Microwave observations (part 2): cloud and precipitation; applications

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EUMETSAT/ECMWF NWP-SAF satellite data assimilation training course, 24 March 2026

ECMWF

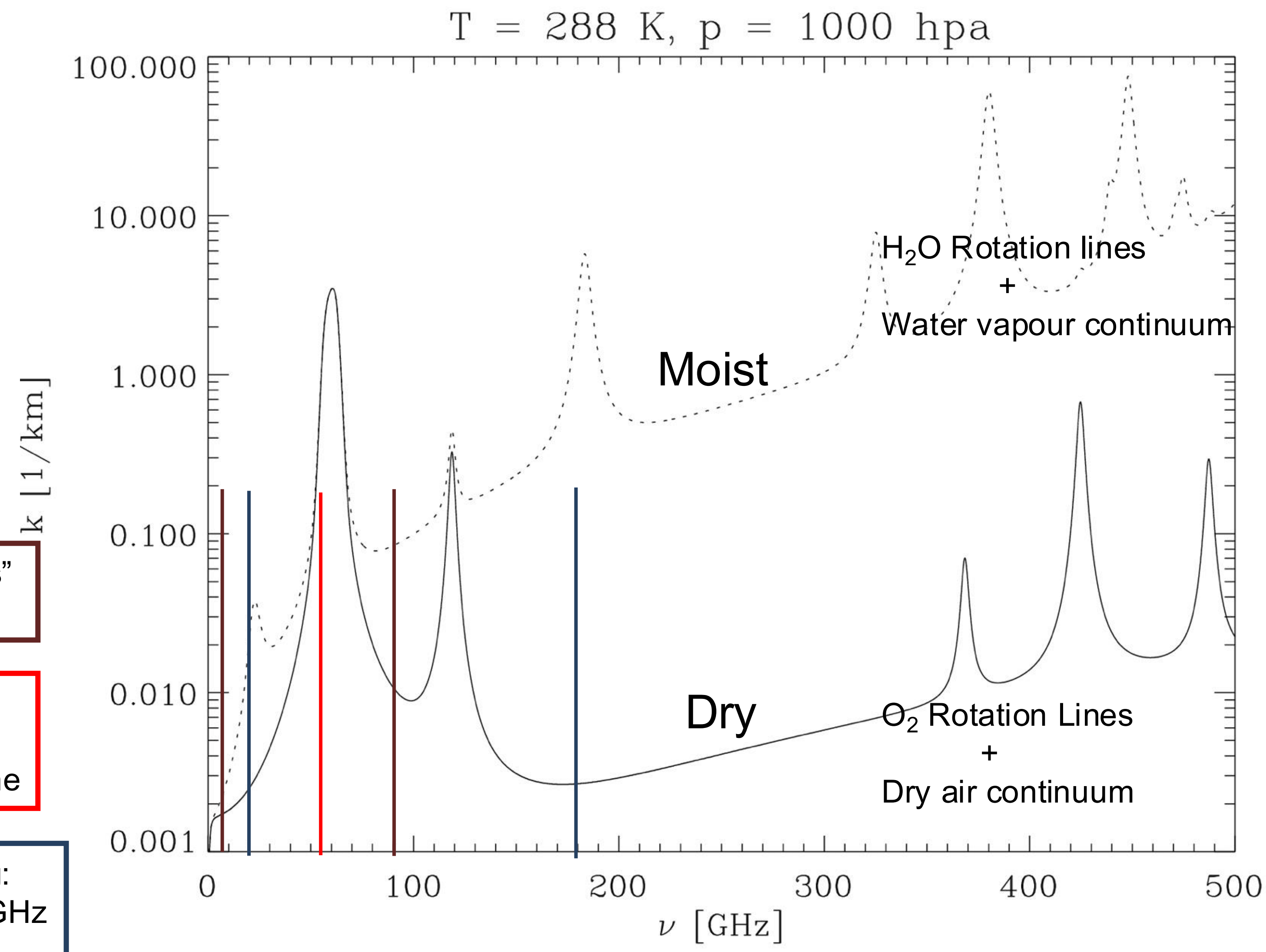
Last time: gas absorption: the microwave spectrum

Absorption coefficient β_a [1/km]

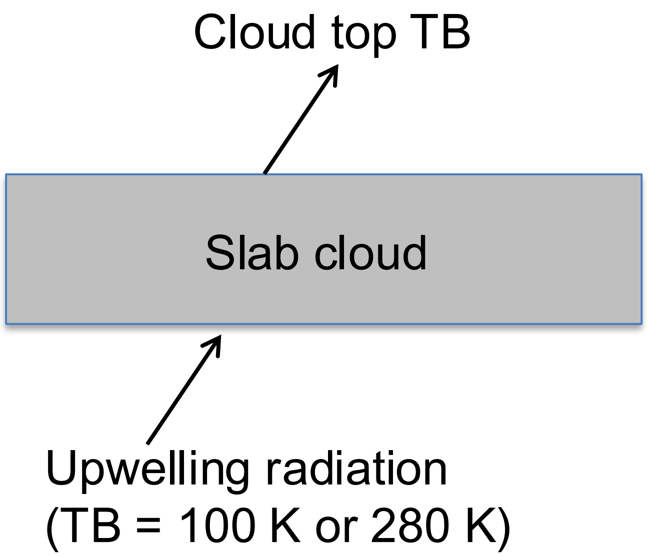
“Imaging channels” in the windows

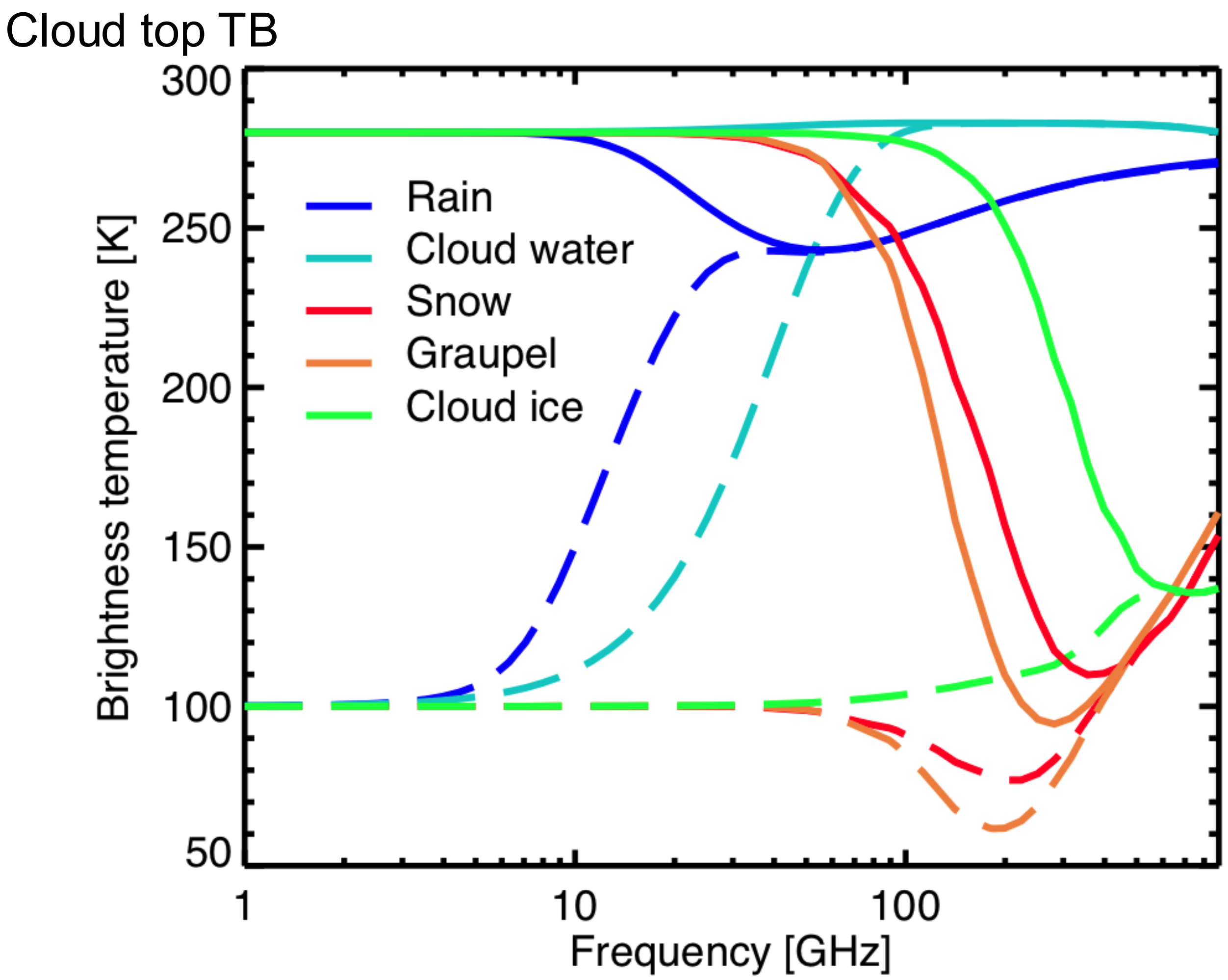
Temperature sounding: 60 GHz oxygen line

Moisture sounding: 22 GHz and 183 GHz water vapour lines



Cloud and precipitation optical properties: the microwave spectrum





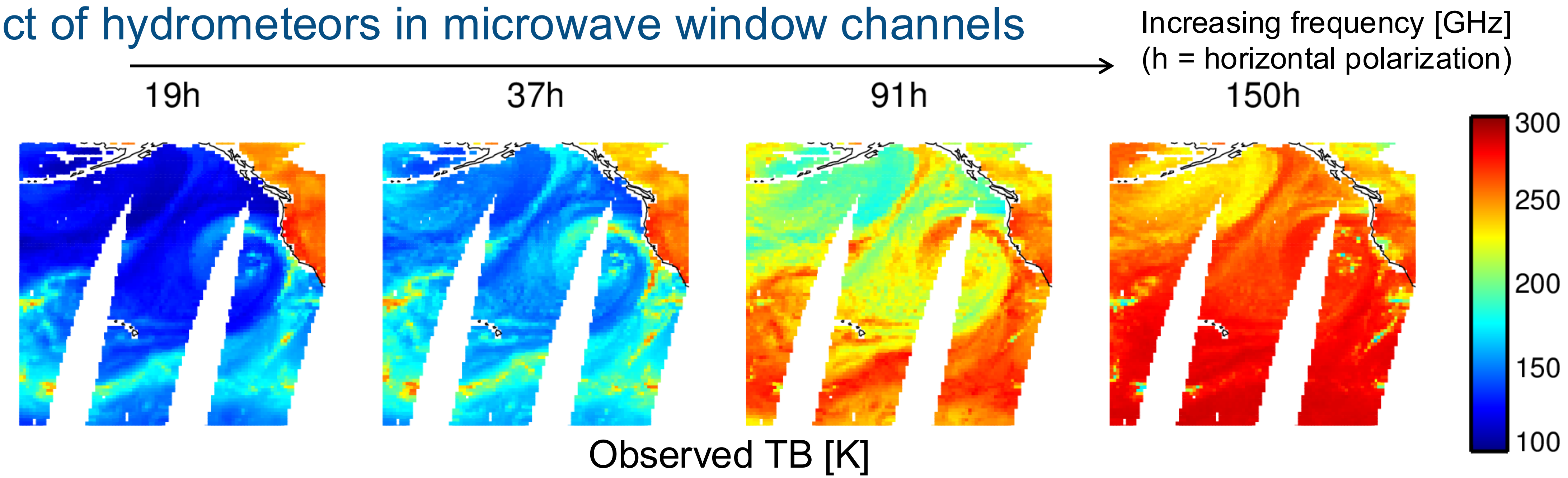
Slab cloud at 283K above a 280K surface (solid)

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)

