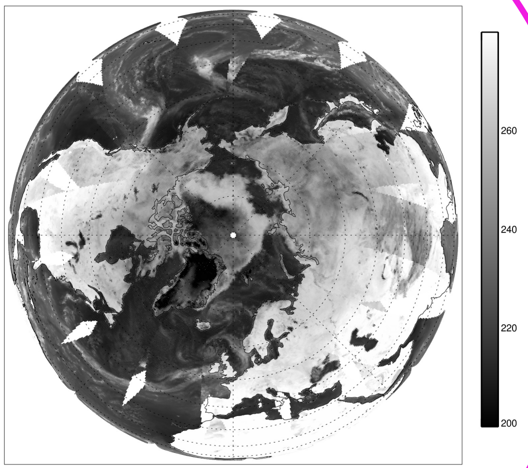
Microwave observations (part 2): cloud and precipitation; applications

Alan Geer

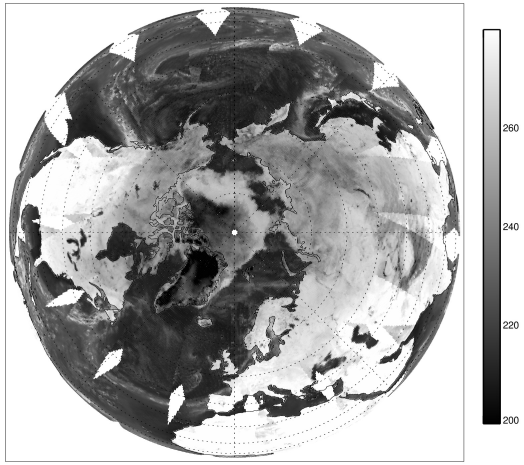
EUMETSAT/ECMWF NWP-SAF satellite data assimilation training course, 15 – 19 May 2023

Observations

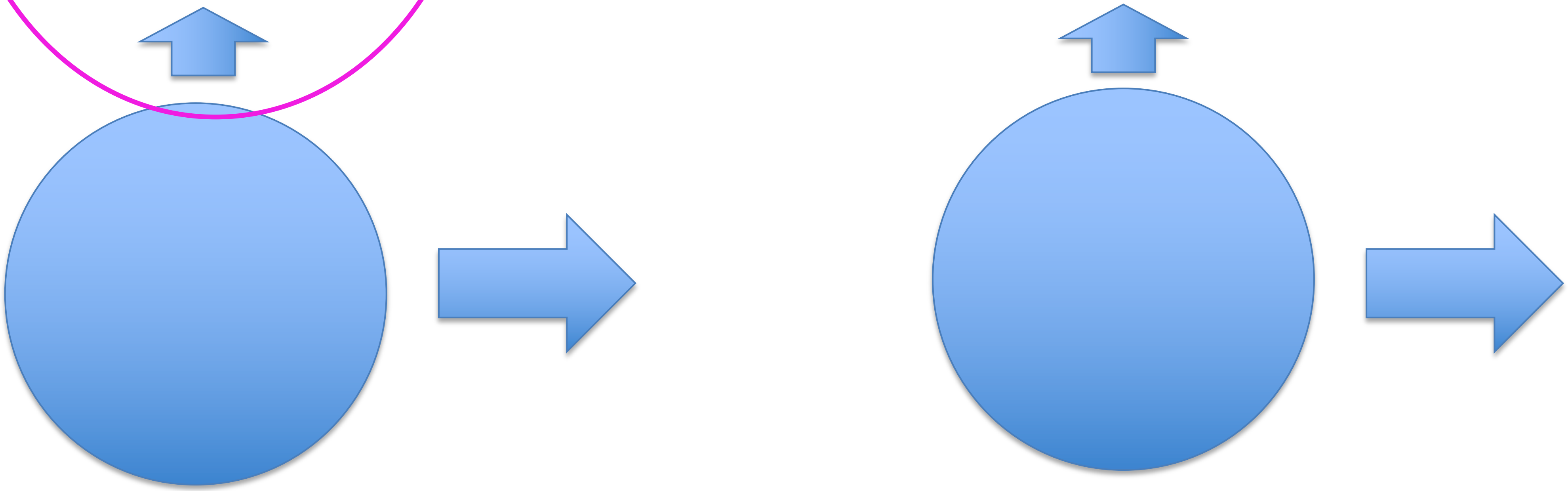
1st Nov



2nd Nov

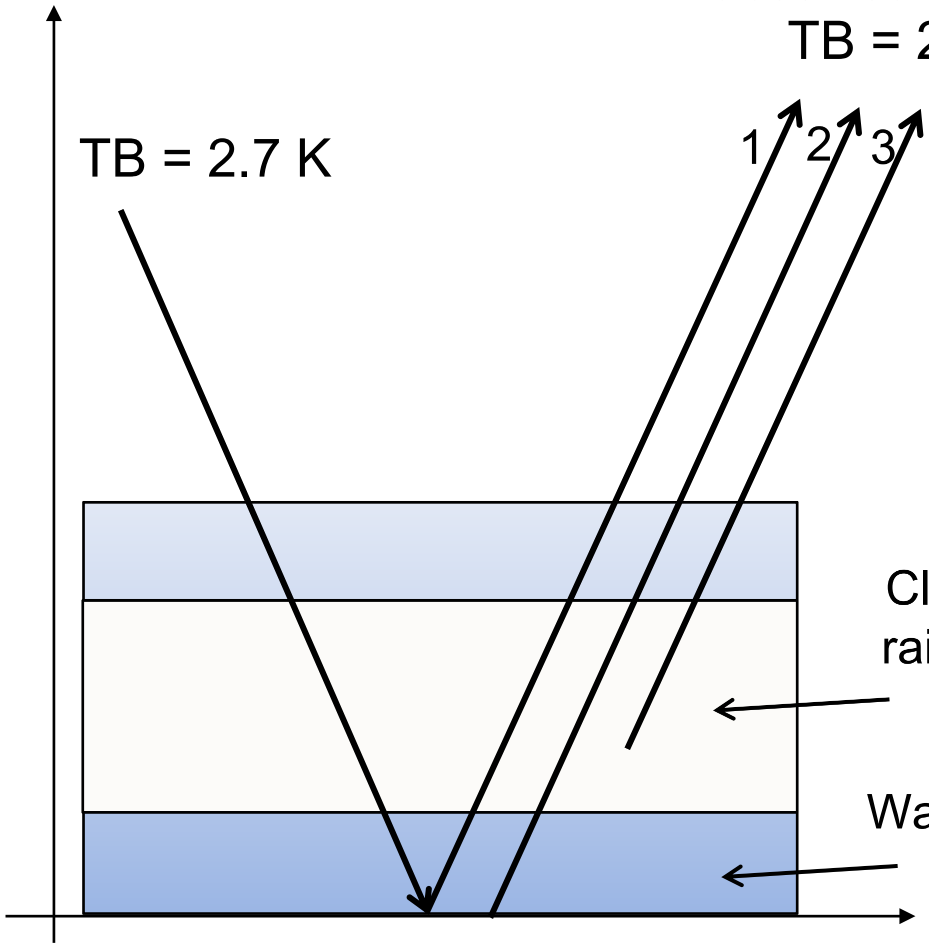


Earth system model: geophysical state and its forward propagation in time



Scattering radiative transfer

Radiative transfer: window channels (ignoring scattering)



Observed by satellite
TB = 240 K

TB = 2.7 K

1 2 3

T = 280 K

Cloud (and often rain): acts like an emitting gas

Water vapour: is an emitting gas

Ocean or land / snow / sea-ice surface

Three sources of radiation:

