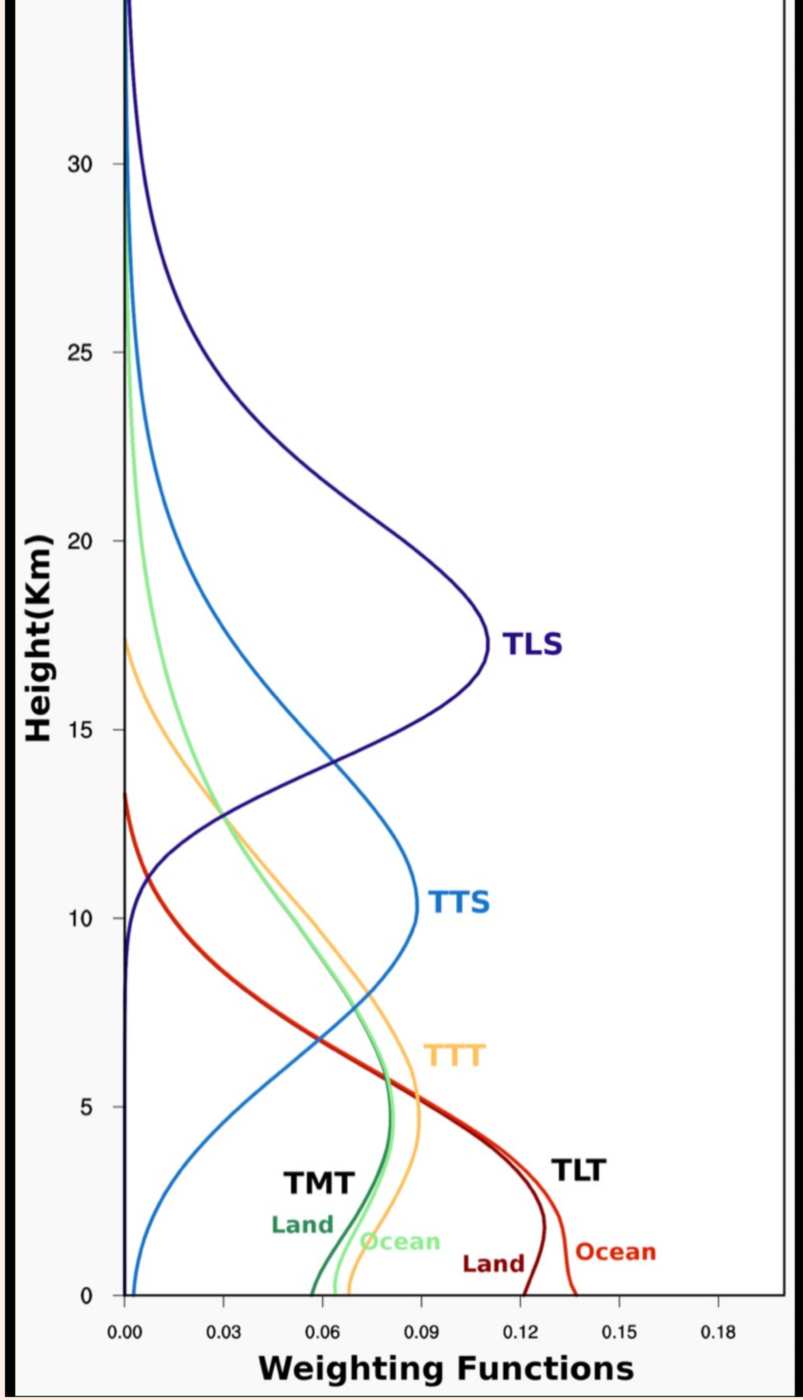


L = k * B(λ,T)

L = radiation
k = scaling factor
B(λ,T) is the Planck function, dependent on wavelength and temperature

Satellite measures L in the thermal infrared or microwave range, for a given λ, we can invert the *integrated* temperature of the column.

But, absorption and emission of gases in the atmosphere are also a function of λ. Depending on l, the scale height represented by the integrated T will vary.



The very beginning of satellite Earth observations belongs to atmospheric science

Name the first satellite in space

Sputnik 1, October 1957

What about the first U.S. satellite in space?

Explorer 1, January 1958

What did Explorer 1 do?

Carried cosmic ray detectors and discovered the Van Allen belt of charged particles

What was the first U.S. Earth-imaging satellite?

Vanguard 2, February 1959 (but it had technical issues and returned no data)

Then, what was the first successful Earth-imaging satellite?

Television Infrared Observation Satellite (TIROS) April 1960

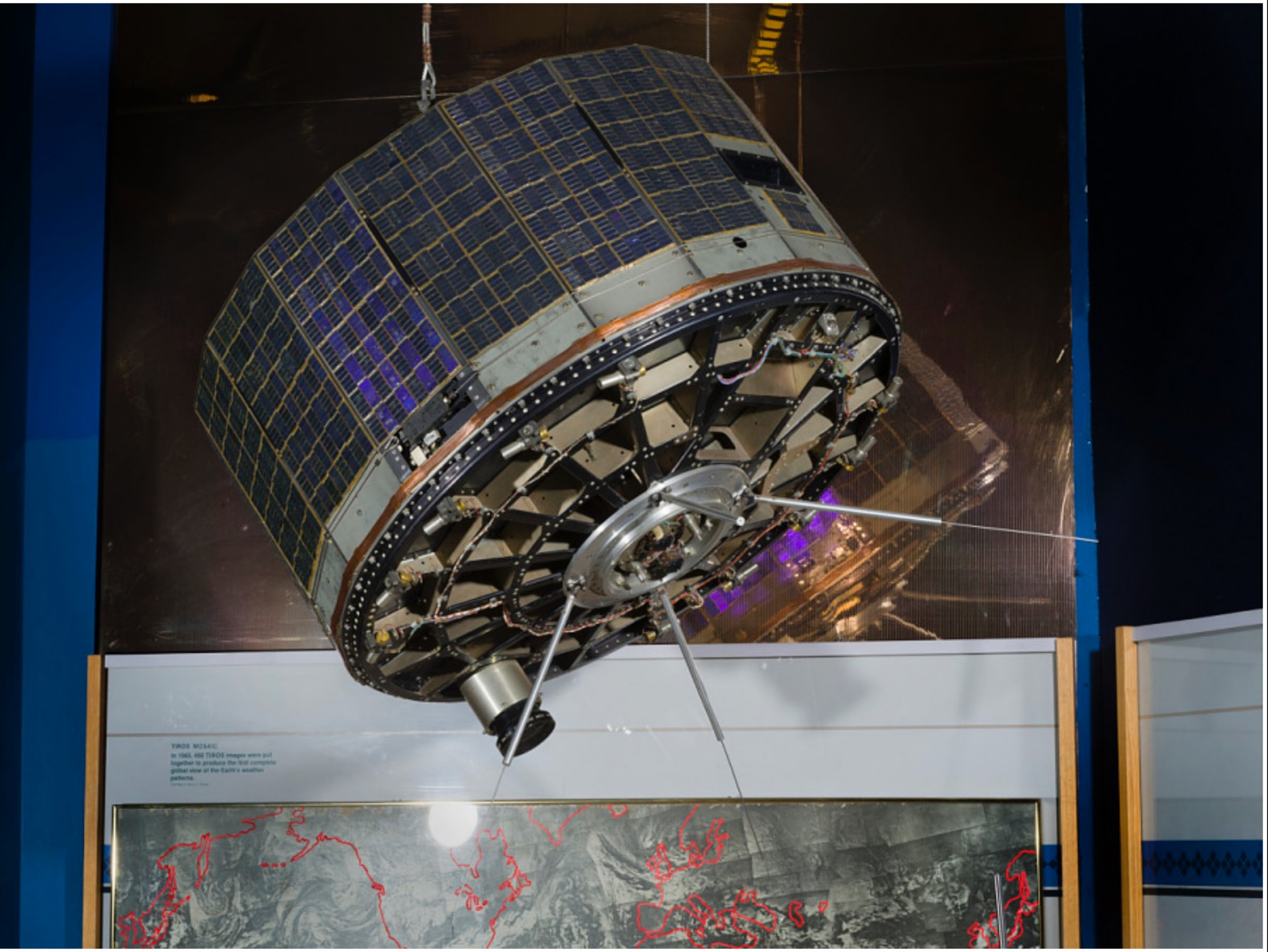
What did TIROS observe?

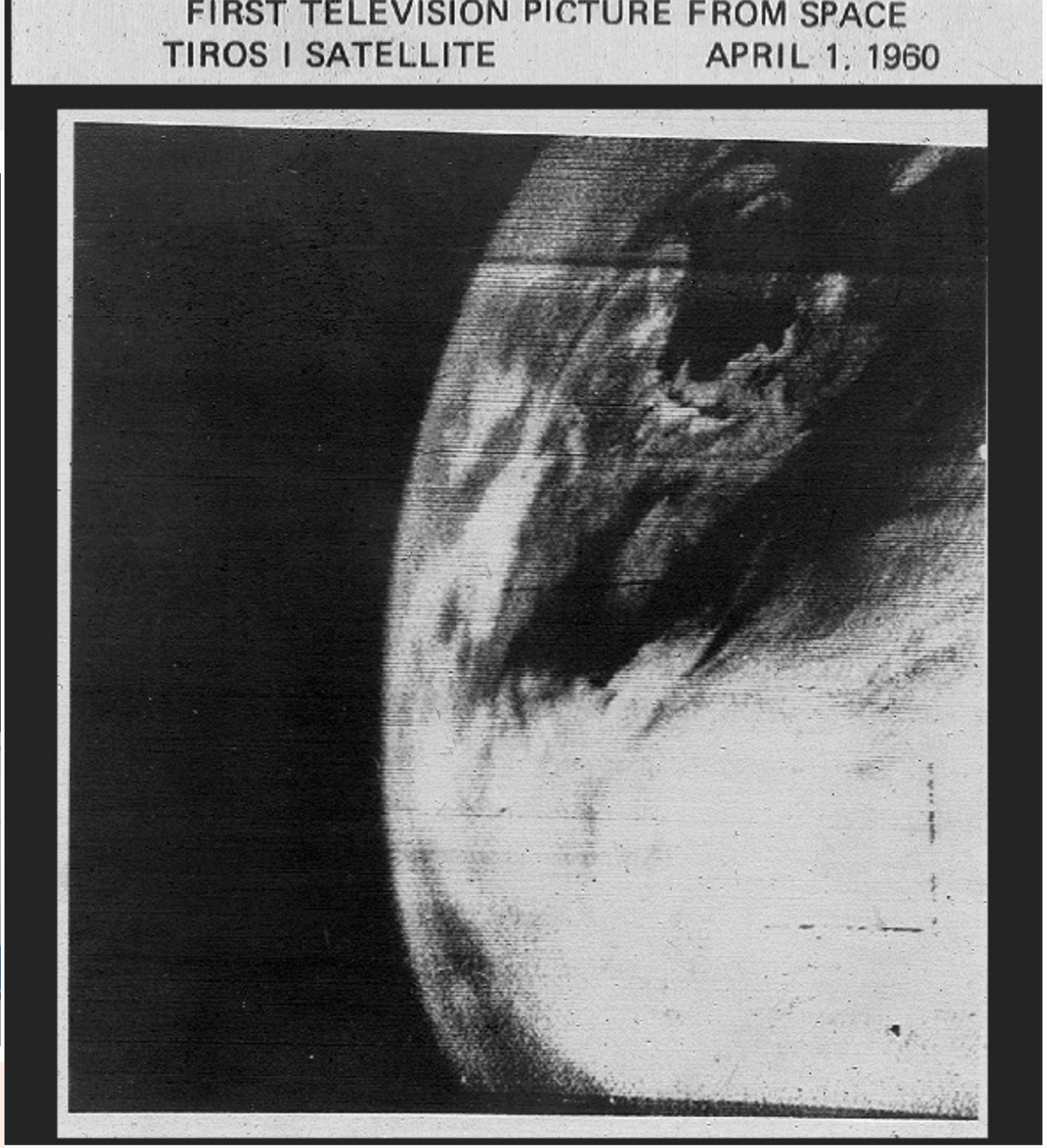
The TIROS Program's first priority was the development of a meteorological satellite information system.

