Microwave spectrum

Measurement, modelling and information content

Alan Geer

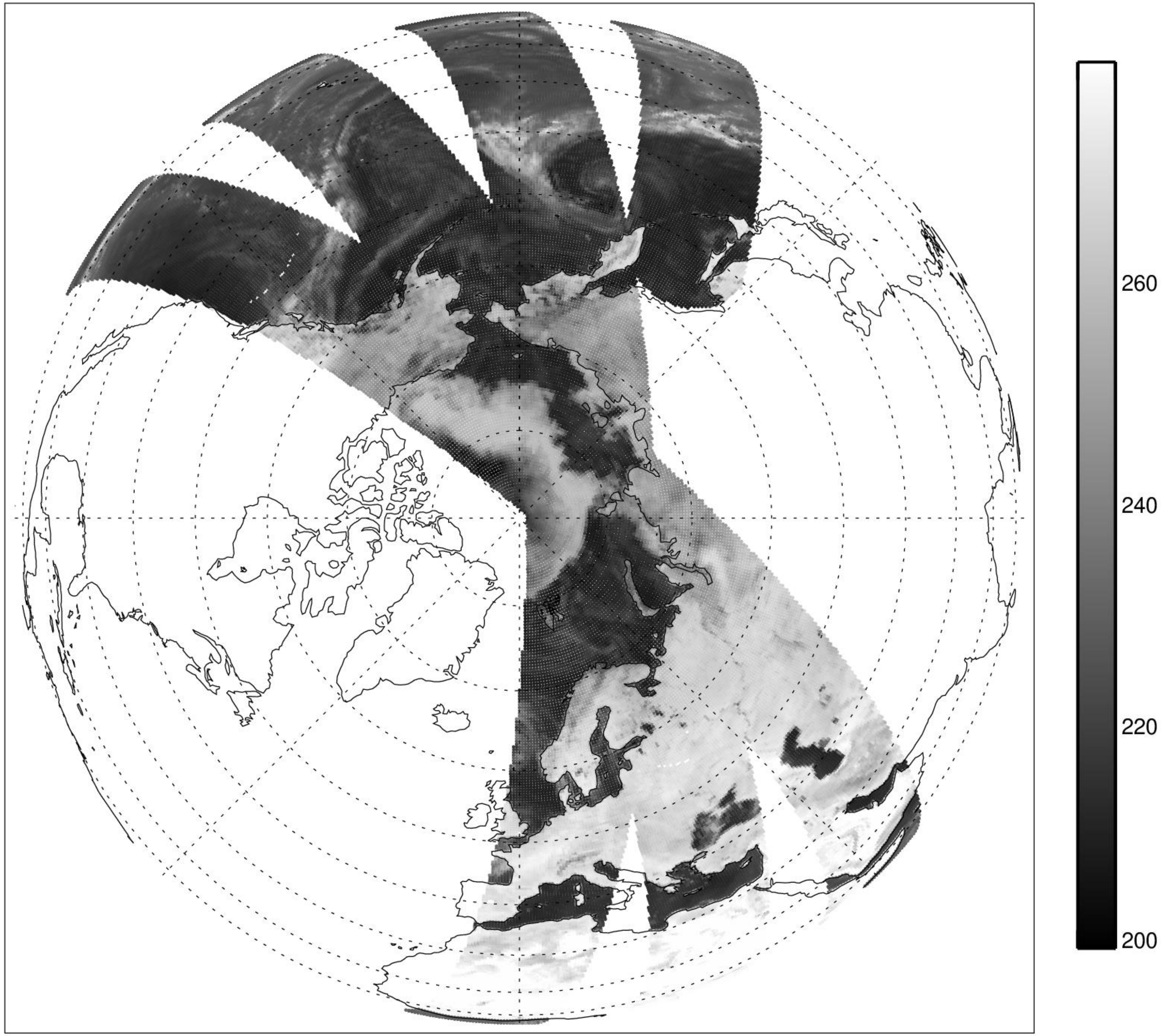
Thanks to: Peter Bauer, Bill Bell

EUMETSAT/ECMWF NWP-SAF satellite data assimilation training course, 15 – 19 May, 2023

Advanced Scanning Microwave Radiometer (AMSR-2)

Observation composite for 1st Nov 2021

Brightness temperatures [Kelvin] at 37 GHz, v-polarised



ECMWF

Advanced Scanning Microwave Radiometer (AMSR-2)

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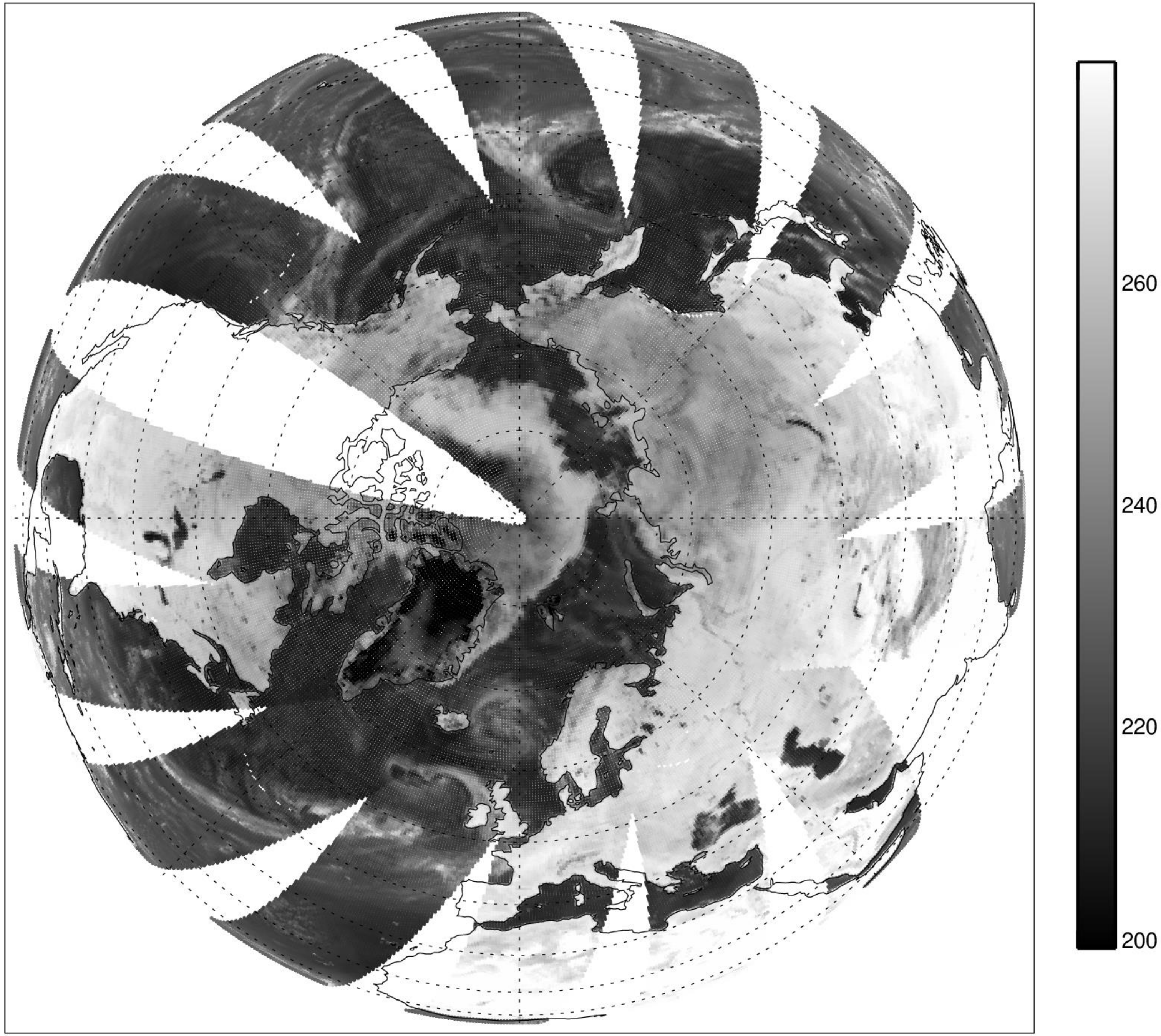

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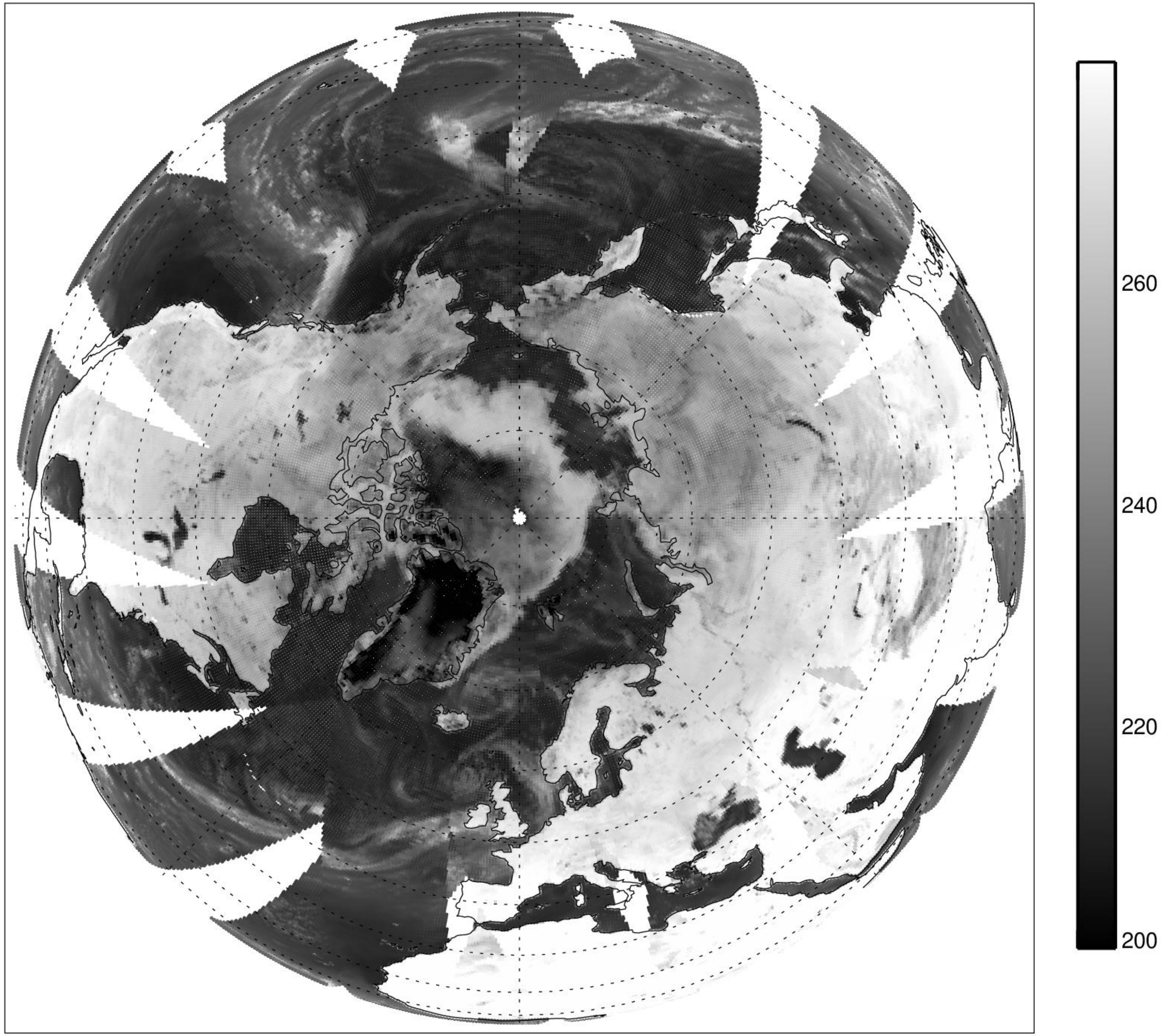

ECMWF

Advanced Scanning Microwave Radiometer (AMSR-2)

Observation composite for 1st Nov 2021

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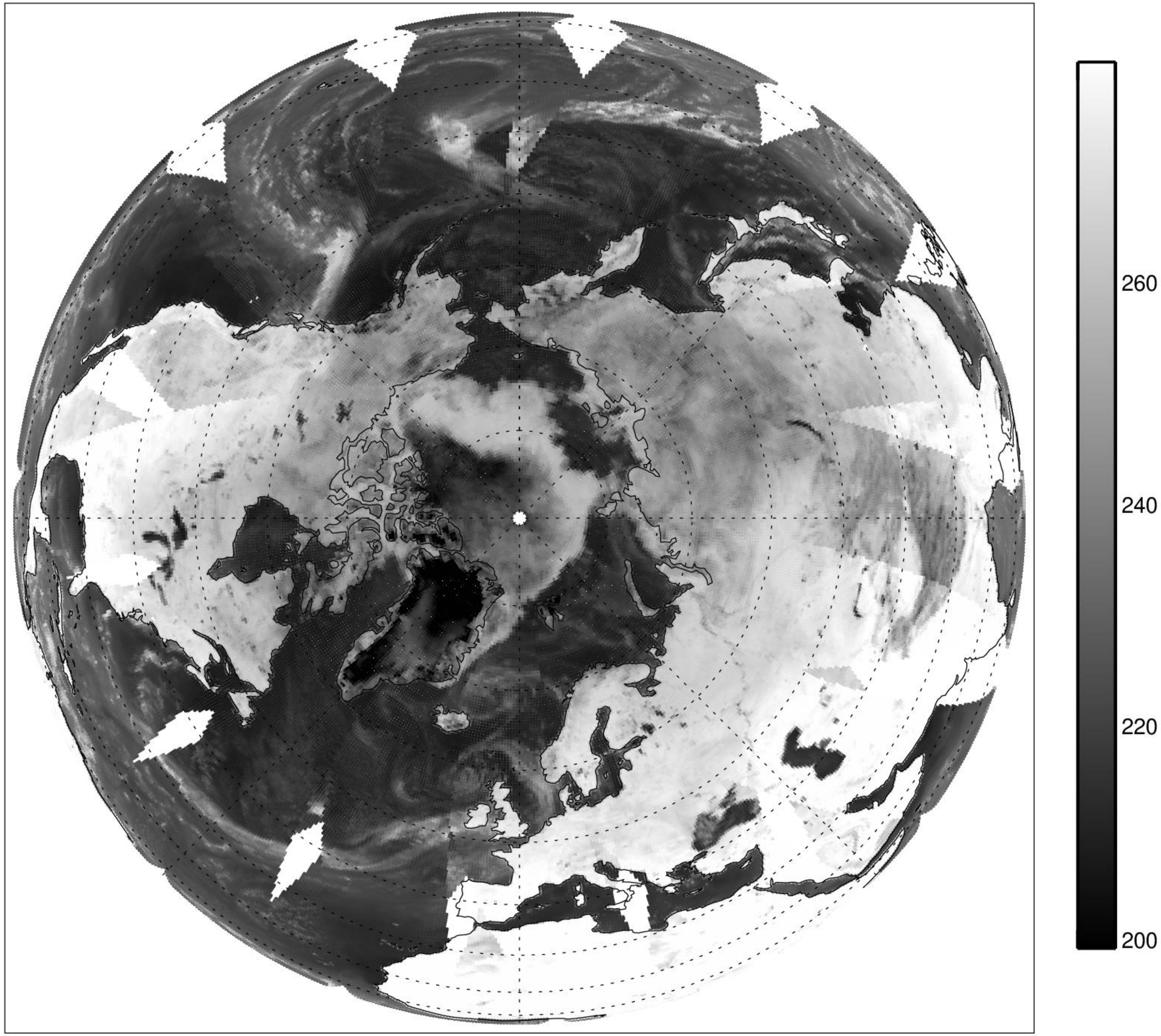
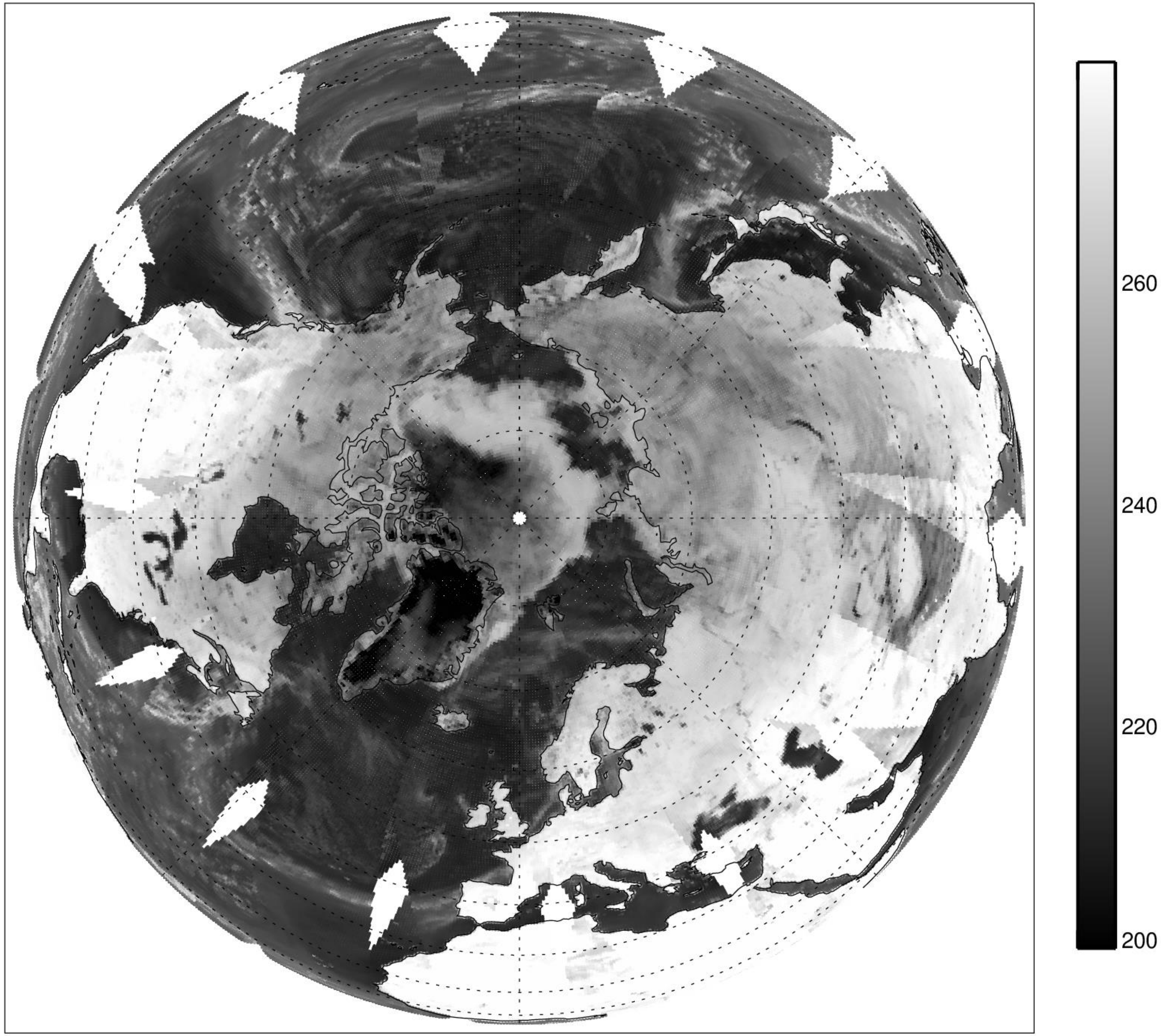