Cloud effects in observations

Effect of hydrometeors in microwave window channels



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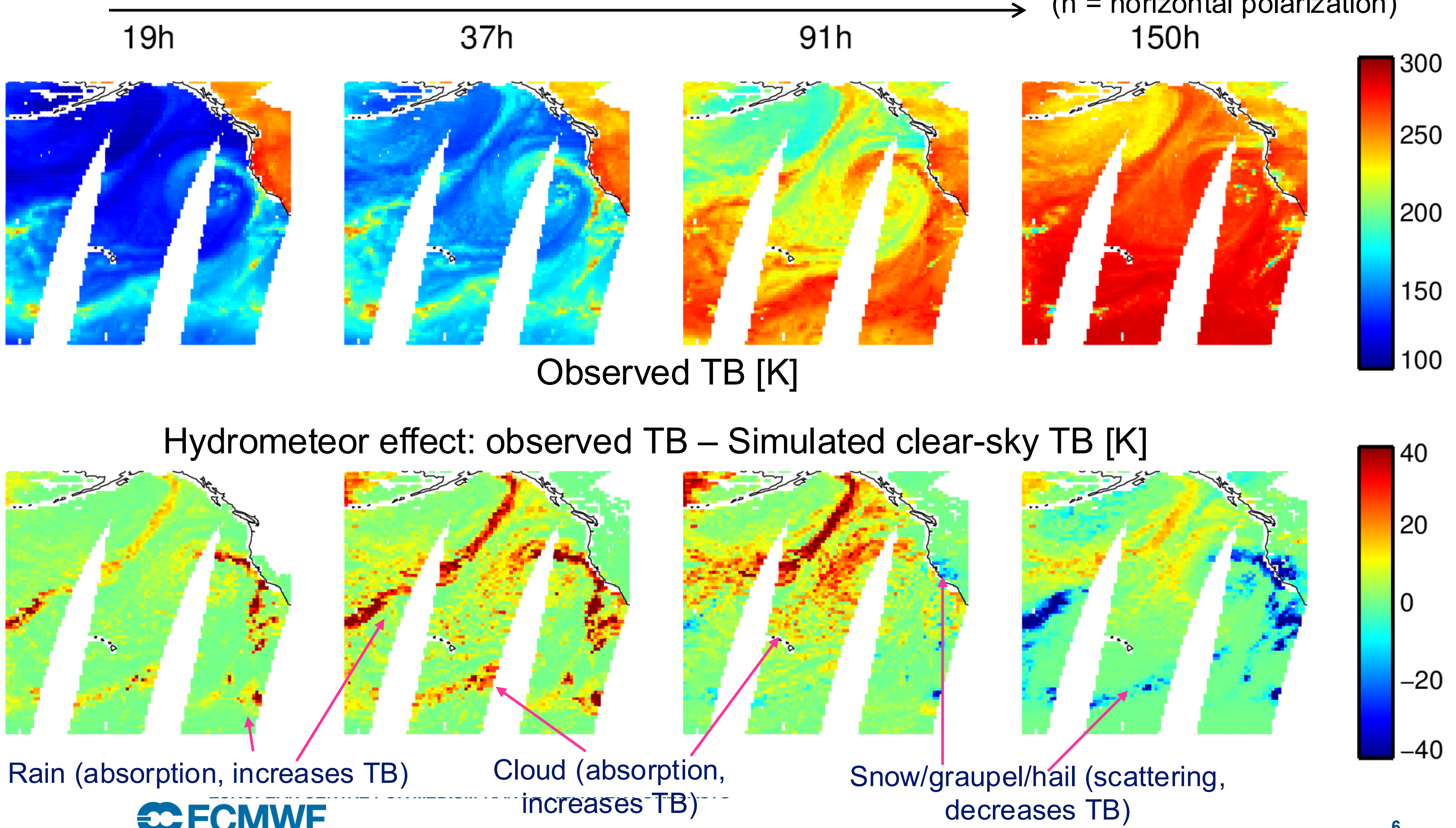
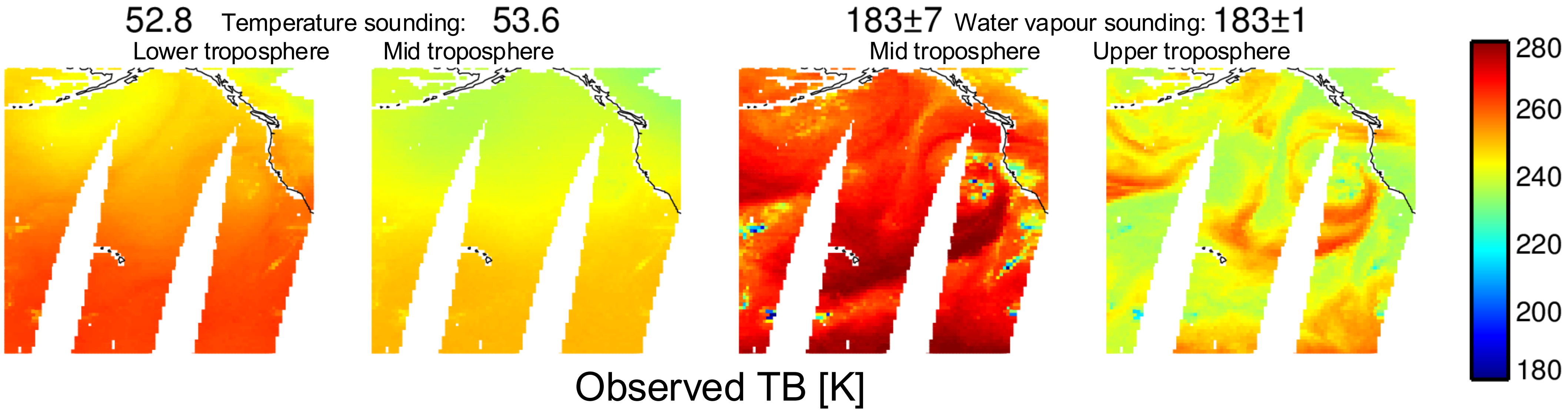
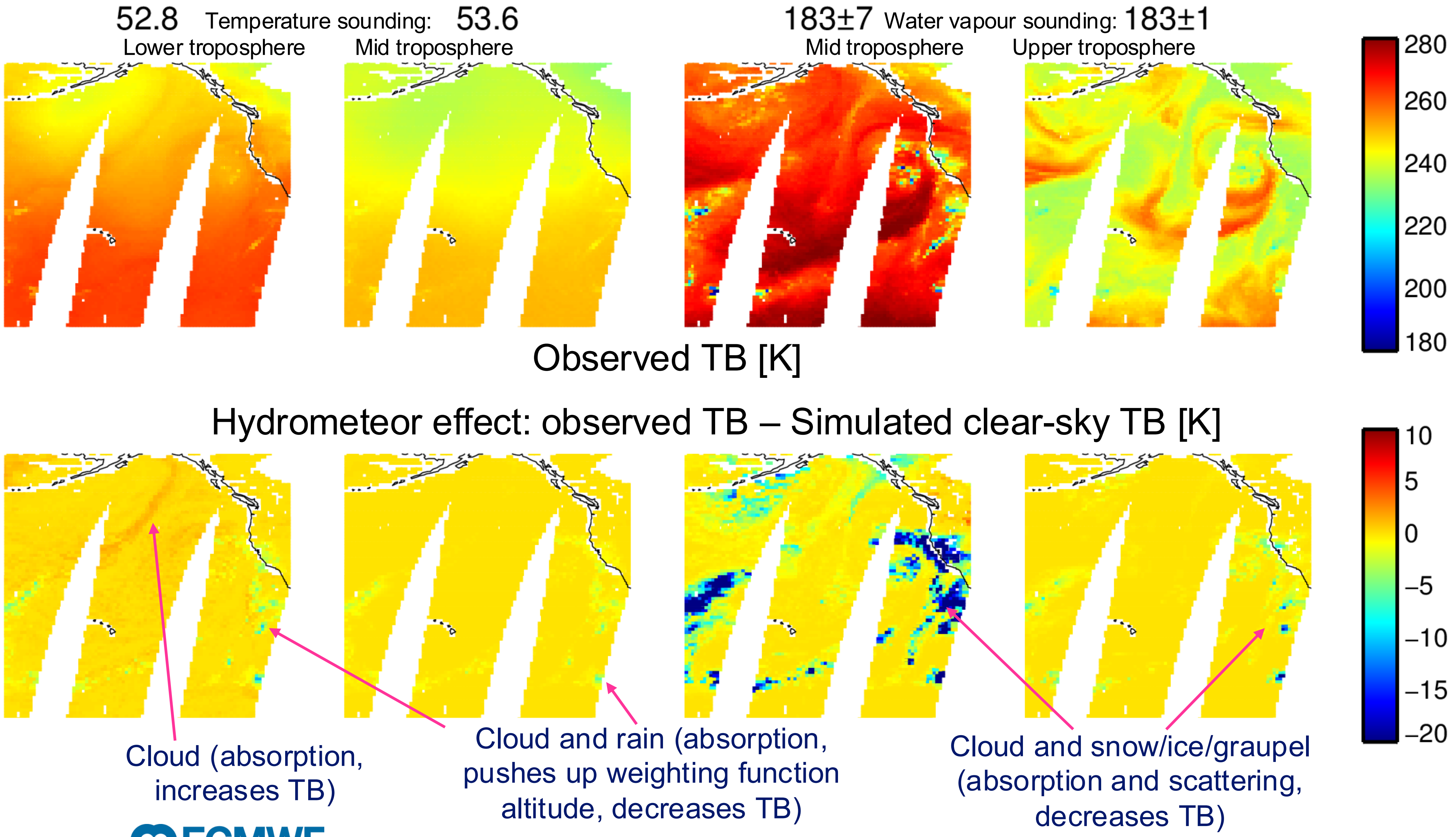
Effect of hydrometeors in microwave window channels



Effect of hydrometeors in microwave sounding channels



Effect of hydrometeors in microwave sounding channels



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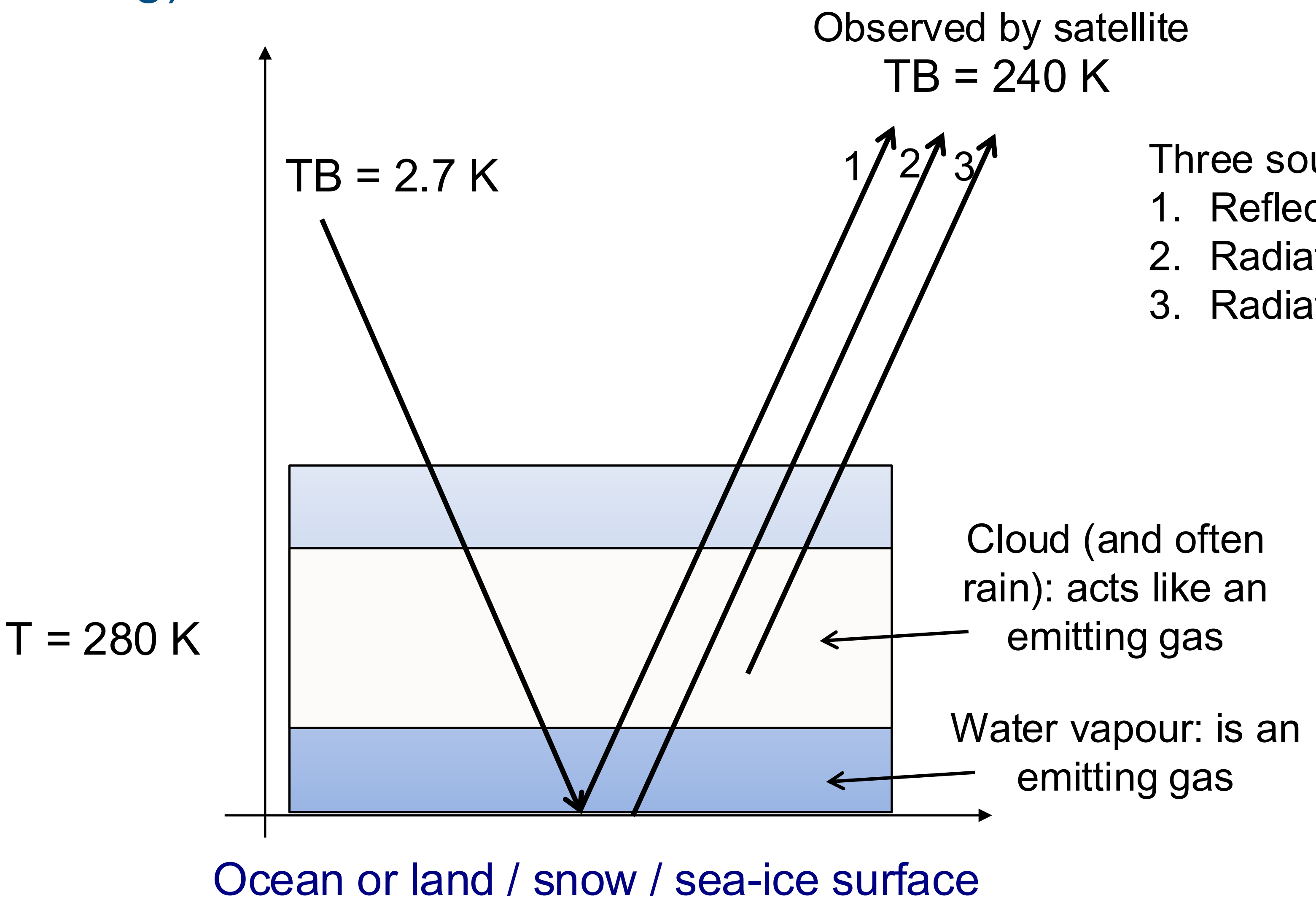
Scattering radiative transfer

Last time: 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

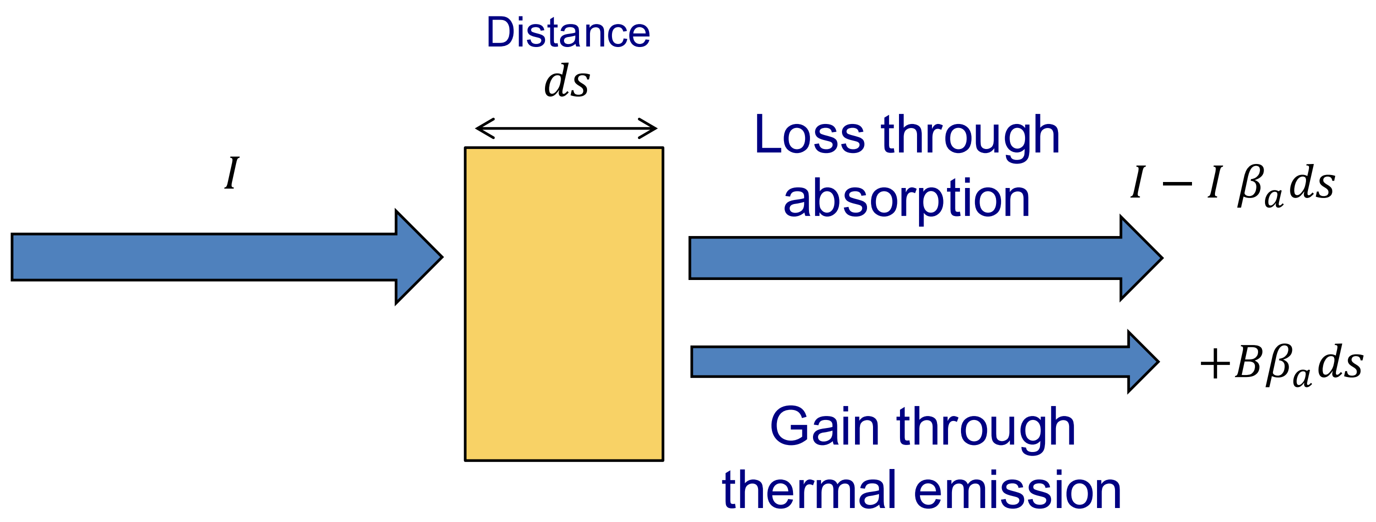
Planck function – this is the main way that temperature influences atmospheric radiation