Weather forecasting was deemed the most promising application of space-based observations.

https://science.nasa.gov/missions/tiros

TIROS Meteorological Satellite





One of the first TV Images of Earth from Space recorded by TIROS-1 (1960), [6]

Smithsonian

1991
Yoram Kaufman

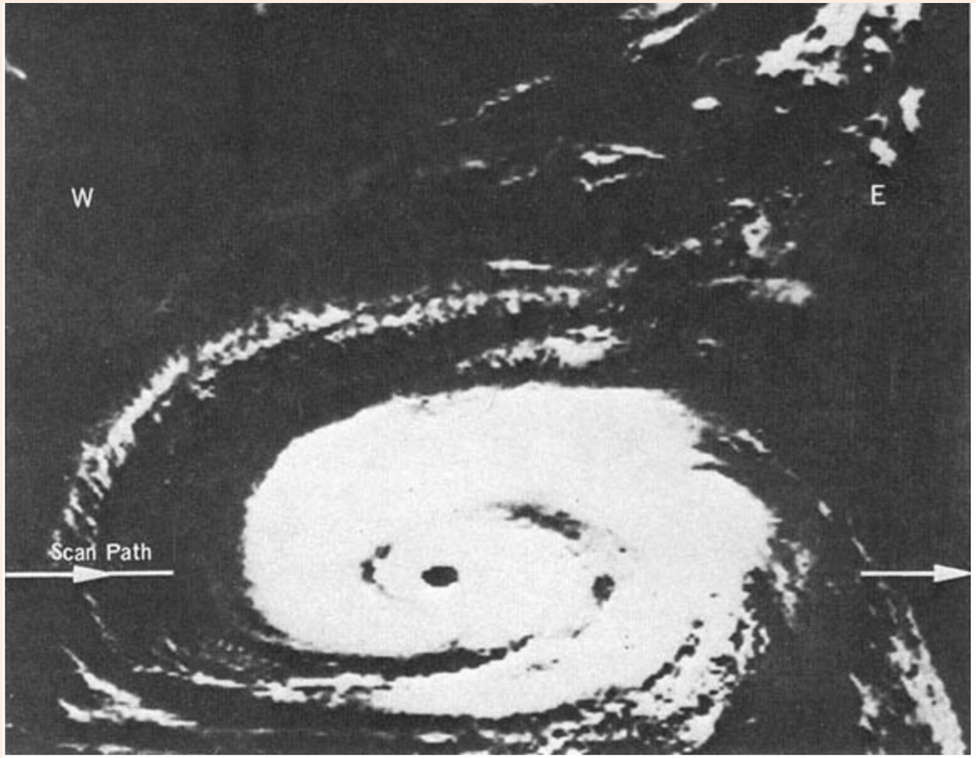
1991
William (Bill) Lazenby

Weather Satellite Era (1964 to 2000)

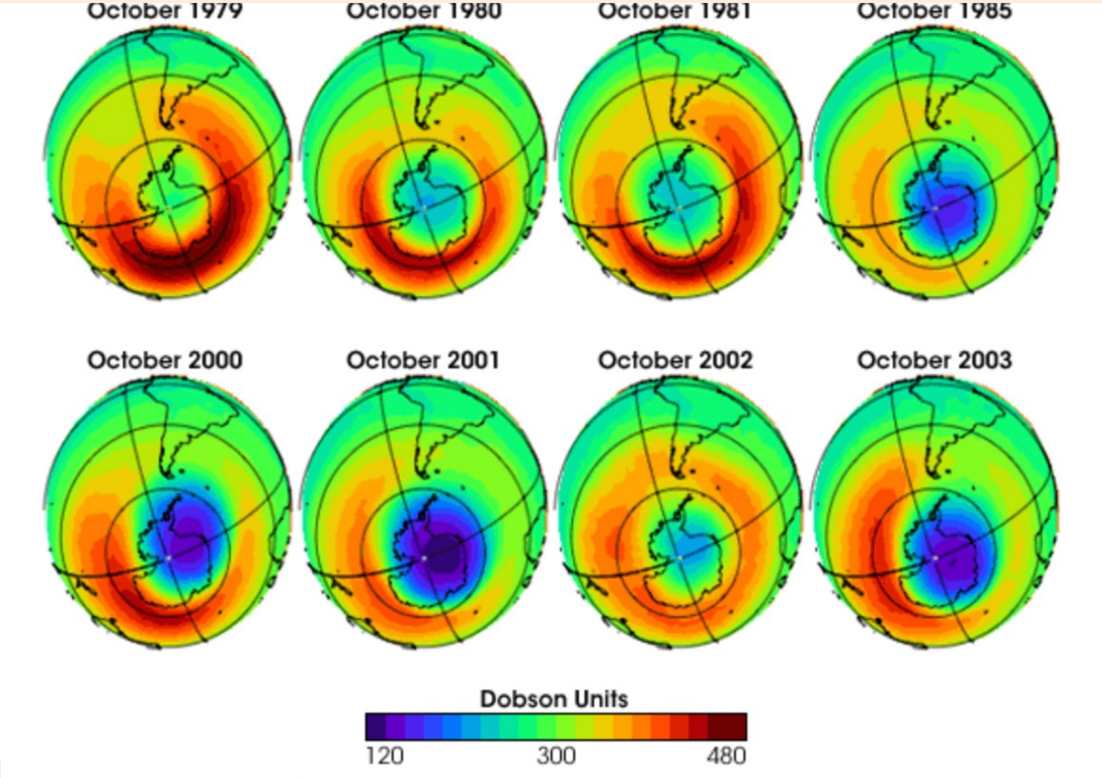
NIMBUS 1964 – 1978, seven satellites launched (one did not achieve orbit)
carried 33 sensors
provided images of Earth for 30 years
ozone mappers (gases)
thermal infrared radiometers (clouds)
microwave radiometers (precipitation)
and the Coastal Zone Color Scanner (CZCS)

NIMBUS images

Hurricane Gladys 1964
Thermal Infrared Radiometer on NIMBUS-1



The Ozone hole
Total Ozone Mapping Spectrometer (TOMS) on NIMBUS



https://www.nasa.gov/content/goddard/nimbus-nasa-remembers-first-earth-observations

Initially:
ocean and air temperatures, air pressure, and cloudiness

By NIMBUS-3 in 1969, atmospheric profiles of temperature and water vapor
>>>>> first time had initialization data over ocean for forecast models

Microwave could “see through clouds” to retrieve temperature profiles even inside hurricanes

Radiation budget at top of atmosphere (ERB)

Stratospheric aerosols and temperature measurements using limb measurements (SAM)