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

Schwarzchild’s equation

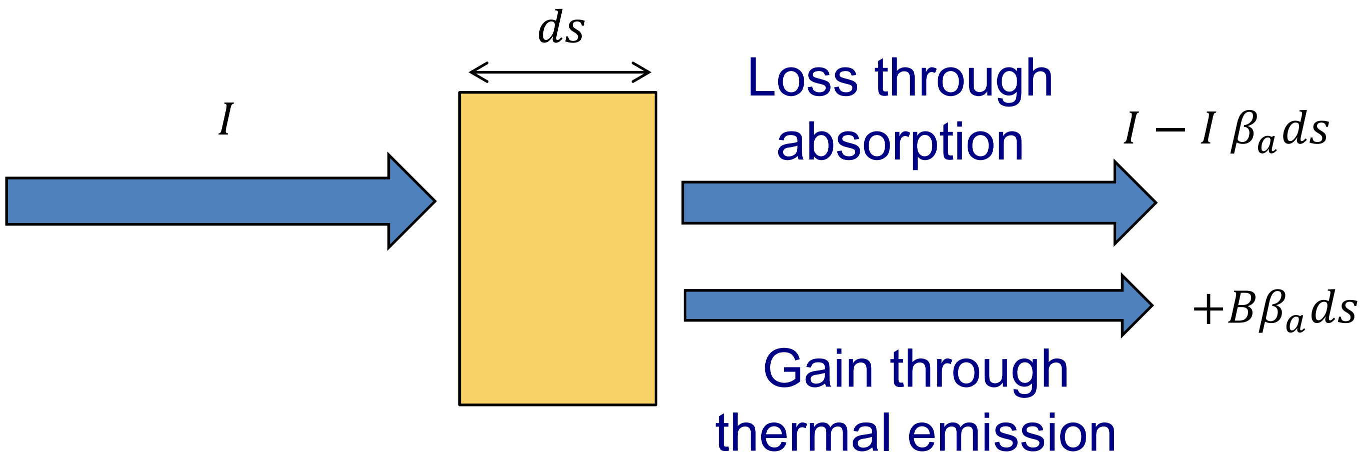
Planck function

Radiance

Change in radiance per distance

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

Absorption coefficient



ds

I

Loss through absorption

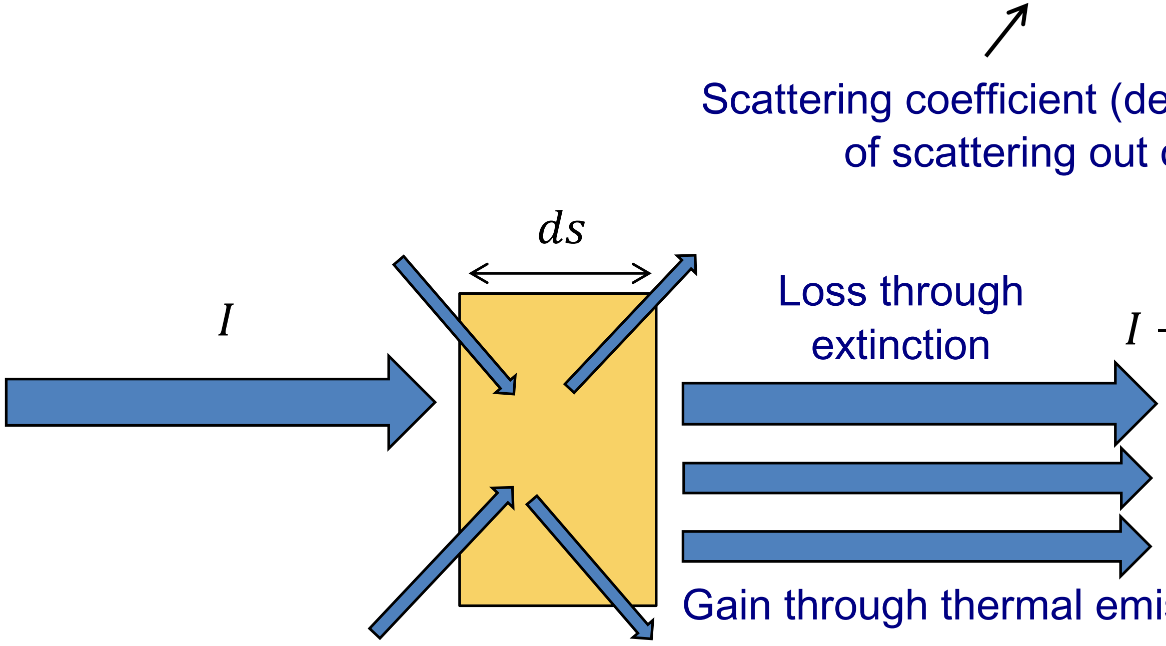
$I - I\,\beta_a ds$

$+B\beta_a ds$

Gain through thermal emission

Adding scattering

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



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

ds

I

Loss through extinction

$I - I\,\beta_e ds$

$+?$ Gain from scattering into the beam

$+B\beta_a ds$

Gain through thermal emission

Change in coordinates: optical depth

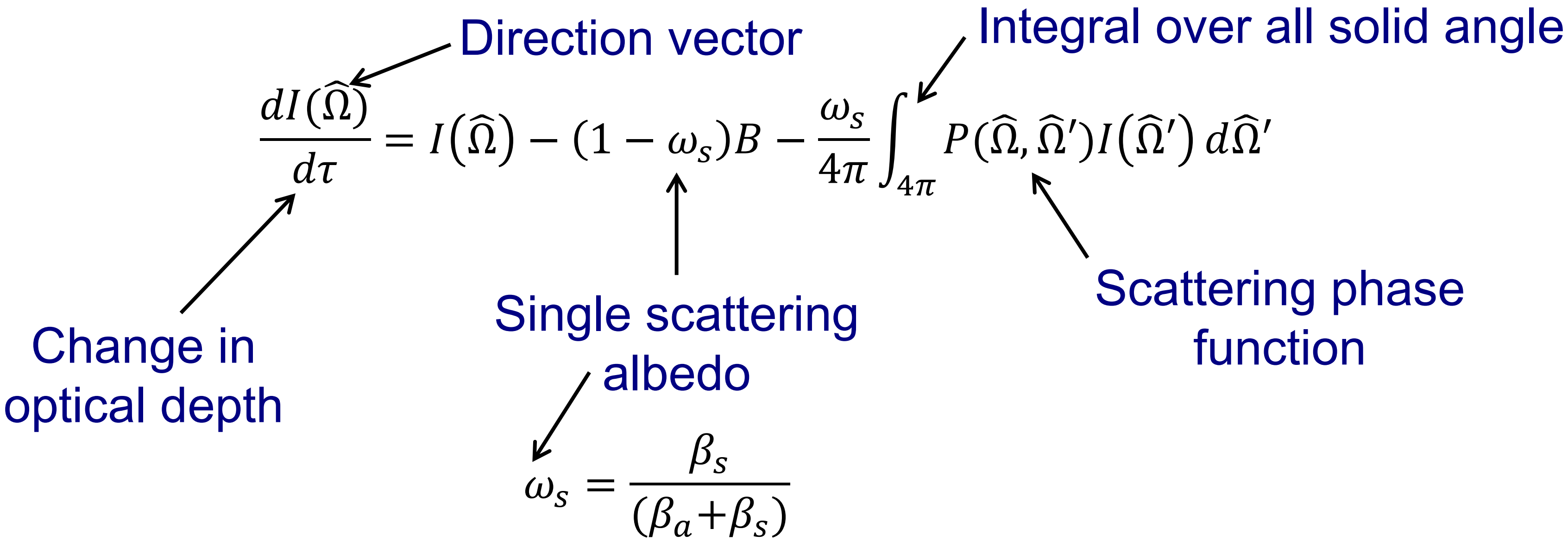
Change in optical depth $\mathrm{d}\tau$ in a non-scattering atmosphere

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

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

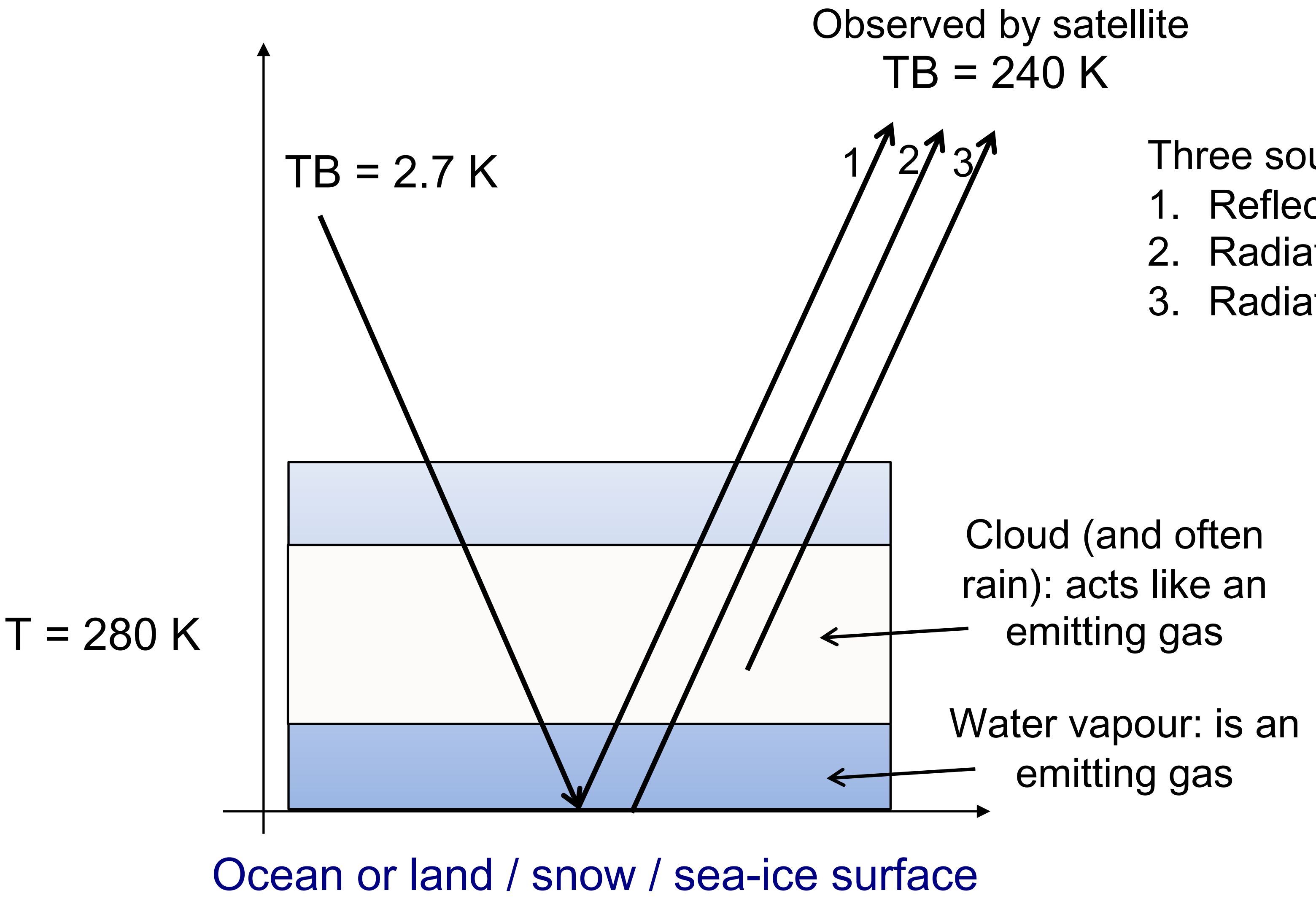
$$\omega_s = \frac{\beta_s}{(\beta_a+\beta_s)}$$

- 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

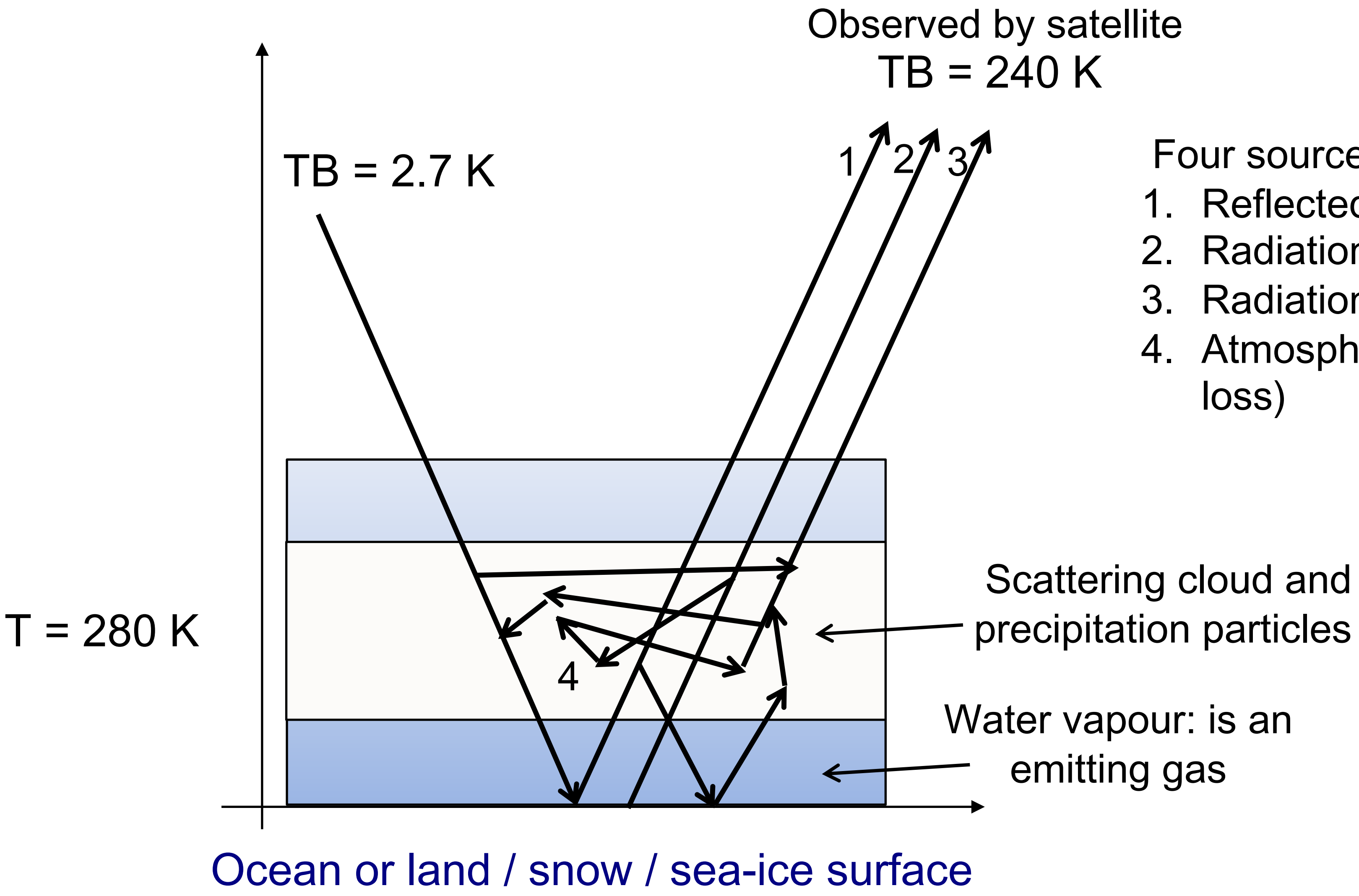
Radiative transfer: window channels (ignoring scattering)



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)

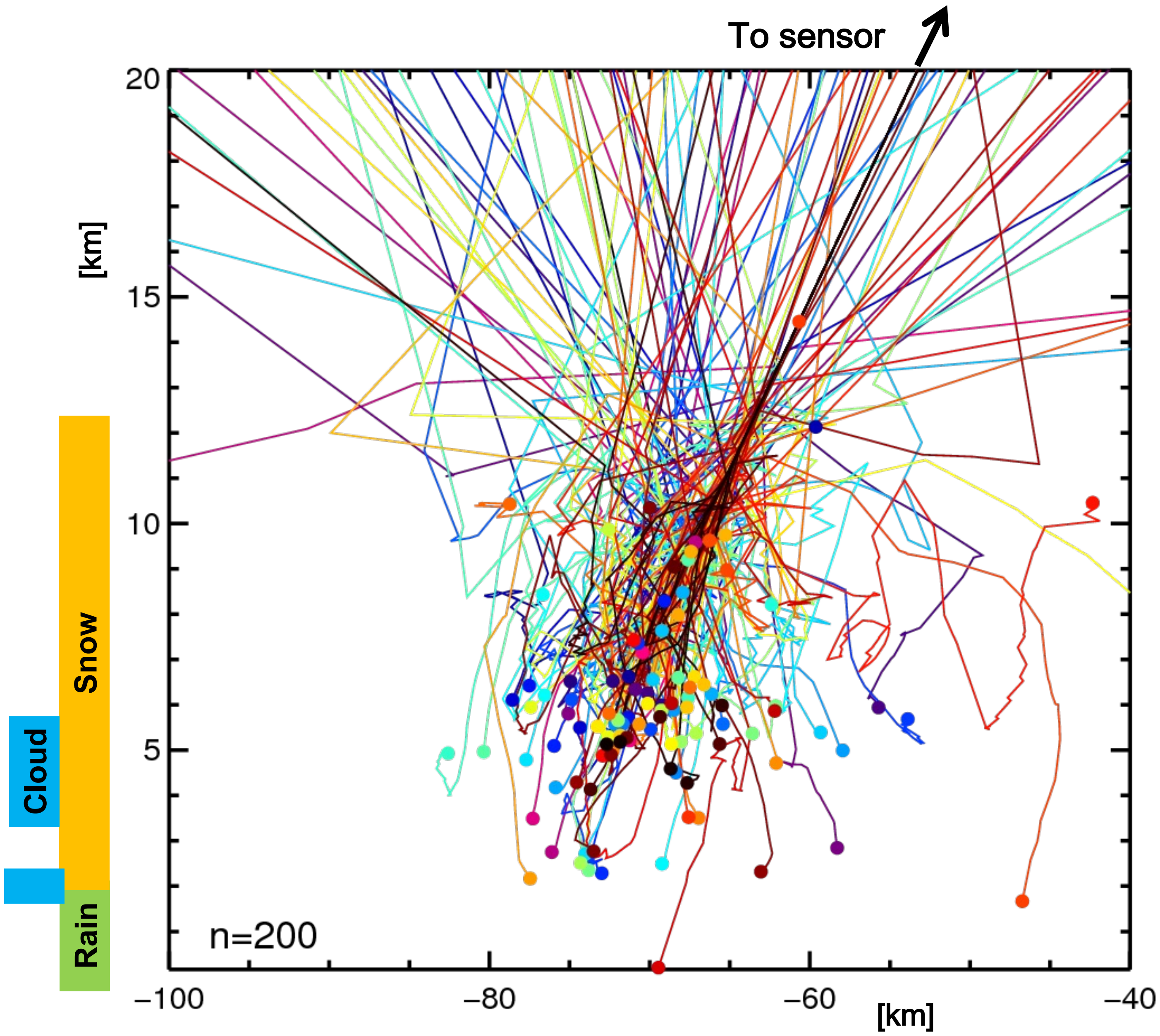


Four sources of radiation:

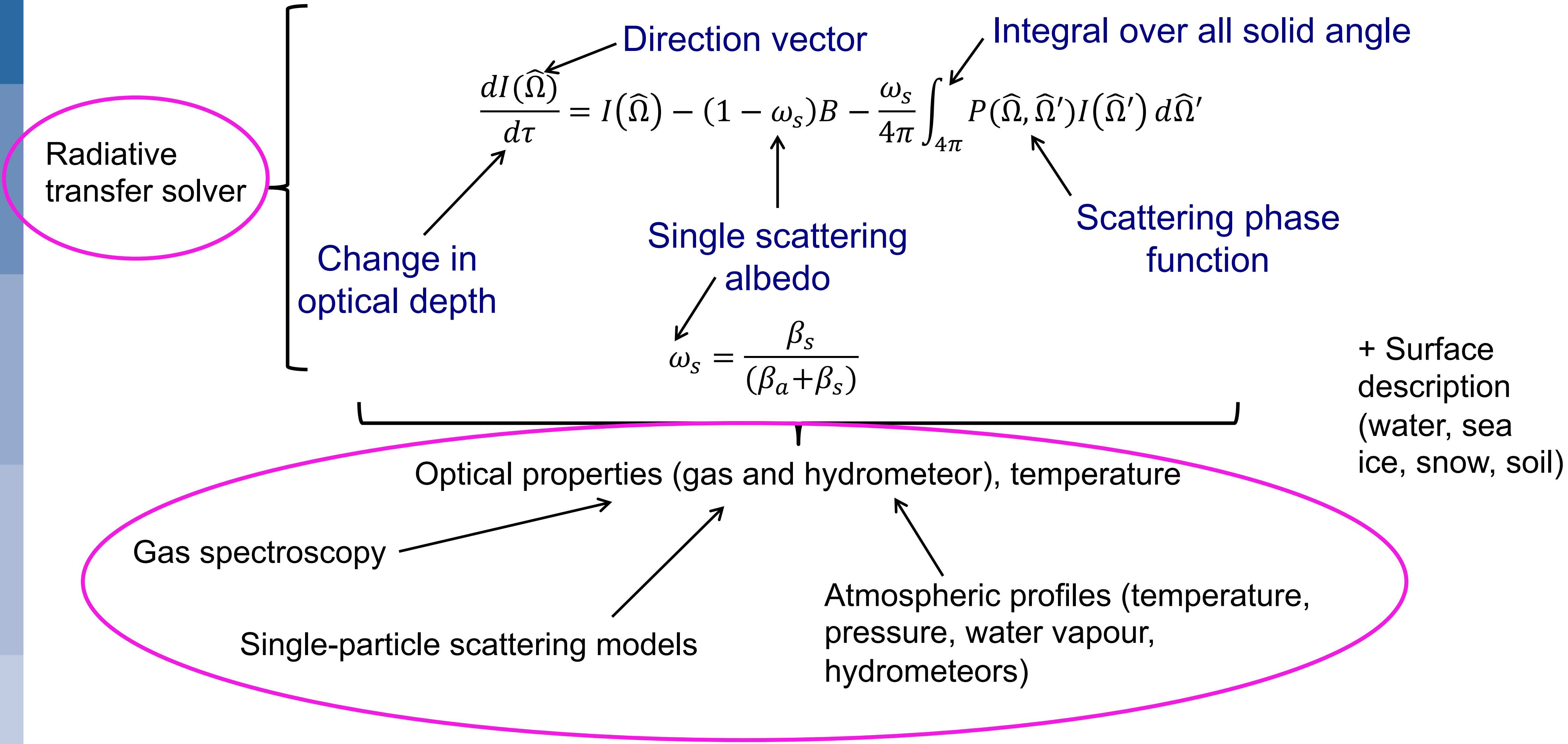
1. Reflected downwelling
2. Radiation emitted by the surface
3. Radiation emitted by the atmosphere
4. Atmospheric scattering (gain and loss)

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

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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

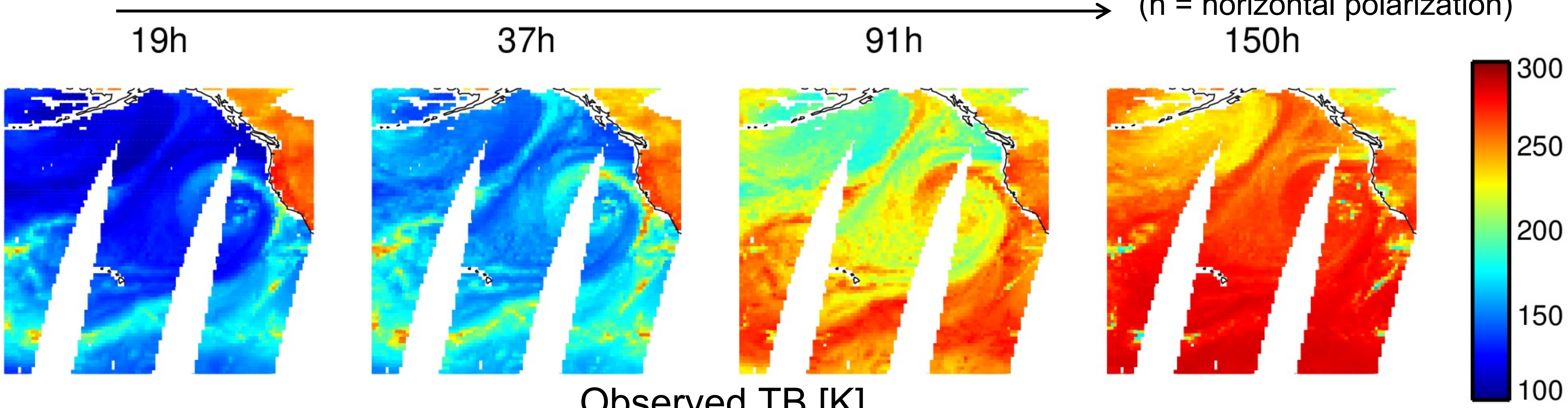
Single-particle scattering models

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

Cloud effects in observations

Effect of hydrometeors in microwave window channels

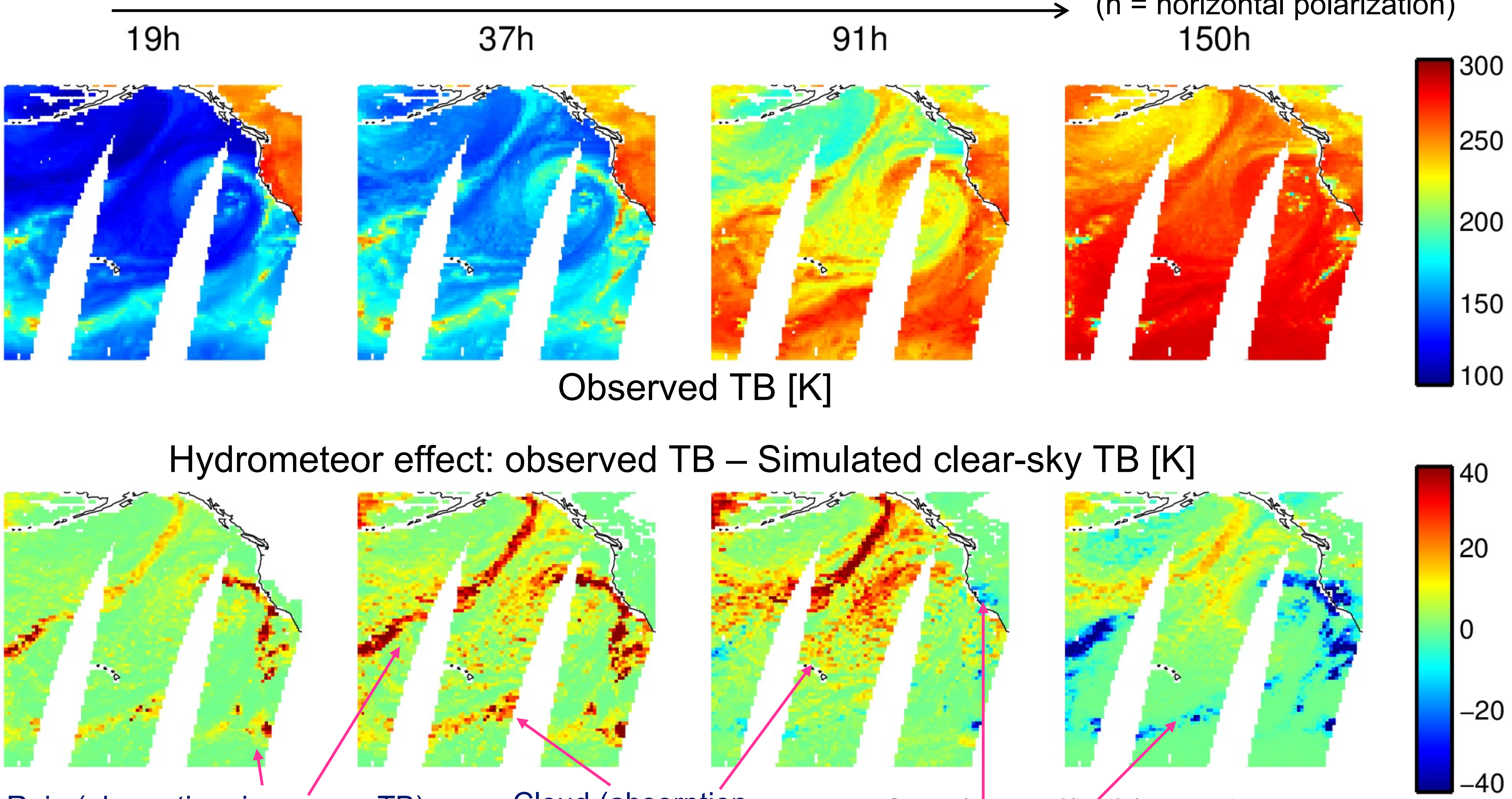
Increasing frequency [GHz]
(h = horizontal polarization)



Observed TB [K]

Effect of hydrometeors in microwave window channels

Increasing frequency [GHz]
(h = horizontal polarization)

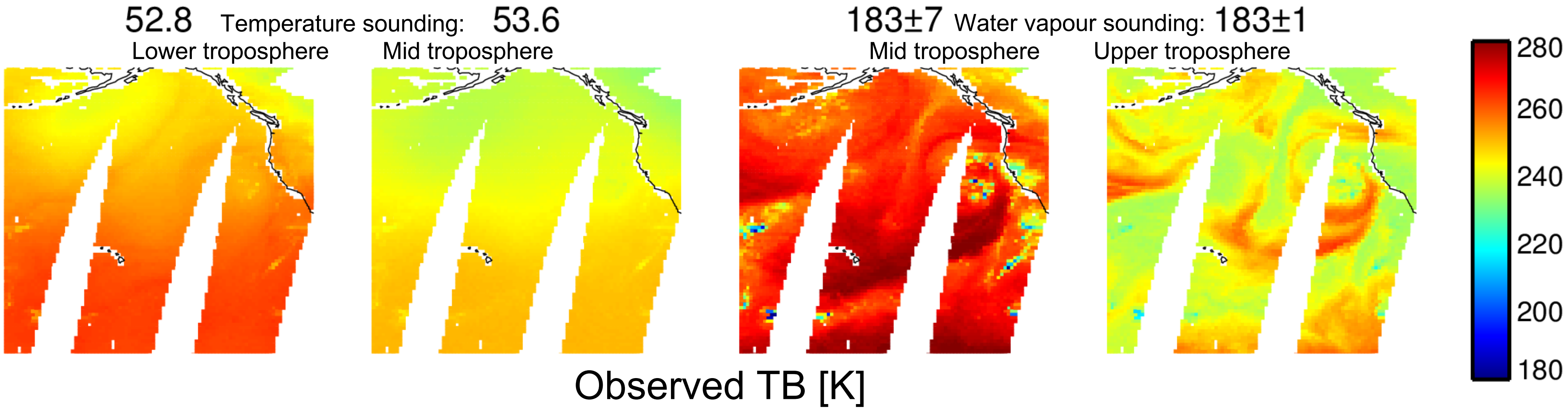


Rain (absorption, increases TB)