Radiance

Change in radiance per distance

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

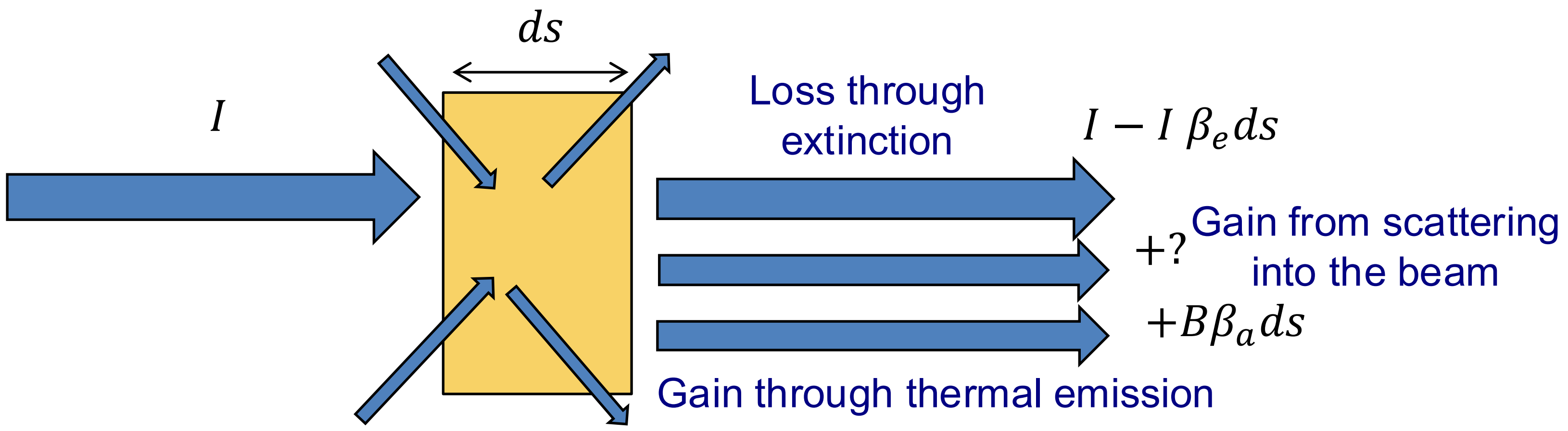
Absorption coefficient



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

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

Direction vector

Integral over all solid angle

Change in optical depth

Single scattering albedo

Scattering phase function

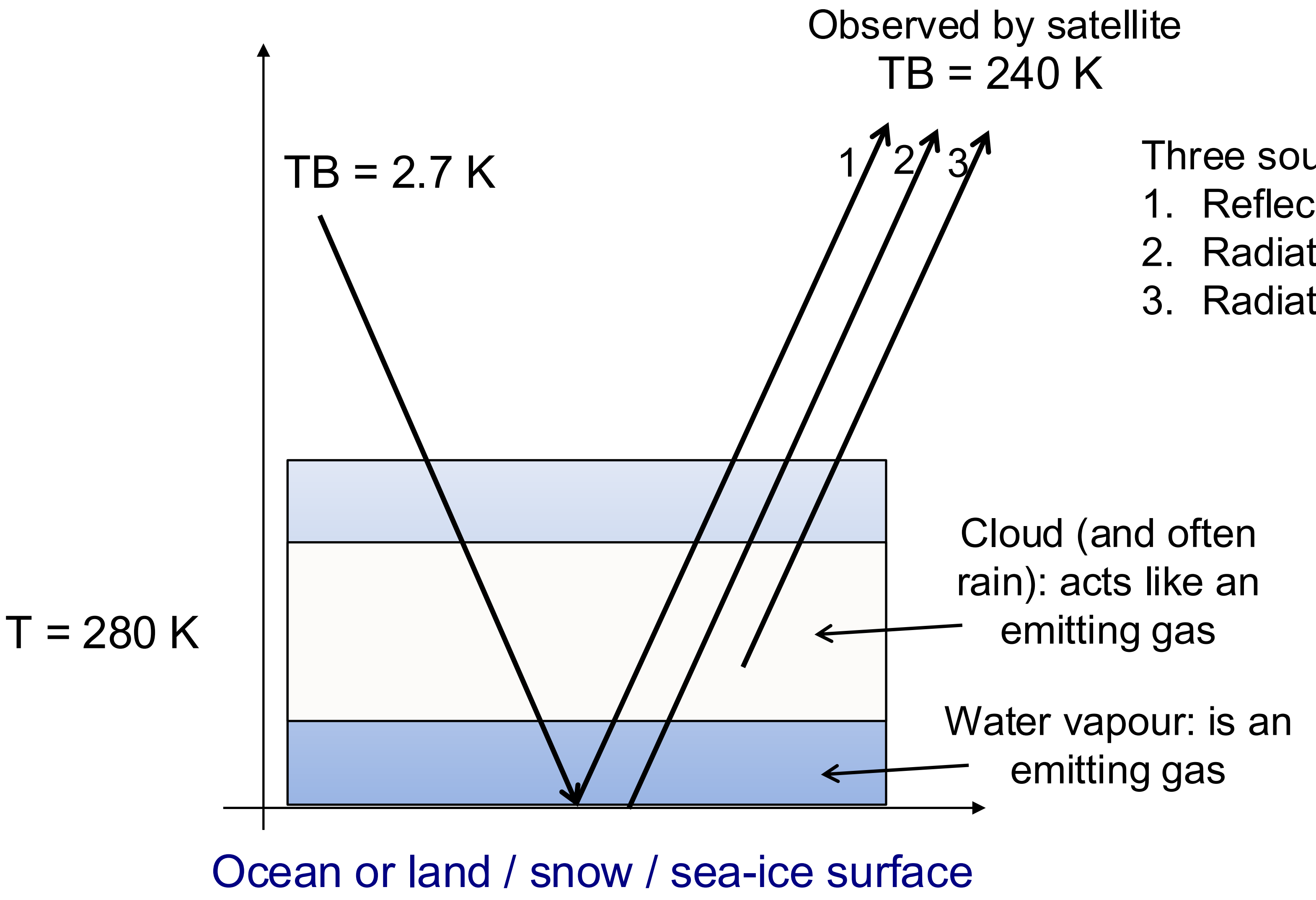
$$\omega_s = \frac{\beta_s}{(\beta_a+\beta_s)}$$

- Without scattering, just integrate this equation along the path travelled by the radiation
- 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

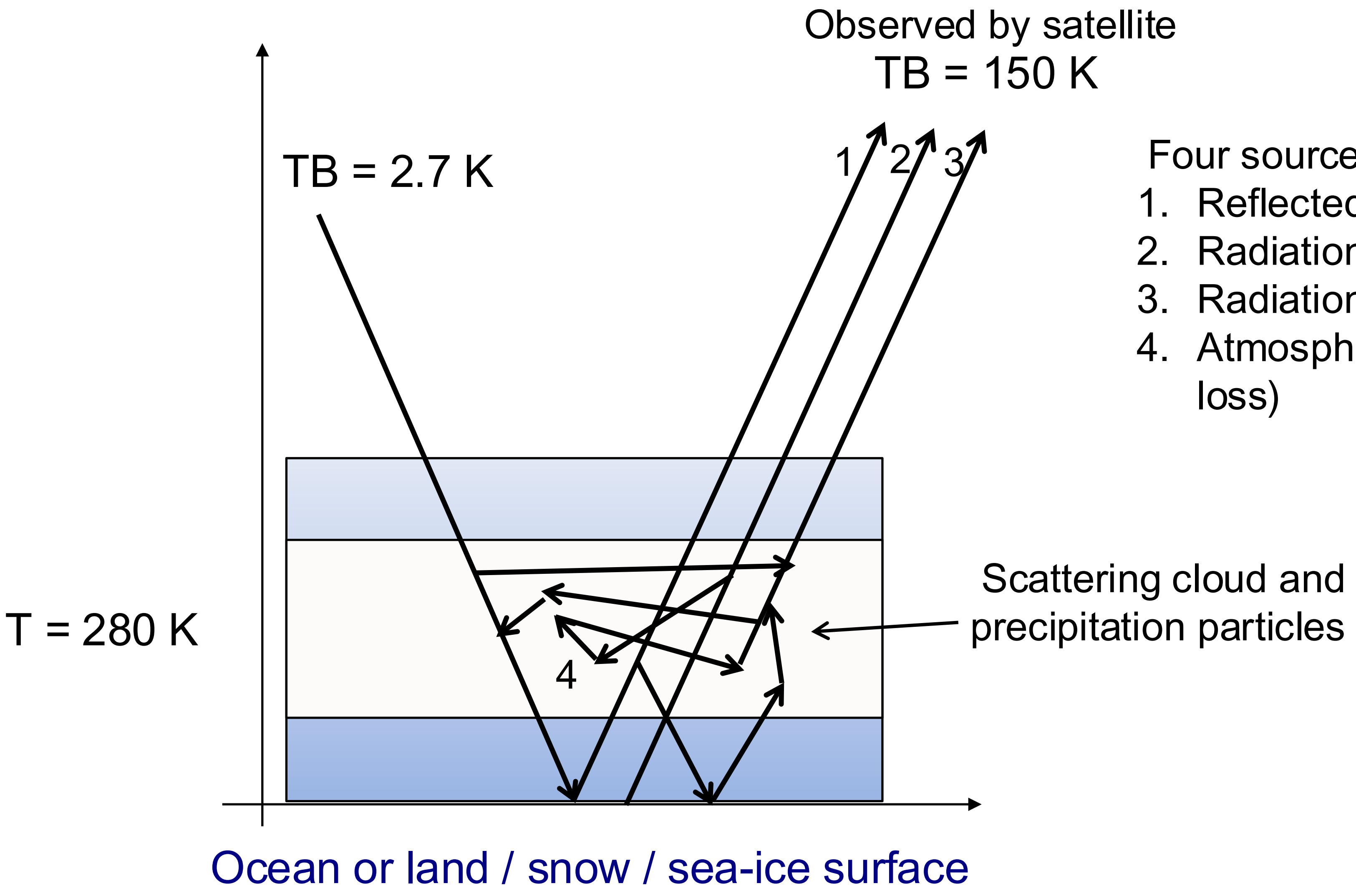
Radiative transfer: window channels (ignoring scattering)



Three sources of radiation:

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

Radiative transfer: window channels (with scattering)

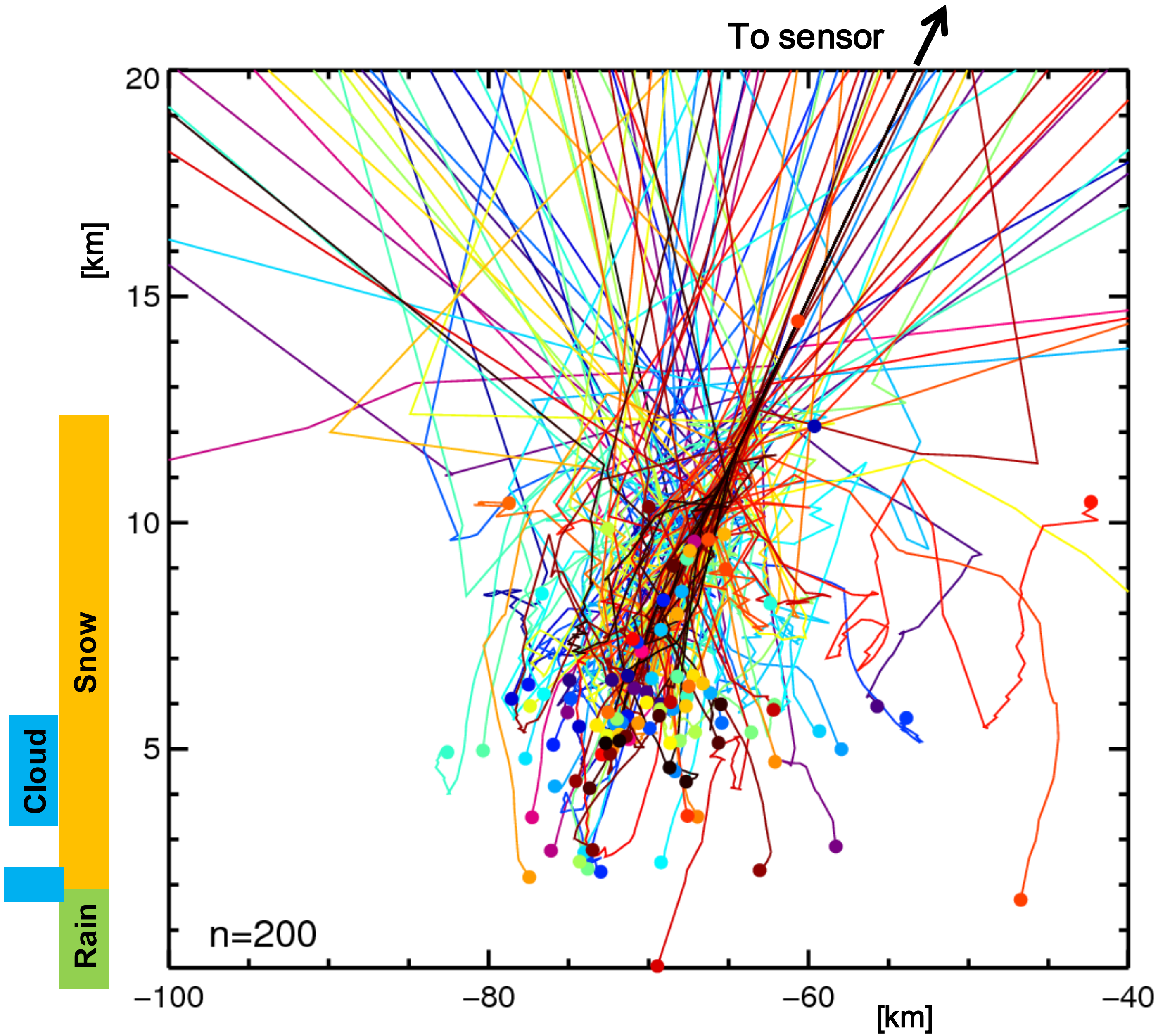


Four sources of radiation:

1. Reflected downwelling
2. Radiation emitted by the surface
3. Radiation emitted by the atmosphere
4. Atmospheric scattering (gain and loss)

Strong scattering at 91 GHz

Reverse Monte-Carlo radiative transfer solver



The full scattering radiative transfer equation

Radiative transfer solver

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

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

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

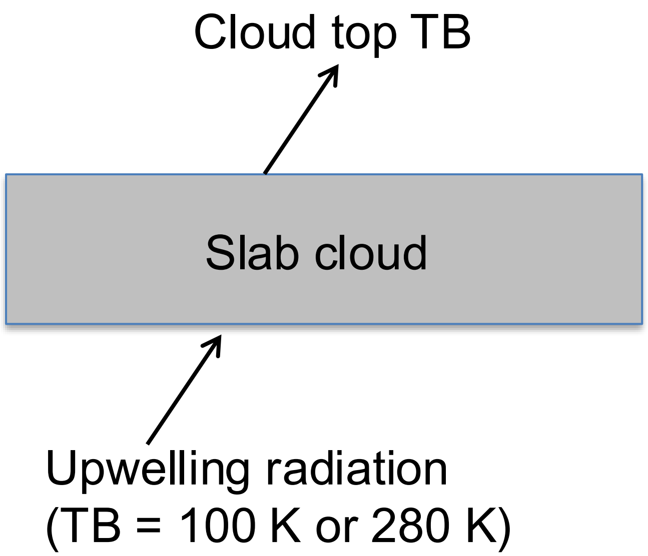
Optical properties (gas and hydrometeor), temperature

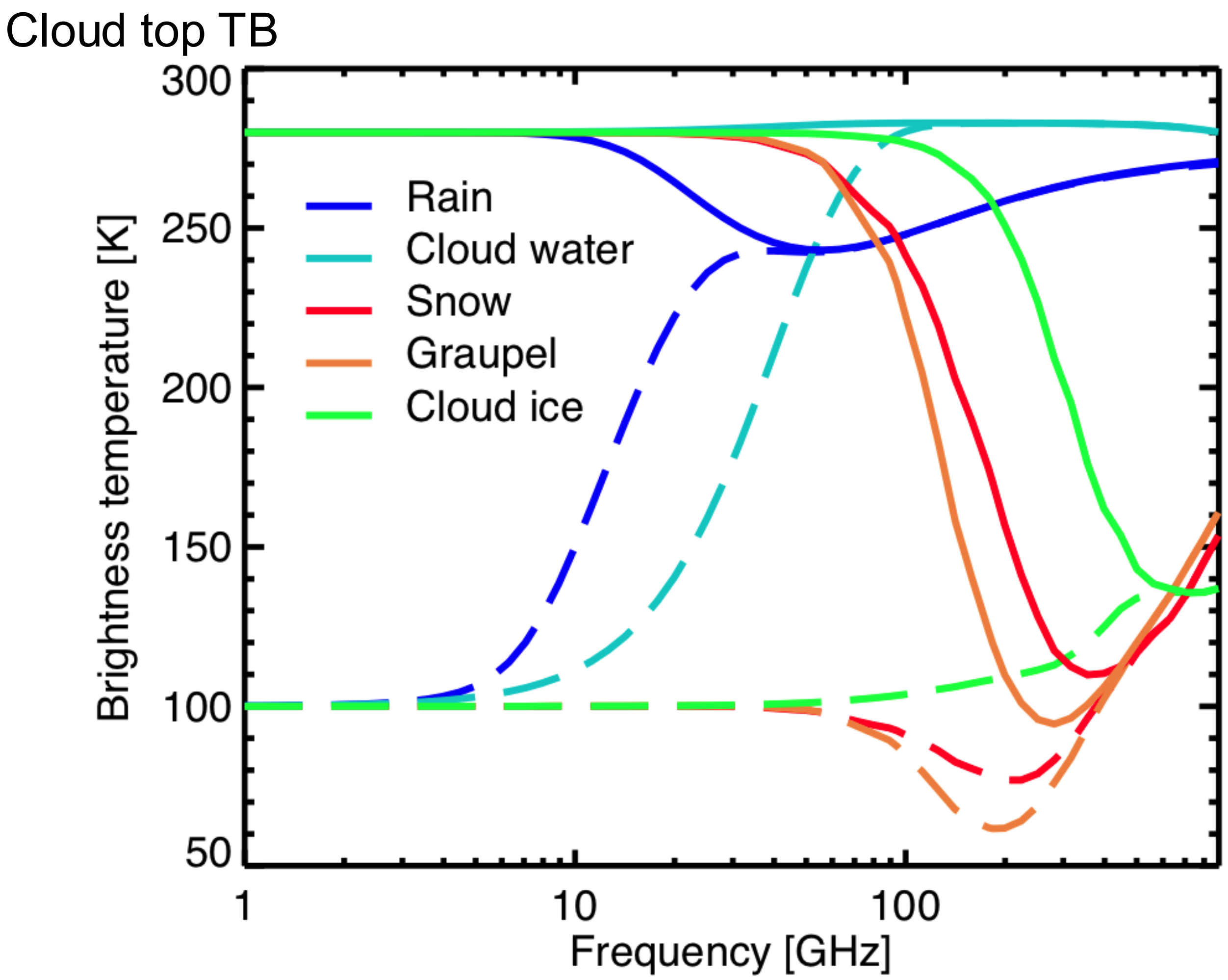
Gas spectroscopy

Single-particle scattering models

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

Cloud and precipitation optical properties: the microwave spectrum





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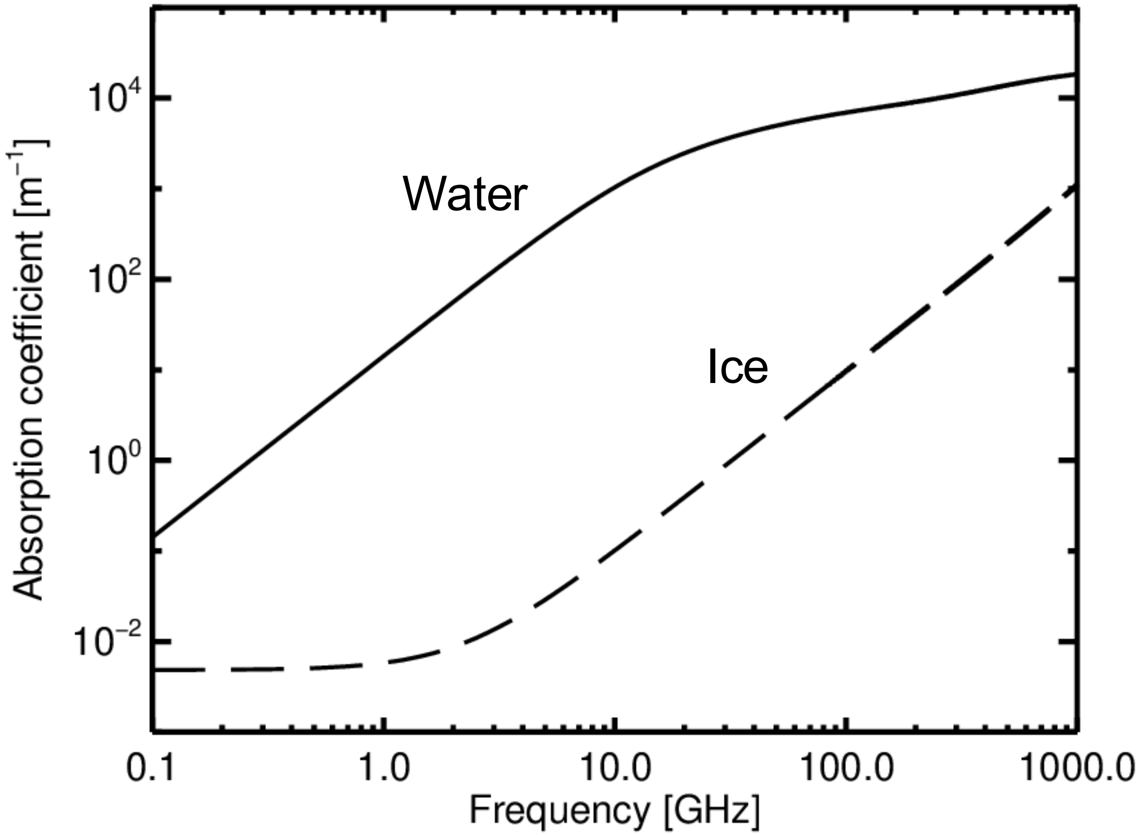
Absorption in pure water or ice



Effect of hydrometeors – particles

- 30 GHz frequency ↔ 10mm wavelength (λ)

Size parameter

$$x = \frac{2\pi r}{\lambda}$$

x << 1: Rayleigh scattering

x ~ 1: Mie sphere, discrete dipole approximation, etc.

x >> 1: Geometric optics

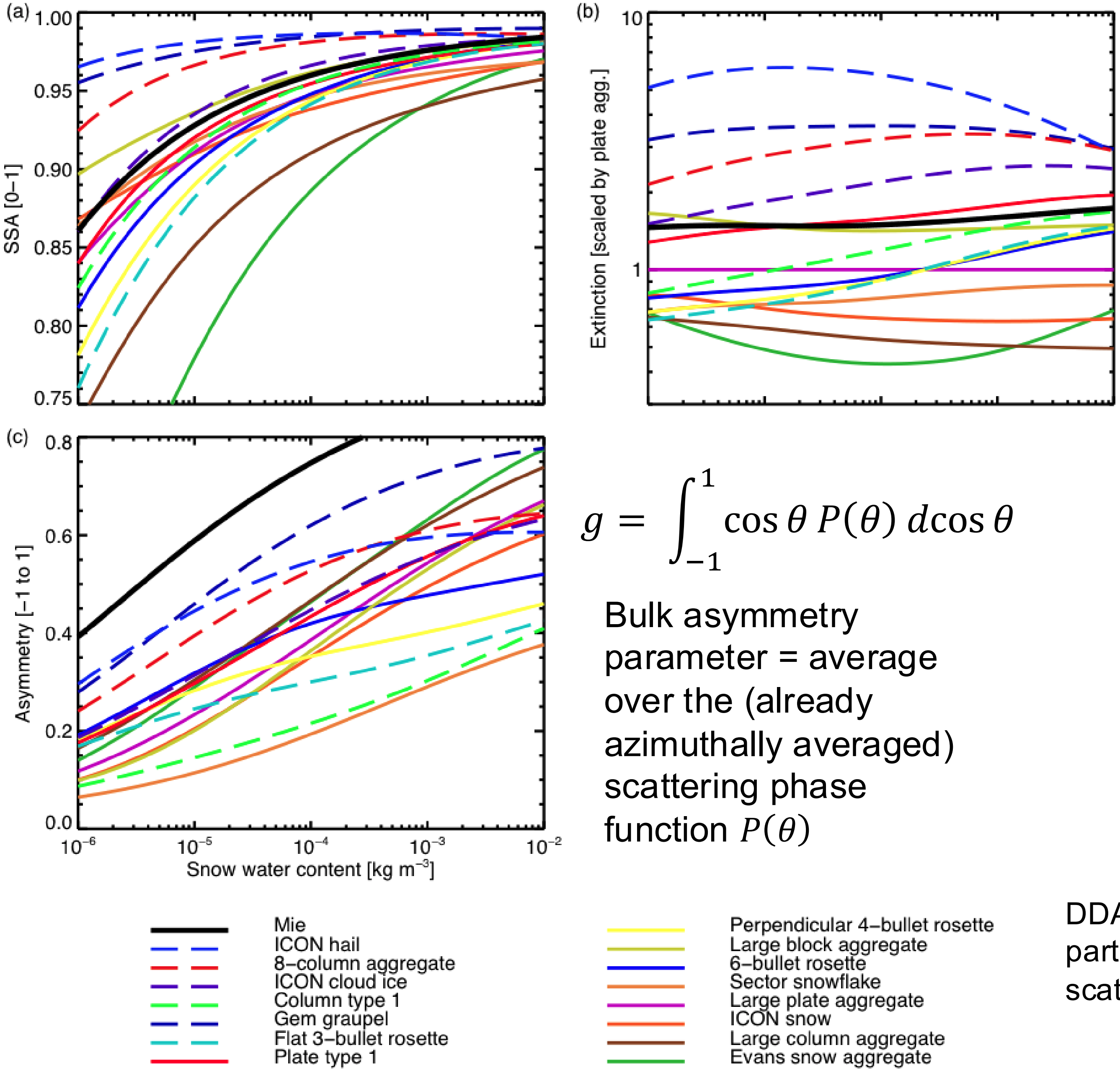
Particle type	Size range, r	Size parameter, x
Cloud droplets	5 – 50 μm	0.003 – 0.03
Drizzle	~100 μm	0.06
Rain drop	0.1 – 3 mm	0.06 – 1.8
Ice crystals	10 – 100 μm	0.006 – 0.06
Snow	1 – 10 mm	0.6 – 6
Hailstone	~10 mm	6