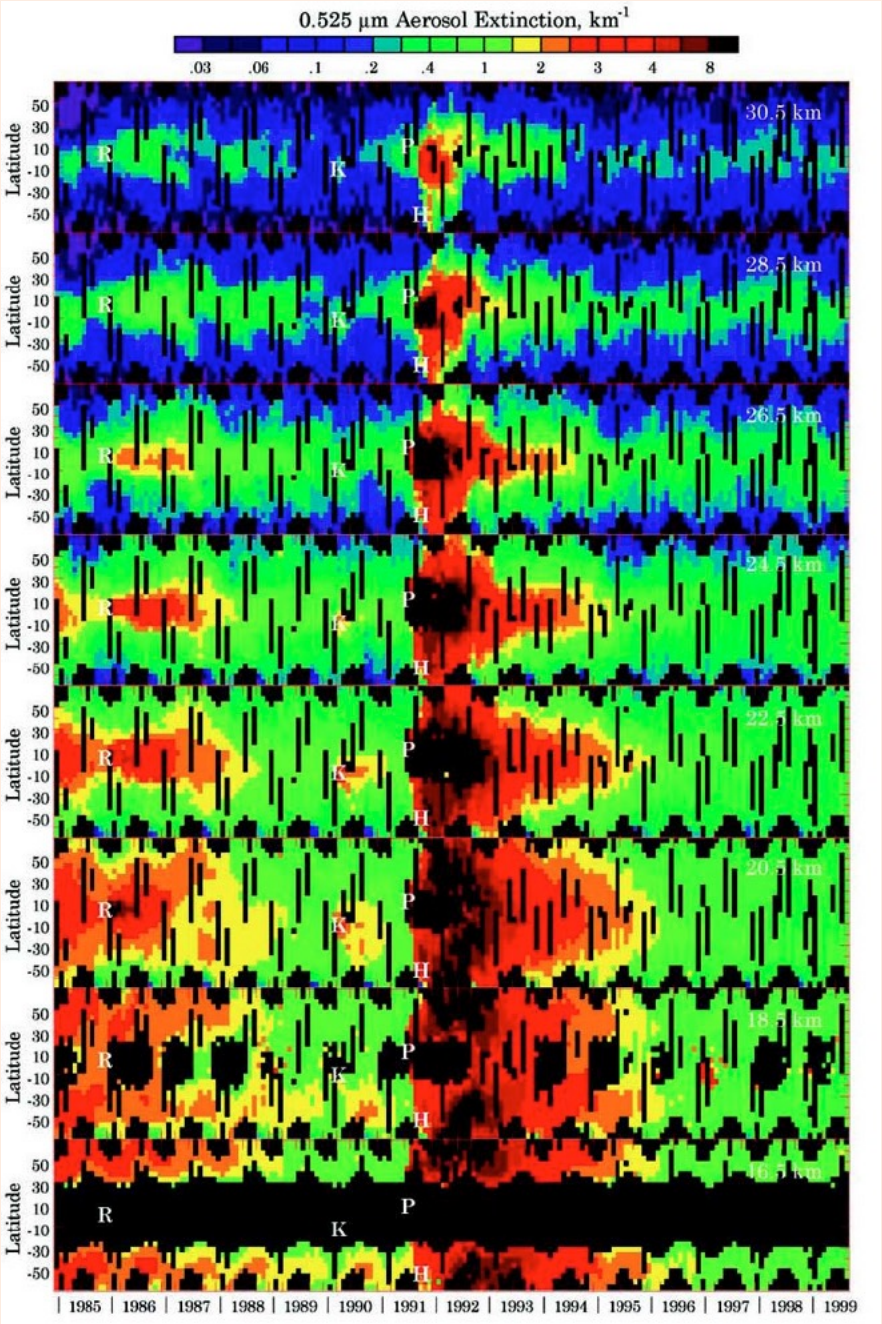
Other weather satellites

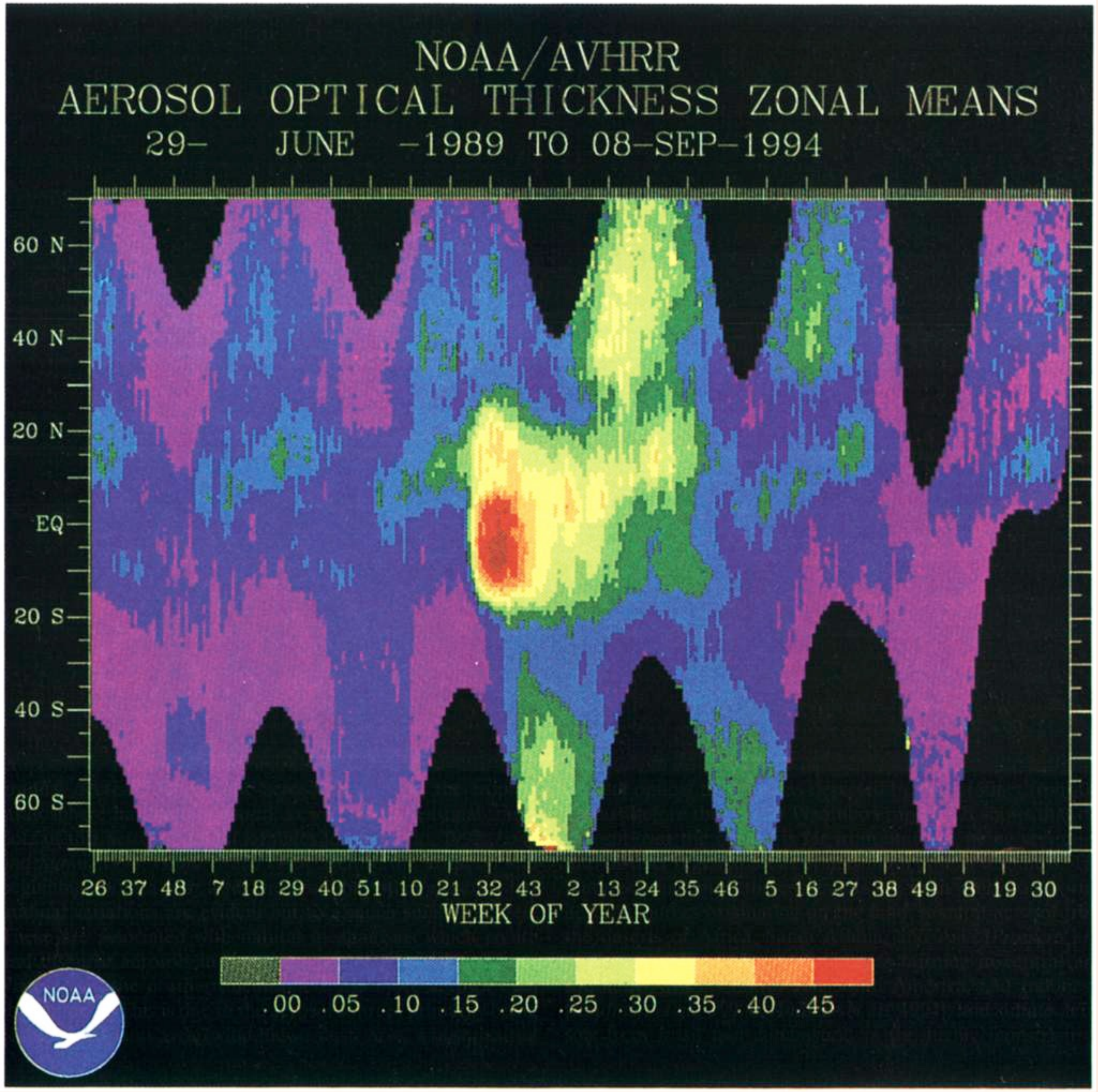
Geostationary (movies)
Synchronous Meteorological Satellite (SMS) in 1974
And then Geostationary Operational Environmental Satellite (GOES) 1975 to present

NOAA series polar orbiting carrying
A Very High Resolution Radiometer (AVHRR) 1978 to (last NOAA launch 2009)
(last Metop launch 2019)
1.1 Km spatial resolution at nadir. NIMBUS had been 8 km

Summary: TIROS, NIMBUS, GOES, AVHRR, Landsat 1960 to 2000

- Work horse operational weather satellites
- Improved weather forecasting
- Cloud images, cloud top temperature
- Temperature profiles, water vapor
- Earth’s energy budget
- Stratospheric aerosols and gases (ozone)
- Pioneering aerosol retrievals from AVHRR (ocean only) and TOMS (very coarse spatial resolution)


0.525 µm Aerosol Extinction, km-1
.03 .06 .1 .2 .4 1 2 3 4 8
30.5 km
28.5 km
26.5 km
24.5 km
22.5 km
20.5 km
18.5 km
16.5 km
Latitude
50 30 10 -10 -30 -50
R
K
P
H
1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999


NOAA/AVHRR
AEROSOL OPTICAL THICKNESS ZONAL MEANS
29- JUNE -1989 TO 08-SEP-1994
60 N
40 N
20 N
EQ
20 S
40 S
60 S
26 37 48 7 18 29 40 51 10 21 32 43 2 13 24 35 46 5 16 27 38 49 8 19 30
WEEK OF YEAR
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45
NOAA

The Earth Observing System (EOS) era
From weather to climate….

Terra (2000): MODerate resolution Imaging Spectroradiometer (MODIS)
Multiangle Imaging SpectroRadiometer (MISR)
Clouds and Earth's Radiant Energy System (CERES)

Aqua (2002): MODIS, CERES and atmospheric profilers

Aura (2004): Ozone Monitoring Instrument and instruments focused on gases

Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (PARASOL) (2004): POLarization and Directionality of the Earth's Reflectances (POLDER)

Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (2006):
Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP)
Cloud Satellite (CloudSat) (2006): Cloud Profiling Radar (CPR)

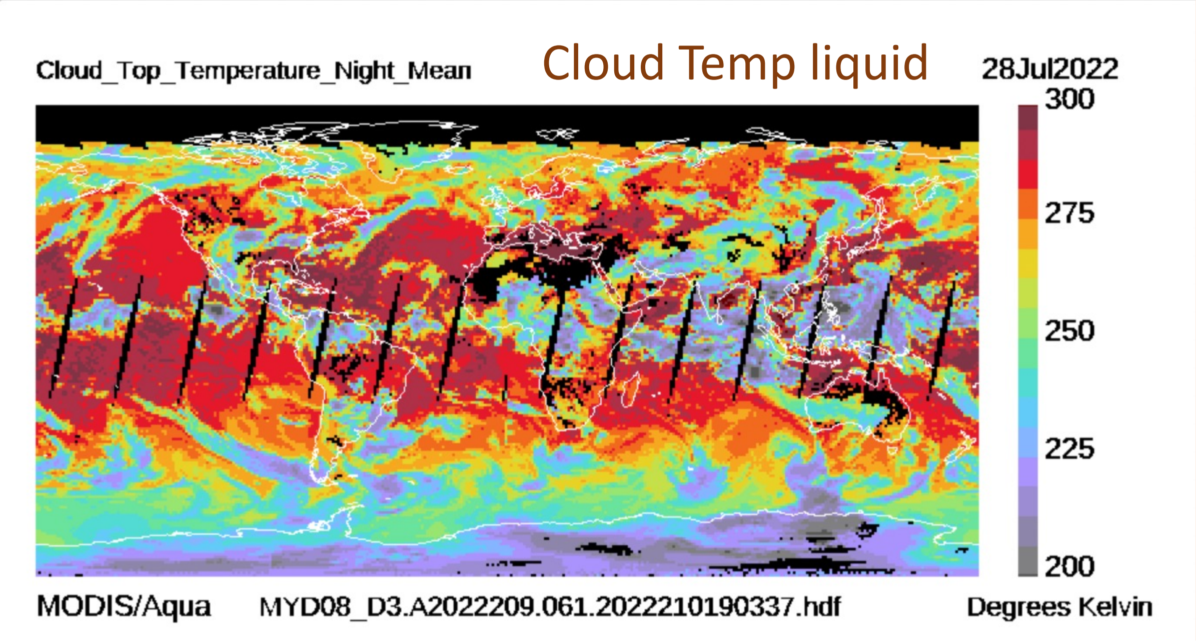
The Earth Observing System (EOS) era
From weather to climate….

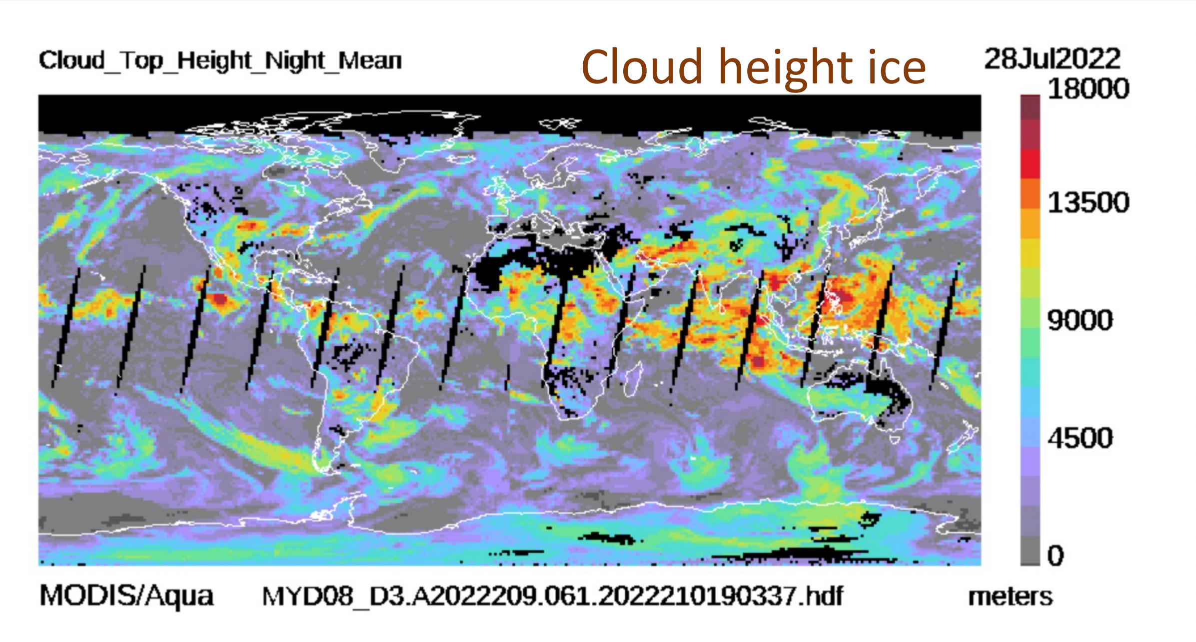
<u>Pre-EOS satellites</u>
Offered users with radiances, reflectance, temperatures
Calibrated and geo-referenced, if you were lucky

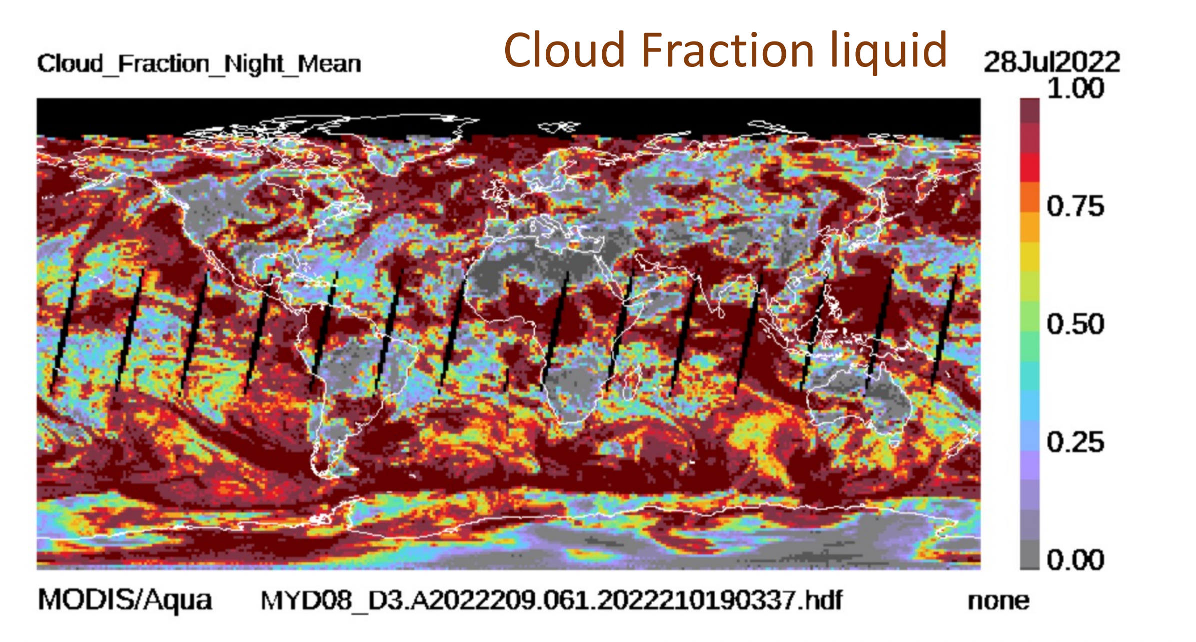
<u>EOS satellites</u>
Offered users with validated geo-physical products