ECMWF

Advanced Scanning Microwave Radiometer (AMSR-2)

Observation composite for 2nd Nov 2021

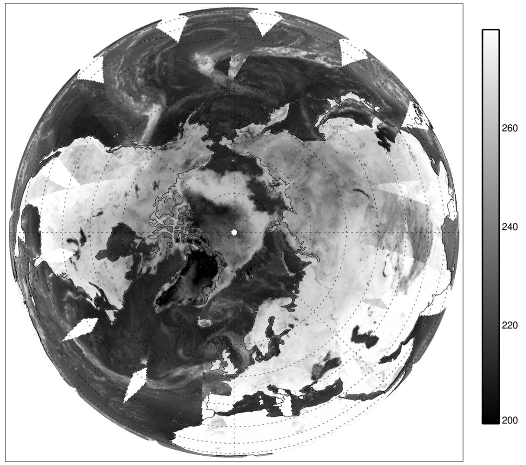
Radiances shown as brightness temperatures [Kelvin] at 37 GHz, v-polarised

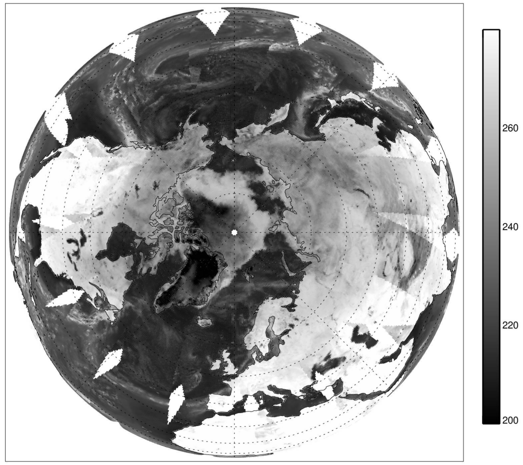


1st Nov

2nd Nov

Observations

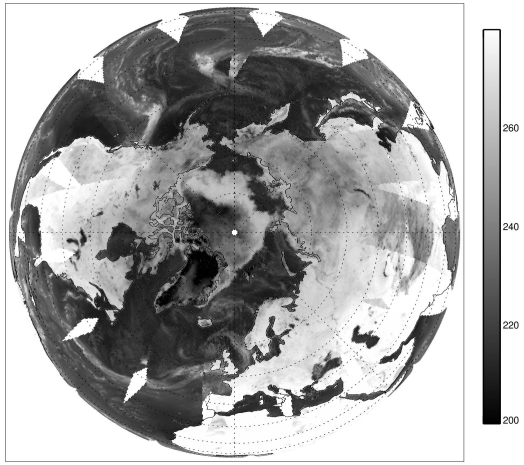




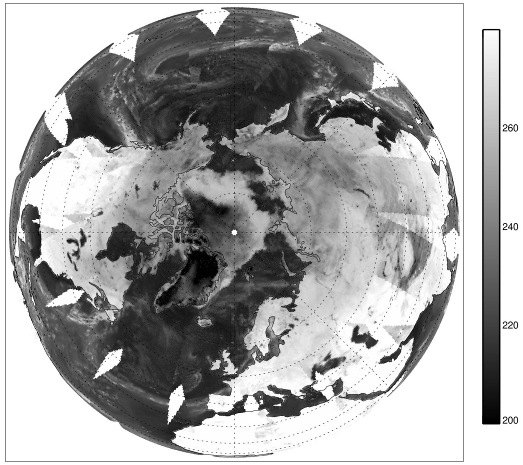
Machine learning:

- Learn how to forecast the observations

1st Nov



2nd Nov



Observations

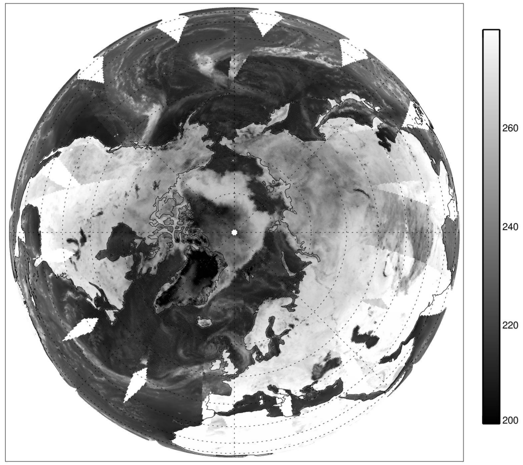
Machine learning:

- *Learn how to interpret the observations*
- Learn how to forecast the geophysical state

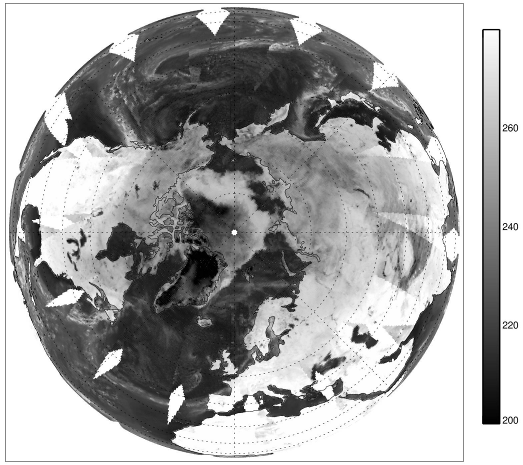
Earth system model: geophysical state and its forward propagation in time

Observations

1st Nov



2nd Nov

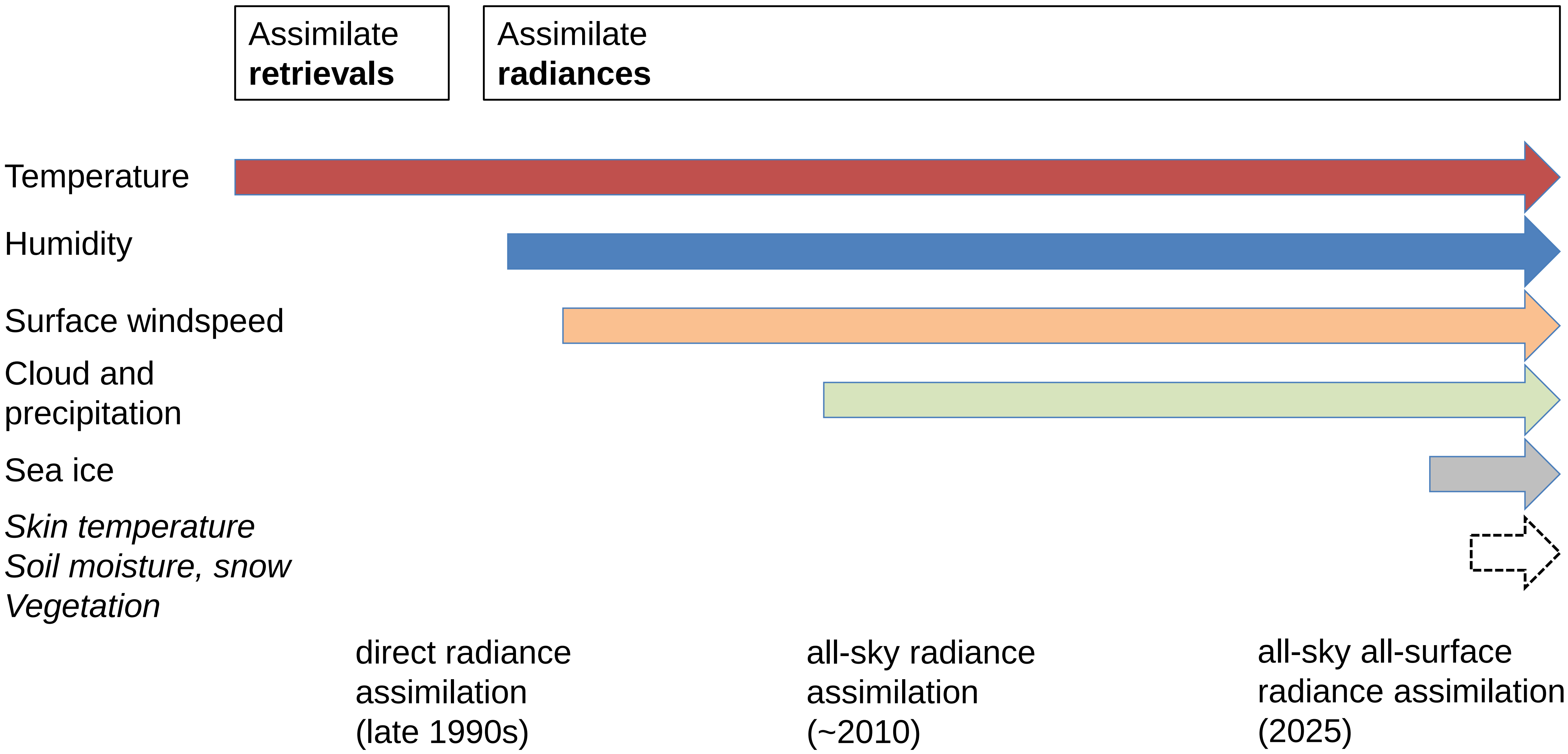


Data assimilation:

- Use physics to forward model the observations
- Data assimilation extracts information from observations
- Use physics to propagate the state
- *(machine) learn model components from observations too*

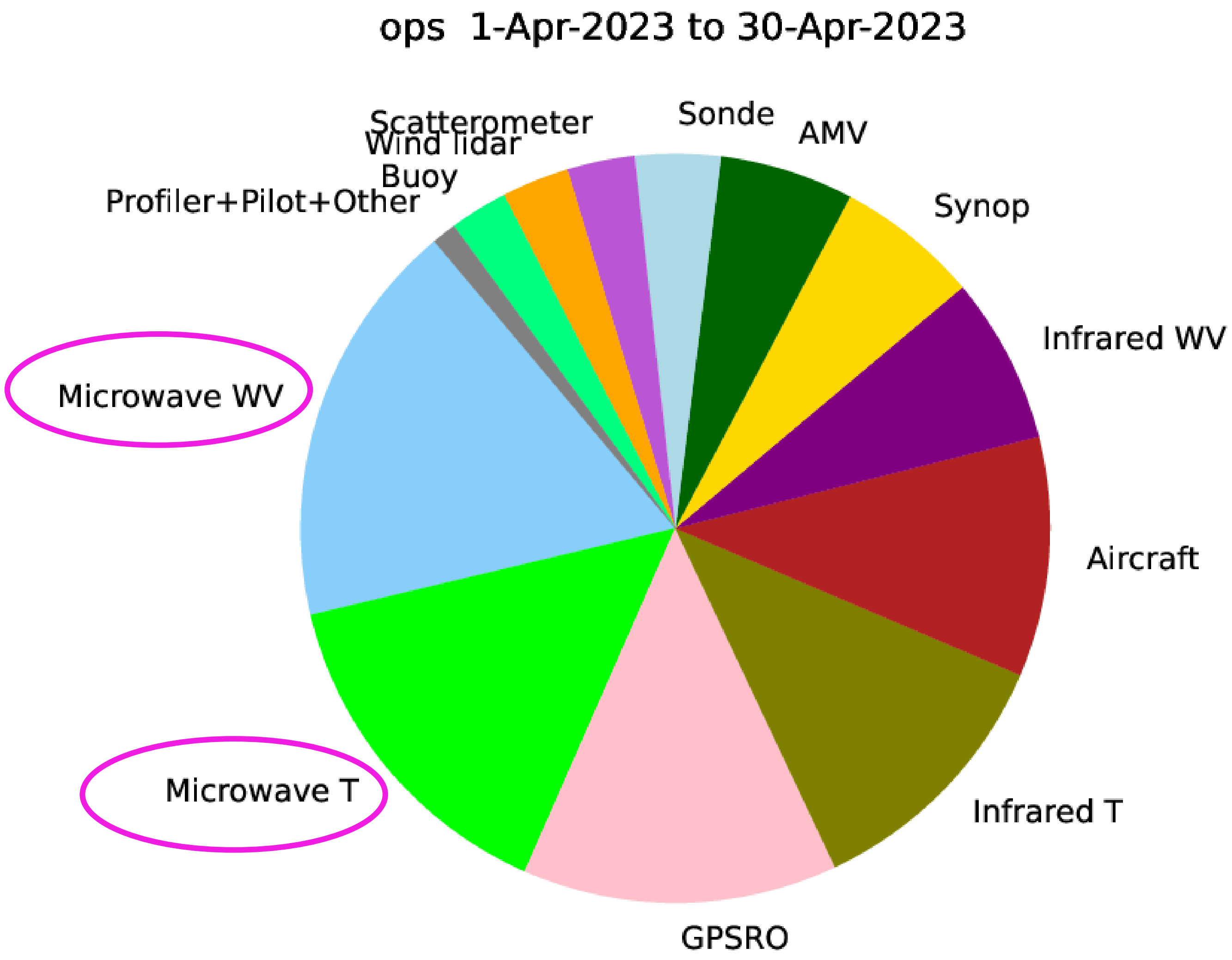
Earth system model: geophysical state and its forward propagation in time