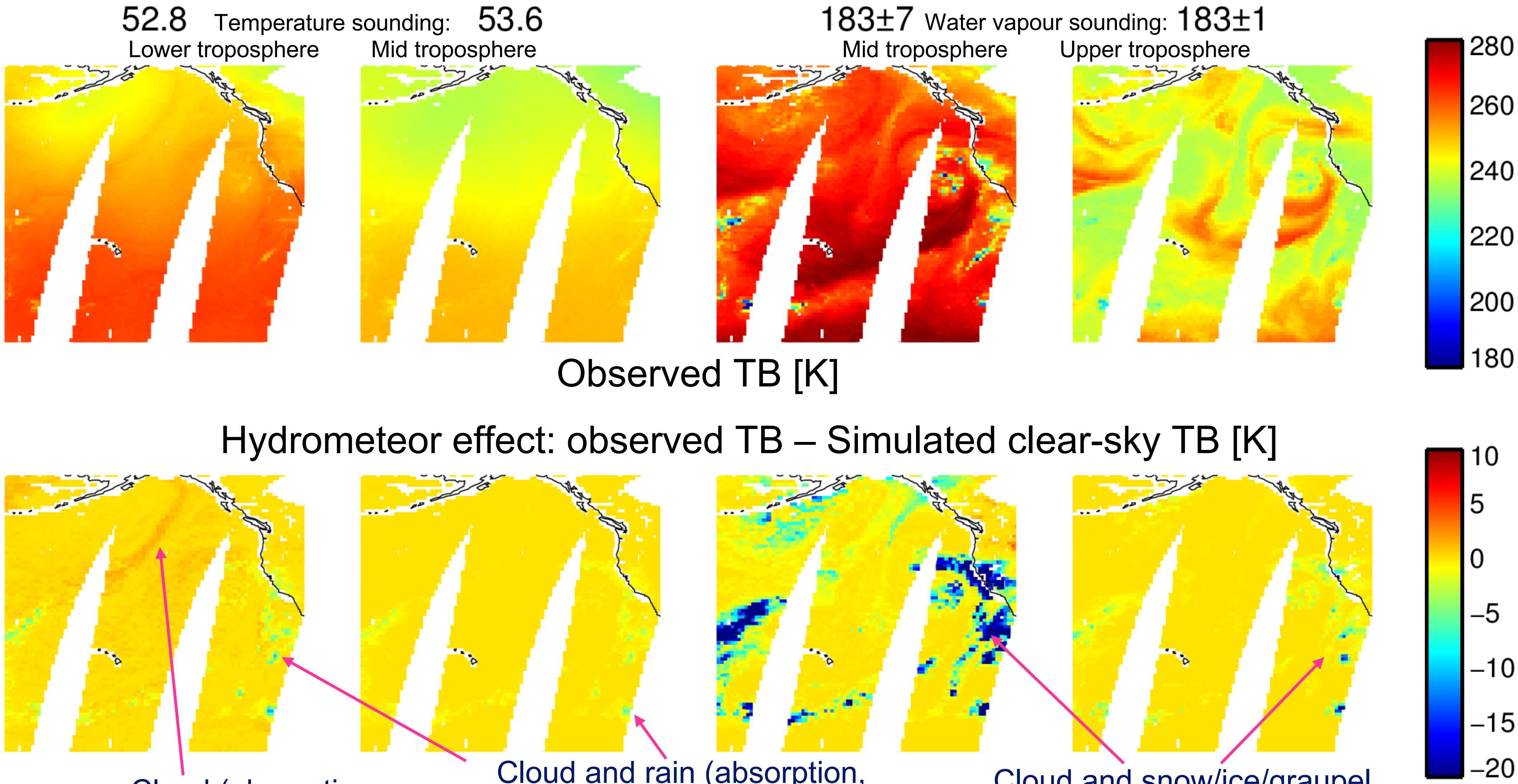
Cloud (absorption, increases TB)

Snow/graupel/hail (scattering, decreases TB)

Effect of hydrometeors in microwave sounding channels



Effect of hydrometeors in microwave sounding channels



Observed TB [K]

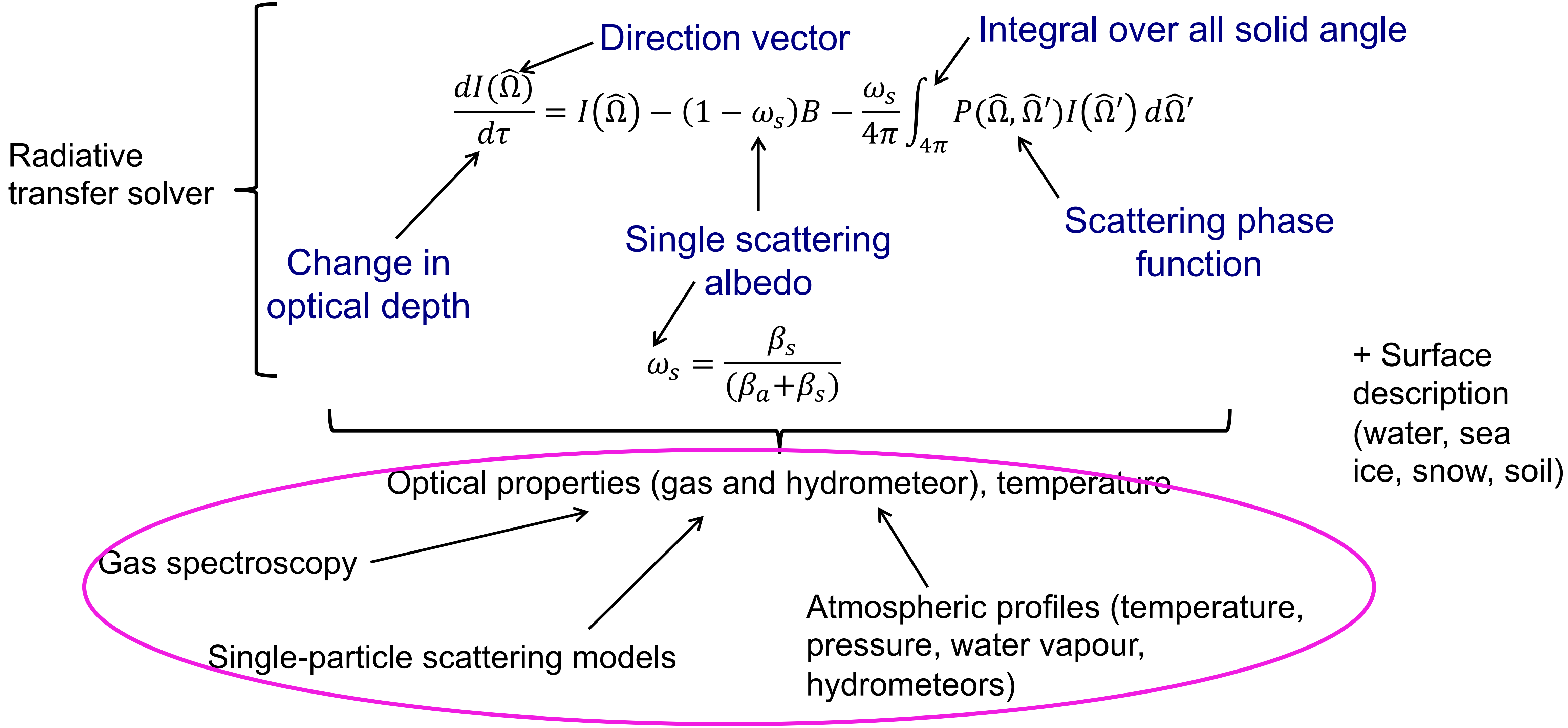
Hydrometeor effect: observed TB – Simulated clear-sky TB [K]

Cloud (absorption, increases TB)

Cloud and rain (absorption, pushes up weighting function altitude, decreases TB)

Cloud and snow/ice/graupel (absorption and scattering, decreases TB)

The full scattering radiative transfer equation



Radiative transfer solver

Direction vector

Integral over all solid angle

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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

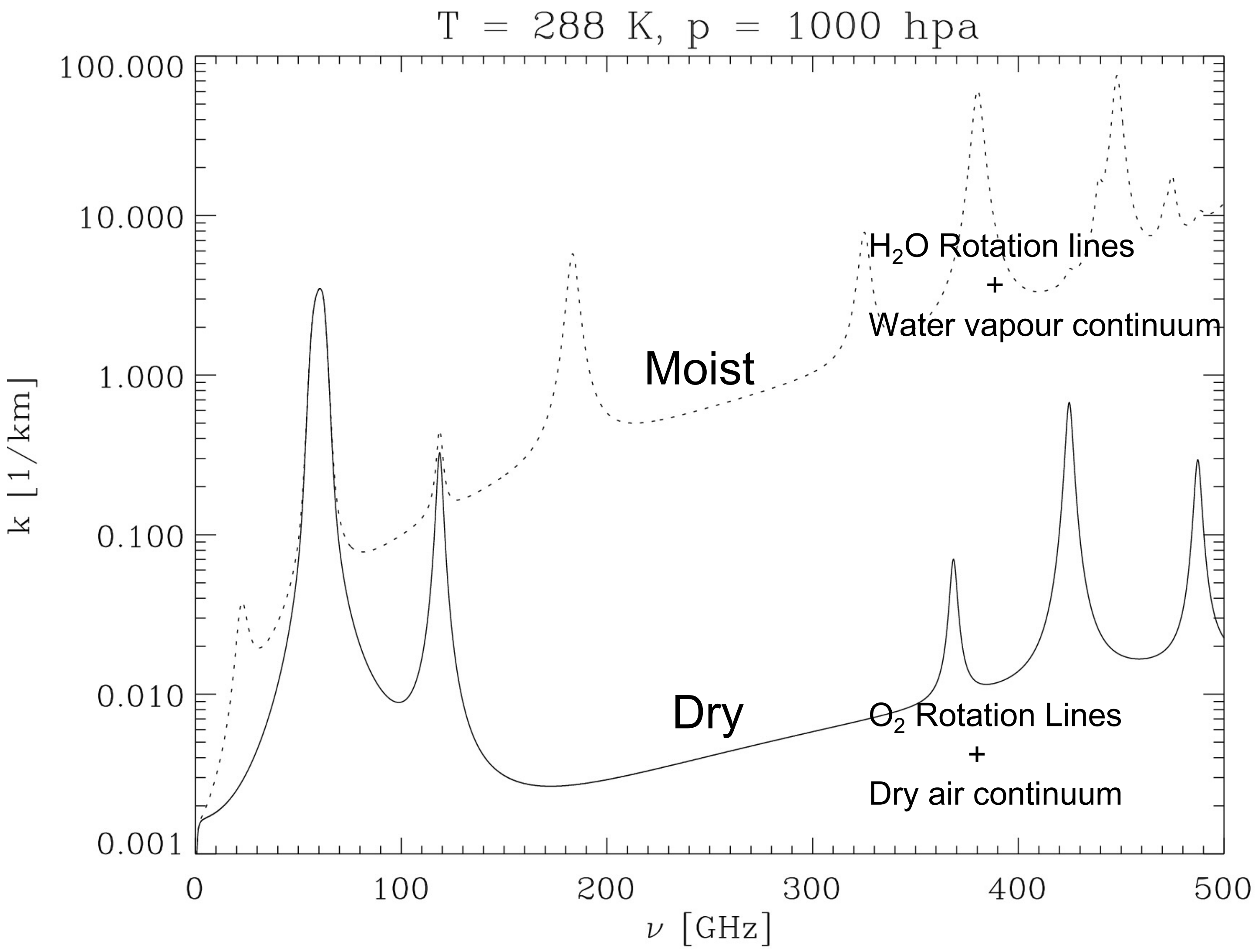
Gas spectroscopy

Single-particle scattering models

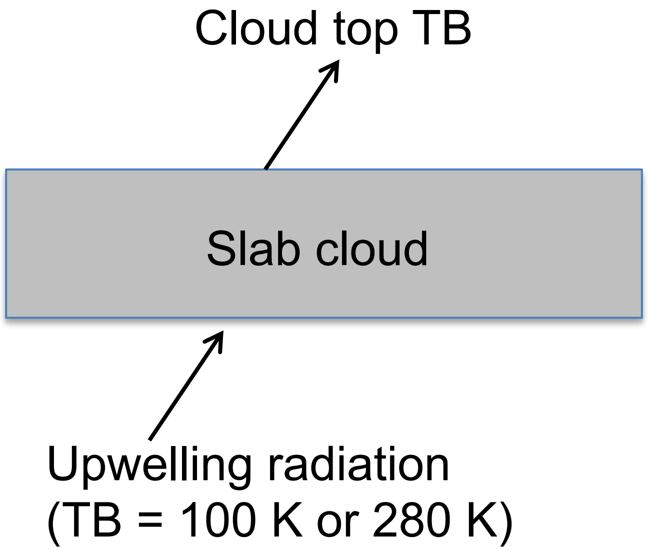
Atmospheric profiles (temperature, pressure, water vapour, hydrometeors)

Gas absorption: the microwave spectrum

Absorption coefficient β_a [1/km]