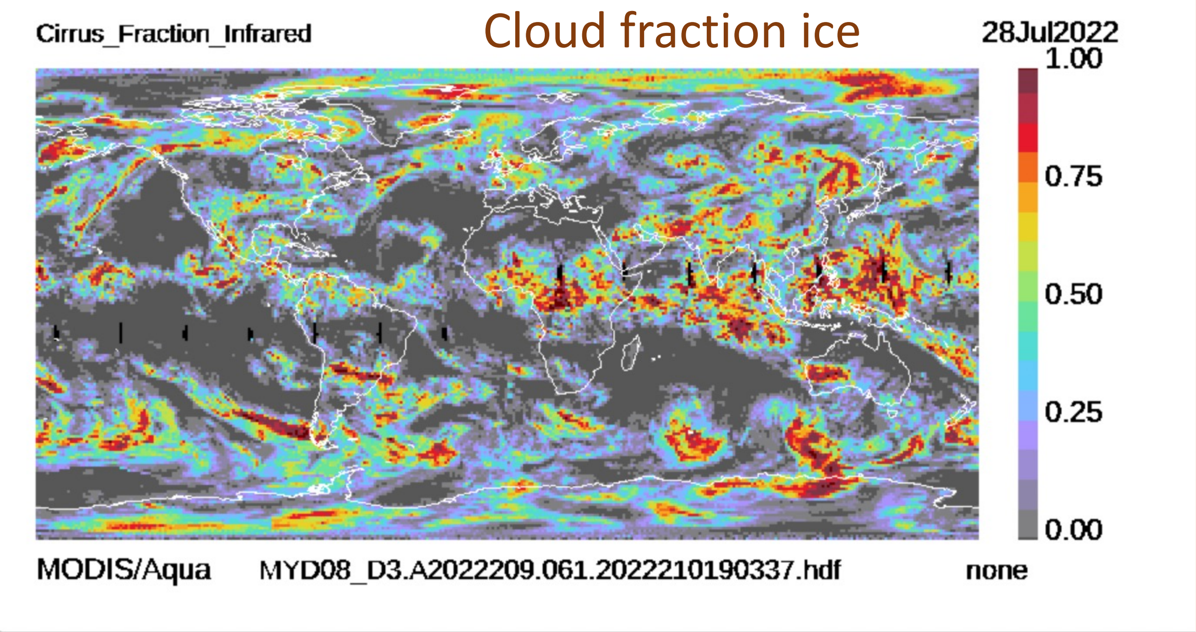
From MODIS: cloud products using IR

https://atmosphere-imager.gsfc.nasa.gov/images/l3/daily



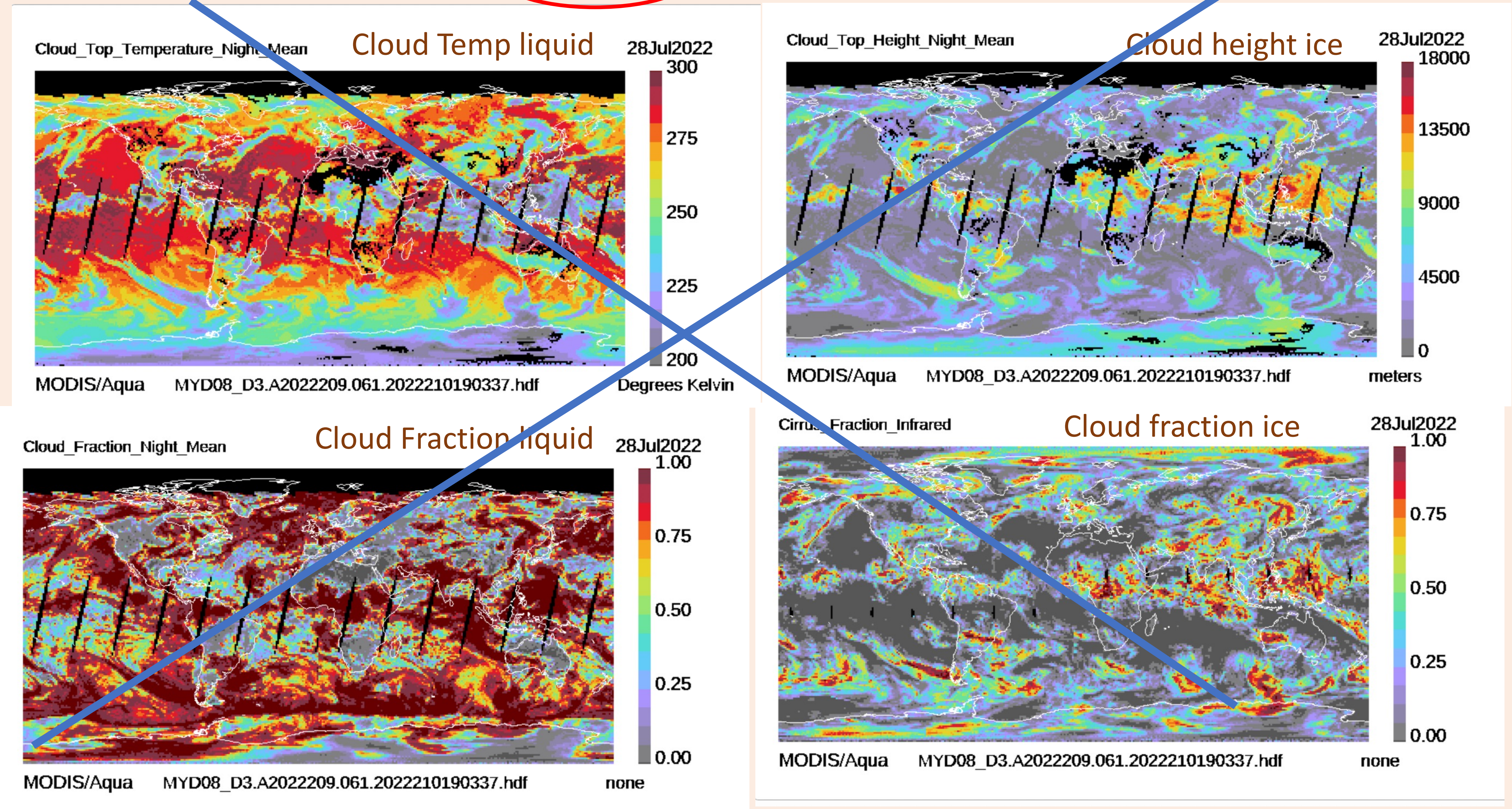


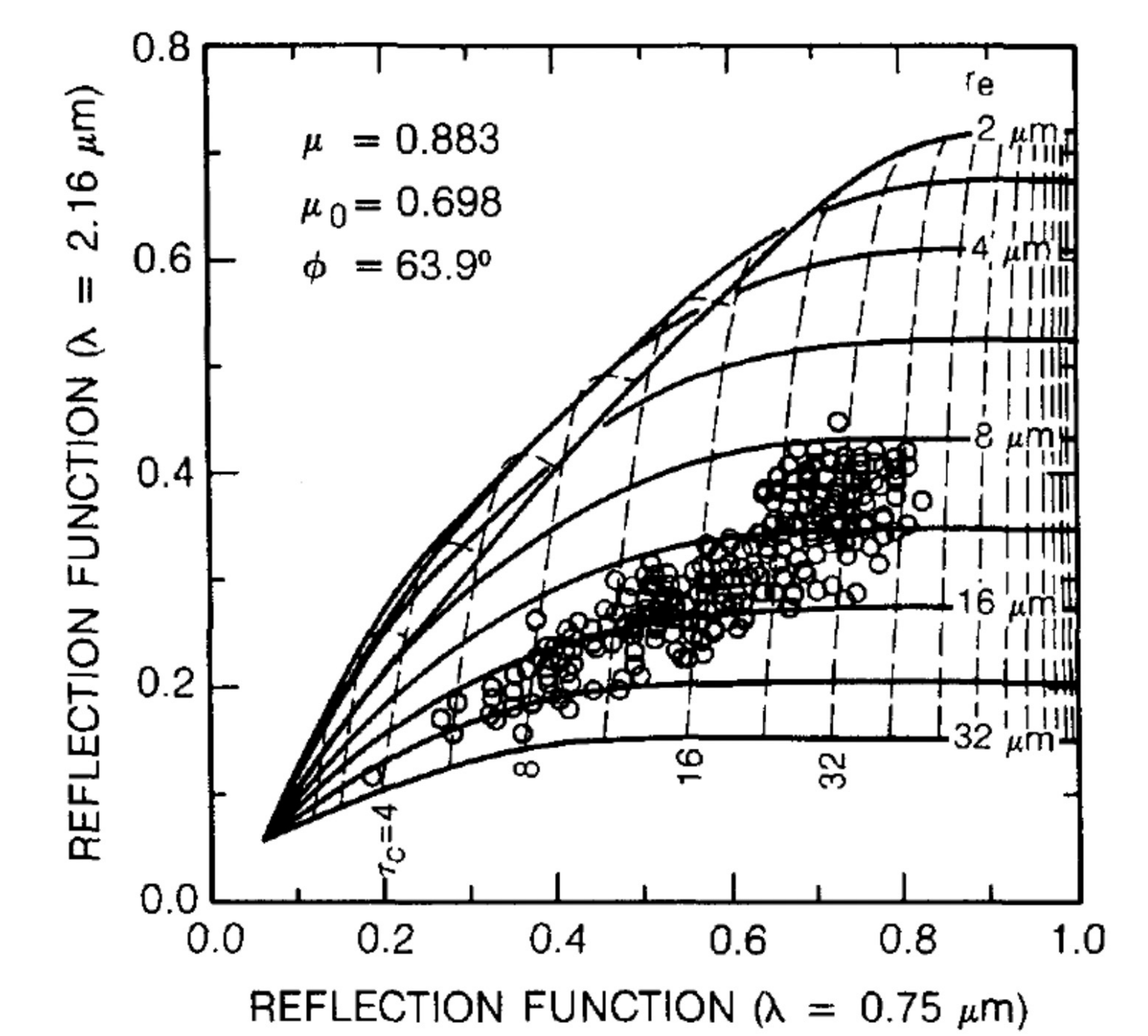




From MODIS: cloud products using IR

https://atmosphere-imager.gsfc.nasa.gov/images/l3/daily





Cloud optical properties

New for MODIS because of SWIR

Cloud Optical Thickness

Cloud Droplet Effective Radius

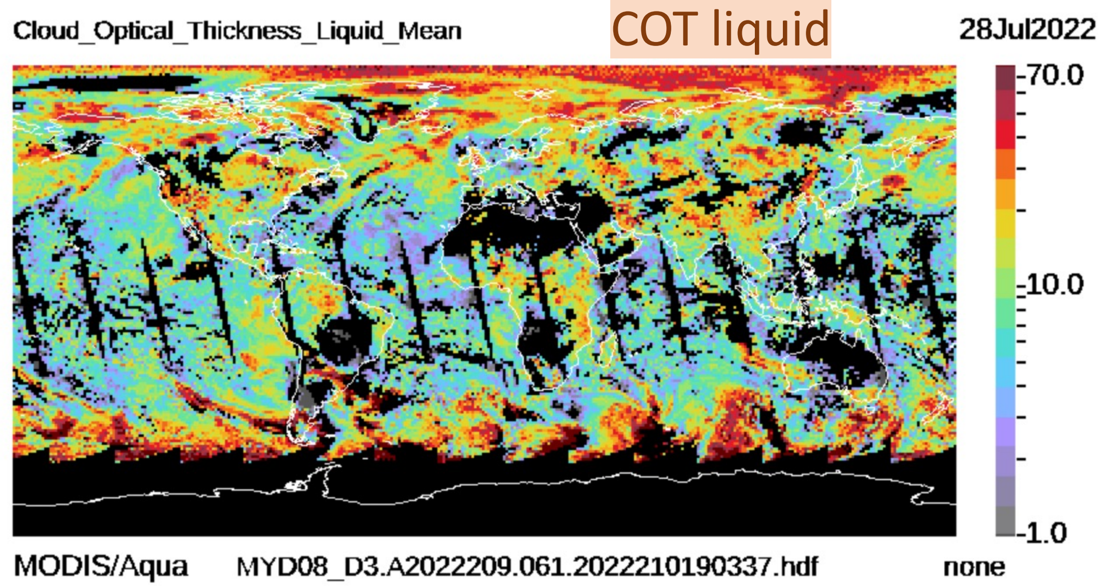
Dr. Michael D. King

Teruyuki Nakajima

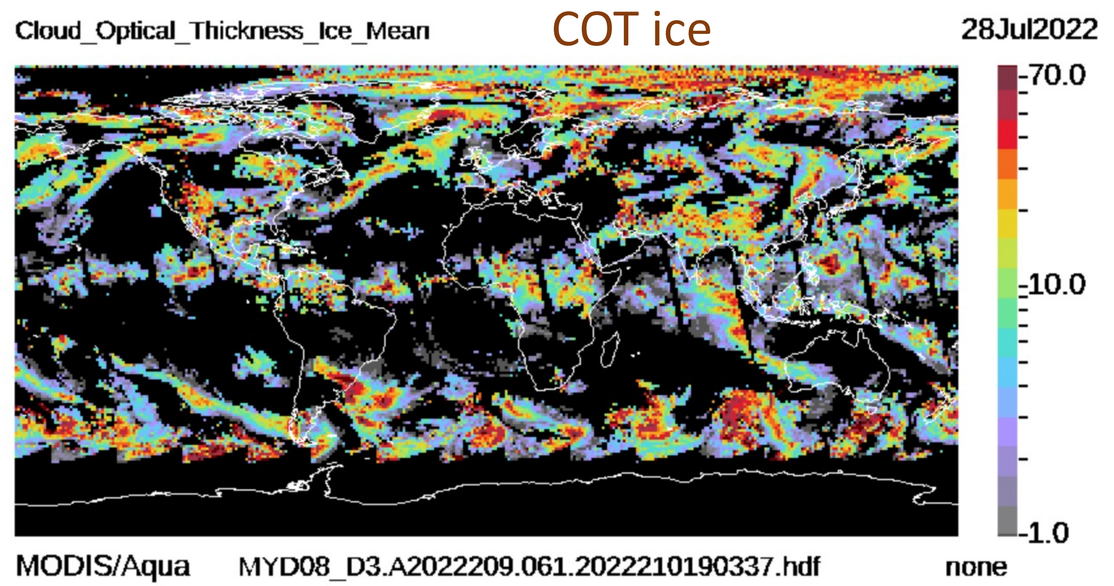
From MODIS: cloud products using VIS + SWIR (Optical Properties)