Rough timeline of satellite microwave data assimilation in ‘atmospheric’ DA

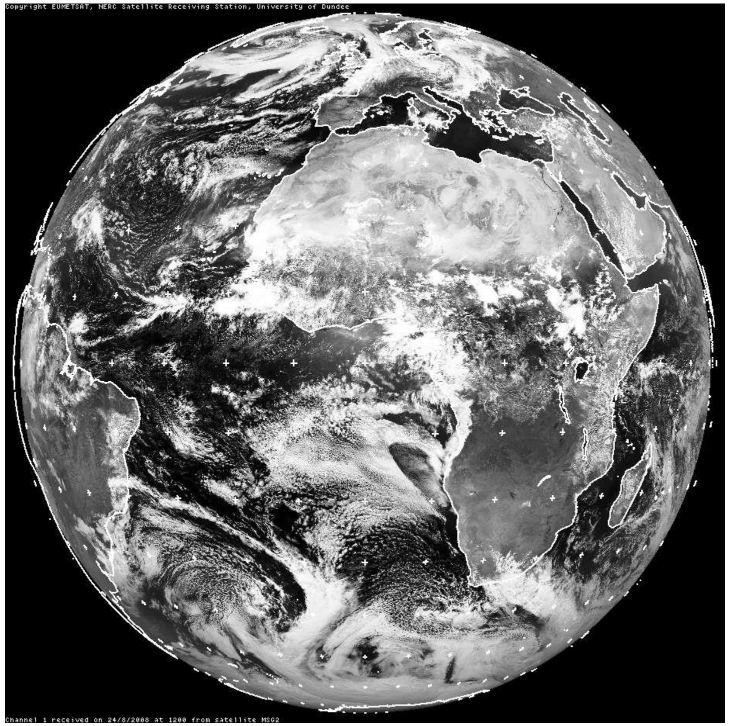


Relative impact of observations at ECMWF: April 2023

Relative sensitivity of 24 hour forecast error to observation impact (FSOI)

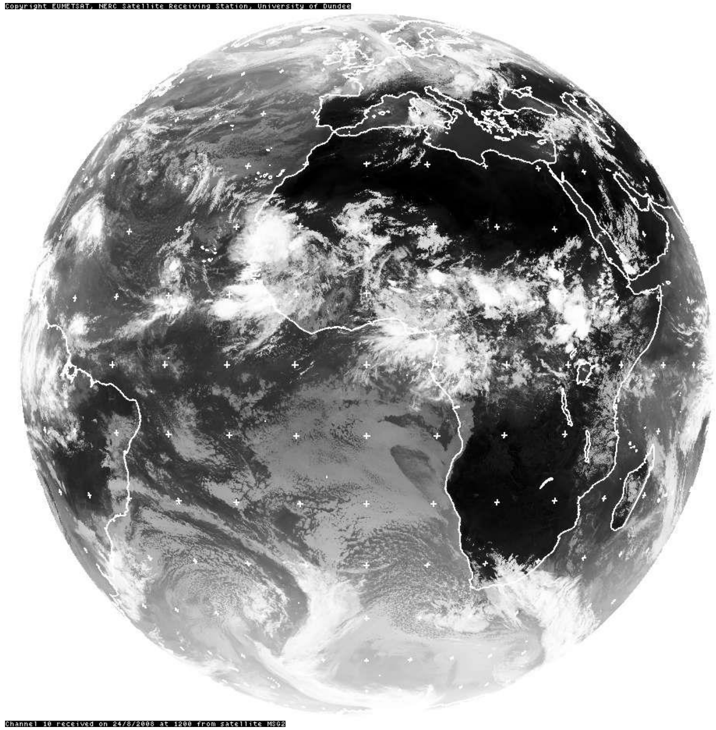


Visible, infrared and microwave views of the earth



Visible

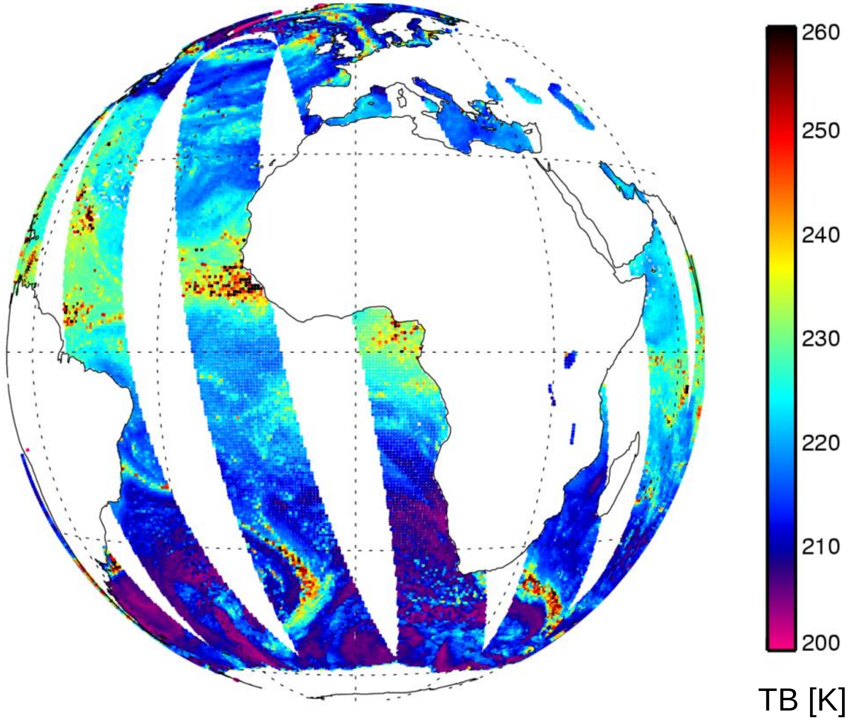
SEVIRI channel 1
0.56-0.71 µm



Infrared

SEVIRI channel 10
11-13 µm

*reverse colour scale – bright is really cold/dim



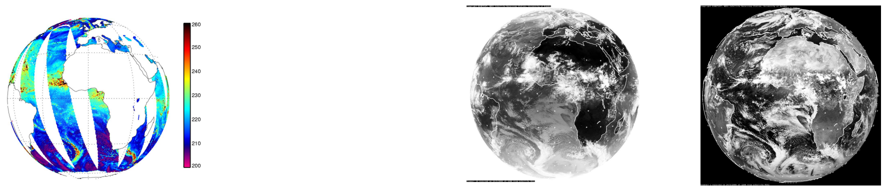
Microwave

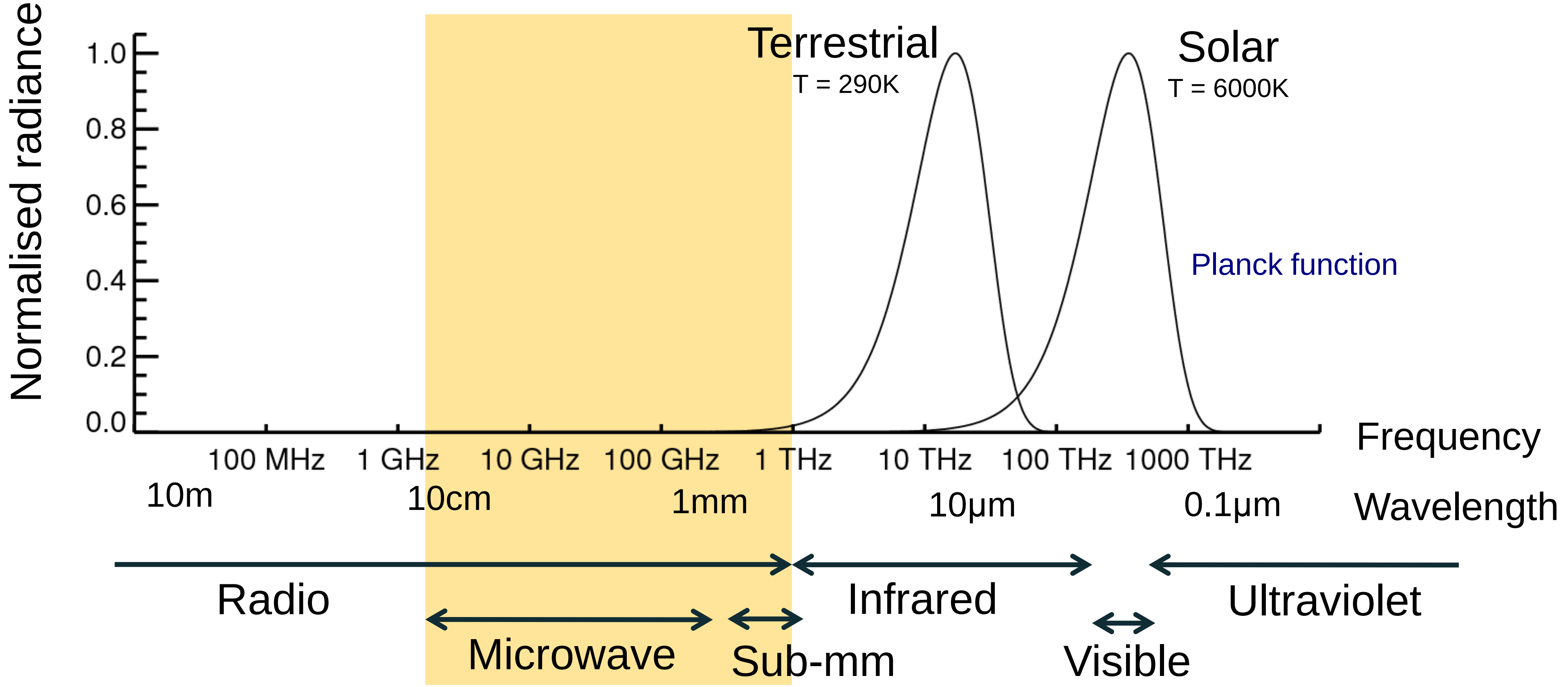
AMSR-E channel 37v
8108 µm (37 GHz v-pol)

Window channels 24th August 2008 at around 12UTC

SEVIRI from Dundee Satellite Receiving Station, © Eumetsat

Where is the microwave in the electromagnetic spectrum?

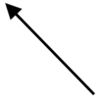




How much energy?

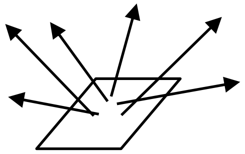
Planck Function Radiance
W m^{-2} sr^{-1} Hz^{-1}

Travelling in a beam

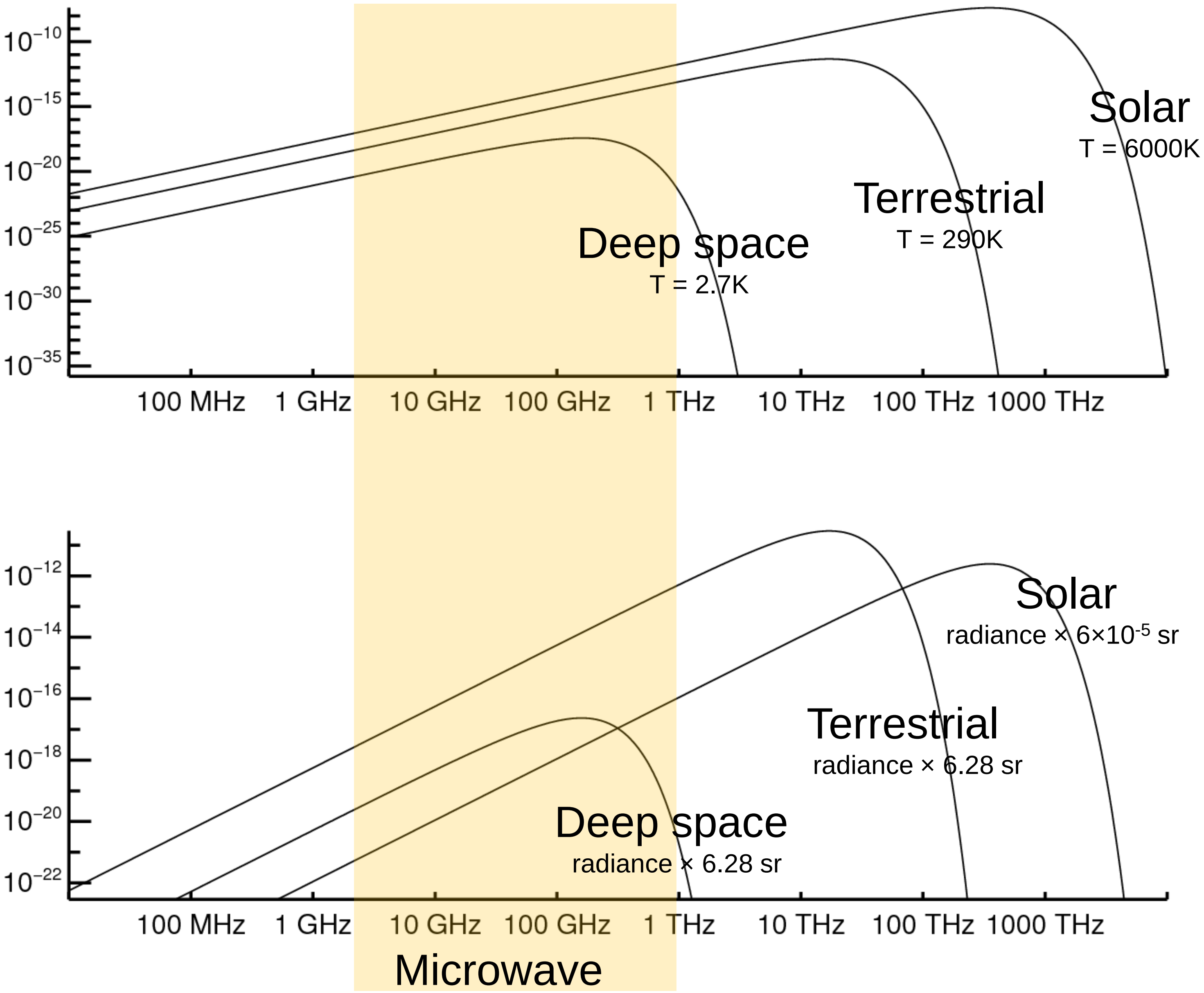


Flux
W m^{-2} Hz^{-1}

Travelling through an area (in one direction)



sr – Steradian (unit of solid angle)



Radiance and brightness temperature

- Radiance: W m^{-2} sr^{-1} Hz^{-1}
  - Watts (energy)
  - per metre squared
  - per unit of “direction” (solid angle)
  - per unit frequency

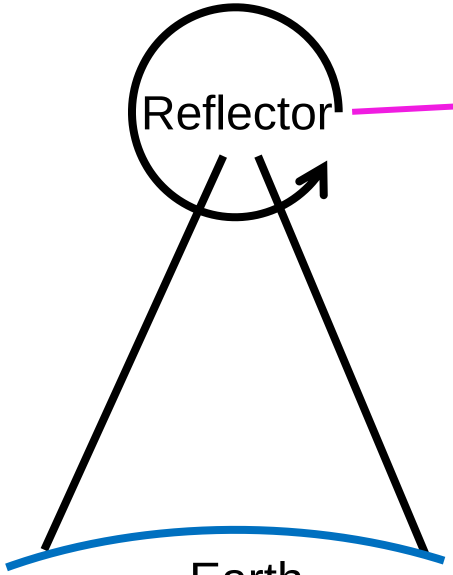
- Planck’s function (Rayleigh-Jeans approximation, valid in microwave)