- Effect of particles on radiation is a function of the particle shape and structure, size relative to the radiation, and composition (complex refractive index / permittivity)
- Bulk effect of particles is an integral over the particle size distribution (PSD)

Optical properties of hydrometeors in RTTOV-SCATT: at 183 GHz

Lookup tables for snow hydrometeors as a function of snow water content

ω_s



$$\beta_e = \beta_a + \beta_s$$

Bulk extinction coefficient scaled relative to a large plate aggregate

$$g = \int_{-1}^{1} \cos\theta \, P(\theta) \, d\cos\theta$$

Bulk asymmetry parameter = average over the (already azimuthally averaged) scattering phase function $P(\theta)$

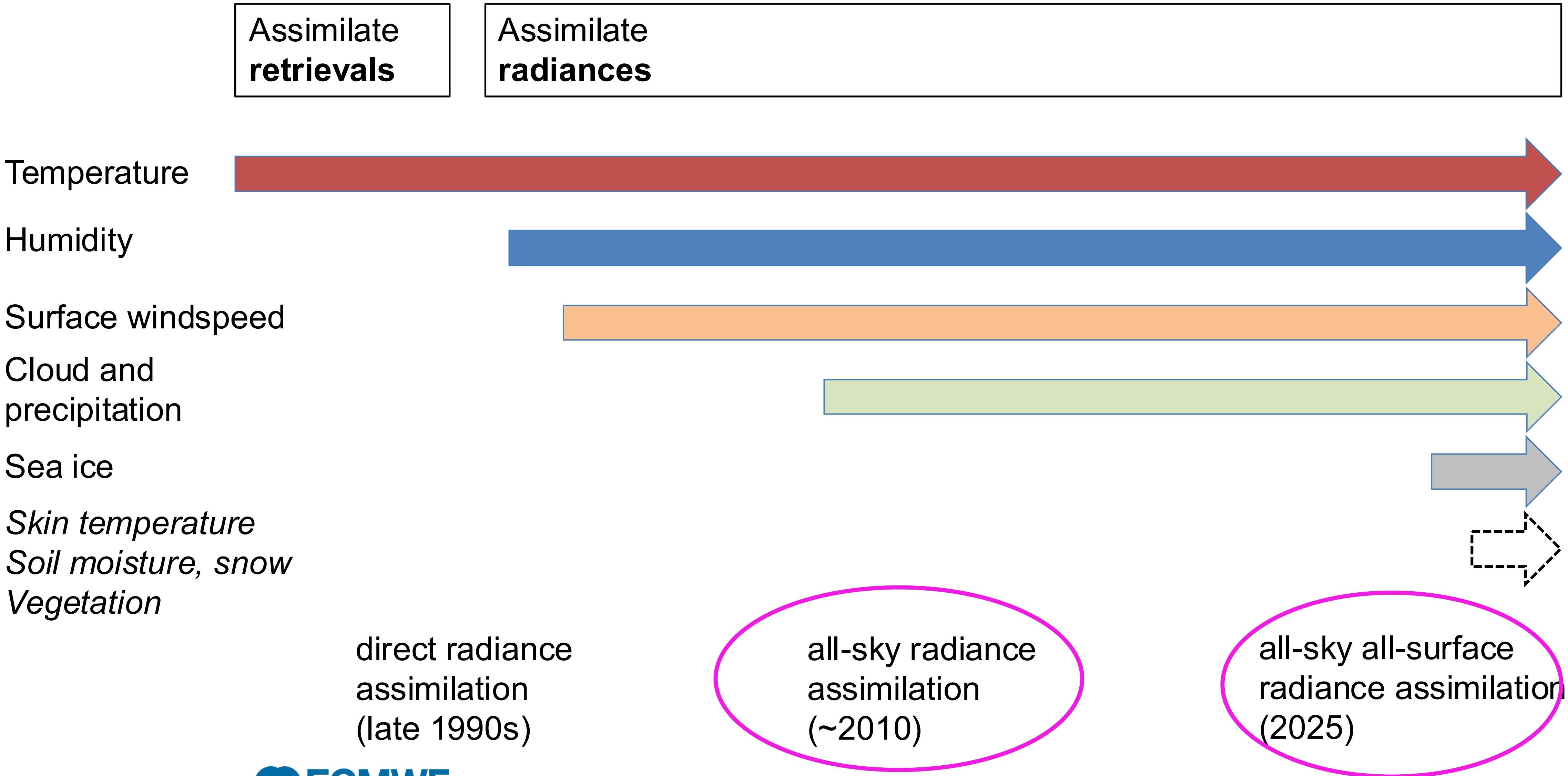
DDA non-spherical particles from the ARTS scattering database

Geer et al. (2021, GMD)

Applications

(depending on time available)

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



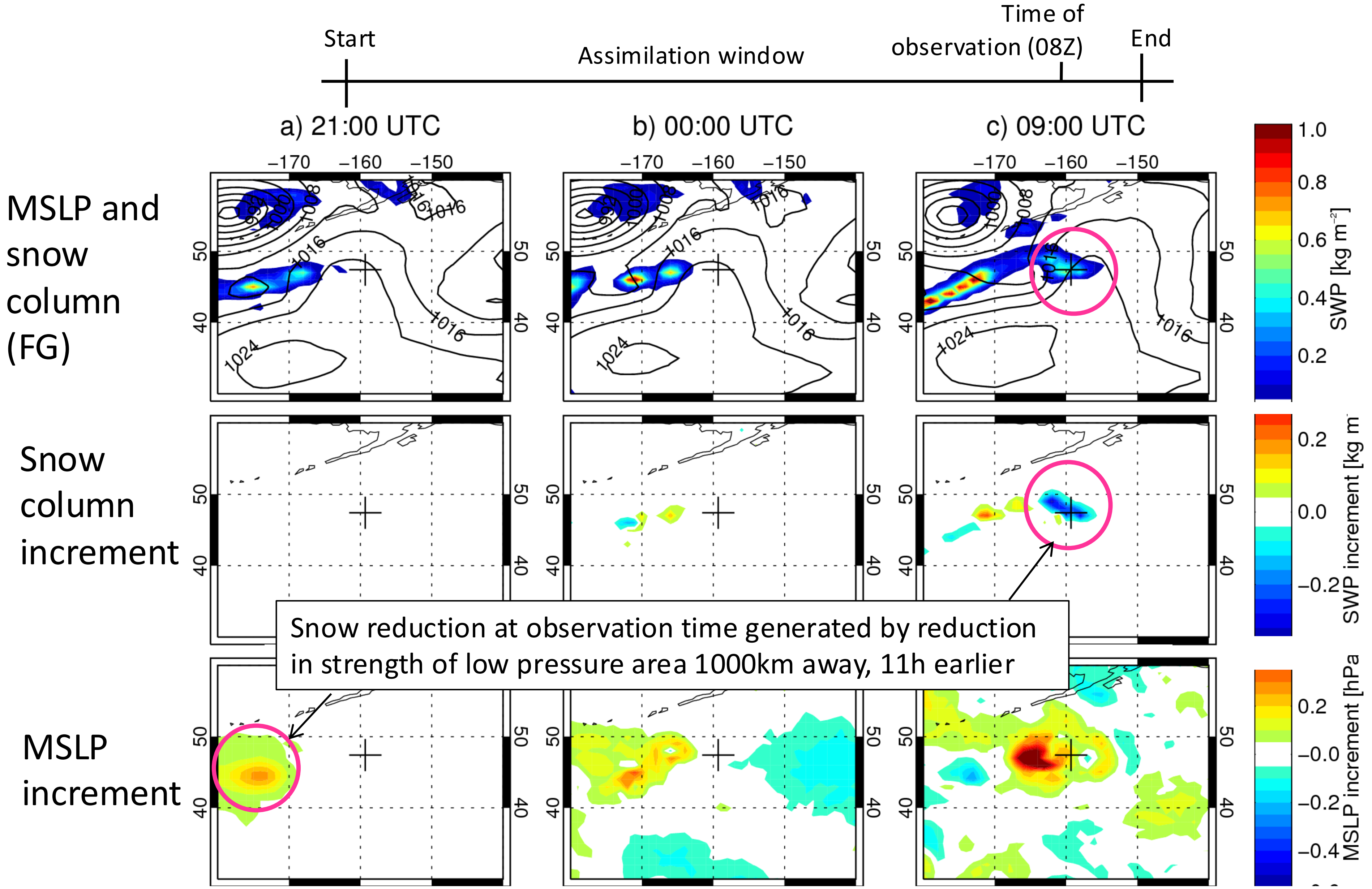
All-sky assimilation

Clear-sky or all-sky?

- Clear-sky assimilation:
  - Remove any cloud-contaminated observations
  - Do not model the effect of cloud on brightness temperatures
  - Traditionally used for all satellite radiances, with particular benefit in temperature sounding
  - Extract small signals of temperature forecast errors (order 0.1K) that would be swamped by errors from displaced clouds and precipitation (10-100K)
- All-sky assimilation
  - Model the effect of cloud and precipitation on the observations
  - Assimilate all data, whether clear, cloudy or precipitating
  - Initially developed for water-vapour sounding and imaging channels, but now also applied to temperature-sounding channels
  - Use the tracing mechanism of 4D-Var to infer the dynamical state from errors in the location/intensity of water vapour, cloud and precipitation
- Broadly, the clear-sky approach is now outdated at microwave frequencies
  - At ECMWF, all but a handful of microwave sensors are now assimilated in all-sky conditions
  - Broadly, going to all-sky assimilation doubles the impact of a sensor (ECMWF TM 741, 2014)

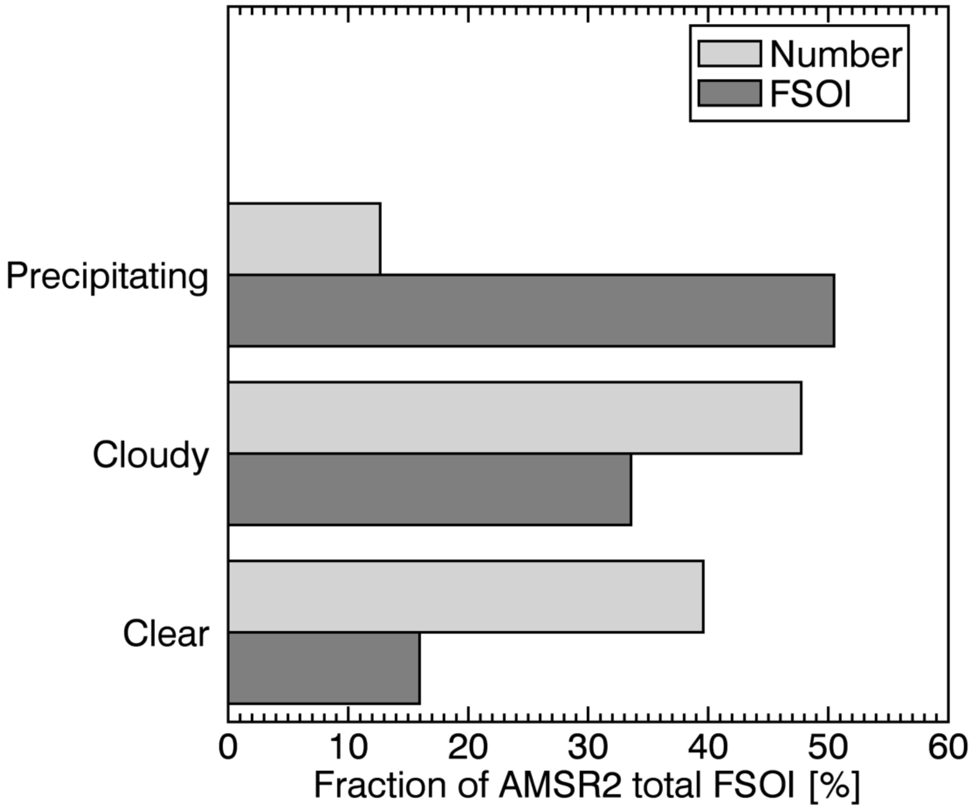
All-sky 'tracer' effect

Single 190 GHz observation column assimilation test case



All-sky microwave imagers: a unique contribution from precipitation-affected observations