https://atmosphere-imager.gsfc.nasa.gov/images/l3/daily

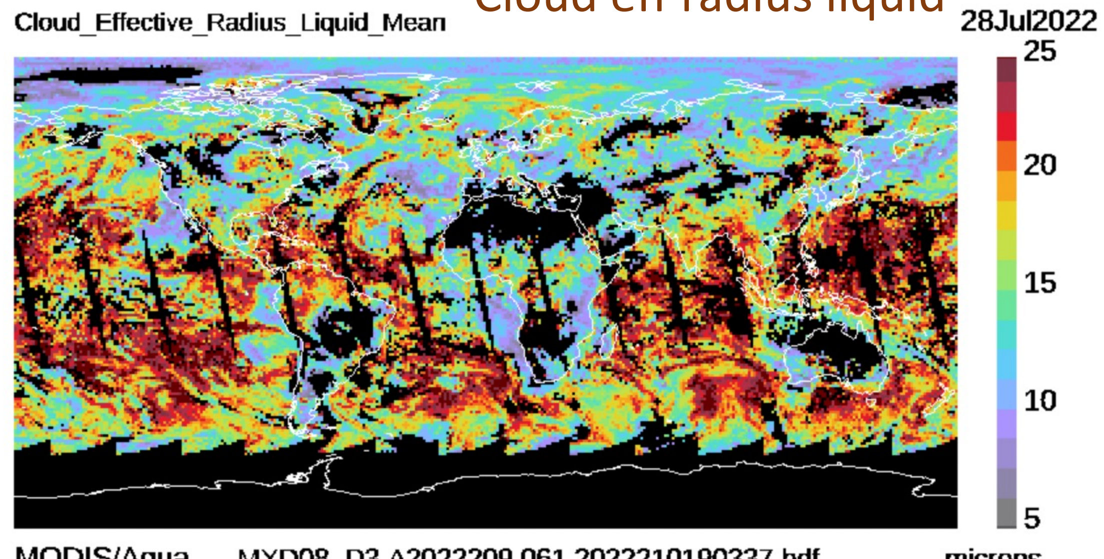
COT liquid



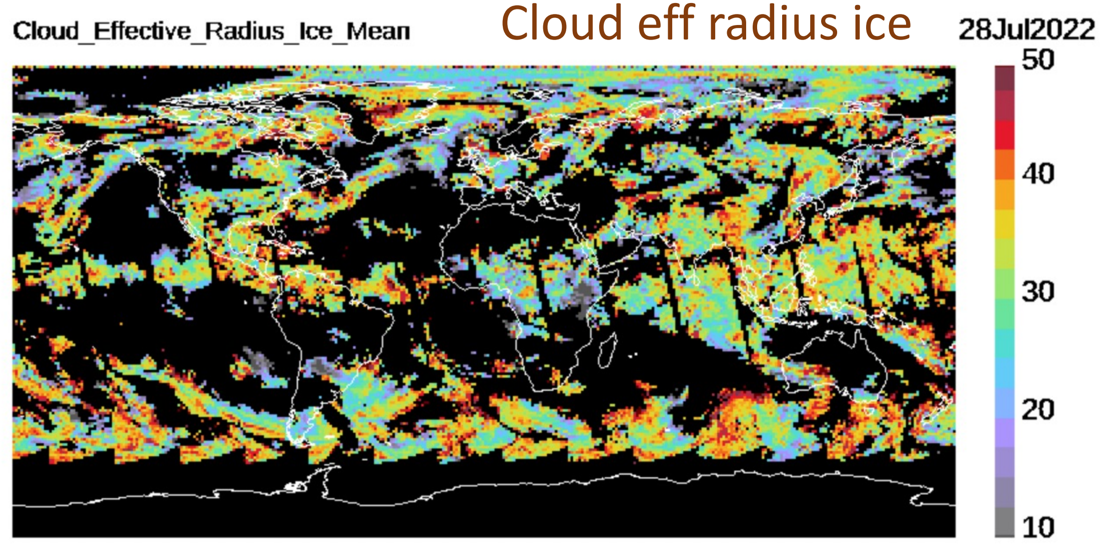
COT ice



Cloud eff radius liquid



Cloud eff radius ice



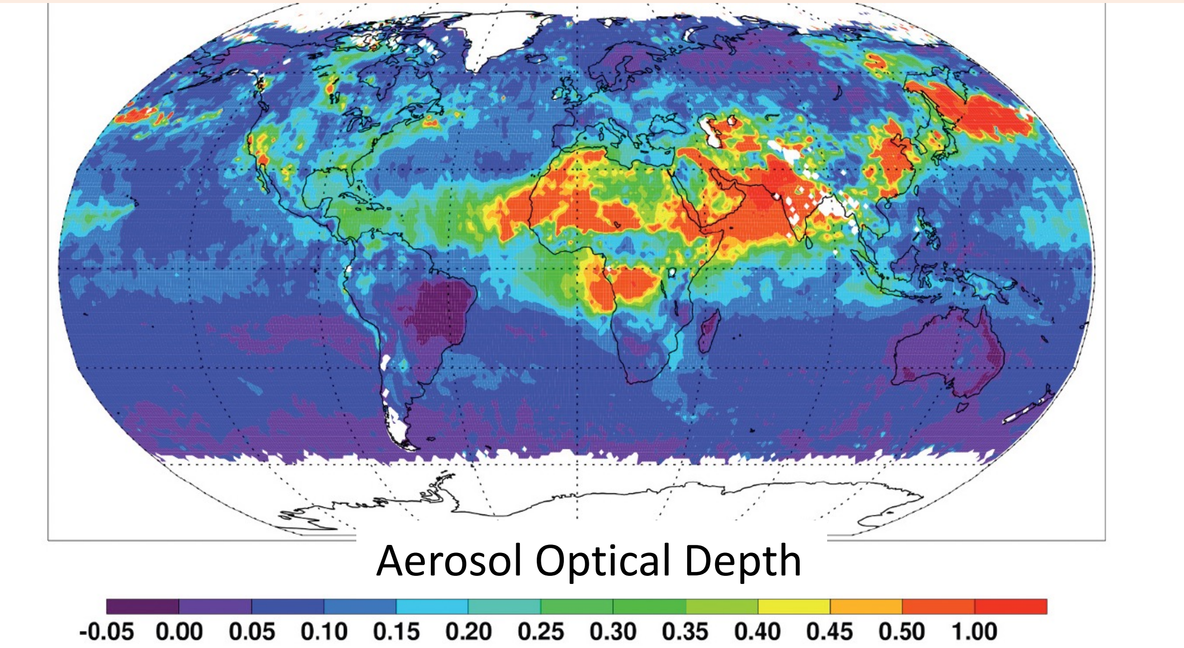
Didier Tanré

Yoram Kaufman (left)

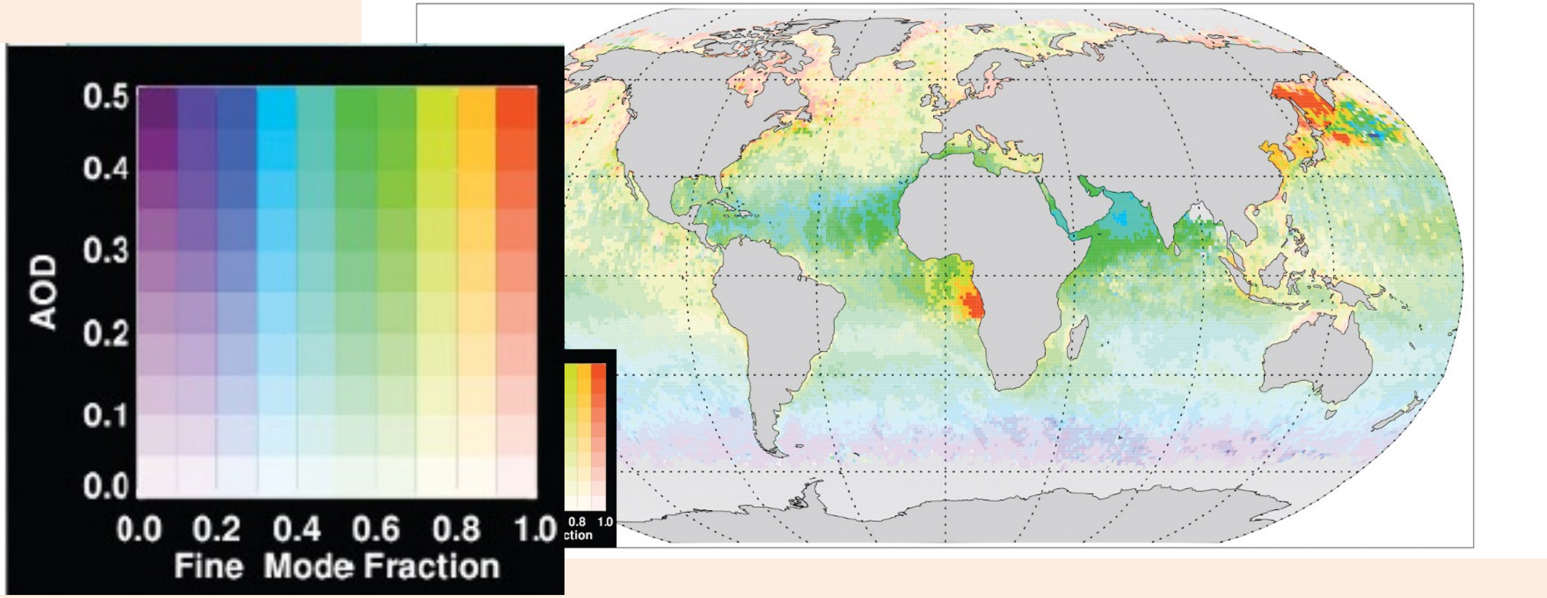
The two people who conceived and delivered the first MODIS aerosol product

Aerosols from MODIS using Visible to SWIR

- Aerosol Optical Depth or Thickness (AOD or AOT)
  Optical measure of the aerosol loading
- Fine mode fraction (FMF)
  The percentage of the total measured radiance attributed to smaller particles.