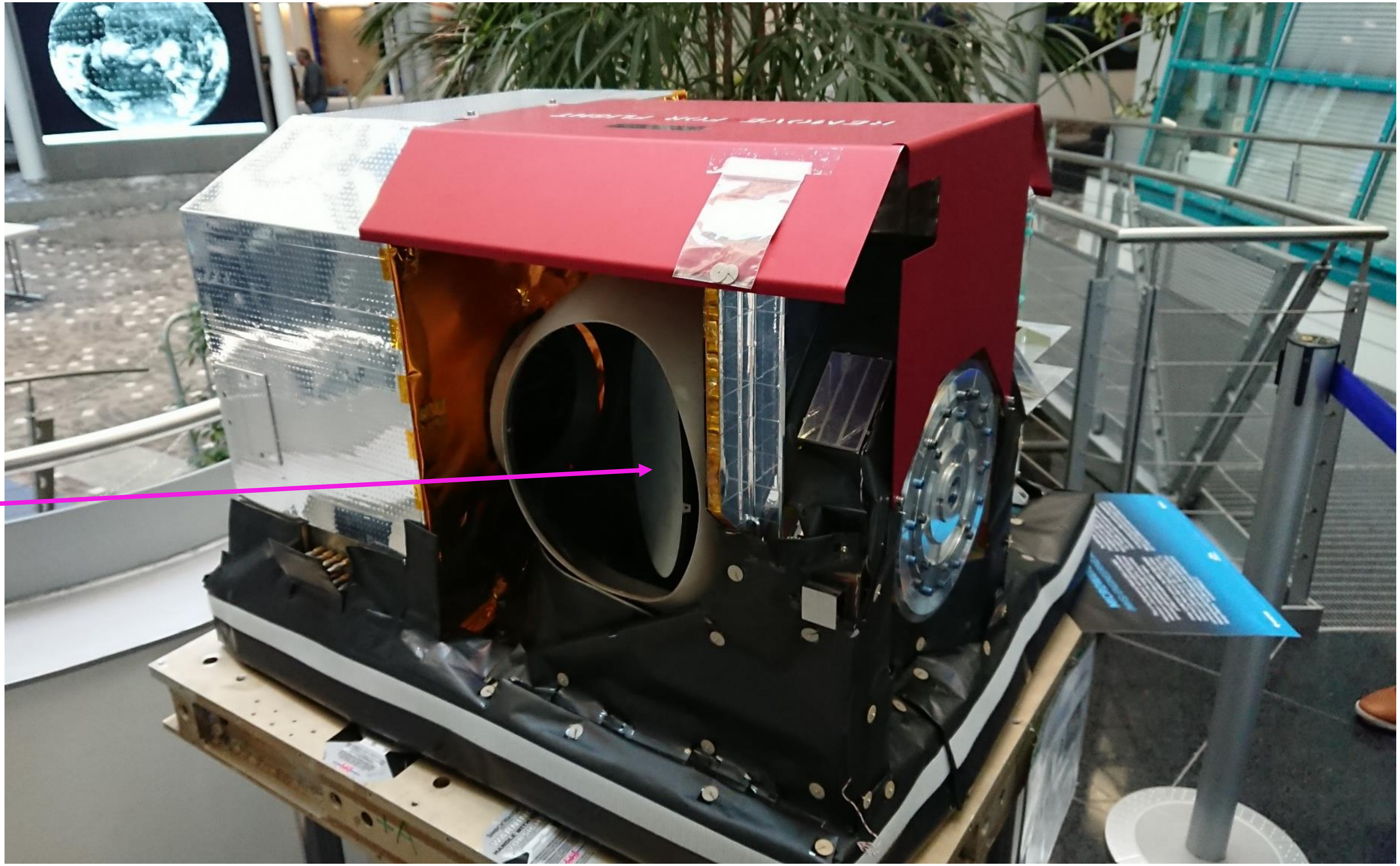
Radiance ⟶ $$B_\lambda(T_B) = \frac{2c}{\lambda^4} k_B T_B$$ ⟵ Brightness temperature

c = speed of light; λ = wavelength; k_B = Boltzmann’s constant

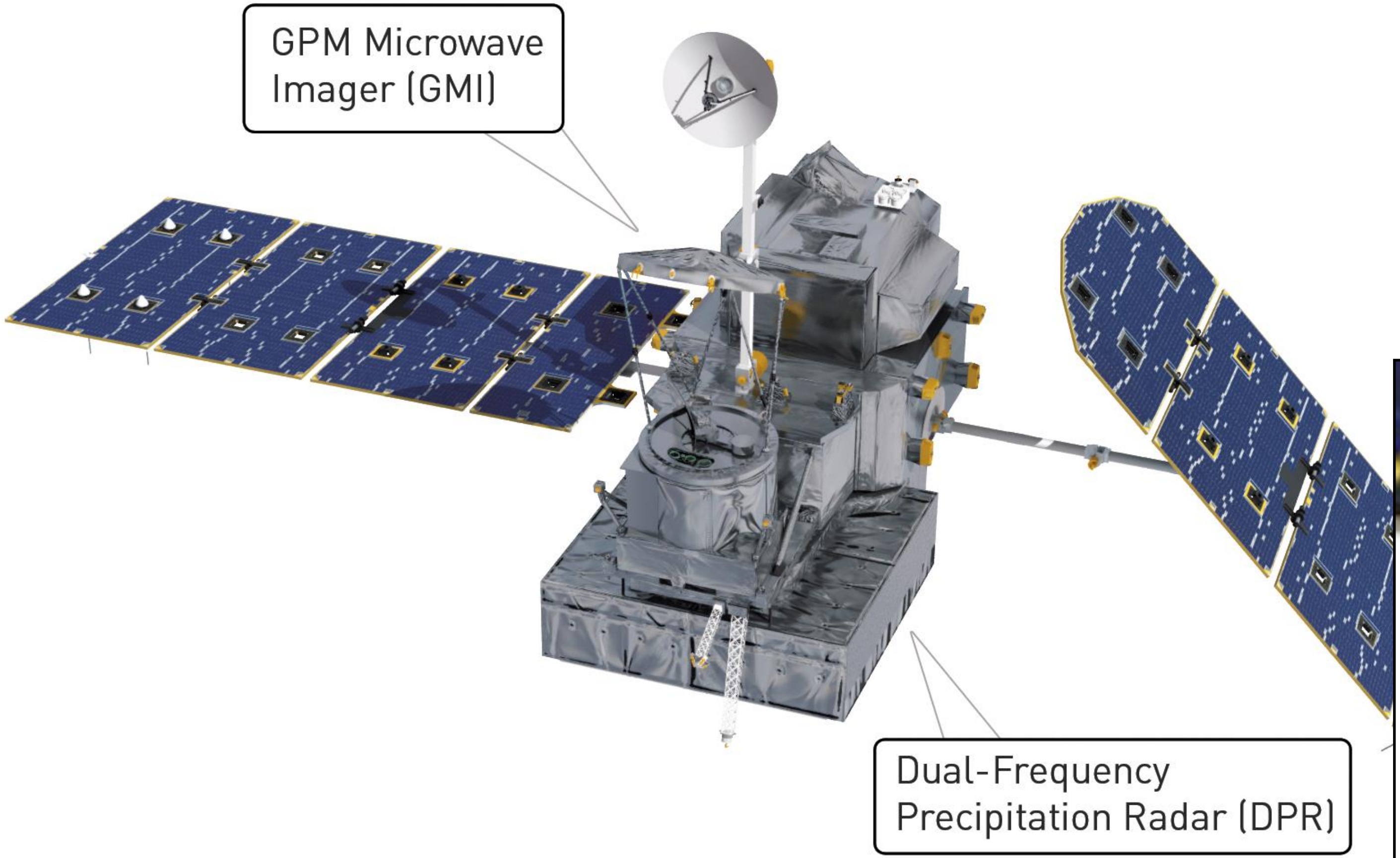
The Microwave Humidity Sounder (MHS) at EUMETSAT

Cross-track sounder



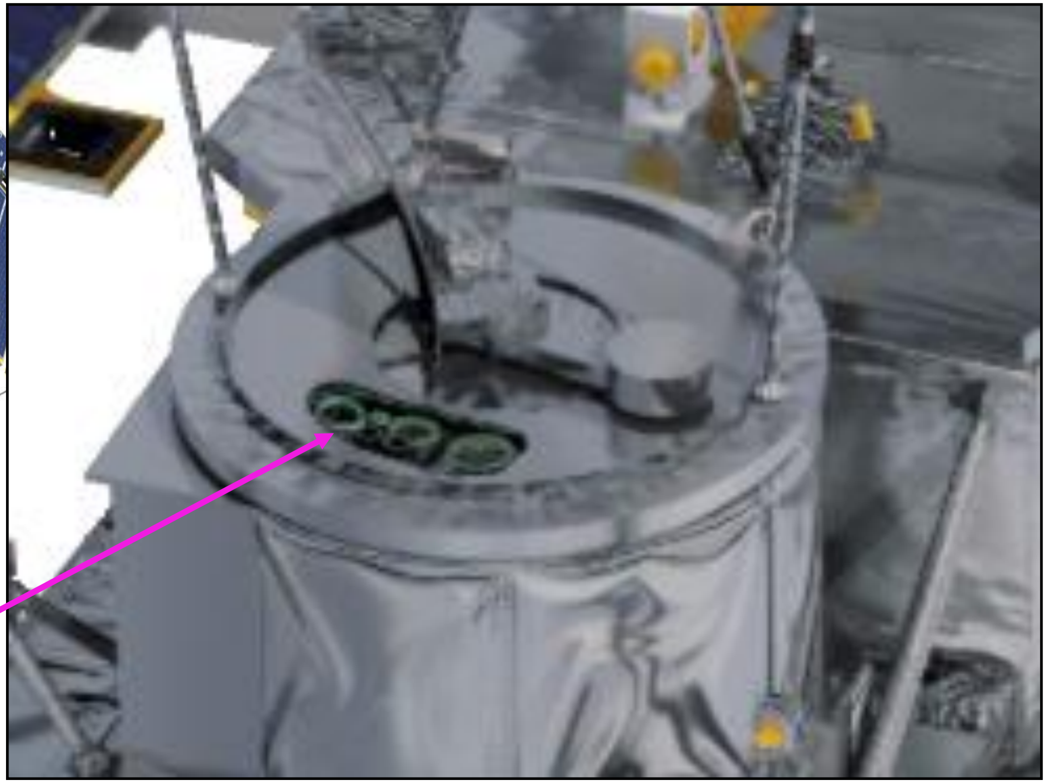


Global precipitation mission (GPM)



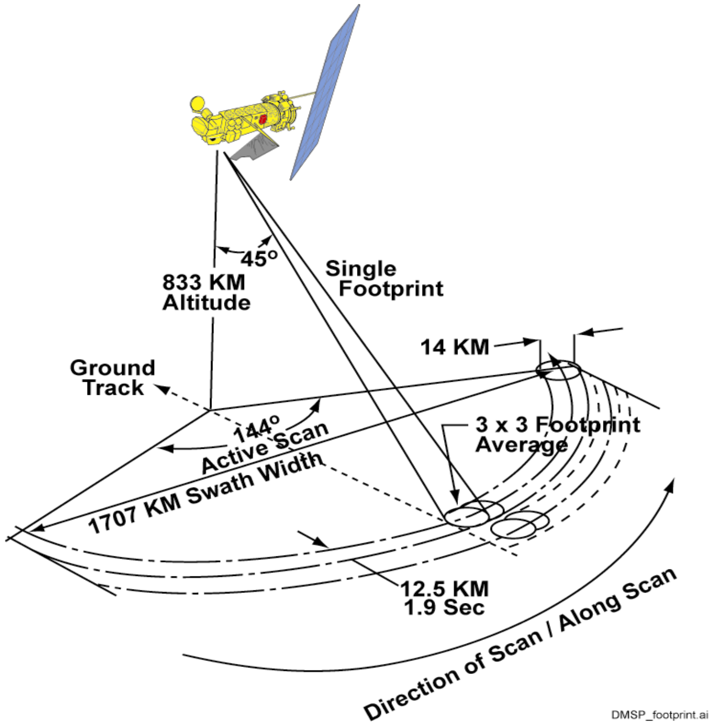
Global precipitation mission:

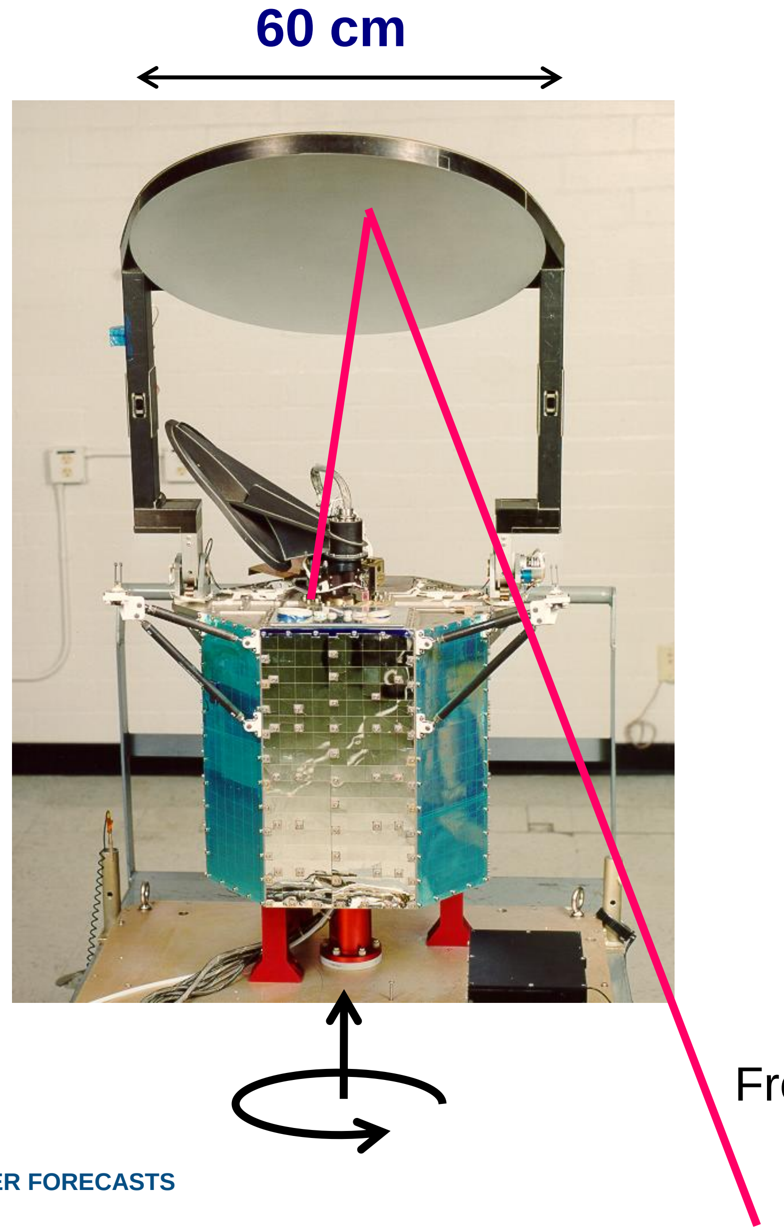
- Launched Feb 2014



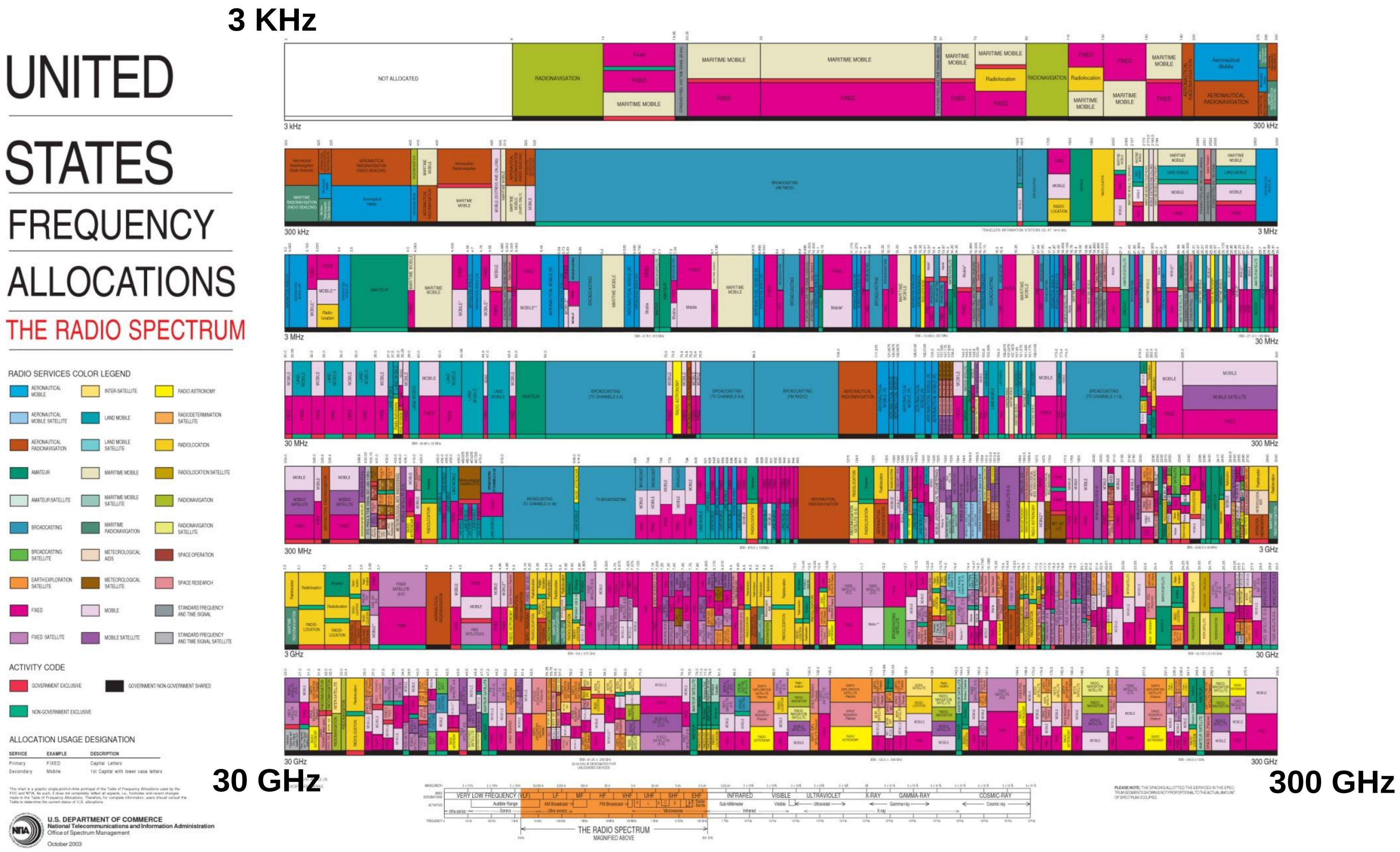
Special Sensor Microwave Imager / Sounder (SSMIS)