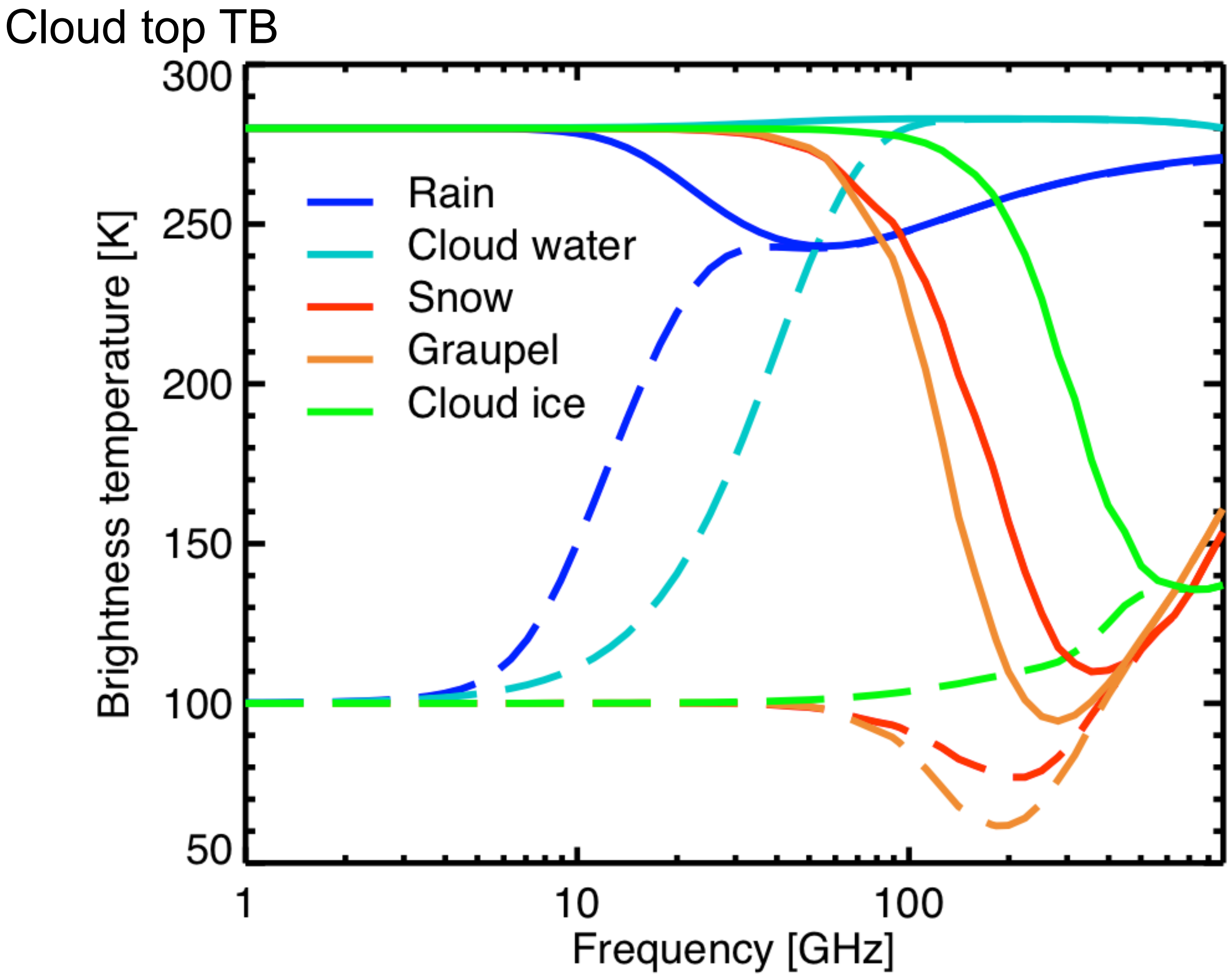
Cloud and precipitation optical properties: the microwave spectrum



Cloud top TB

Slab cloud

Upwelling radiation
(TB = 100 K or 280 K)

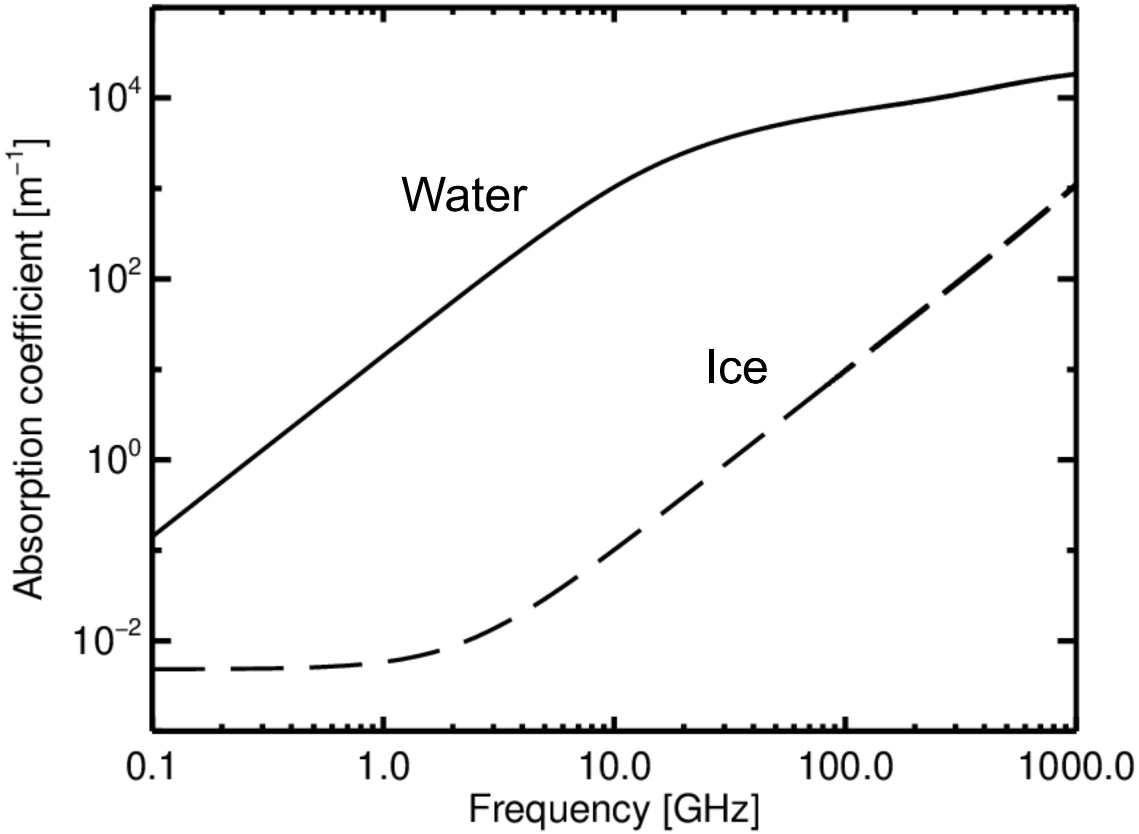


Slab cloud at 283K above a 280K surface (solid)

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)

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

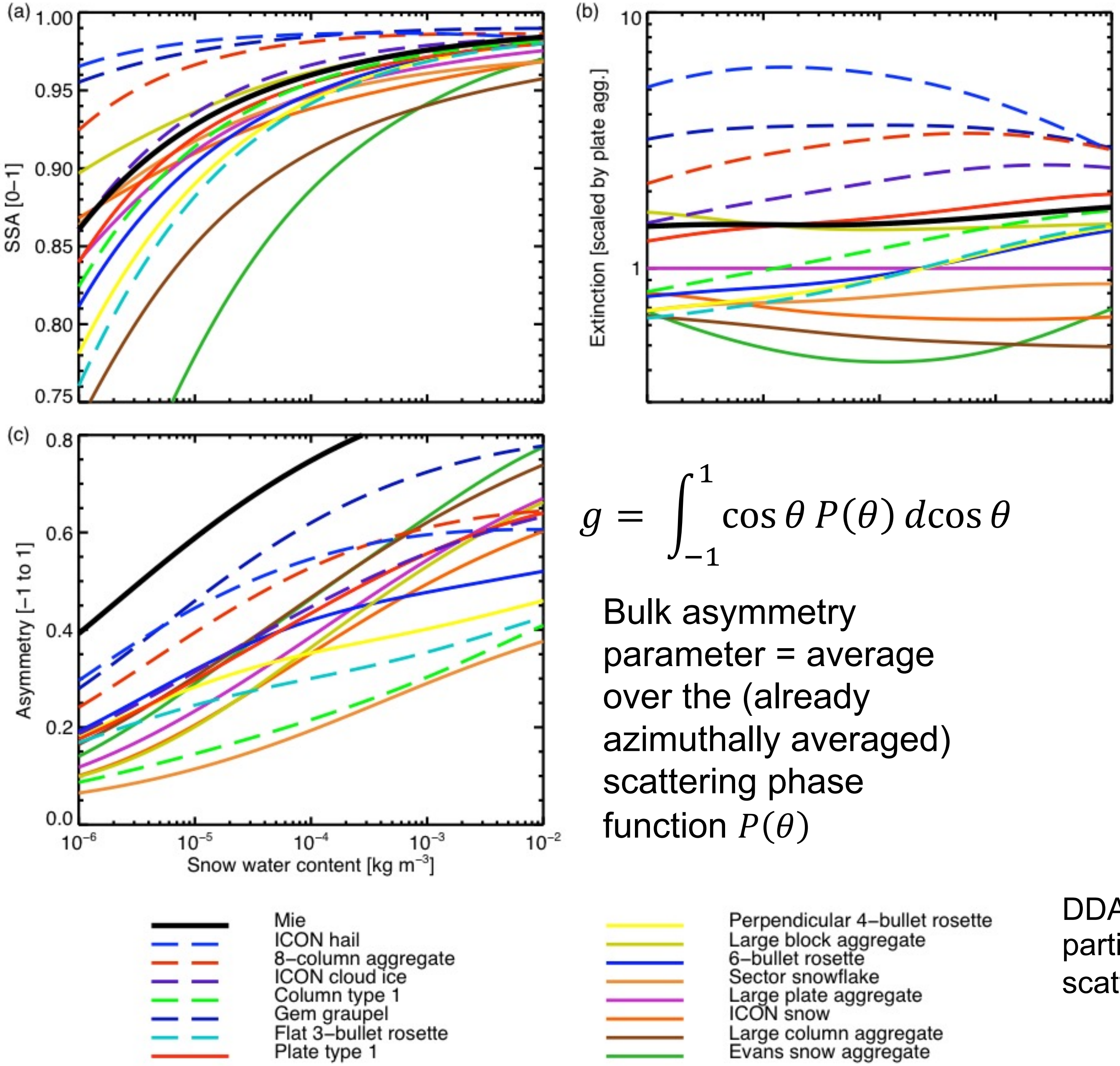
Particle type	Size range, r	Size parameter, x
Cloud droplets	5 – 50 μm	0.003 – 0.03
Drizzle	~100 μm	0.06
Rain drop	0.1 – 3 mm	0.06 – 1.8
Ice crystals	10 – 100 μm	0.006 – 0.06
Snow	1 – 10 mm	0.6 – 6
Hailstone	~10 mm	6

- 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

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

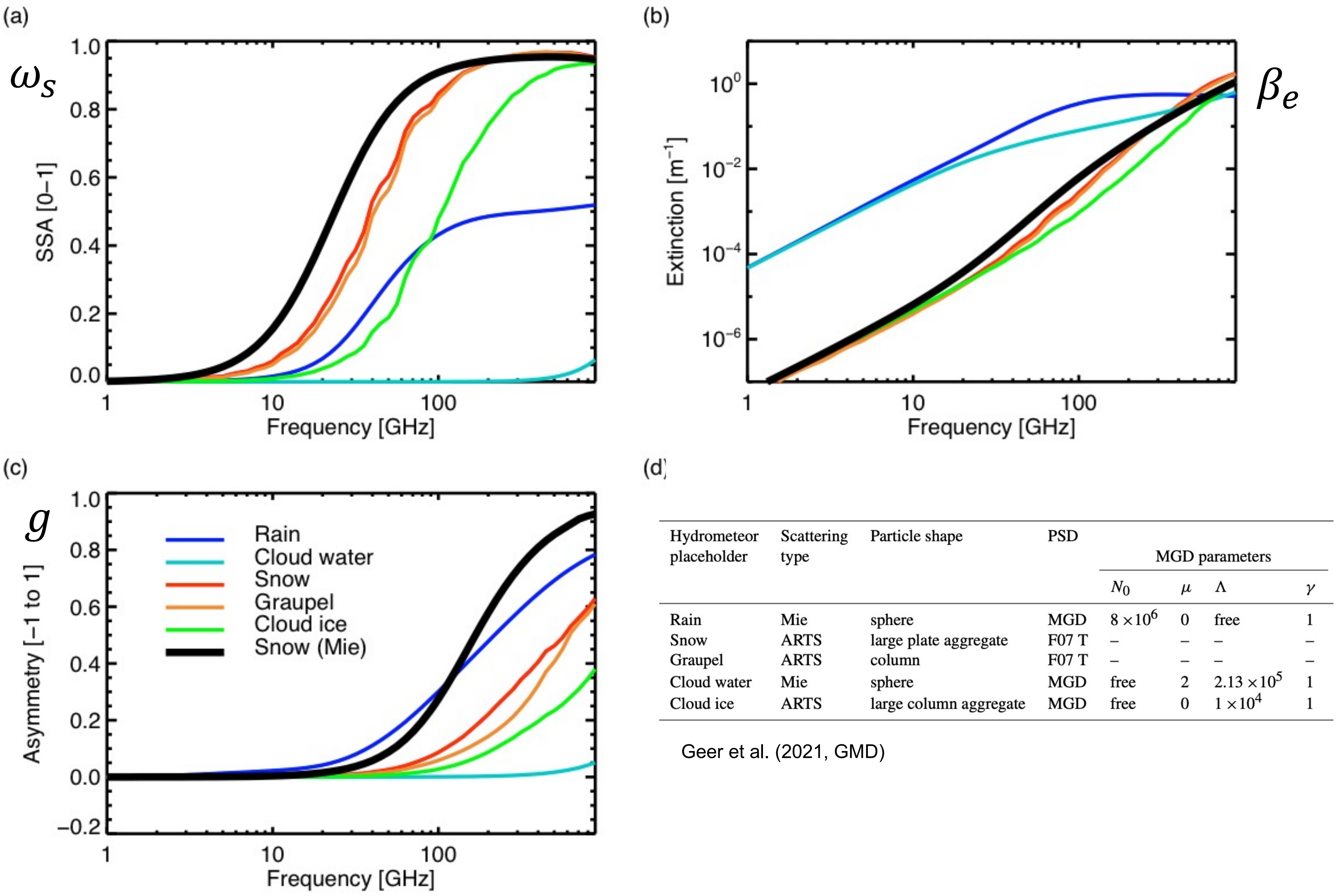
Bulk asymmetry parameter = average over the (already azimuthally averaged) scattering phase function $P(\theta)$