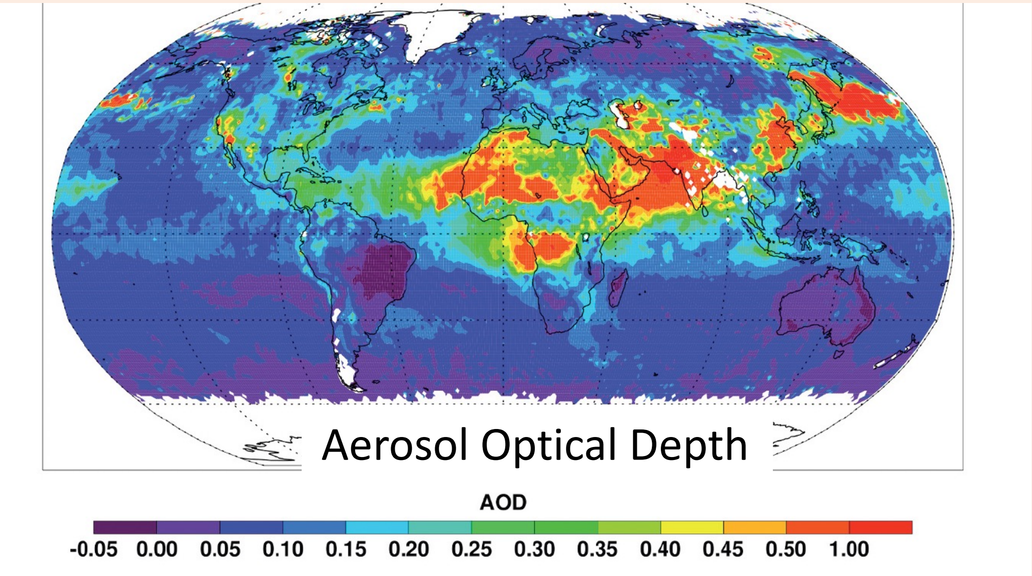


- AOD existed from AVHRR over ocean, but not land
- FMF was brand new



Aerosols from MODIS using Visible to SWIR

- Original MODIS aerosol algorithm minimized uncertainty over land by focusing on dark vegetated surfaces. (Dark Target)
- Here you see retrievals over deserts also.
- This is the contribution of Christina Hsu and her Deep Blue algorithm



Dark Target land

- ➢ Estimates land sfc refl from empirical wavelength band relationships
- ➢ Uses measured elevated refl at satellite to infer aerosol loading above sfc

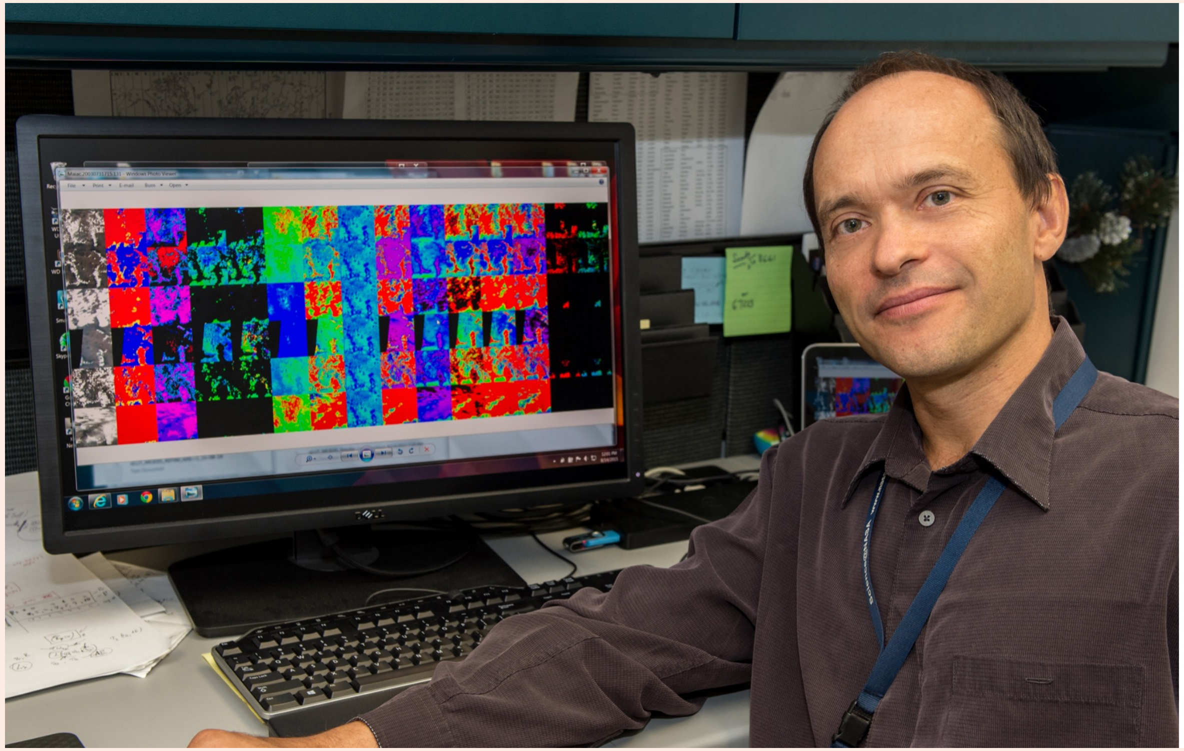
Deep Blue land

- ➢ Uses 0.41 µm where land is dark, even in deserts
- ➢ Uses deviation from expected scattering signal from gases alone to infer aerosol loading.

Aerosols from MODIS using Visible to SWIR

Alexei Lyapustin developed the third aerosol retrieval applied to MODIS (MAIAC)

Here the temporal dimension is added to help constrain surface reflectance over land.



MAIAC over land

- Assumes land scene is “constant” over an 8 day period while aerosol varies day to day
- Assumes aerosol is “constant” spatially over a defined retrieval box while land surface varies spatially.
- Allows 1 km aerosol retrievals

Dark Target land

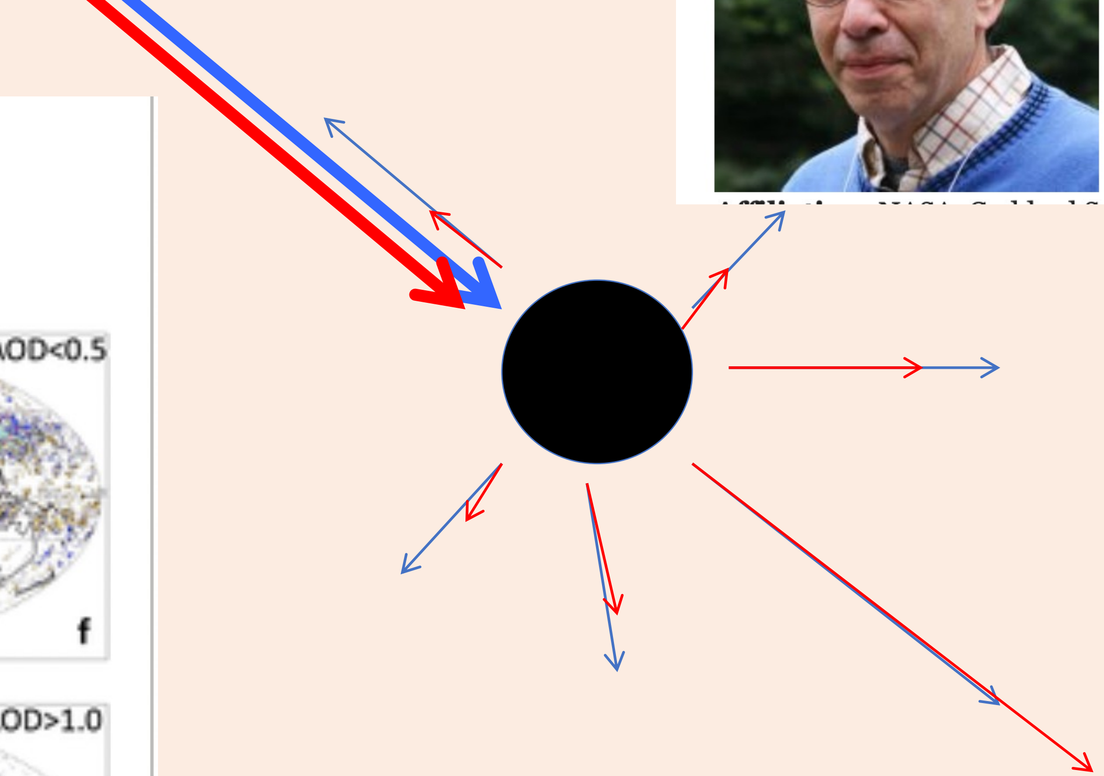
- Estimates land sfc refl from empirical wavelength band relationships
- Uses measured elevated refl at satellite to infer aerosol loading above sfc

Deep Blue land

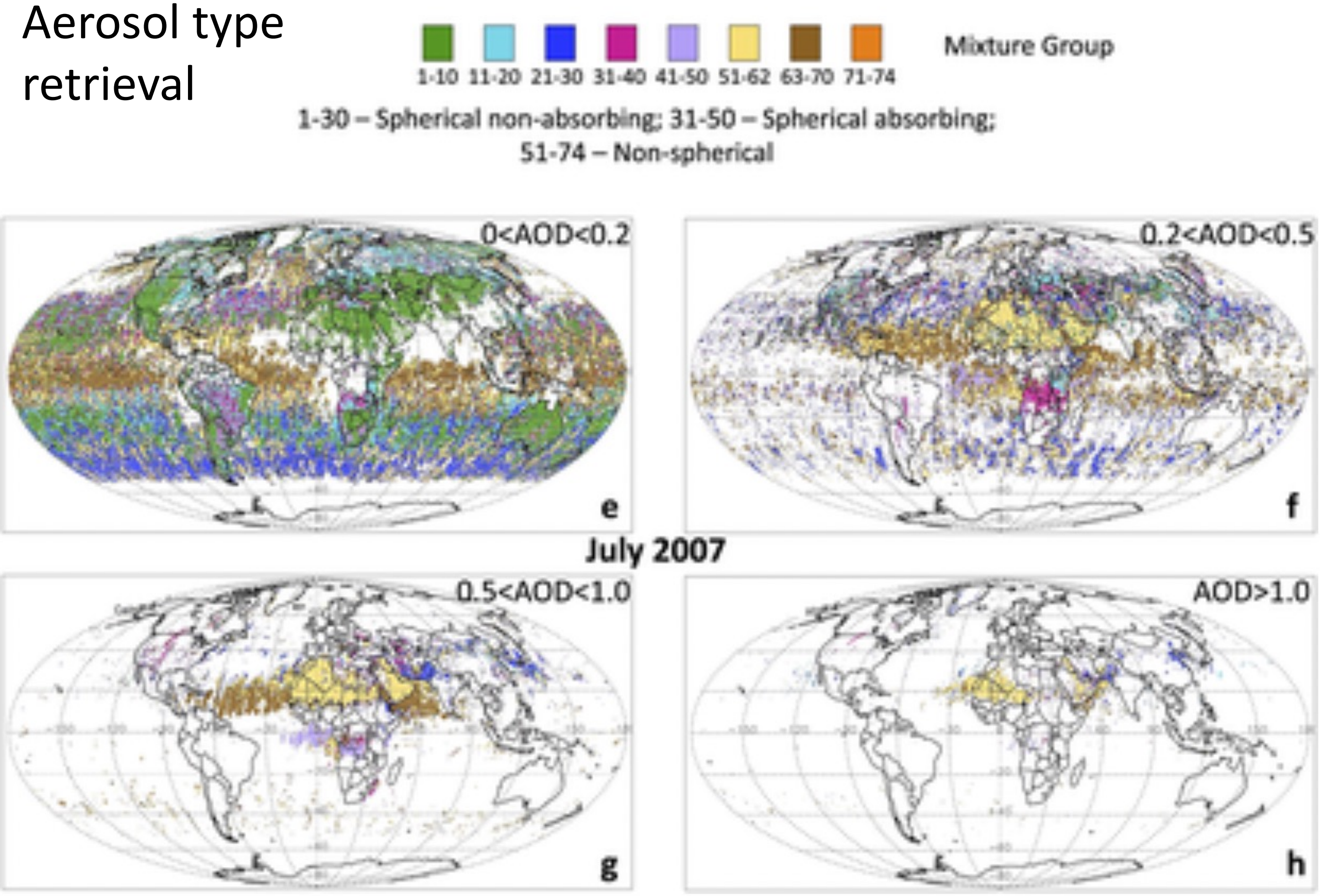
- Uses 0.41 μm where land is dark, even in deserts
- Uses deviation from expected scattering signal from gases alone to infer aerosol loading.