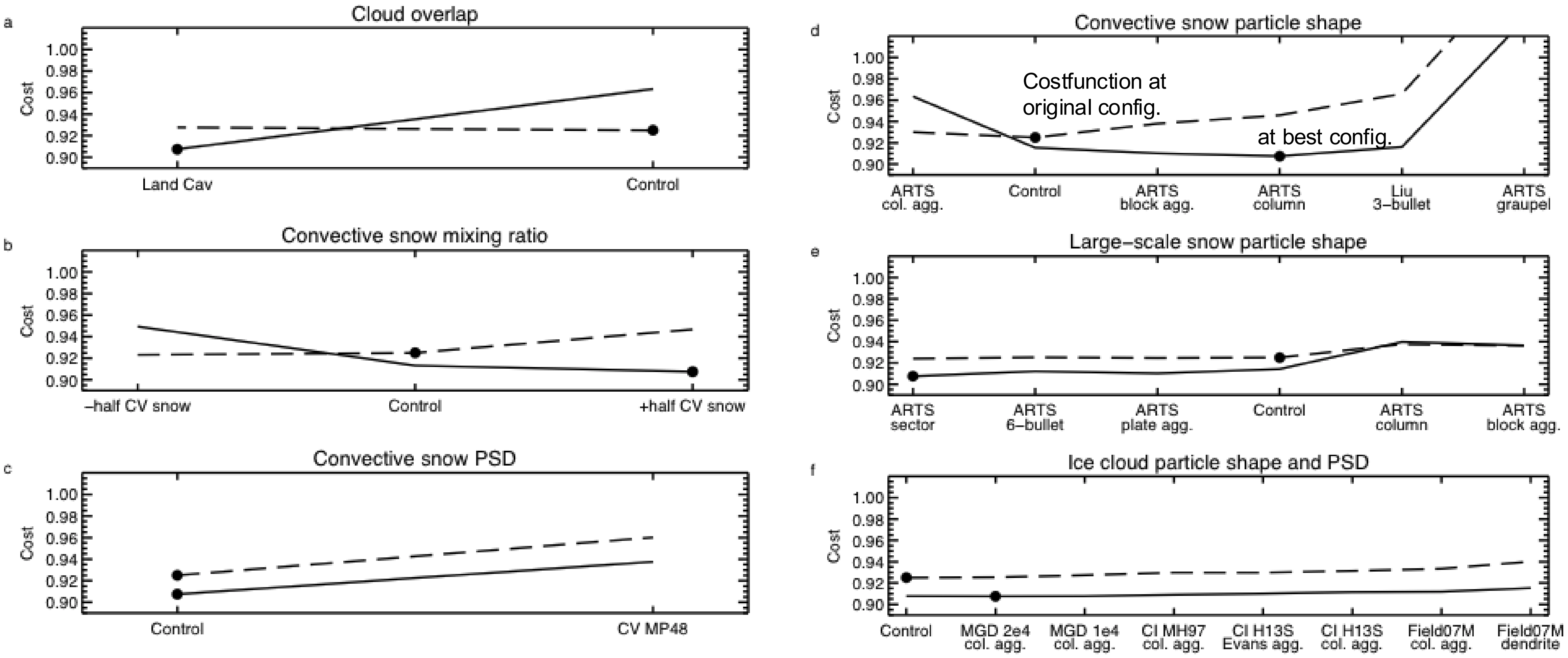
Microwave imagers give their largest forecast impact from a small fraction of precipitating scenes.

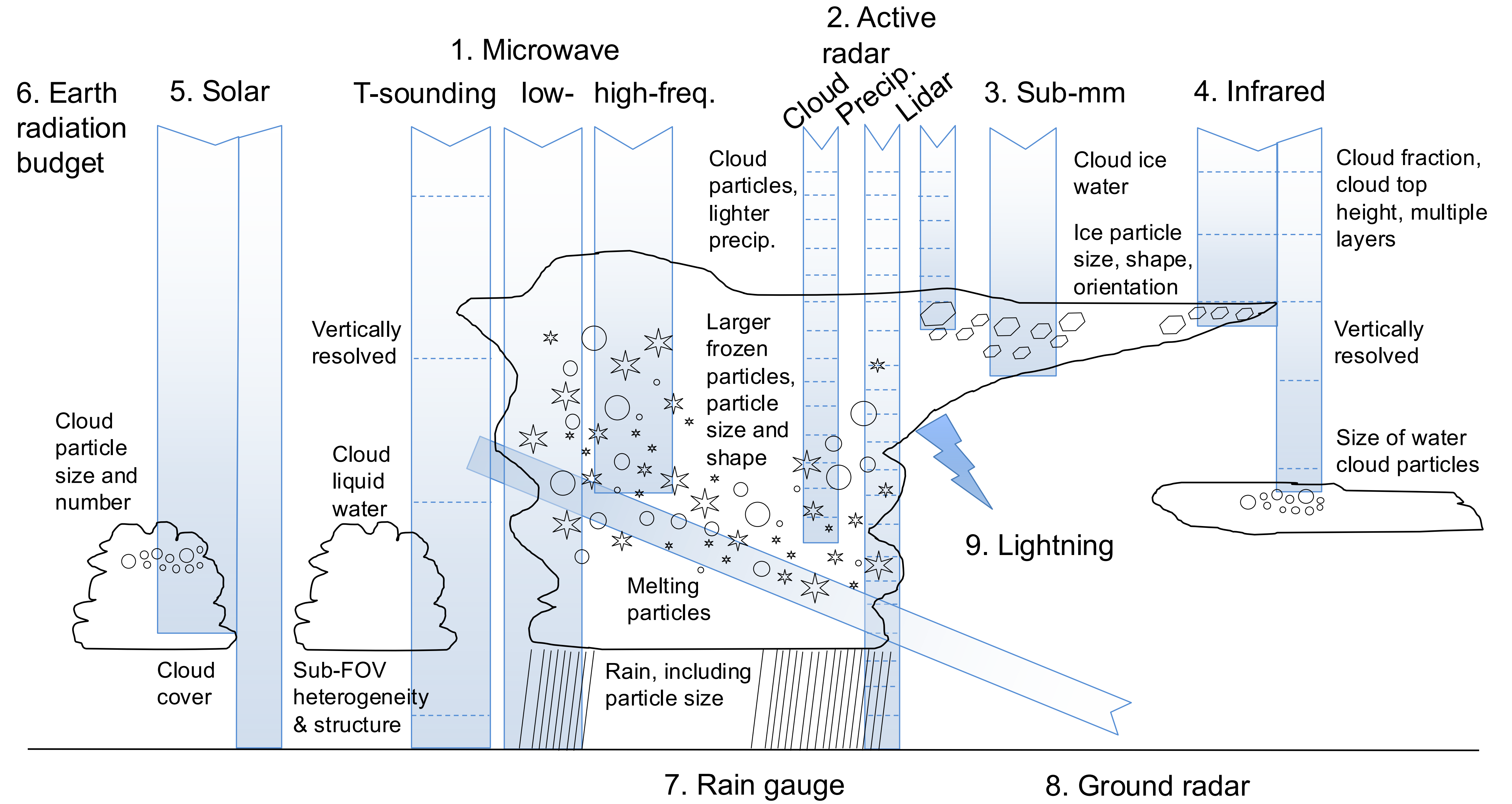


AMSR2, July-August 2016

Parameter estimation for 6 macro- and microphysical variables

Geer (2021, AMT): Physical characteristics of frozen hydrometeors inferred using parameter estimation

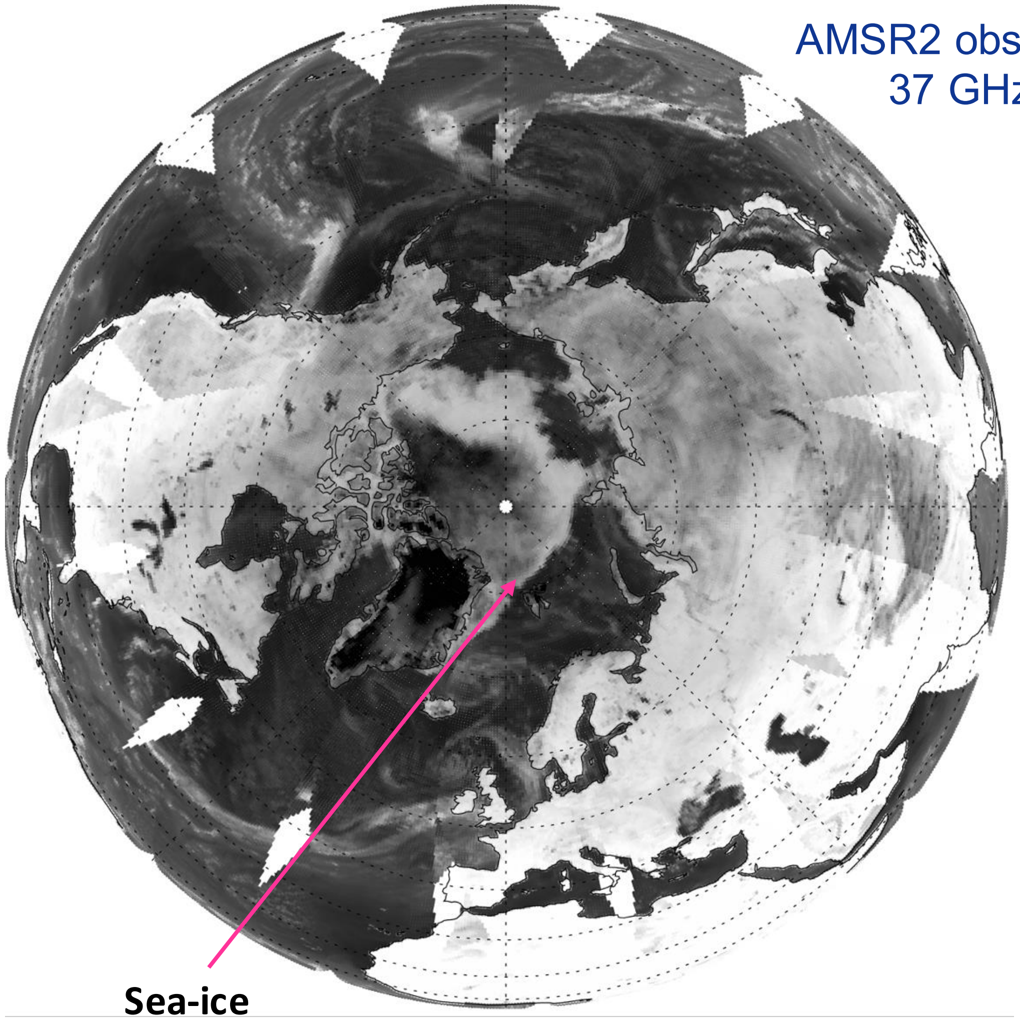



1. Microwave
2. Active radar
T-sounding
low-
high-freq.
Cloud
Precip.
Lidar
3. Sub-mm
4. Infrared
6. Earth radiation budget
5. Solar
Cloud particles, lighter precip.
Cloud ice water
Ice particle size, shape, orientation
Cloud fraction, cloud top height, multiple layers
Vertically resolved
Larger frozen particles, particle size and shape
Vertically resolved
Cloud particle size and number
Cloud liquid water
Size of water cloud particles
9. Lightning
Melting particles
Cloud cover
Sub-FOV heterogeneity & structure
Rain, including particle size
7. Rain gauge
8. Ground radar

All-sky all-surface assimilation

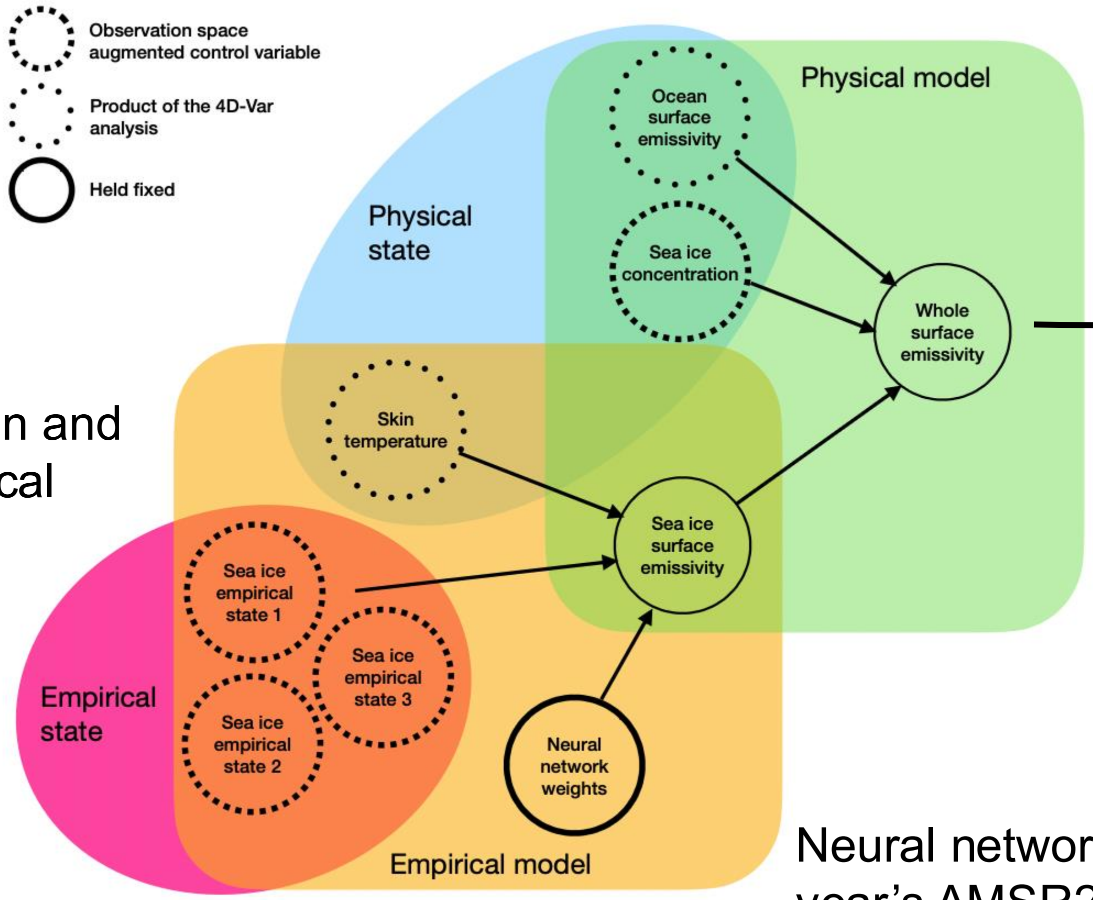
Information content: window (i.e. surface sensitive) channels