DDA non-spherical particles from the ARTS scattering database

Geer et al. (2021, GMD)

Optical properties of hydrometeors in RTTOV-SCATT: across frequencies

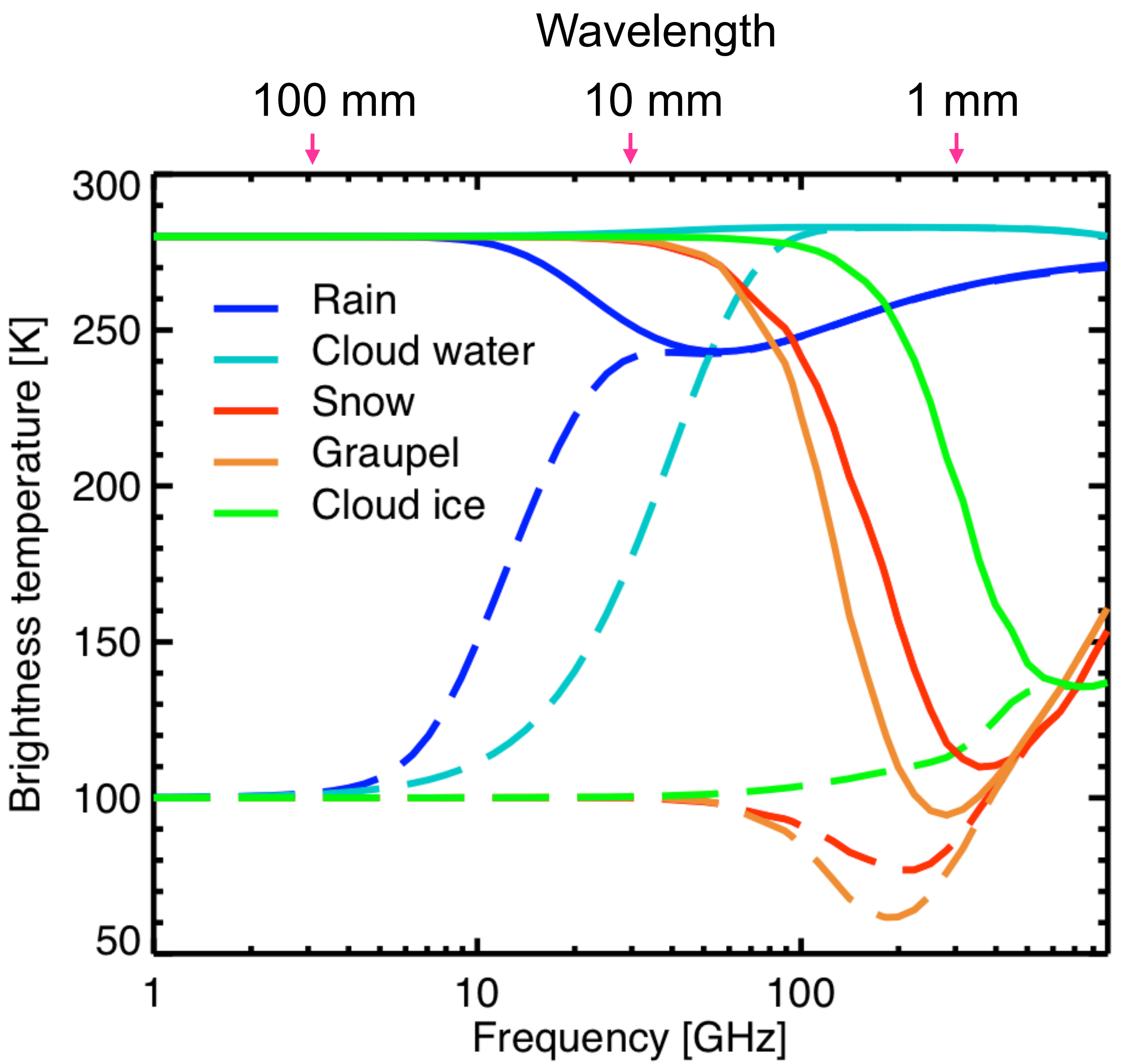
Lookup tables for snow hydrometeors of water content 10^-4 kg/m^3 as a function of frequency



Hydrometeor placeholder	Scattering type	Particle shape	PSD	MGD parameters			
				N_0	μ	Λ	γ
Rain	Mie	sphere	MGD	8×10^6	0	free	1
Snow	ARTS	large plate aggregate	F07 T	–	–	–	–
Graupel	ARTS	column	F07 T	–	–	–	–
Cloud water	Mie	sphere	MGD	free	2	2.13×10^5	1
Cloud ice	ARTS	large column aggregate	MGD	free	0	1×10^4	1

Geer et al. (2021, GMD)

Cloud and precipitation optical properties: the microwave spectrum



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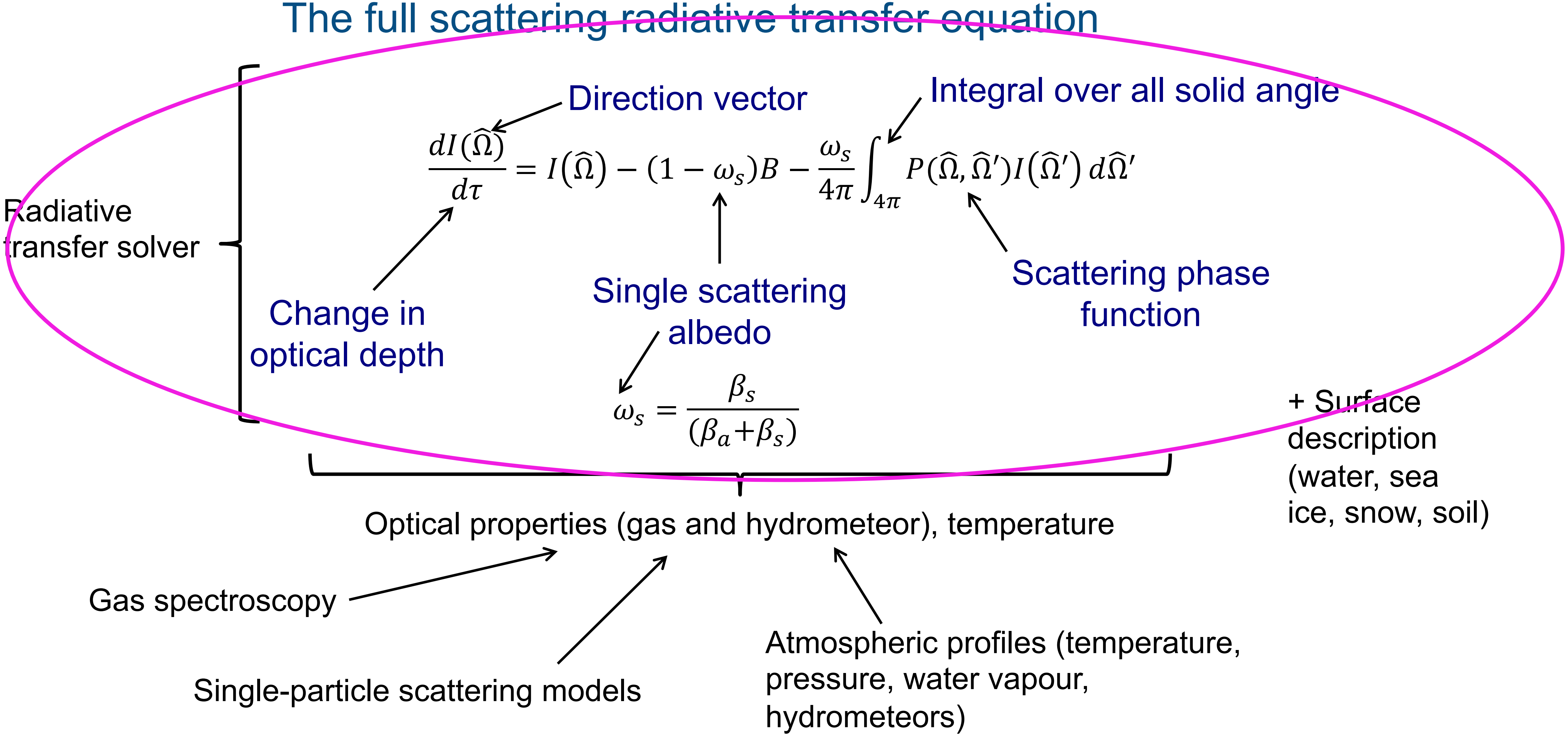
Geer et al. (2021, GMD)

The full scattering radiative transfer equation



Radiative transfer solver

Direction vector

Integral over all solid angle

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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)

Fast approximate solver: RTTOV-SCATT

- For each hydrometeor type (e.g. cloud, rain etc.), compute single-species bulk optical properties as a function of mixing ratio
- Sum up single-species optical properties along with gas optical properties
- Assume a simplified scattering phase-function
- Assume no azimuth dependence of the radiance field
- Assume radiance is a simple function of zenith angle (theta): $I = I_0 + I_1 \cos\theta$ (Eddington approcimation, similar to the two-stream approach)
- delta-scaling (treat sharp peaks in the scattering phase function as no scattering at all)
- Set up coupled equations describing radiance all levels simultaneously; solve using matrix algebra for the approximate radiance field I at each level
- Integrate the radiative transfer equation along the line of sight, using the delta-Eddington solution to provide the 'source terms'

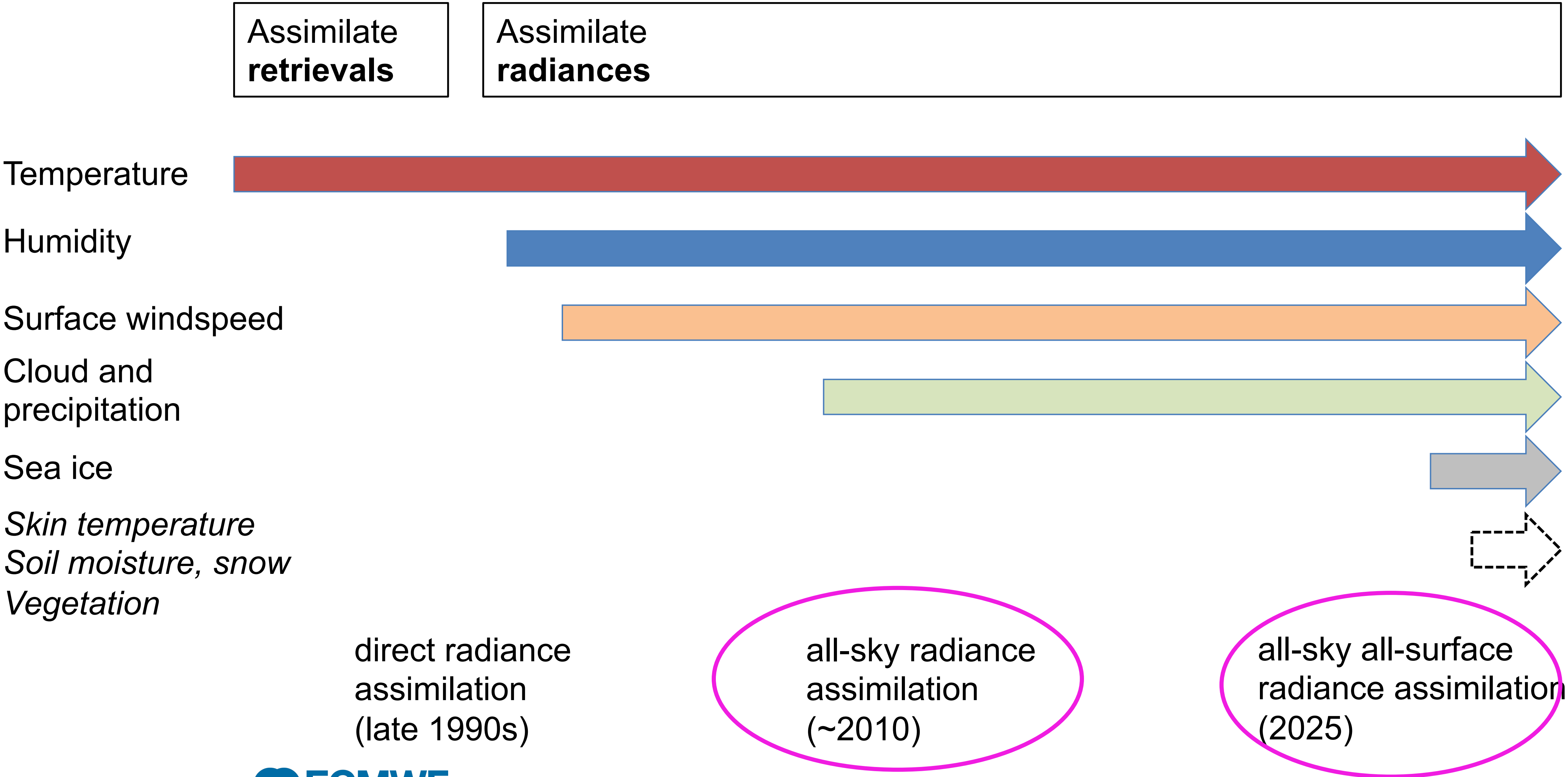
$$\frac{dI(\hat{\Omega})}{d\tau} = I\left(\hat{\Omega}\right) - (1 - \omega_s)B - \frac{\omega_s}{4\pi}\int_{4\pi} P(\hat{\Omega}, \hat{\Omega}')I\left(\hat{\Omega}'\right) d\hat{\Omega}'$$