What else is new for clouds and aerosols in the EOS era?
MISR multiangle retrievals for both aerosols and clouds.

Ralph Kahn



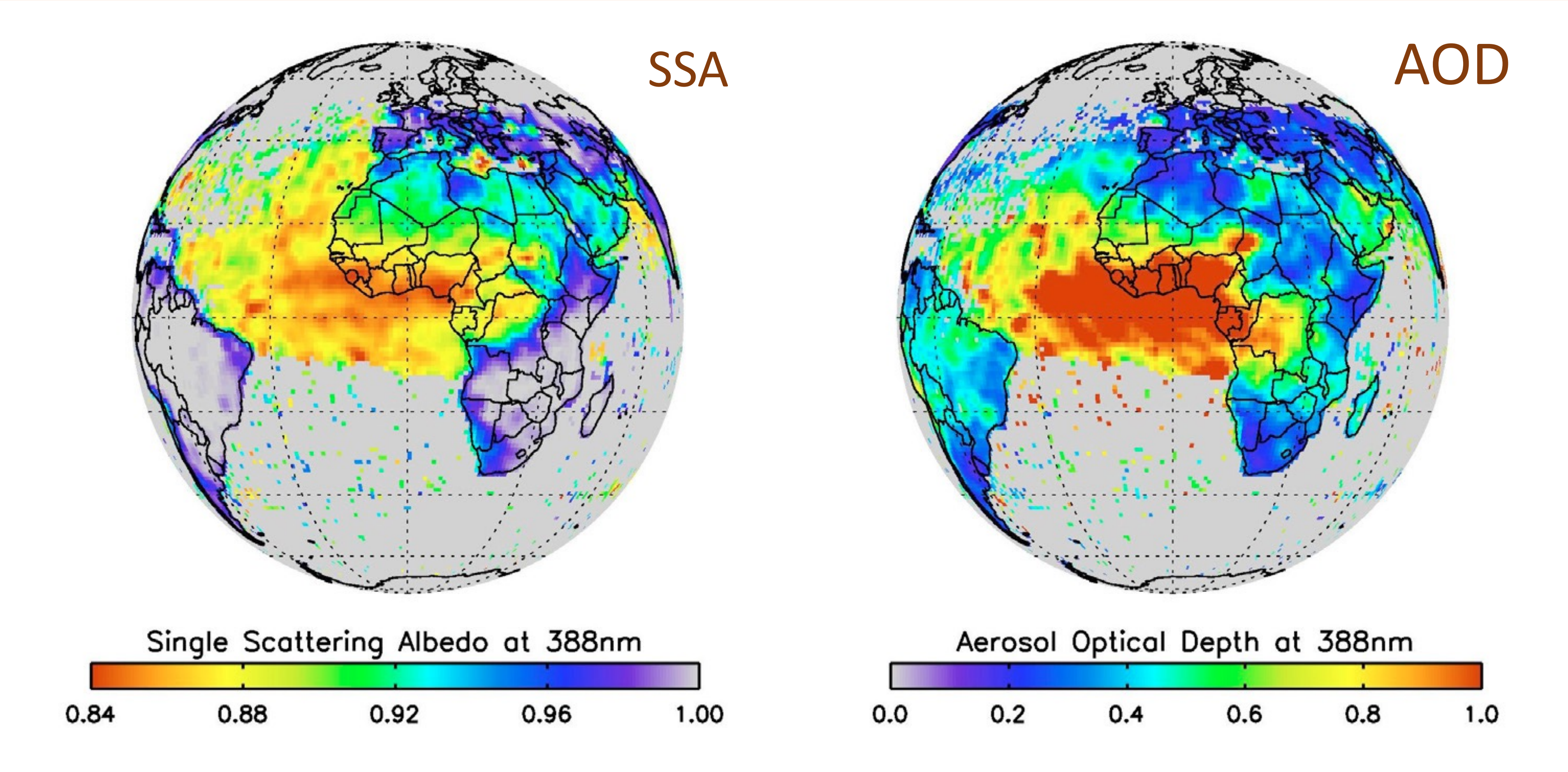
Aerosol type retrieval



Kahn and Gaitley, 2015

What else is new for clouds and aerosols in the EOS era?

Aerosol retrievals from OMI using UV wavelengths, like TOMS, but at 13 x 24 km.
Here the UV wavelengths are sensitive to aerosol absorption, as well as loading.

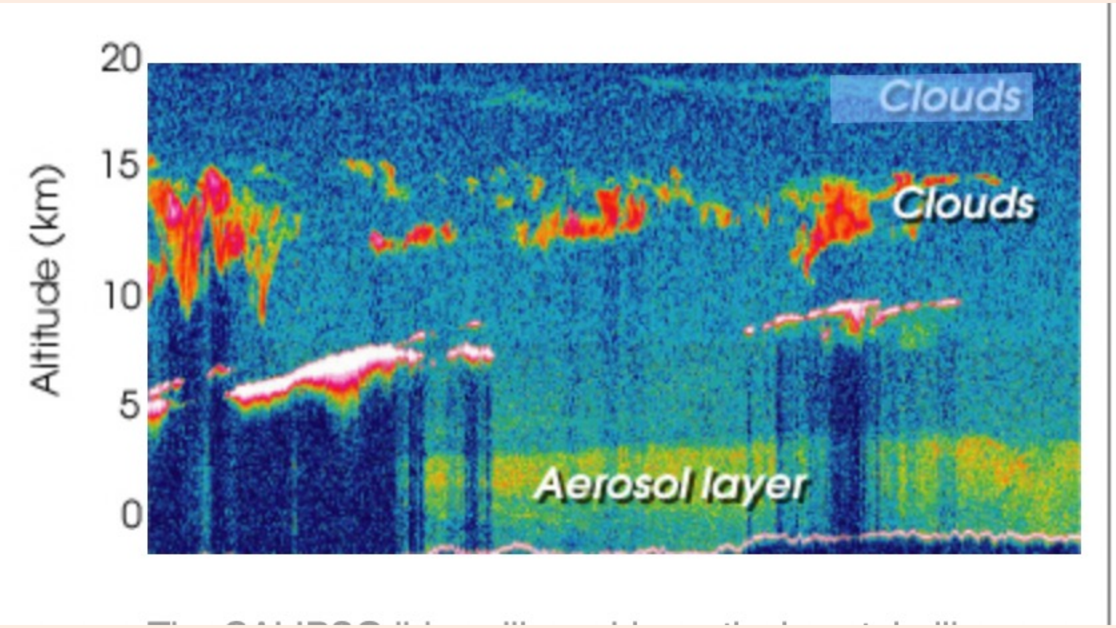


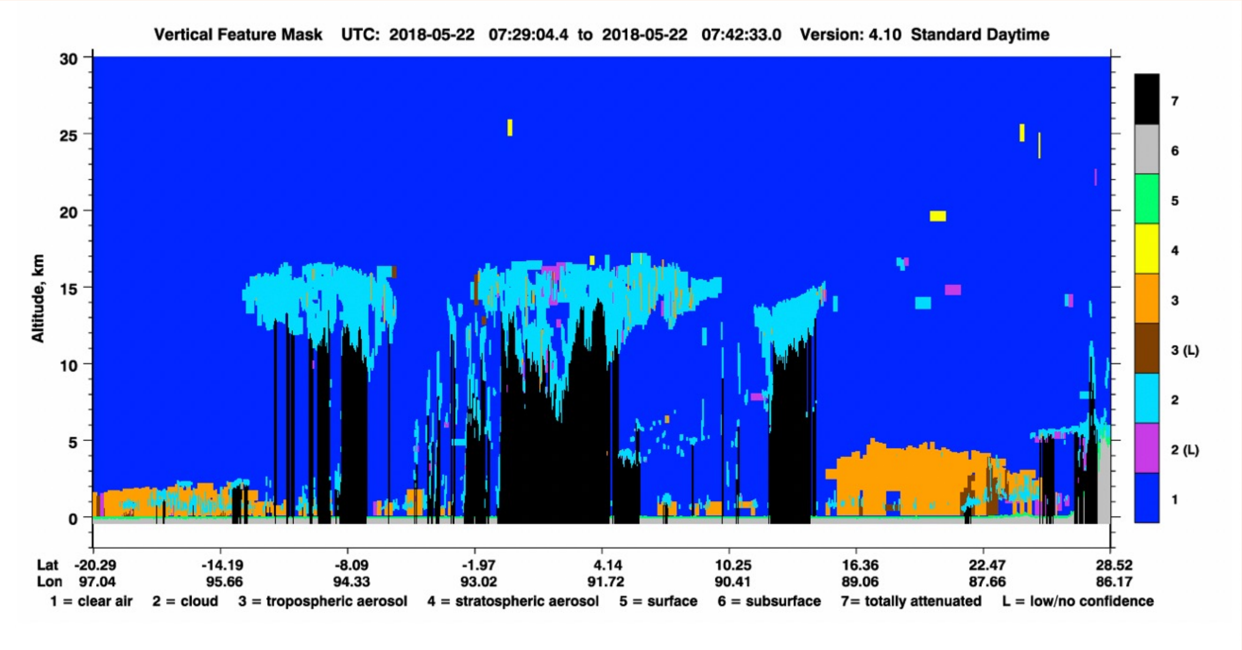
Omar Torres

What else is new for clouds and aerosols in the EOS era?

CloudSat and CALIPSO: active sensors for the first time (radar and lidar)

Vertically resolved atmospheric information.