Conical scanning geometry

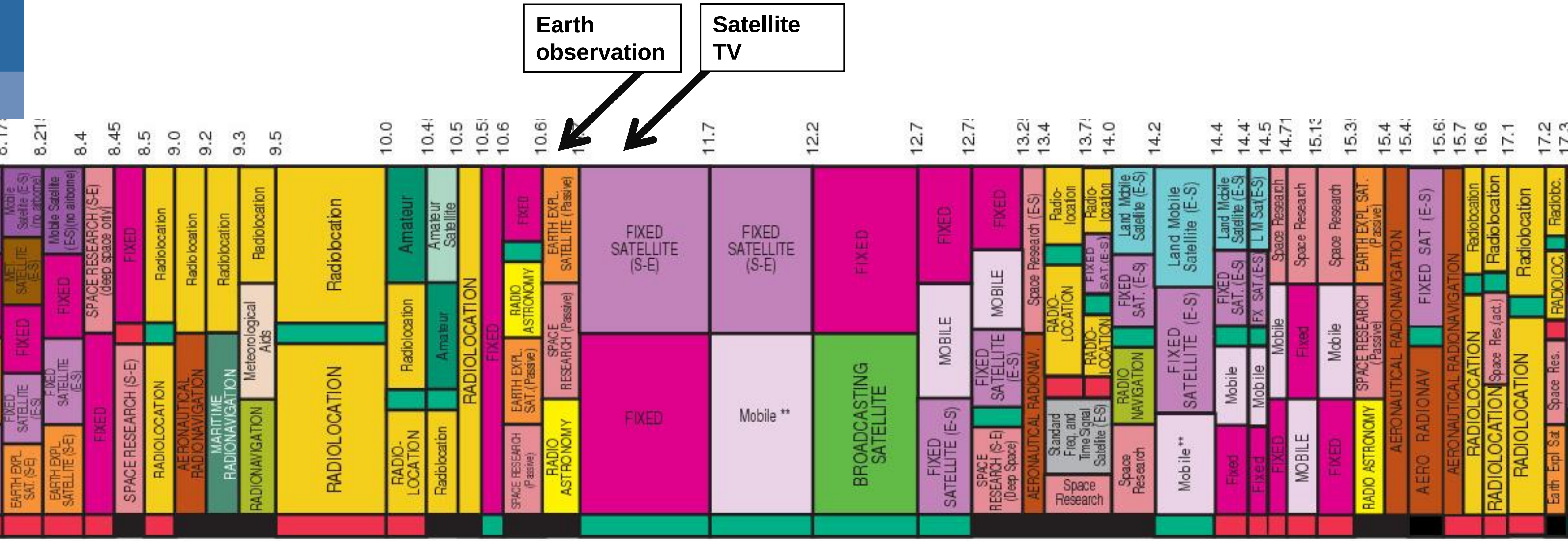




Other users of the spectrum



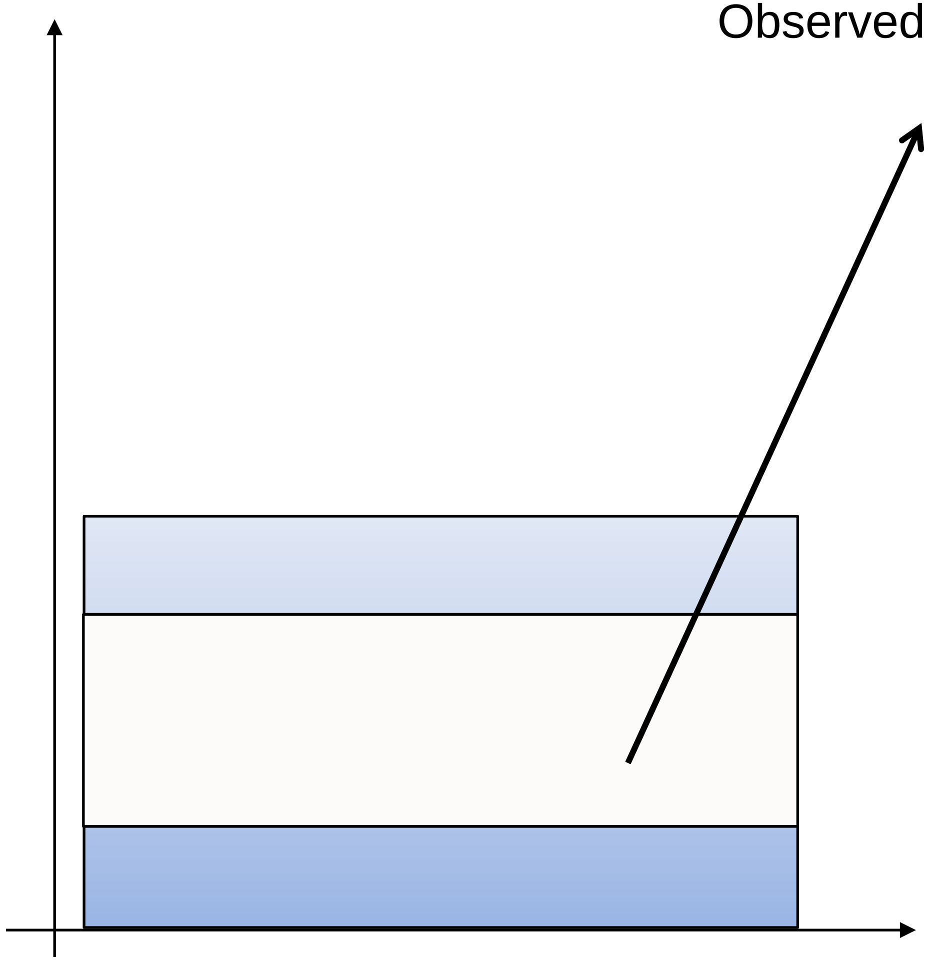
Other users of the spectrum



Information content

Radiative transfer: sounding channels (ignoring scattering)

Observed by satellite



Ocean or land / snow / sea-ice surface

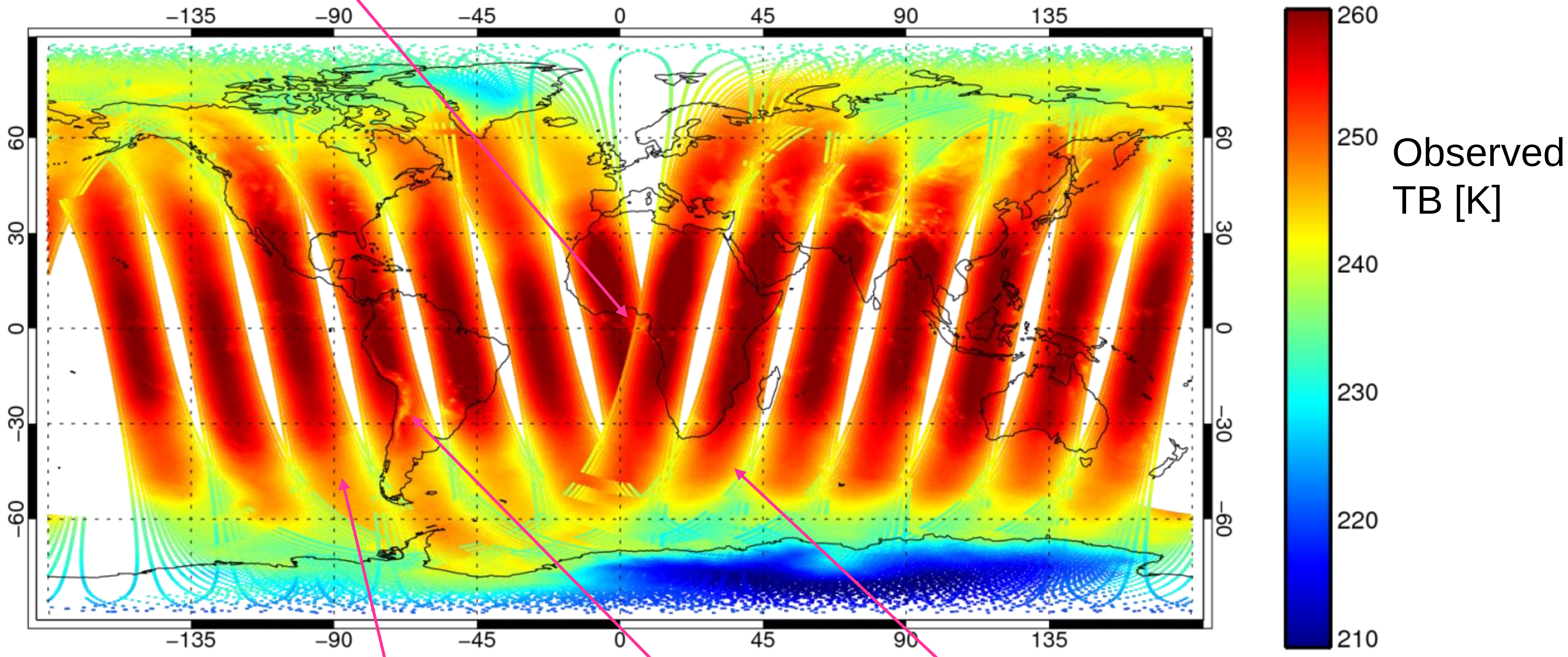
One source of radiation:

1. Radiation emitted by the atmosphere

Sensitivities: temperature sounding channels

AMSU-A channel 5 radiances:
Metop-A satellite, 9pm 25/4 to 9am 26/4/2012
Cross-track scanner

Deep convection

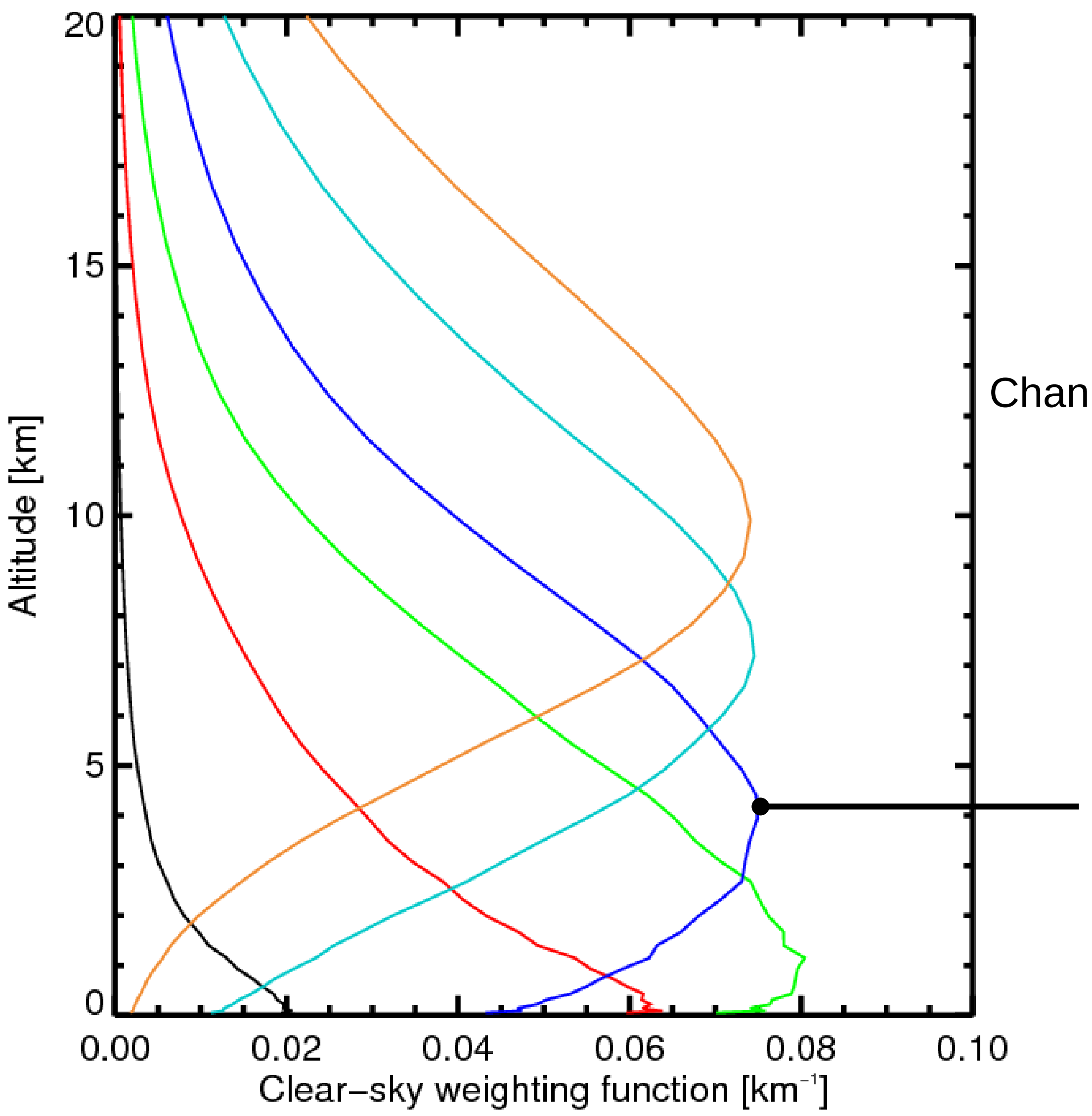


Temperature of approx. lowest 10km of atmosphere

Surface sensitivity

Dependence on angle of travel through atmosphere (zenith angle)

Clear sky AMSU-A weighting functions (nadir)