Applications

(depending on time available)

ECMWF

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)

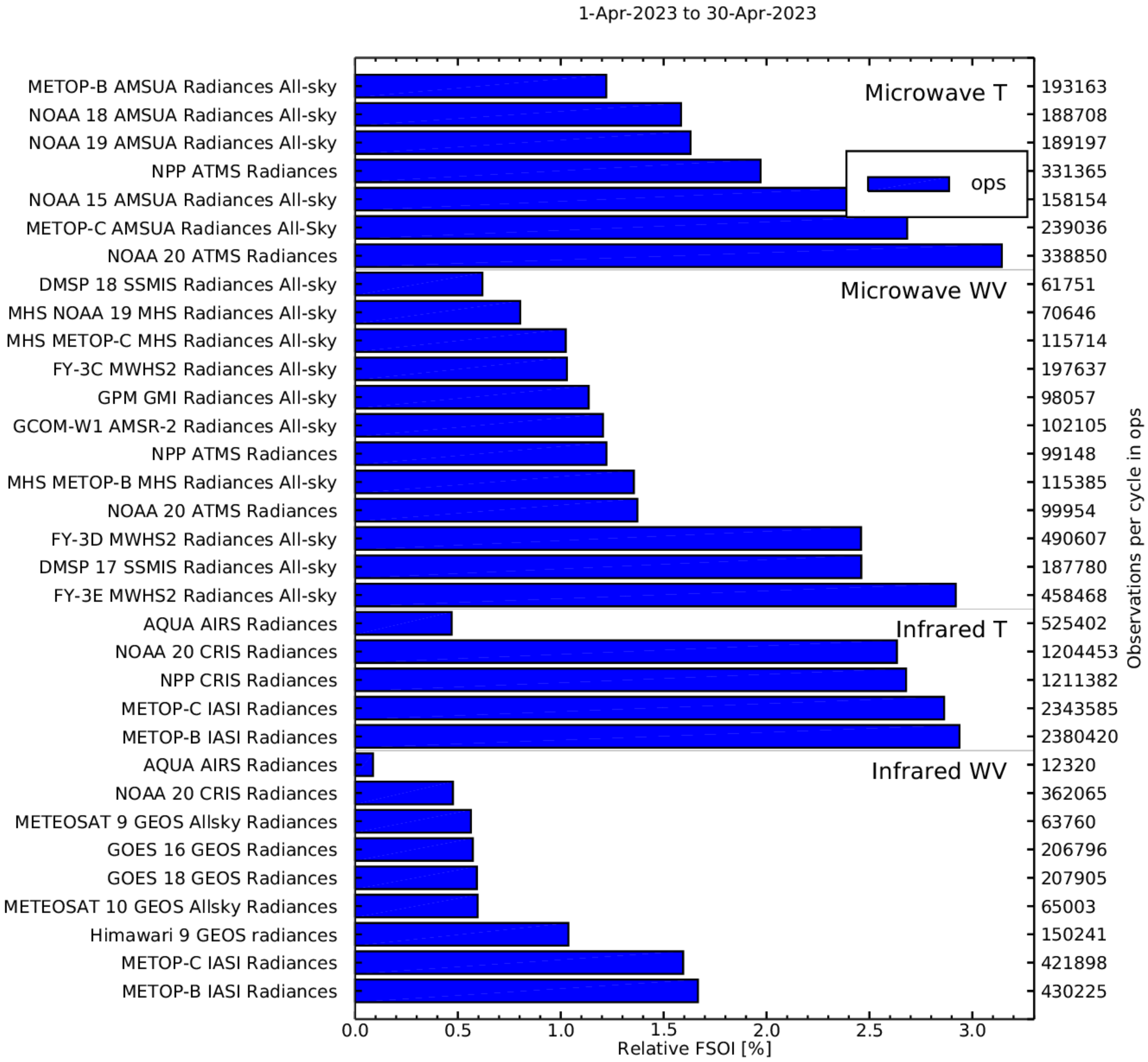
all-sky all-surface
radiance assimilation
(2025)

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 temperature sounding channels (e.g. AMSU-A channel 5)
  - 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)

Impact (FSOI) of satellite radiances at ECMWF on short-range forecast, by sensor (100% = all obs)



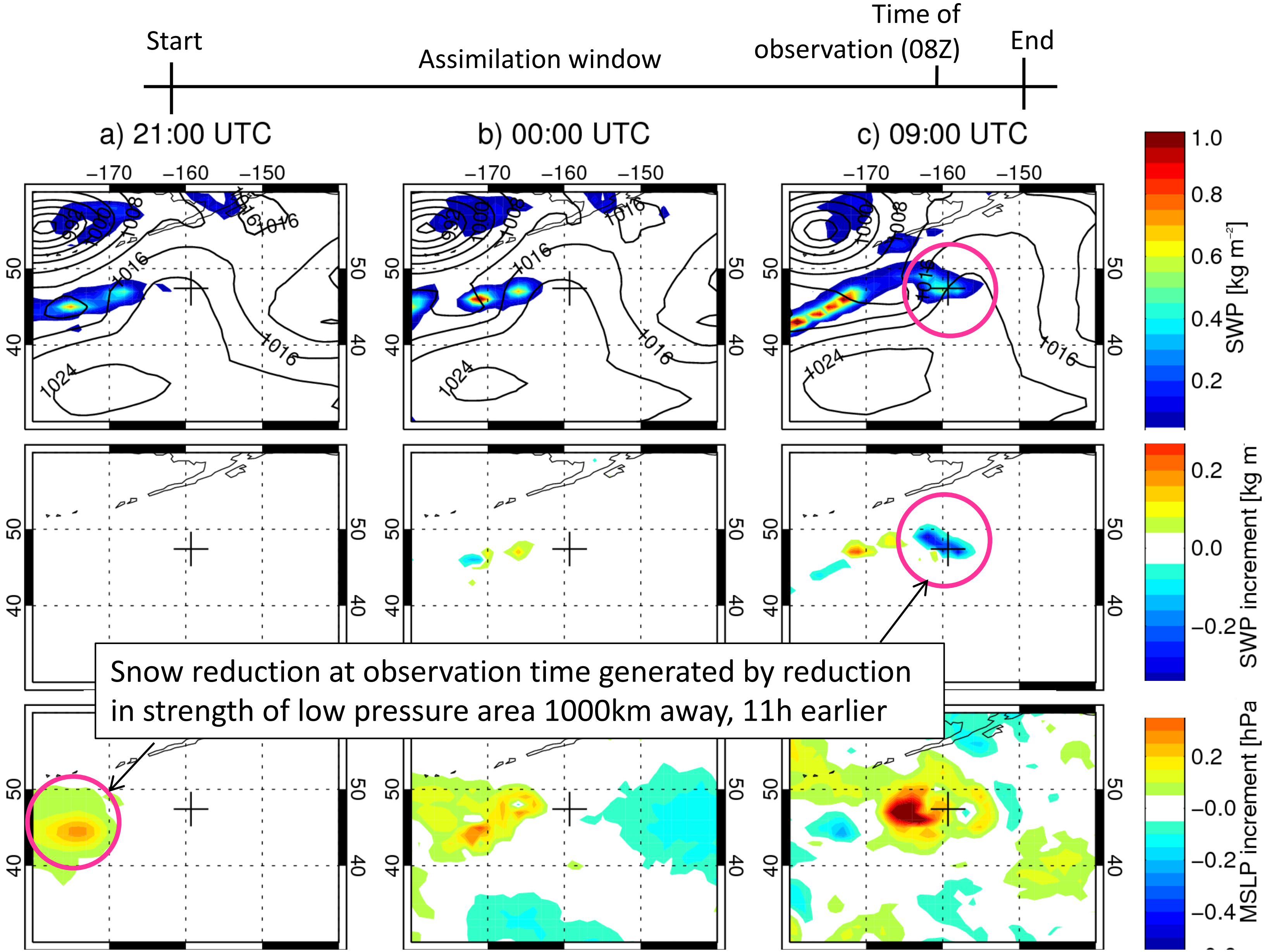
All-sky ‘tracer’ effect

Single 190 GHz observation assimilation test case

MSLP and snow column (FG)

Snow column increment

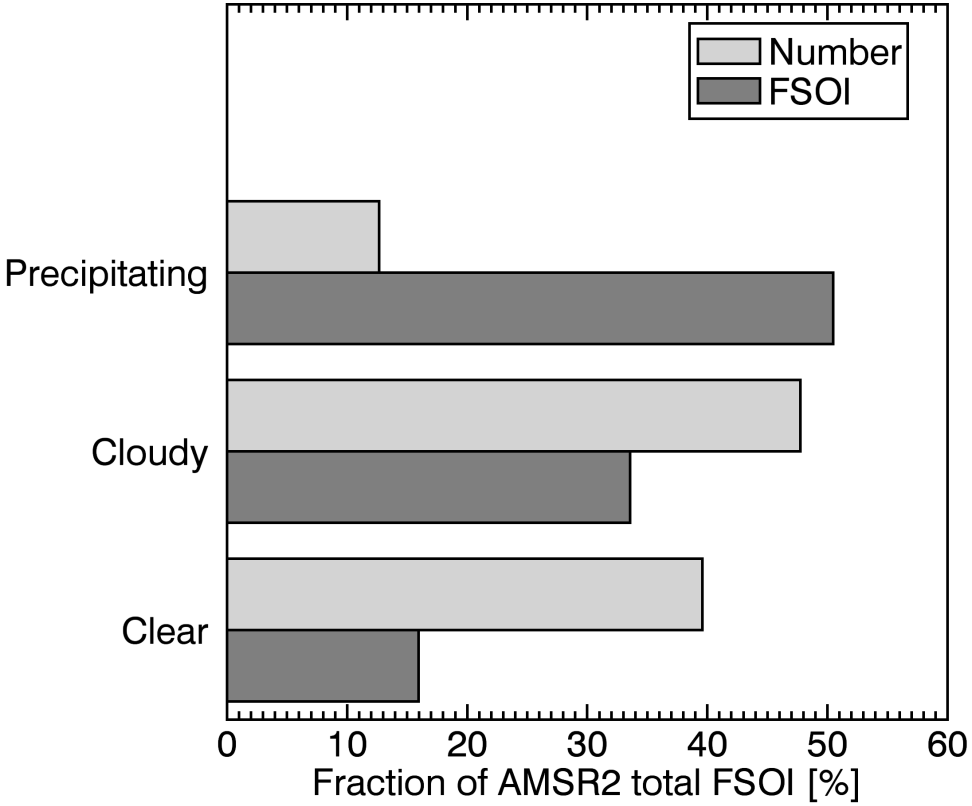
MSLP increment



Snow reduction at observation time generated by reduction in strength of low pressure area 1000km away, 11h earlier

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

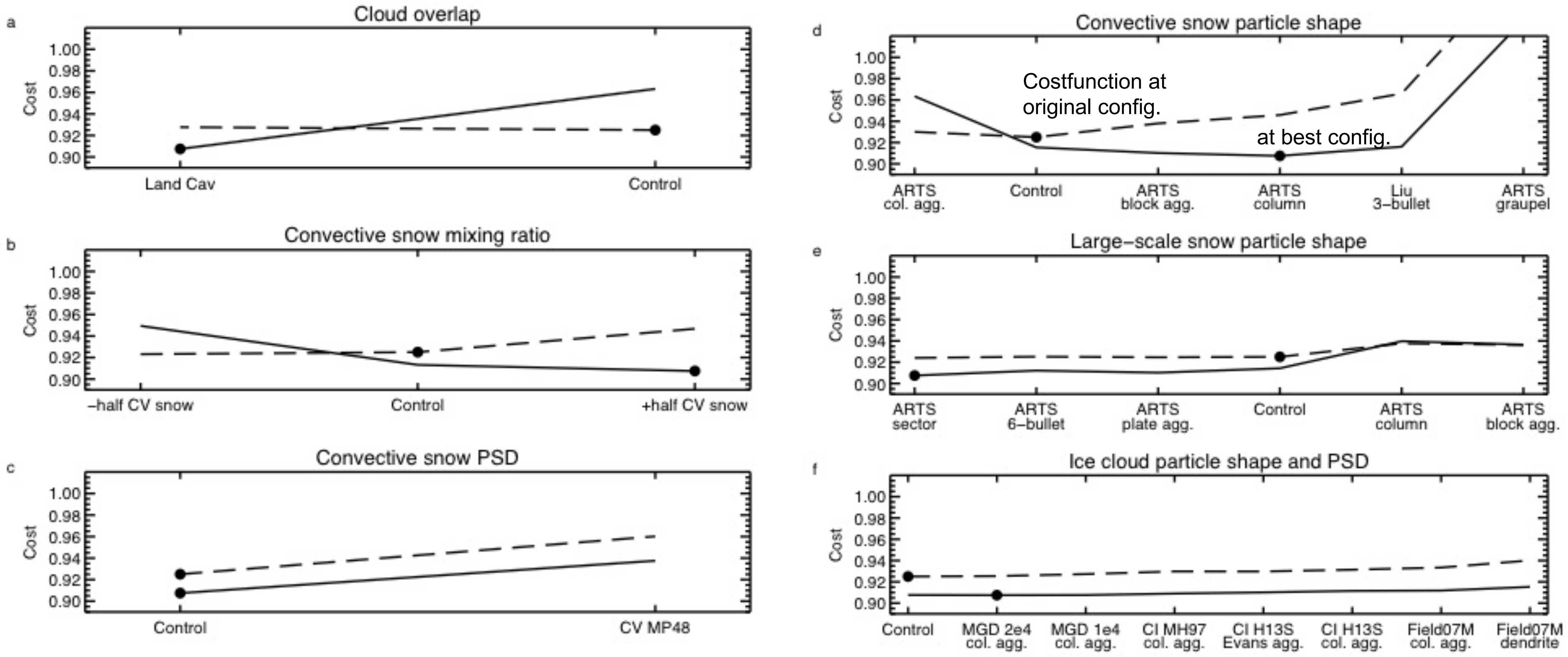
Microwave imagers give their largest forecast impact from a small fraction of precipitating scenes.