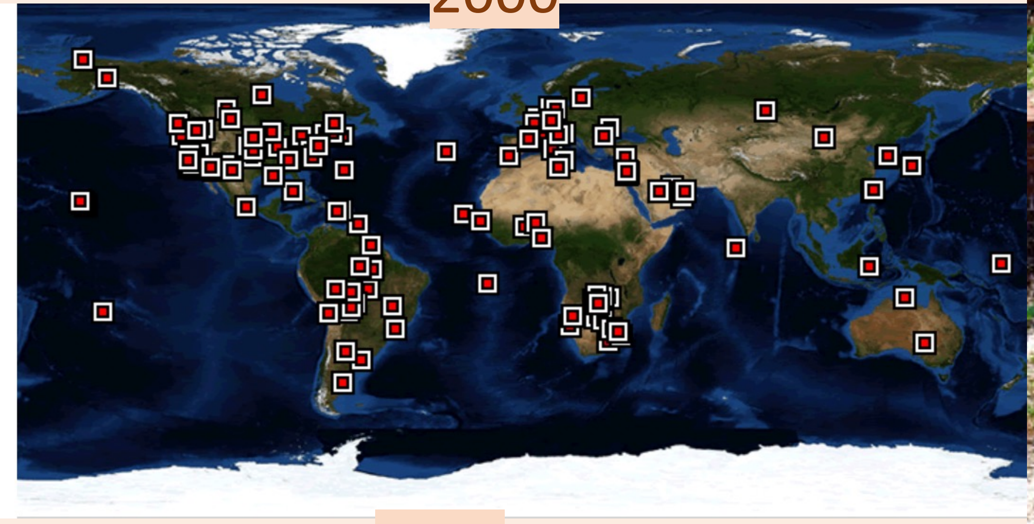




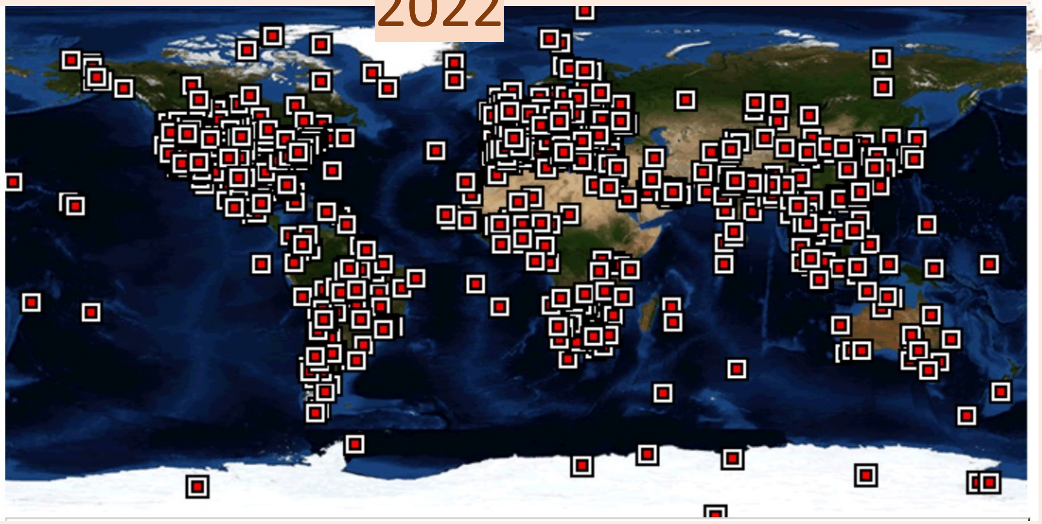
Maybe the most important contribution to the EOS era was not a satellite at all.

AErosol RObotics NETwork (AERONET)

2000

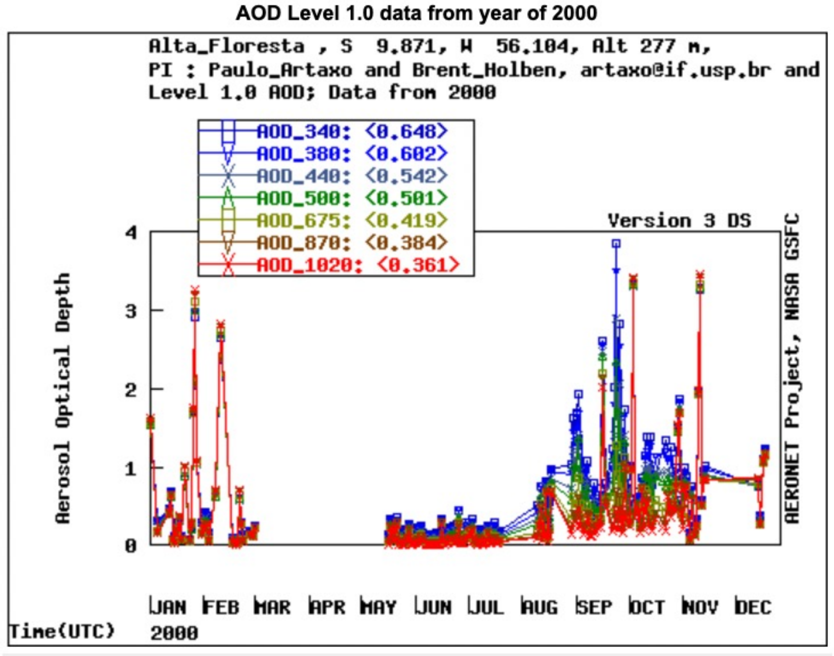


2022



Brent Holben

Maybe the most important contribution to the EOS era was not a satellite at all.

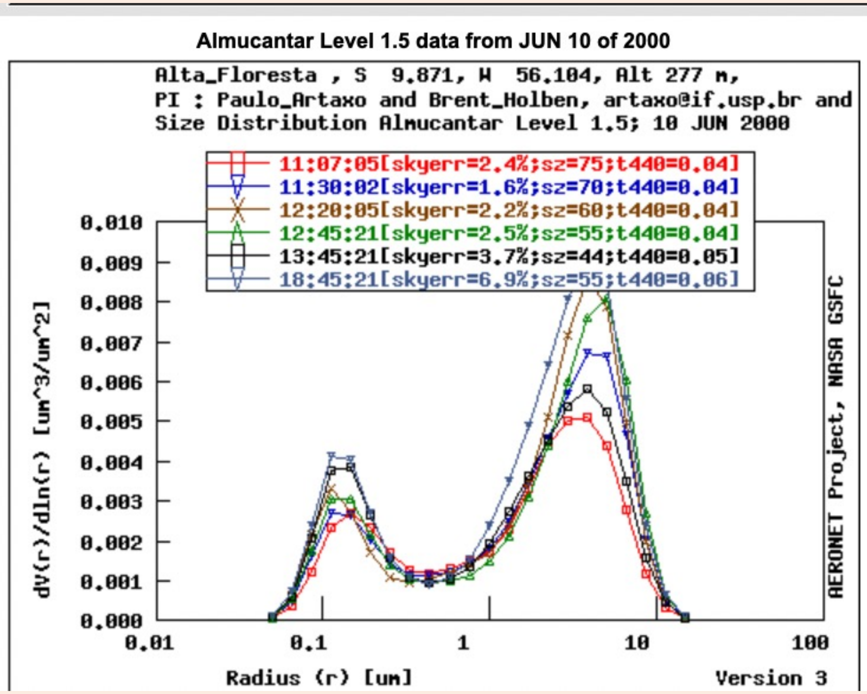


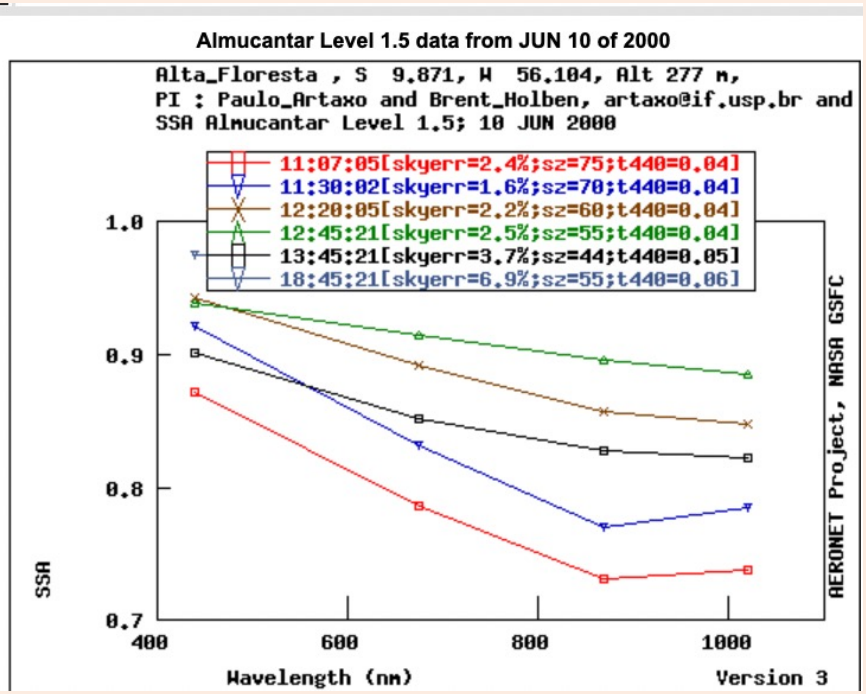
AErosol RObotics NETwork (AERONET)

From the ground looking directly at the sun and then sampling the sky radiance at multiple angles and wavelengths, against the dark back drop of space, the information contained

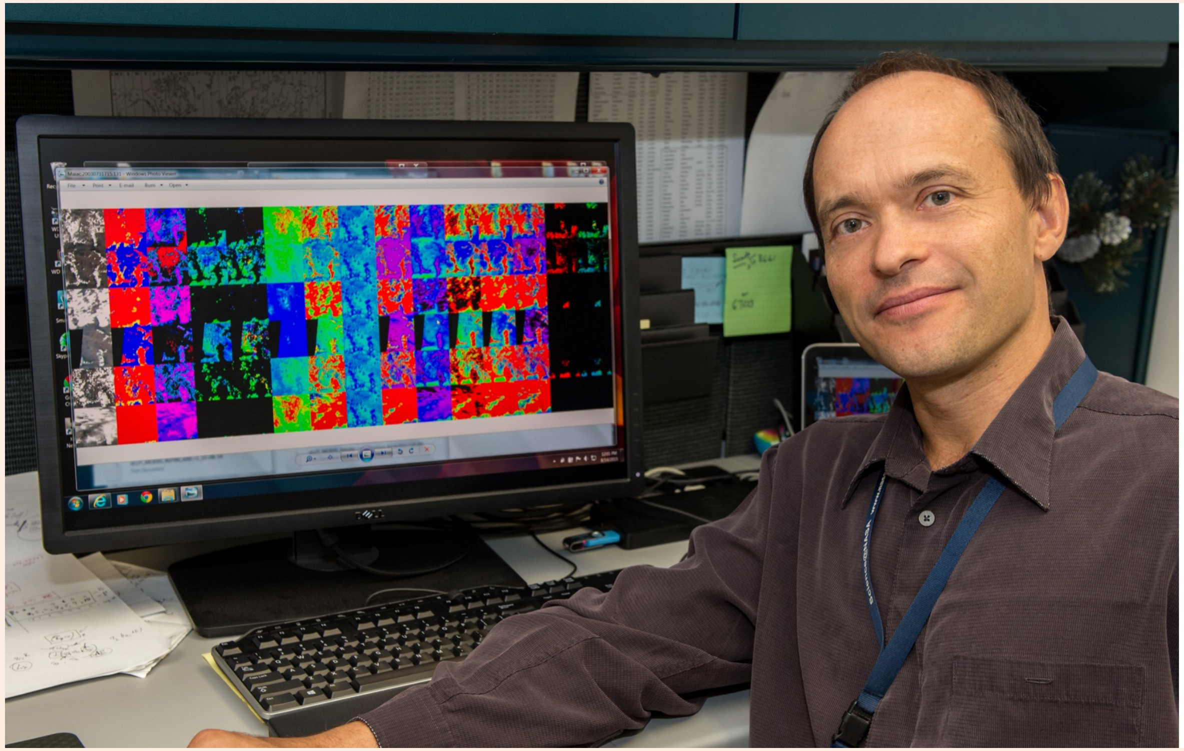
Spectral signals
Angular signals
And sometimes
polarization signals

Which could be inverted to fully characterize the total column ambient aerosol





Links in the chain



Dr. Michael D. King

Ralph Kahn

Lorraine,
Yoram Kaufman
Brent Holben
Israel, 1992

Brent Holben and Lorraine Remer, 1992 in Israel with the pre-AERONET sun/sky photometer

Satellite Remote Sensing began with the space race, but the first application was the need to observe the atmosphere.

Rooted in physics of interaction between particles and the electromagnetic spectrum

Moved from weather satellites to climate satellites

And from images and radiances to validated products

Some of the EOS-era products can be continued from PACE, but not all.

Aerosols will be the easiest to continue, and some clouds

Important message: while rooted in physics, atmospheric remote sensing is also
- about people,
- about building collaborative relationships
- about linking the chain from one generation to the next

And that is why we are here this week.