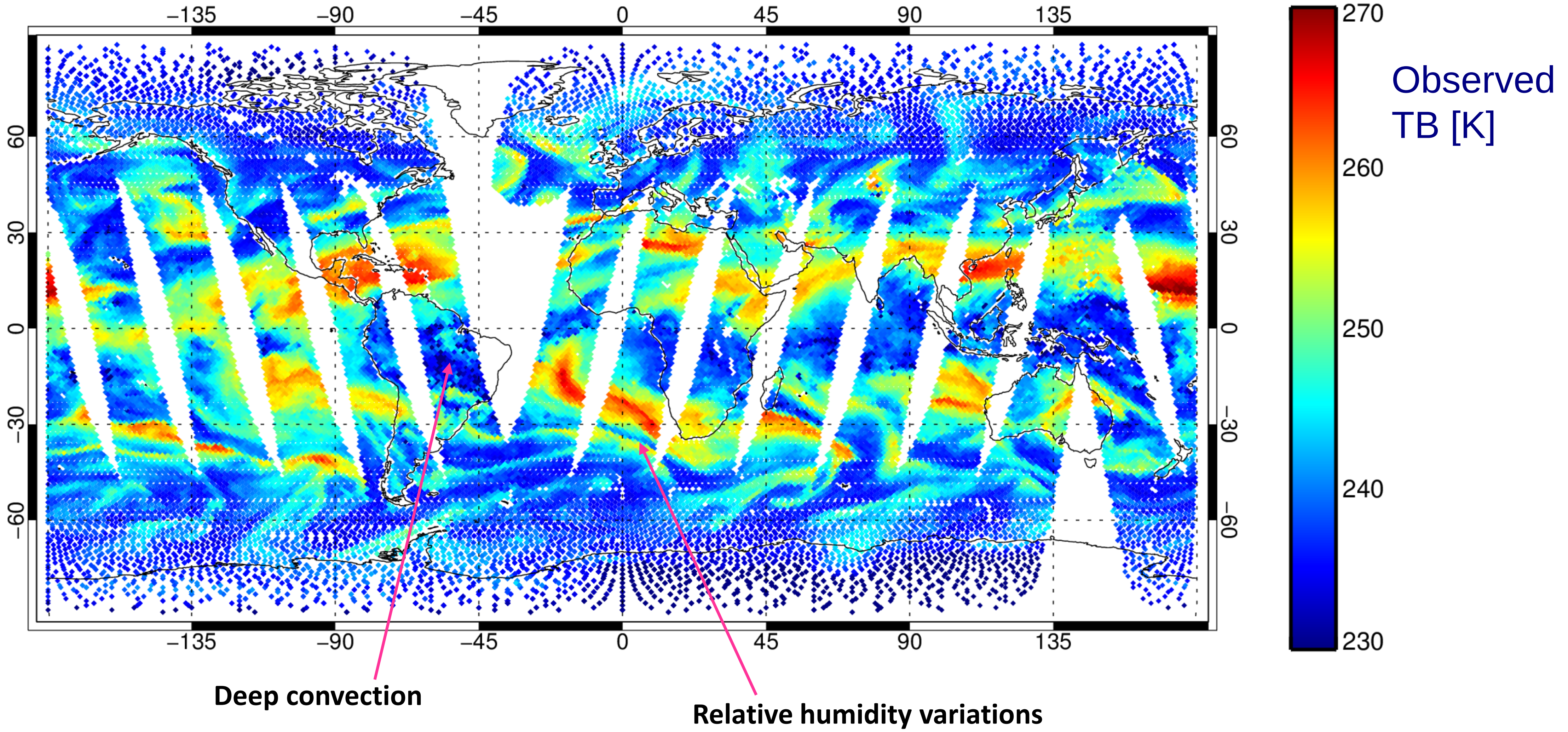


AMSU-A channels are at frequencies mainly sensitive to oxygen, a well-mixed gas: weighting functions are effectively fixed

Channel	Transmittance surface to space
7	0%
6	0%
5	5%
4	19%
3	56%
2	92%

Humidity sounding channels

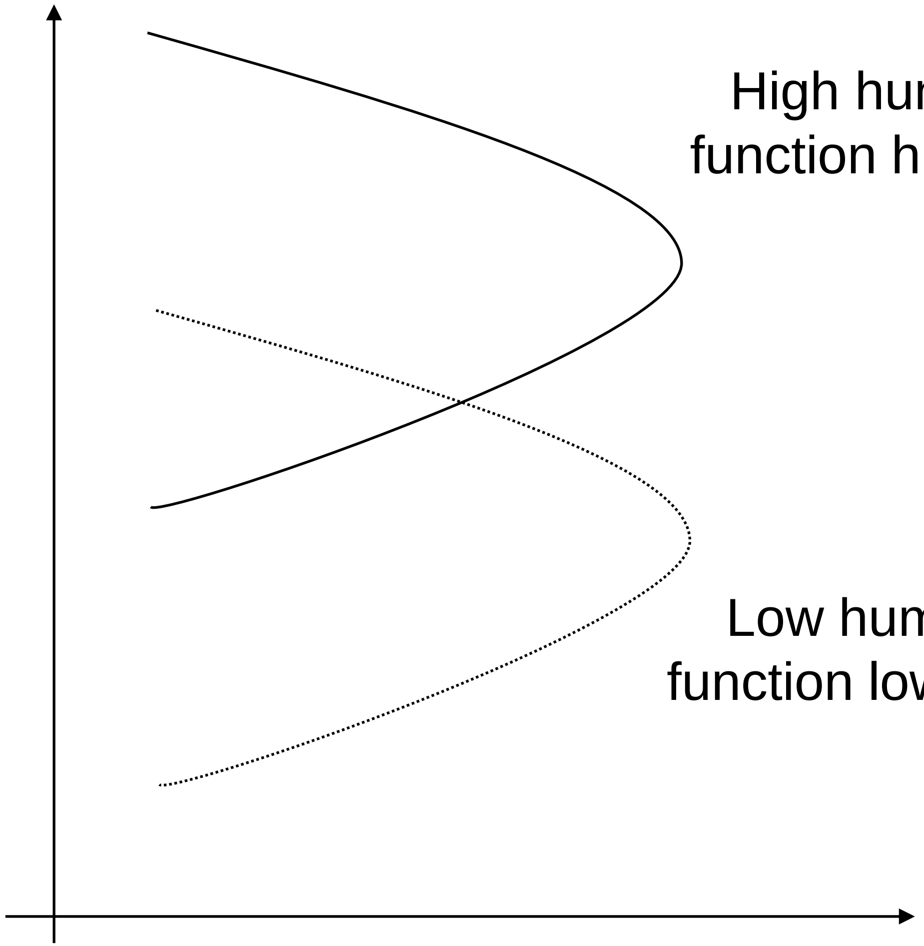
SSMIS F-17 channel 11 (183±1 GHz)
Conical scanning imager and sounder



Water vapour is a highly variable gas in the atmosphere: weighting function is not fixed

TB = 230 K (found at approx. 400 hPa)

TB = 265 K (found at approx. 700 hPa)

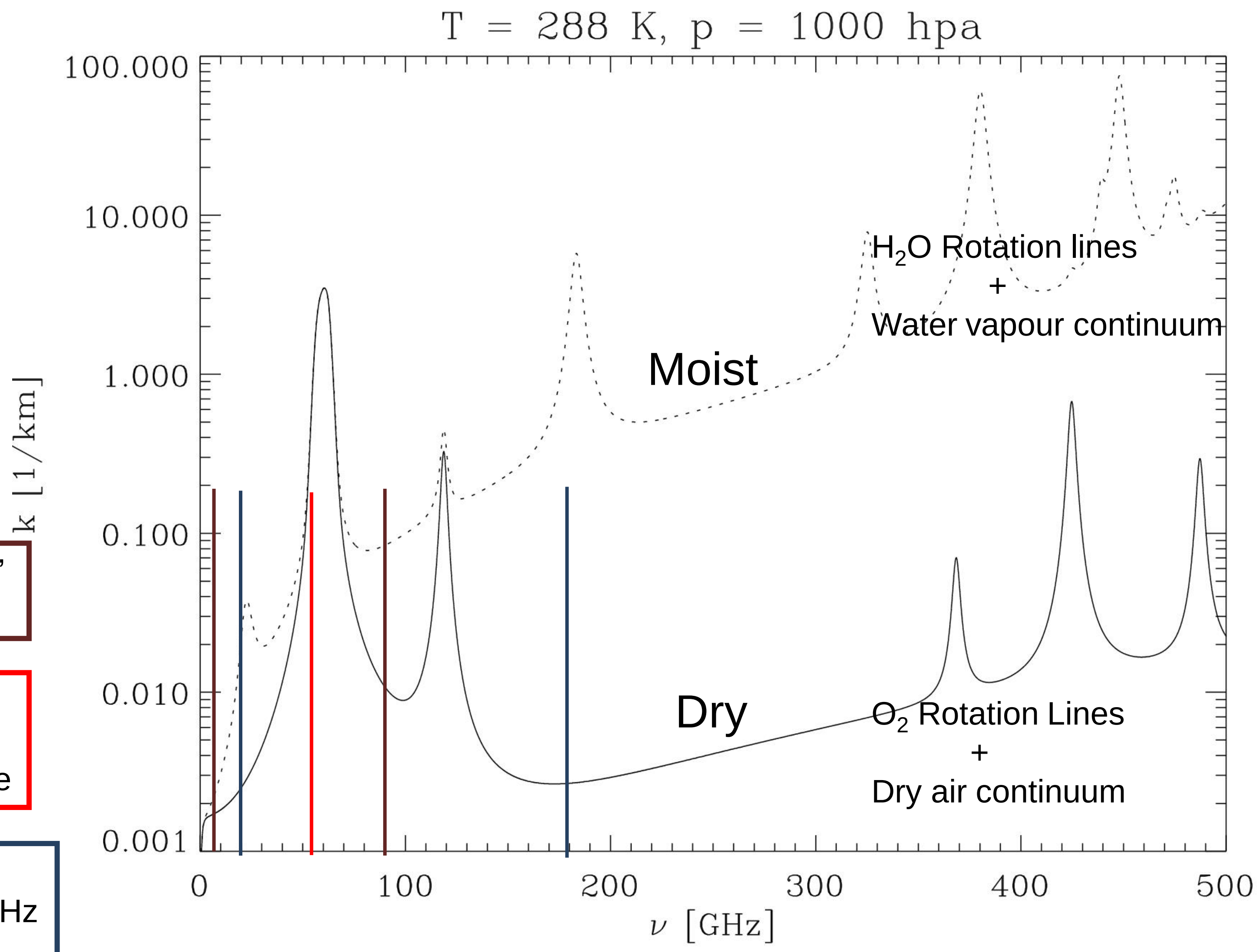


High humidity: weighting function high in troposphere

Low humidity: weighting function lower in troposphere

Gas absorption: the microwave spectrum

Absorption coefficient β_a [1/km]