AMSR2 observation composite for 2nd Nov 2021
37 GHz, v-polarised brightness temperature



Empirical sea ice emissivity model used to retrieve sea ice concentration in atmospheric 4D-Var and to allow radiance assimilation over sea ice: activation in cycle 49r1 (autumn 2024)

Sea ice concentration and three empirical parameters retrieved at observation locations



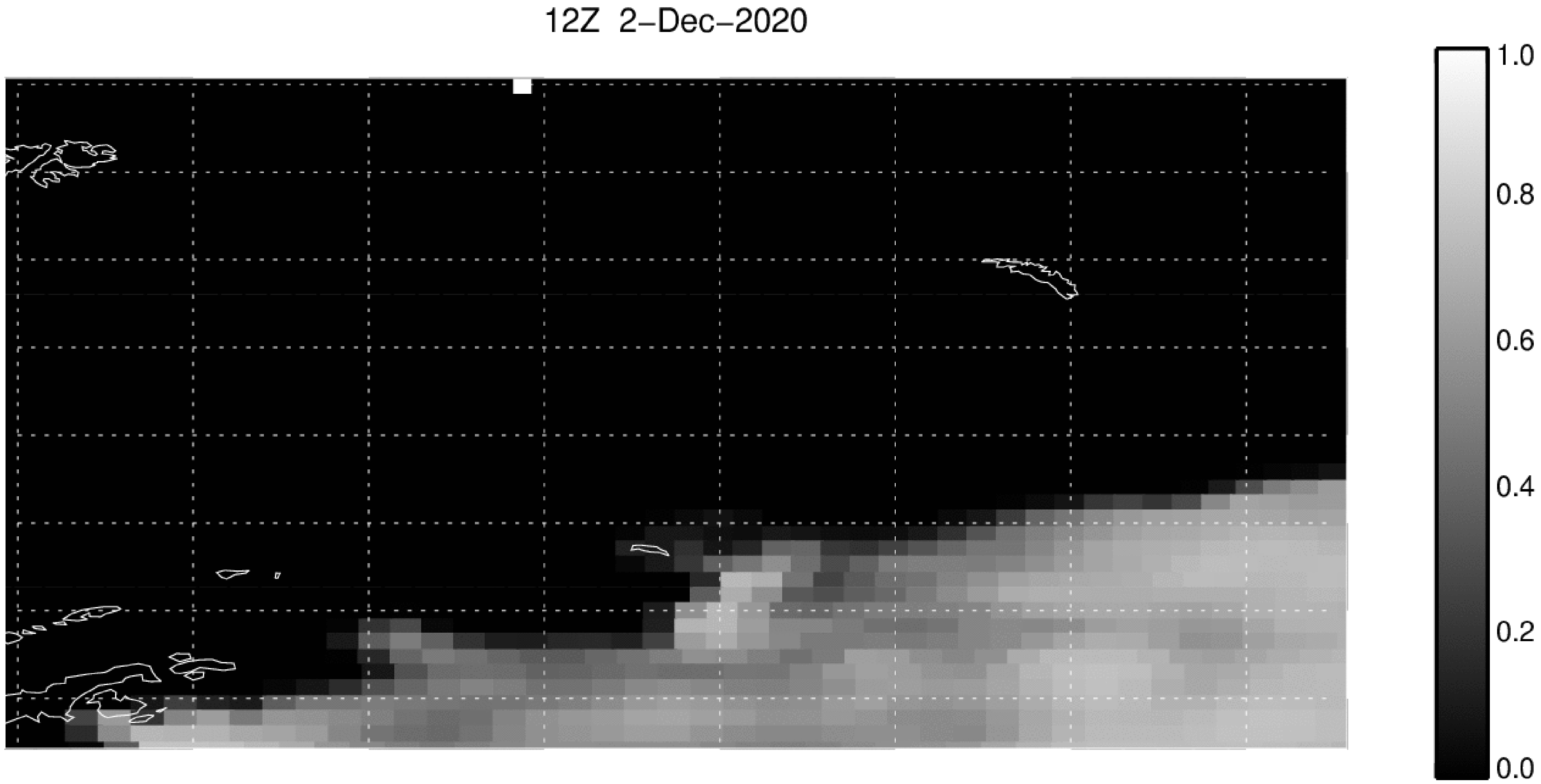
4D-Var updates atmosphere and empirical parameters with the benefit of all other observations.

RTTOV all-sky radiative transfer model

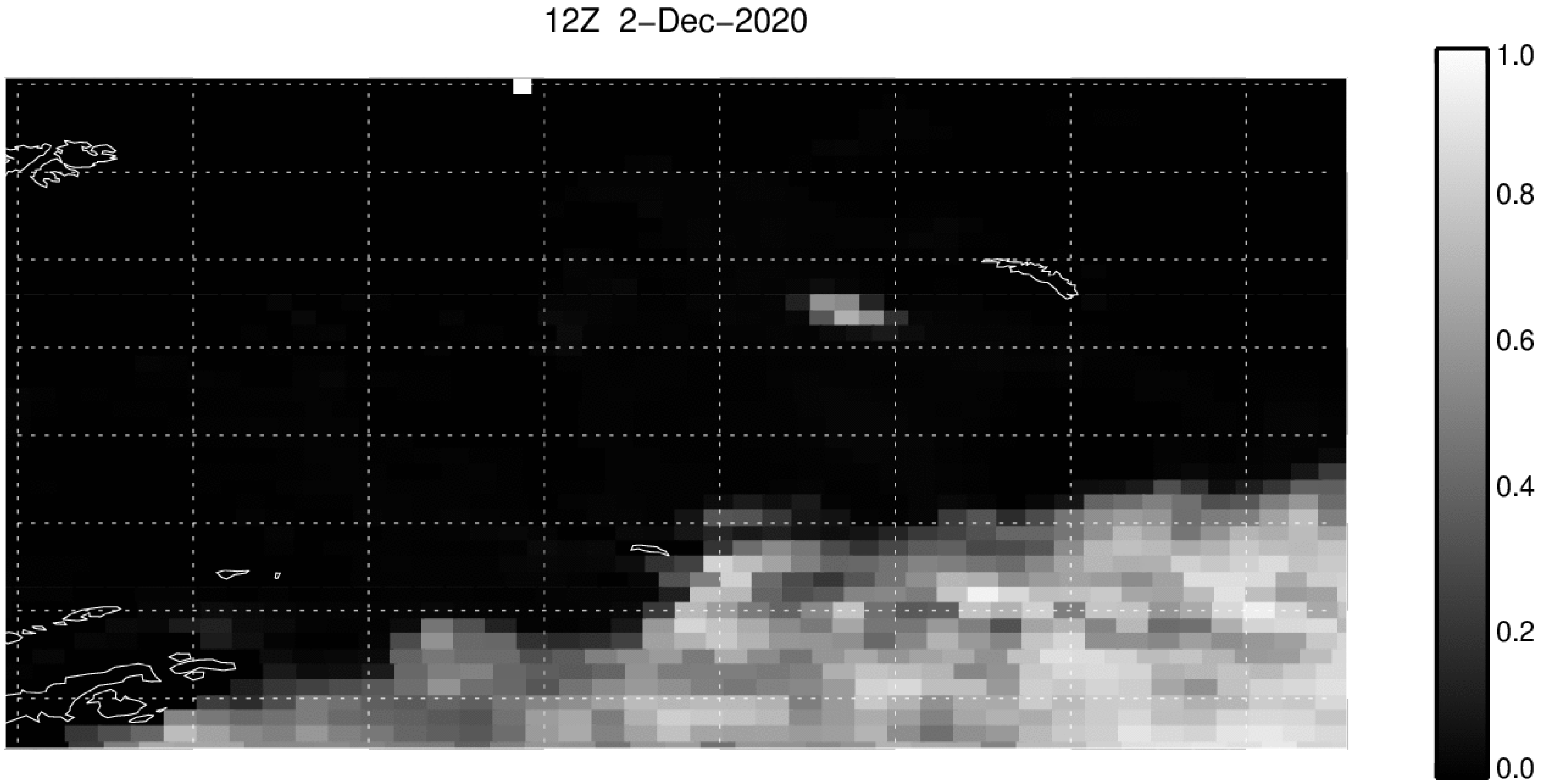
AMSR2 and GMI microwave imager observations

Neural network trained offline on 1 year's AMSR2 data

IFS sea ice concentration at AMSR2 locations



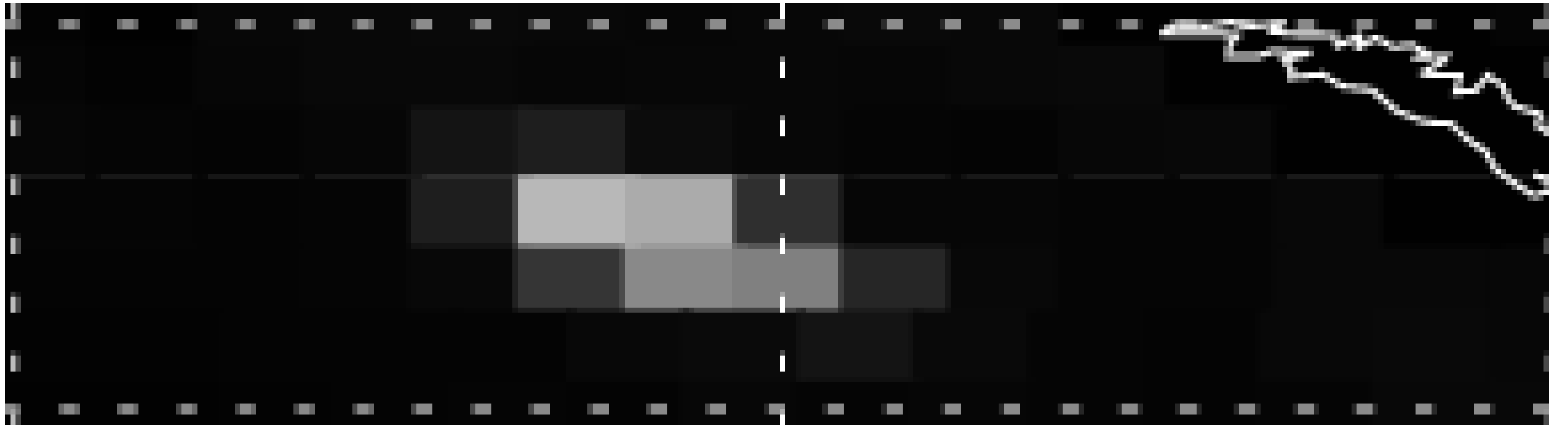
AMSR2 sink variable sea ice concentration



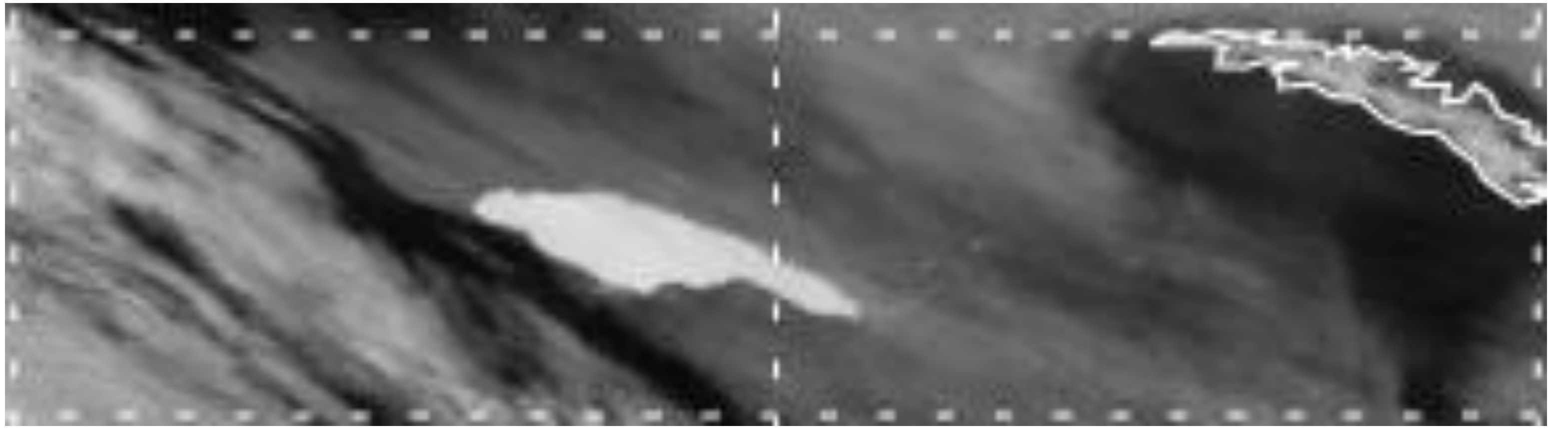
AMSR2 sea ice fraction vs OLCI image: A68A iceberg