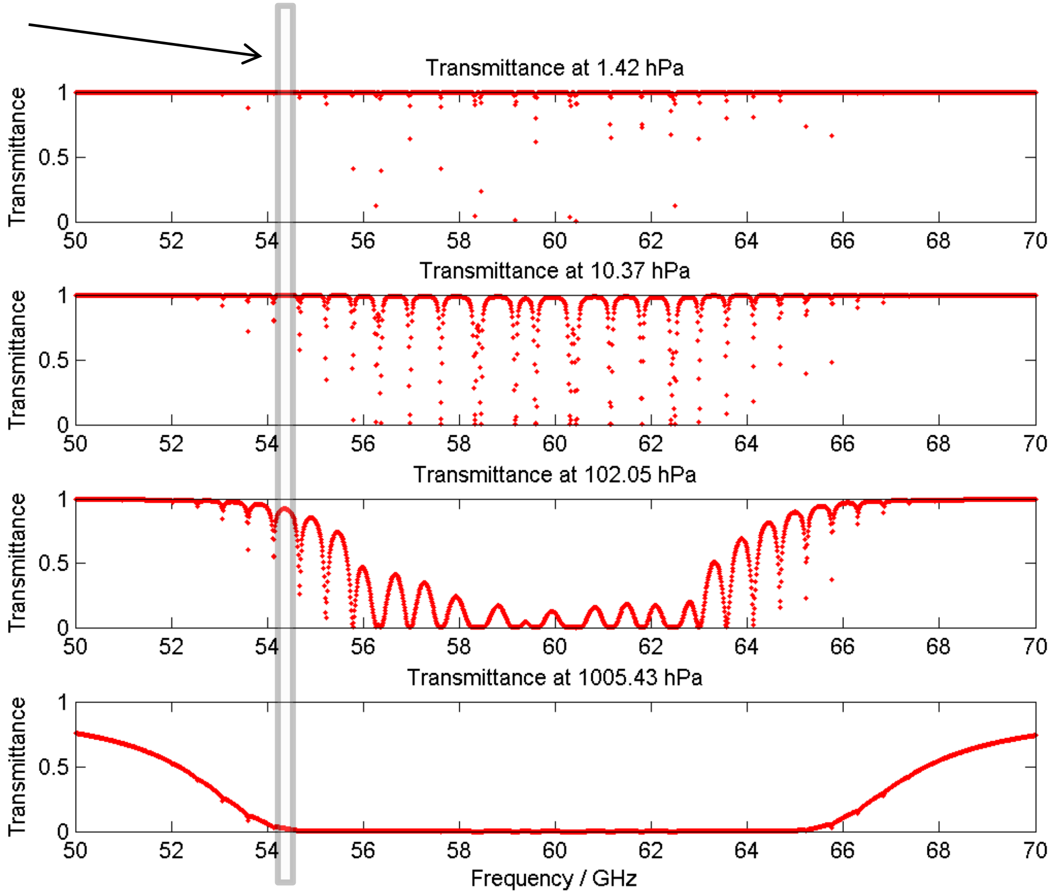
"Imaging channels" in the windows

Temperature sounding: 60 GHz oxygen line

Moisture sounding: 22 GHz and 183 GHz water vapour lines

Fine scale structure in the 60 GHz oxygen line

Typical MW radiometer passband at 54.4 GHz

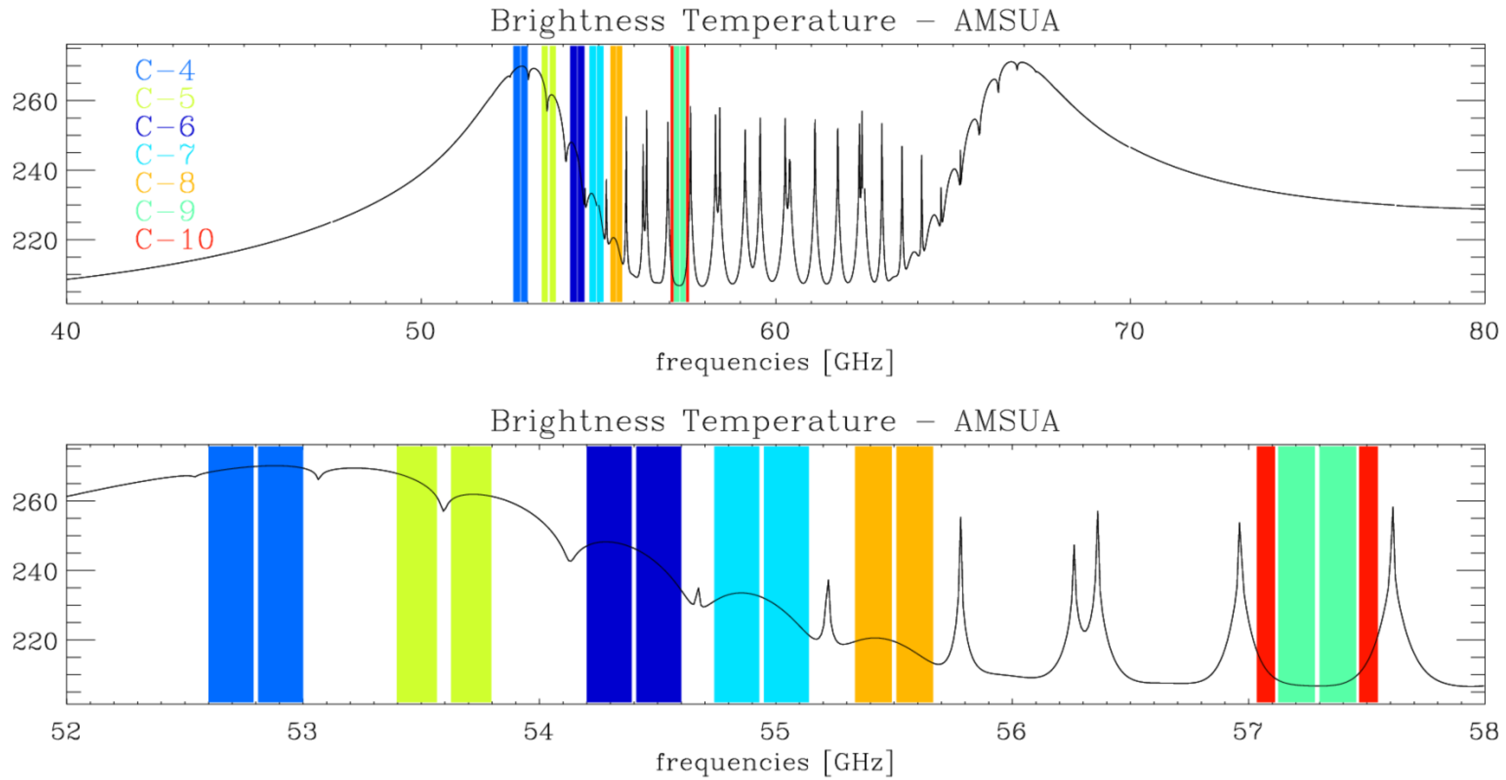


Level to TOA transmittance from Liebe MPM 92 model

Narrow lines ~ several MHz

Increasing pressure broadening

AMSU-A 50 – 60 GHz channels

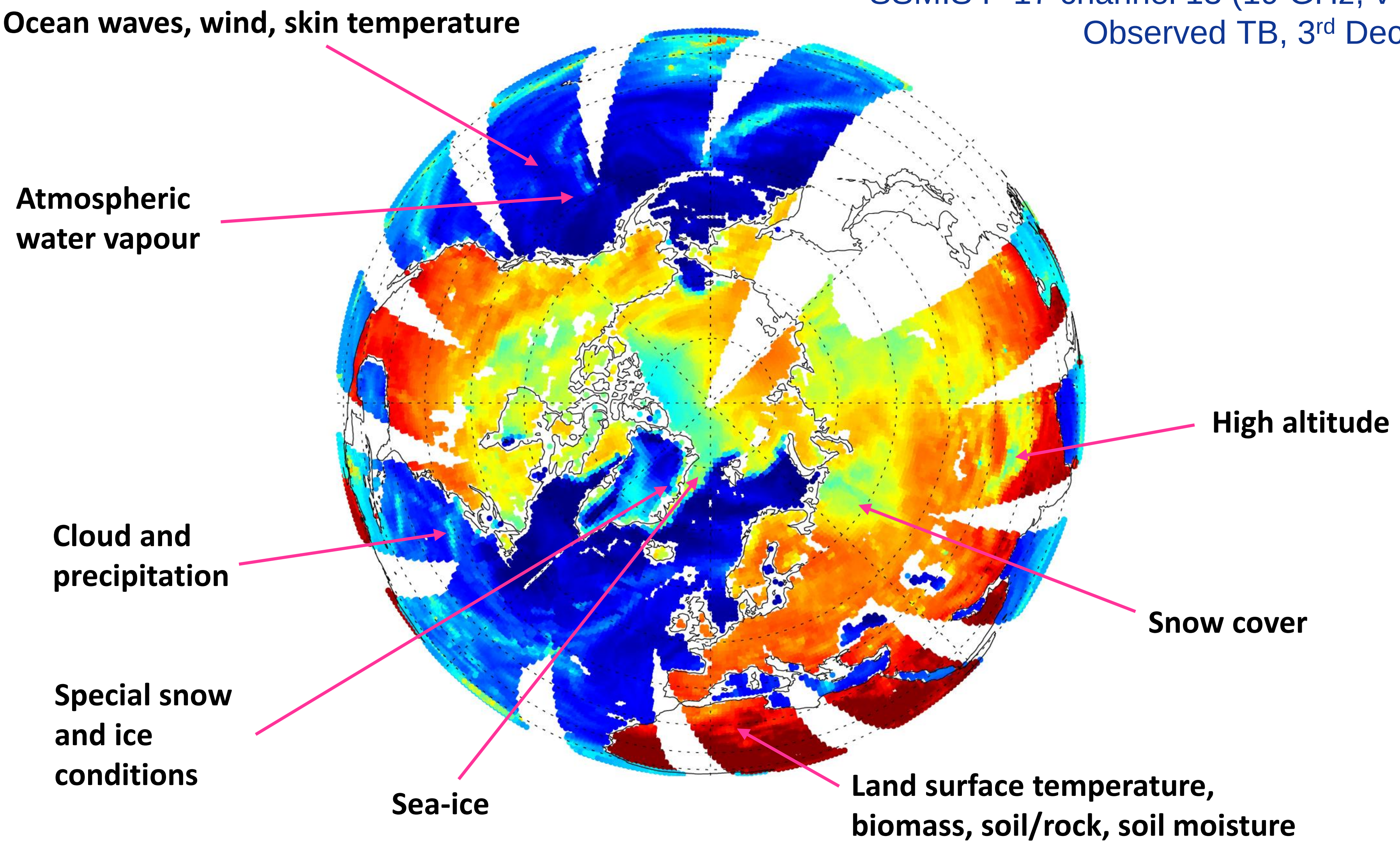


Channel positions and bandwidths are based on trade-offs aimed at simultaneously optimising :

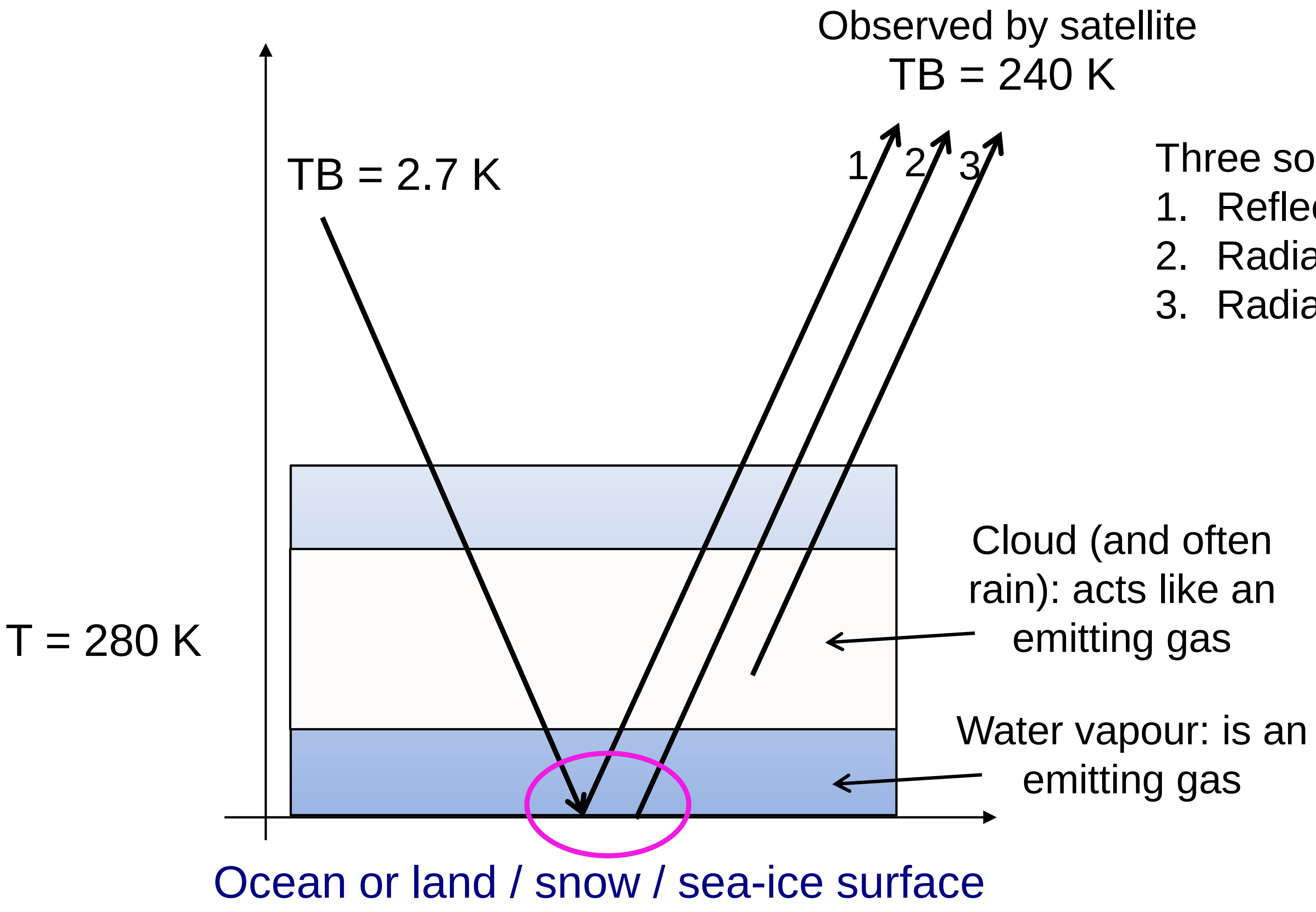
- width of the band (wider bands give lower noise)
- *flatness* of optical depth across the band (narrow weighting functions)

Information content: window (i.e. surface sensitive) channels

SSMIS F-17 channel 13 (19 GHz, v polarisation)
Observed TB, 3rd December 2014



Radiative transfer: window channels (ignoring scattering)



Three sources of radiation:

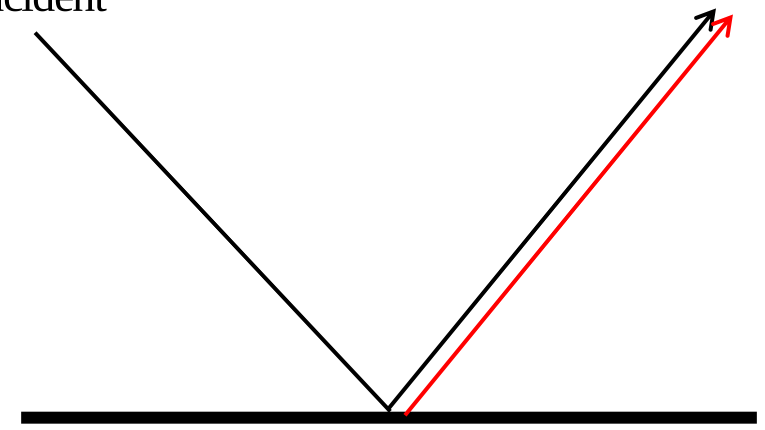
1. Reflected downwelling
2. Radiation emitted by the surface
3. Radiation emitted by the atmosphere

Describing the surface interaction: specular emissivity

Direct reflection Emission

$$T = (1-\varepsilon)T_{\text{Incident}} + \varepsilon T_{\text{Surface}}$$

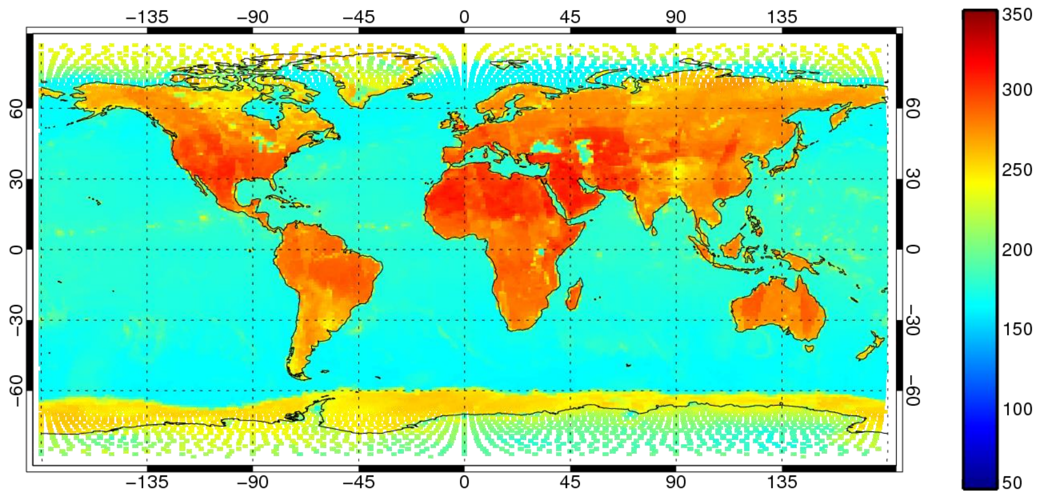
Emissivity



Surface reflection and emission: ocean

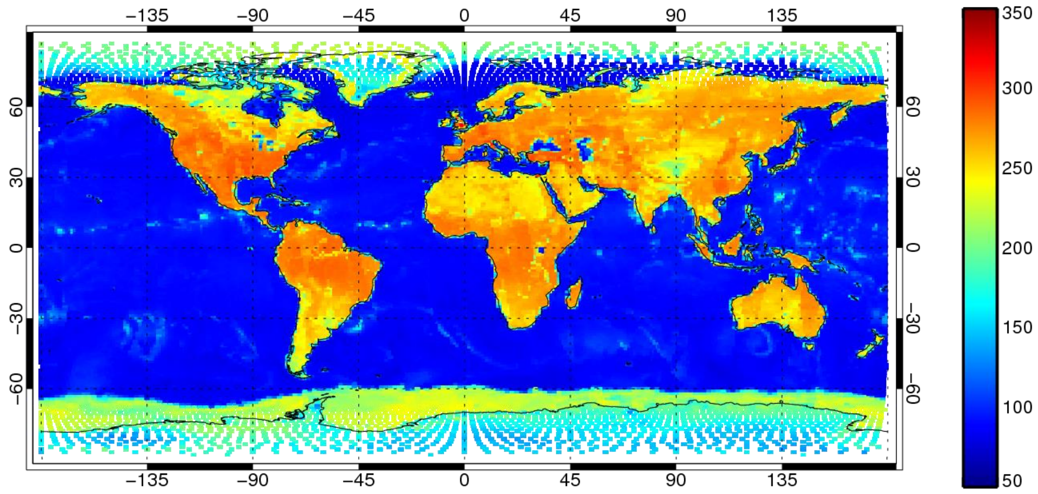
- Plane water surface: low emissivity - Fresnel equations
- Macro structure: waves, swell – geometric optics
- Micro structure, e.g. cm: diffraction from capillary waves
- Foam: much higher emissivity than water
- Correction for non-specular reflection

Ocean surface: is strongly polarised and reflective at low frequencies



TB [K]
10 GHz v-pol

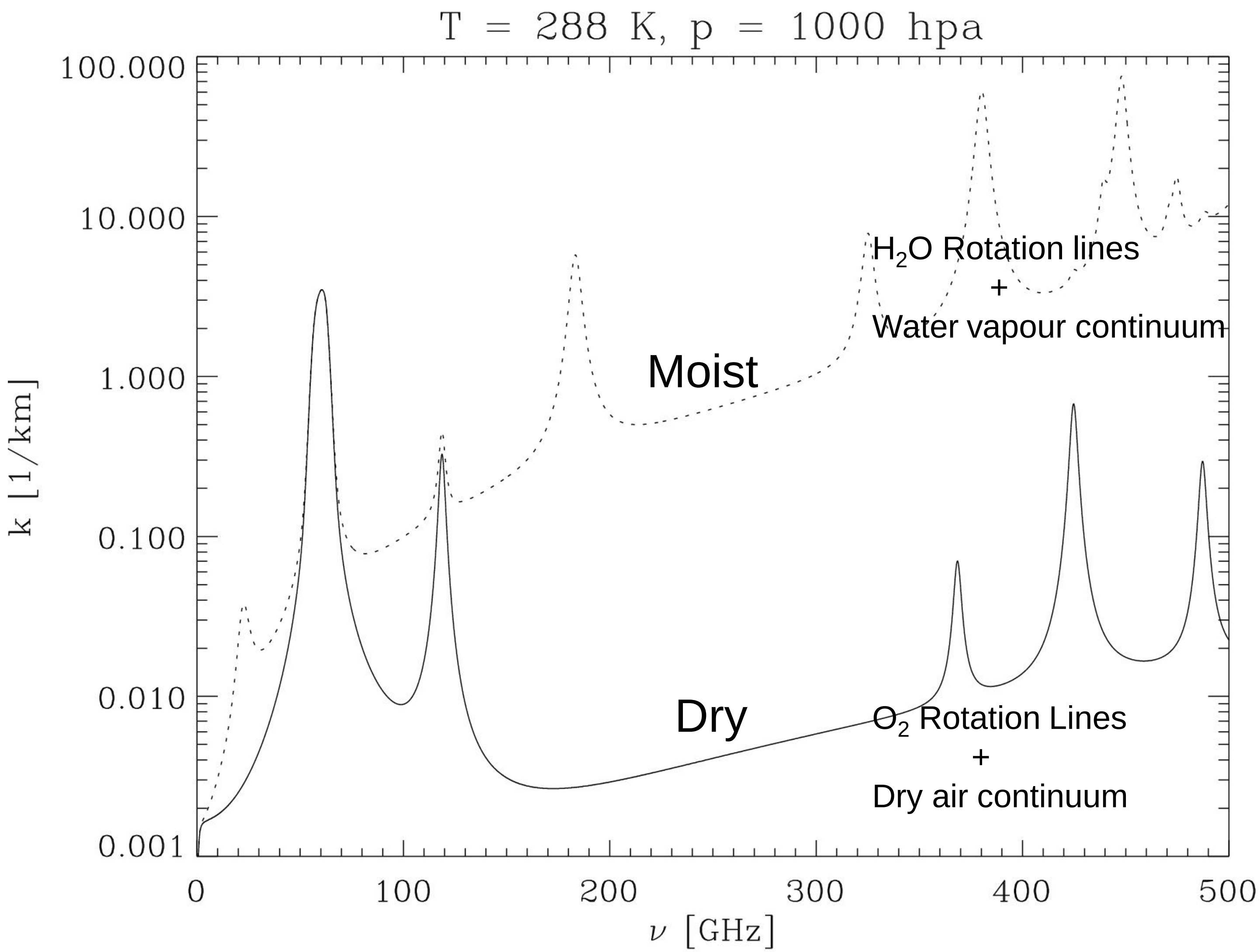
Ocean TB:
~150 K vertical (v)-polarisation
~90 K horizontal (h)-polarisation



TB [K]
10 GHz h-pol

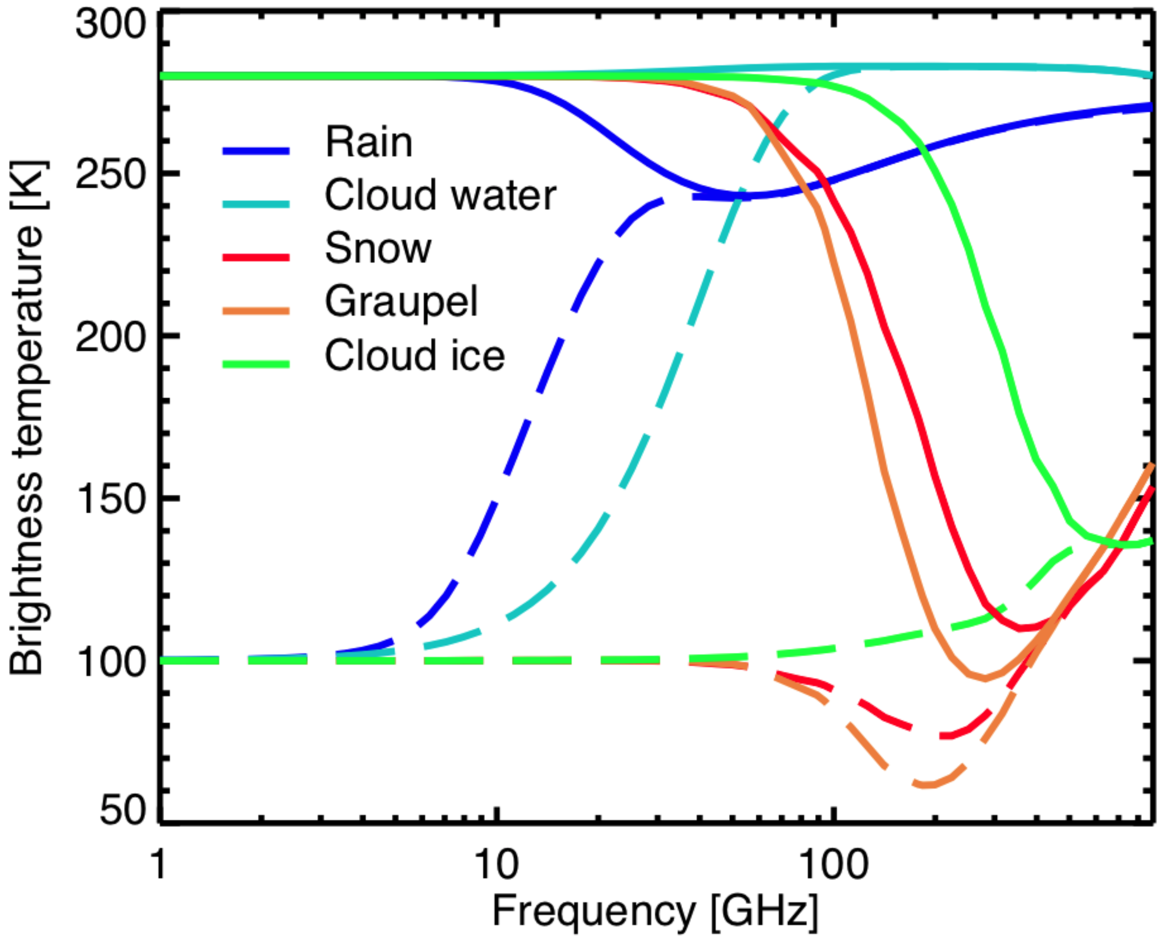
Gas absorption: the microwave spectrum

Absorption coefficient β_a [1/km]



Cloud and precipitation optical properties: the microwave spectrum

More in the next microwave lecture



Slab cloud at 283K above a 280K surface (solid)

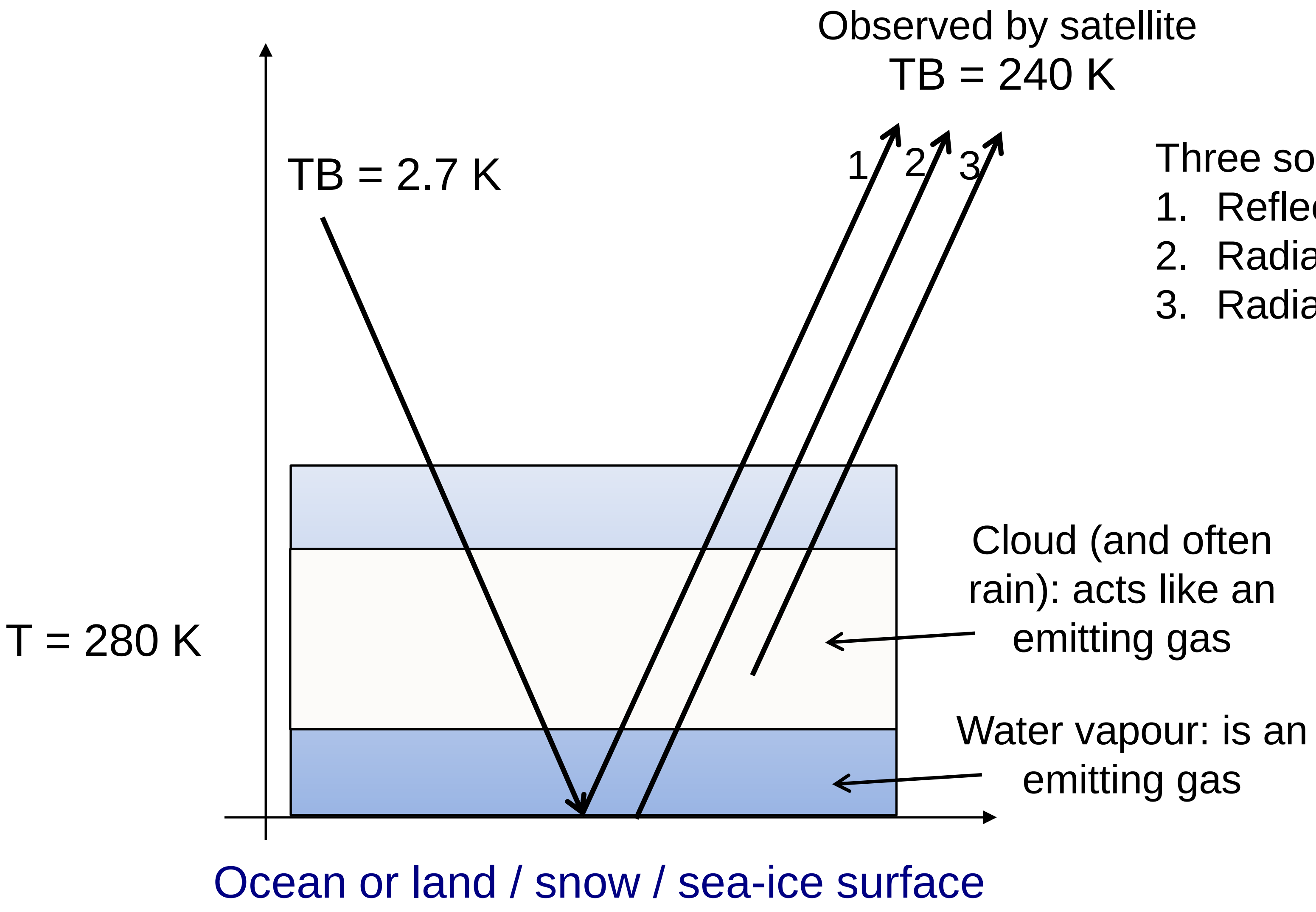
Slab cloud at 283K above a 100K surface (dashed)

Geer et al. (2021, GMD, Bulk hydrometeor optical properties for microwave and sub-millimetre radiative transfer in RTTOV-SCATT v13.0)

Radiative transfer

(if time permits…)

Radiative transfer: window channels (ignoring scattering)



Three sources of radiation:
1. Reflected downwelling
2. Radiation emitted by the surface
3. Radiation emitted by the atmosphere

Schwarzchild's equation

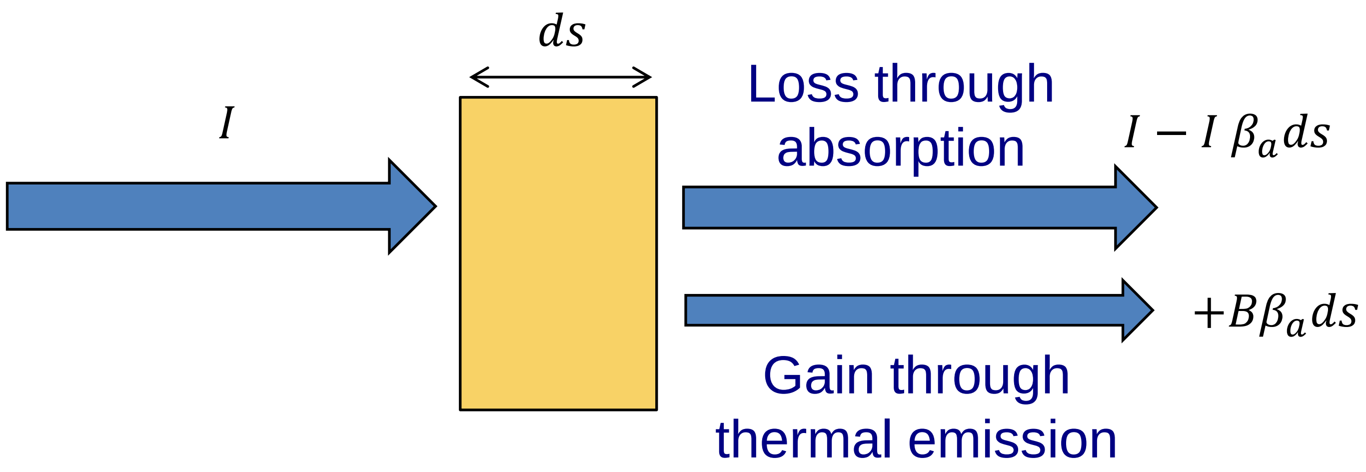
Change in radiance per distance

$$\frac{dI}{ds} = \beta_a (B - I)$$

Planck function

Radiance

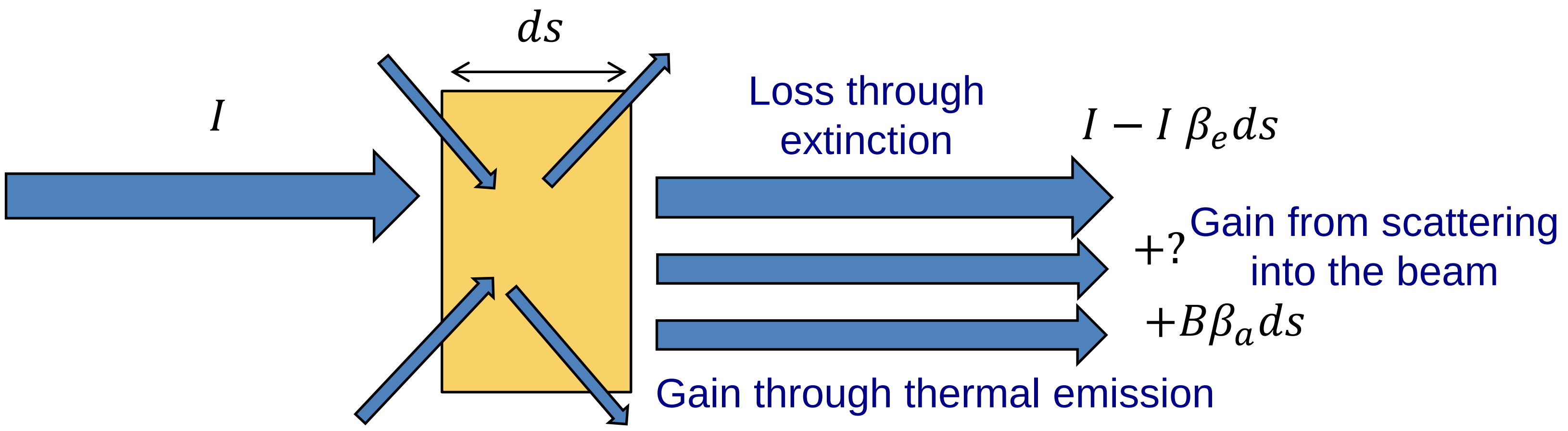
Absorption coefficient



Adding scattering

Extinction coefficient $\beta_e = \beta_a + \beta_s$

Scattering coefficient (describing the amount of scattering out of the beam)



Change in coordinates: optical depth

Change in optical depth $\mathrm{d}\tau$ in a non-scattering atmosphere

$$d\tau = -\beta_a ds$$

Change in optical depth $\mathrm{d}\tau$ including extinction by scattering

$$d\tau = -(\beta_a + \beta_s) ds = -\beta_e ds$$

The full scattering radiative transfer equation

Direction vector

Integral over all solid angle

$$\frac{dI(\hat{\Omega})}{d\tau} = I(\hat{\Omega}) - (1-\omega_s)B - \frac{\omega_s}{4\pi}\int_{4\pi} P(\hat{\Omega},\hat{\Omega}')I(\hat{\Omega}')\,d\hat{\Omega}'$$

Change in optical depth

Single scattering albedo

Scattering phase function

$$\omega_s = \frac{\beta_s}{(\beta_a+\beta_s)}$$

- Without scattering, just integrate this equation along the path travelled by the radiation (Tony's first lecture)
- With scattering, this can be complex to solve:

  $I(\hat{\Omega})$, the radiance in one direction, depends on radiance from all other directions: $I(\hat{\Omega}')$

  and all levels depend on each other

The full scattering radiative transfer equation

Radiative transfer solver

Direction vector

Integral over all solid angle

$$\frac{dI(\widehat{\Omega})}{d\tau} = I(\widehat{\Omega}) - (1-\omega_s)B - \frac{\omega_s}{4\pi}\int_{4\pi} P(\widehat{\Omega},\widehat{\Omega}')I(\widehat{\Omega}')\,d\widehat{\Omega}'$$

Change in optical depth

Single scattering albedo

Scattering phase function

$$\omega_s = \frac{\beta_s}{(\beta_a+\beta_s)}$$

+ Surface description (water, sea ice, snow, soil)

Optical properties (gas and hydrometeor), temperature

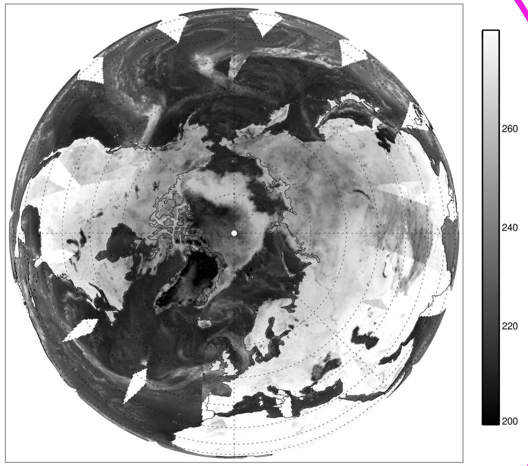
Gas spectroscopy

Single-particle scattering models

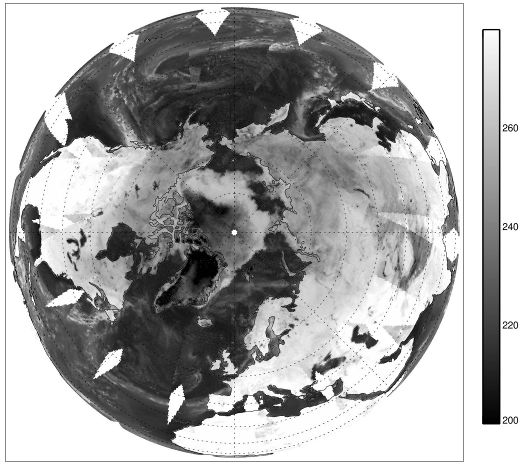
Atmospheric profiles (temperature, pressure, water vapour, hydrometeors)

Observations

1st Nov



2nd Nov



Earth system model: geophysical state and its forward propagation in time

Questions?