AMSR2

1 pixel ~
40x40 km



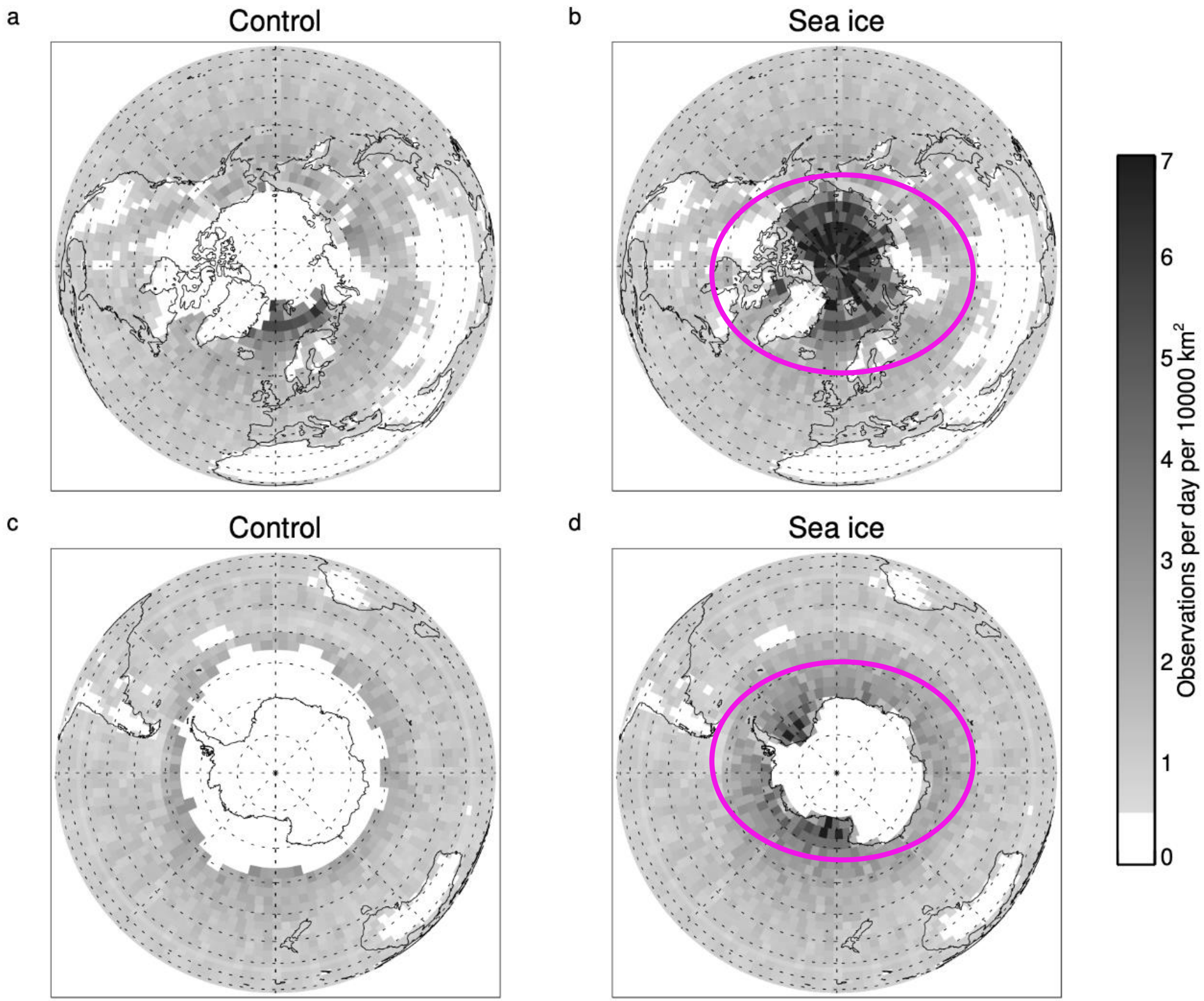
12Z 4th Dec 2020



OLCI channel
10 (681 nm)

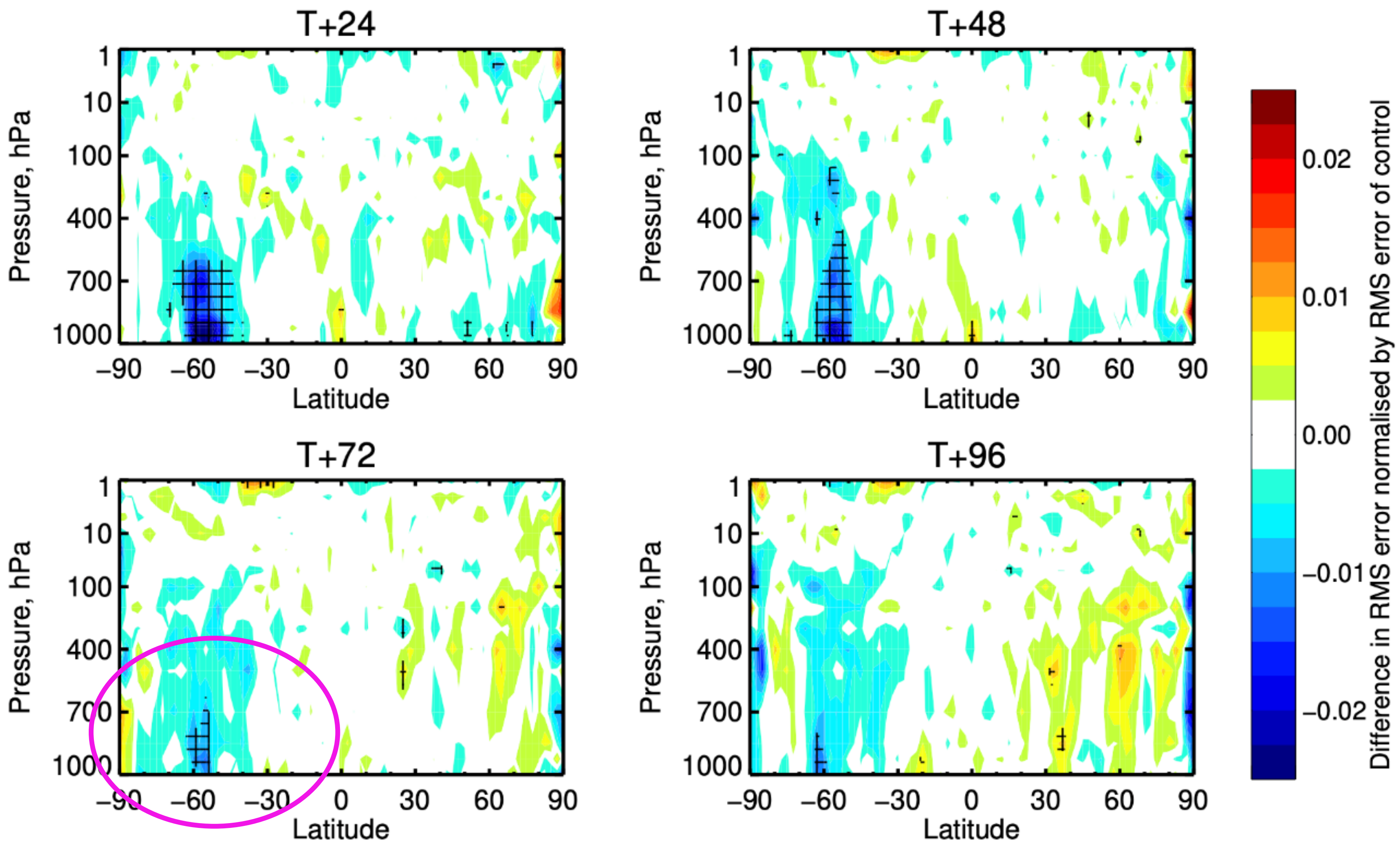
Number of AMSR2 observations added

Up to around 7 observations per day per 10,000 km^2 have been added over sea ice regions



Forecast impact - temperature
(blue = reduced error; +++ = statistical significance)

Improved temperature forecasts out to 72 hours in the Southern Ocean



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

Assimilate **retrievals**

Assimilate **radiances**

Temperature

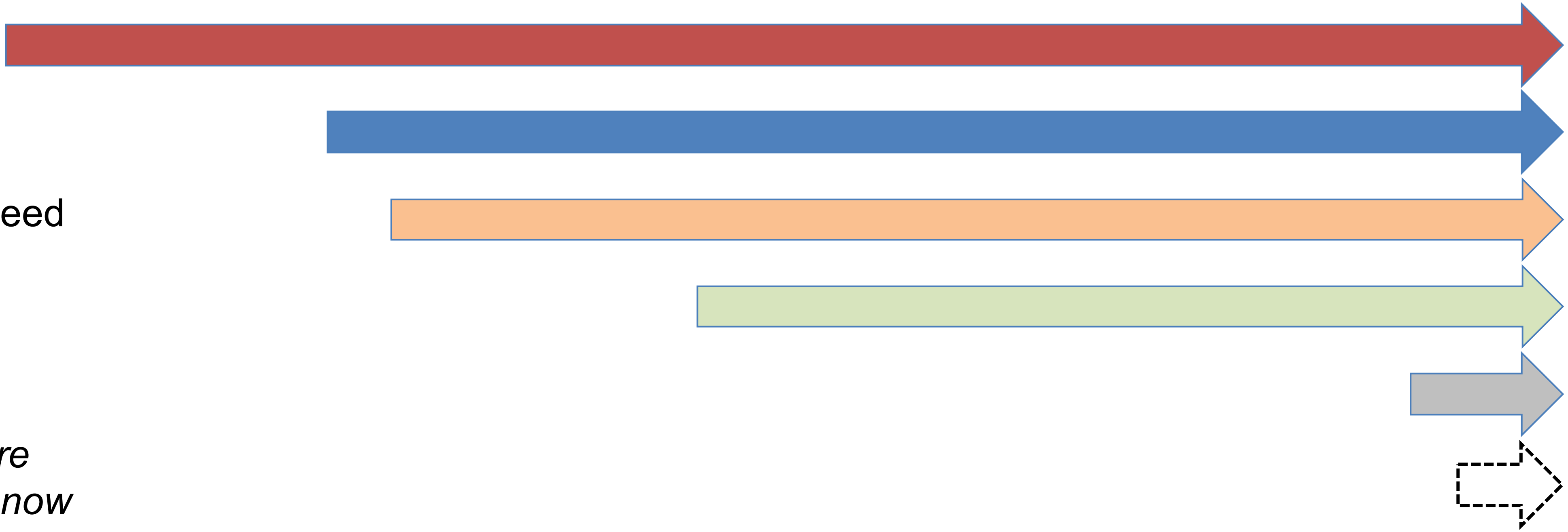
Humidity

Surface windspeed

Cloud and precipitation

Sea ice

Skin temperature
Soil moisture, snow
Vegetation

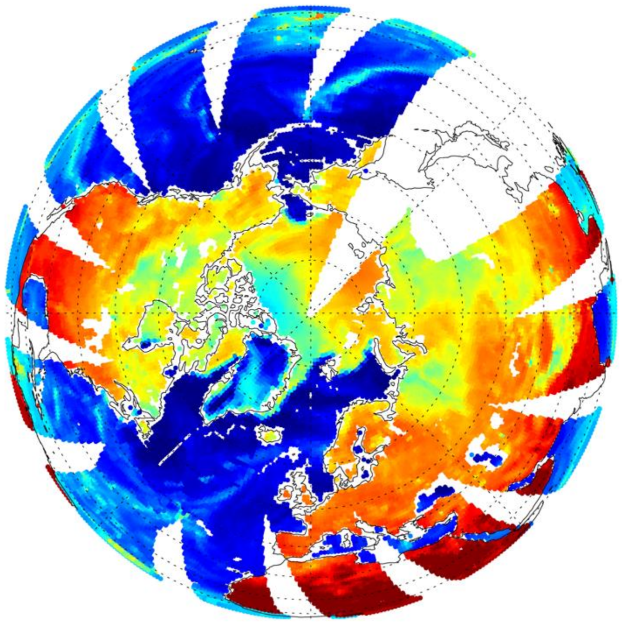


direct radiance assimilation (late 1990s)

all-sky radiance assimilation (~2010)

all-sky all-surface radiance assimilation (2025)

Next step – coupling with land and ocean models in data assimilation



- Cycle 50r1: sea ice concentration and sea surface temperature estimation from microwave imagers (AMSR2, GMI) coupled to ocean model
- After that?
    - Snow on land, soil moisture, vegetation, salinity…

ECMWF

Questions?