AMSR2, July-August 2016

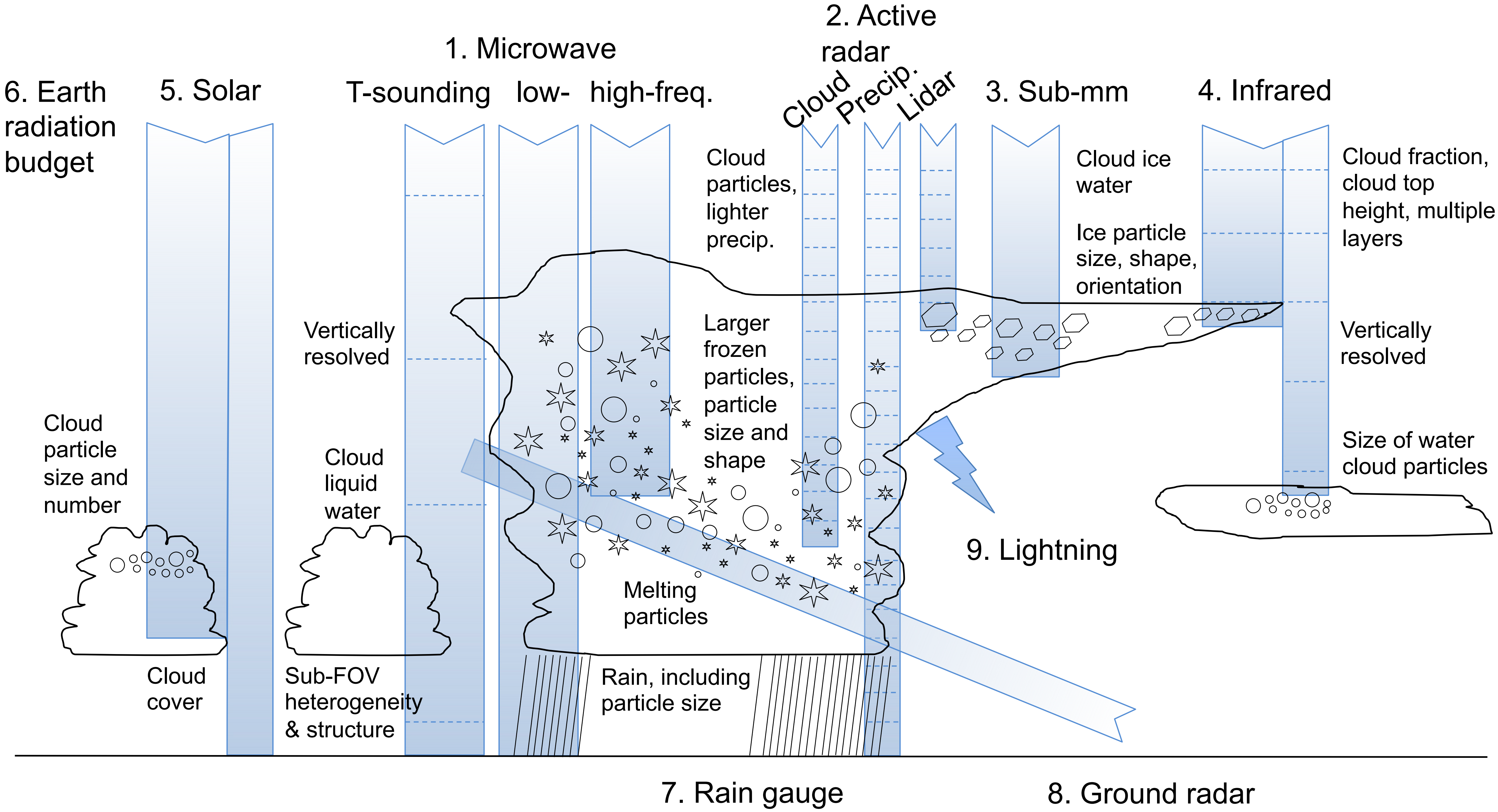
Parameter estimation for 6 macro- and microphysical variables

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



Costfunction at original config.

at best config.



6. Earth radiation budget

5. Solar

1. Microwave

T-sounding

low-

high-freq.

2. Active radar

Cloud

Precip.

Lidar

3. Sub-mm

4. Infrared

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

Size of water cloud particles

Cloud particle size and number

Cloud liquid water

9. Lightning

Melting particles

Cloud cover

Sub-FOV heterogeneity & structure

Rain, including particle size

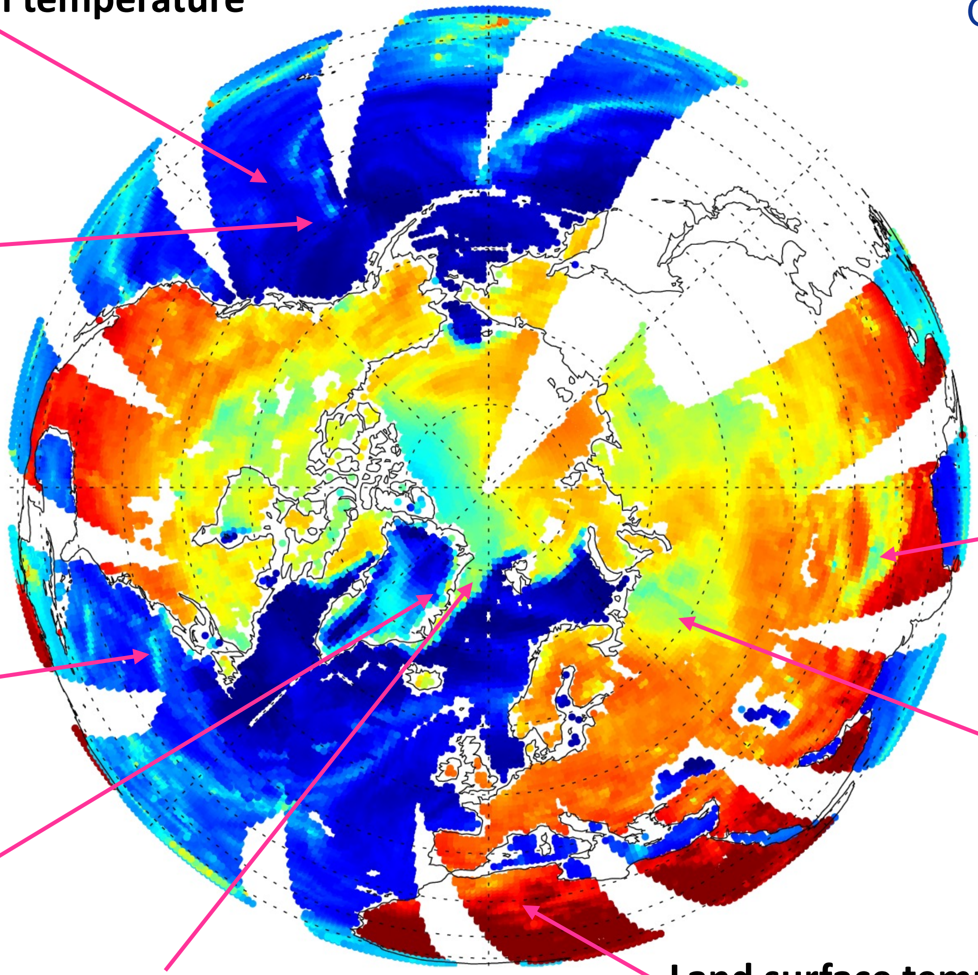
7. Rain gauge

8. Ground radar

All-sky all-surface assimilation

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

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



Ocean waves, wind, skin temperature

Atmospheric water vapour

Cloud and precipitation

Special snow and ice conditions

Sea-ice

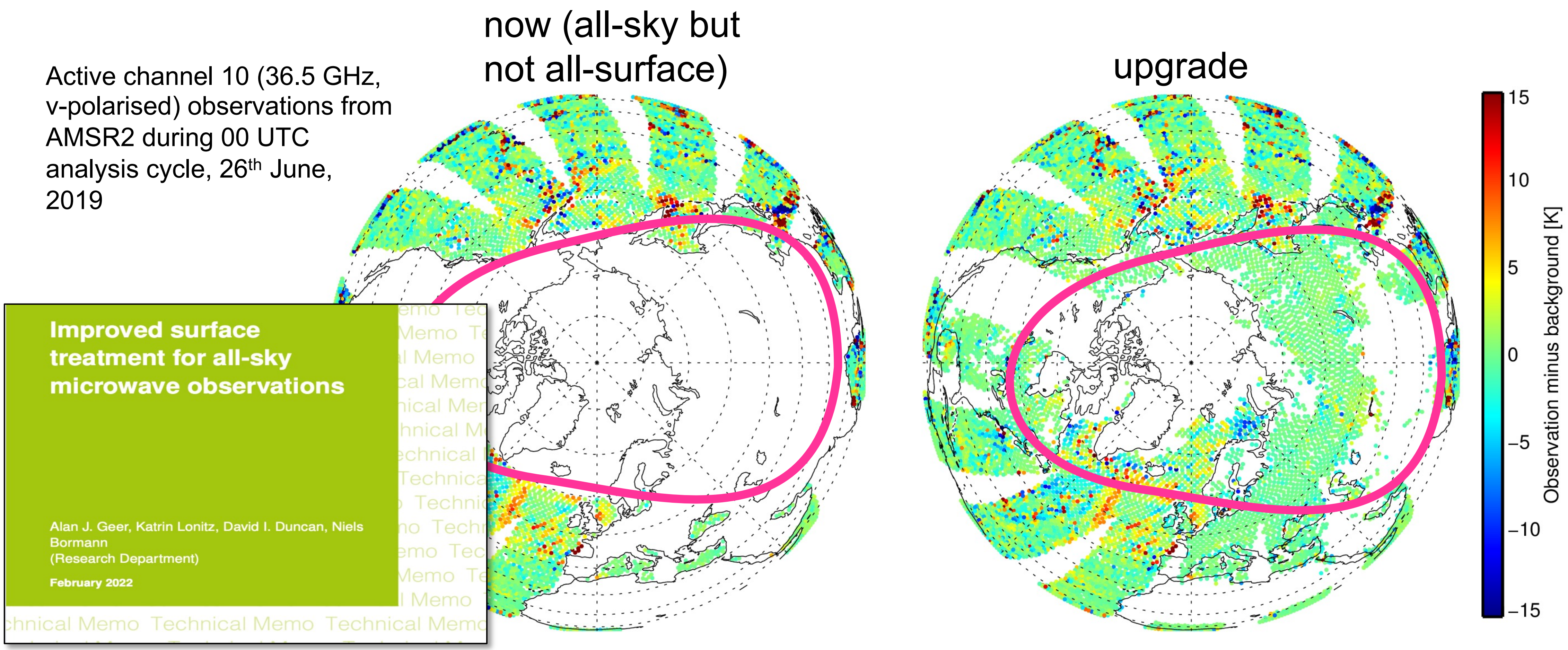
High altitude

Snow cover

Land surface temperature, biomass, soil/rock, soil moisture

Developments for surface-sensitive microwave channels in cycle 48r1 (June 2023)

Active channel 10 (36.5 GHz, v-polarised) observations from AMSR2 during 00 UTC analysis cycle, 26th June, 2019



Improved surface treatment for all-sky microwave observations

Alan J. Geer, Katrin Lonitz, David I. Duncan, Niels Bormann
(Research Department)

February 2022

Technical Memo

adding higher latitudes, land surfaces, mixed scenes (land – water)

(but excluding sea-ice, snow, high altitudes, desert soils)

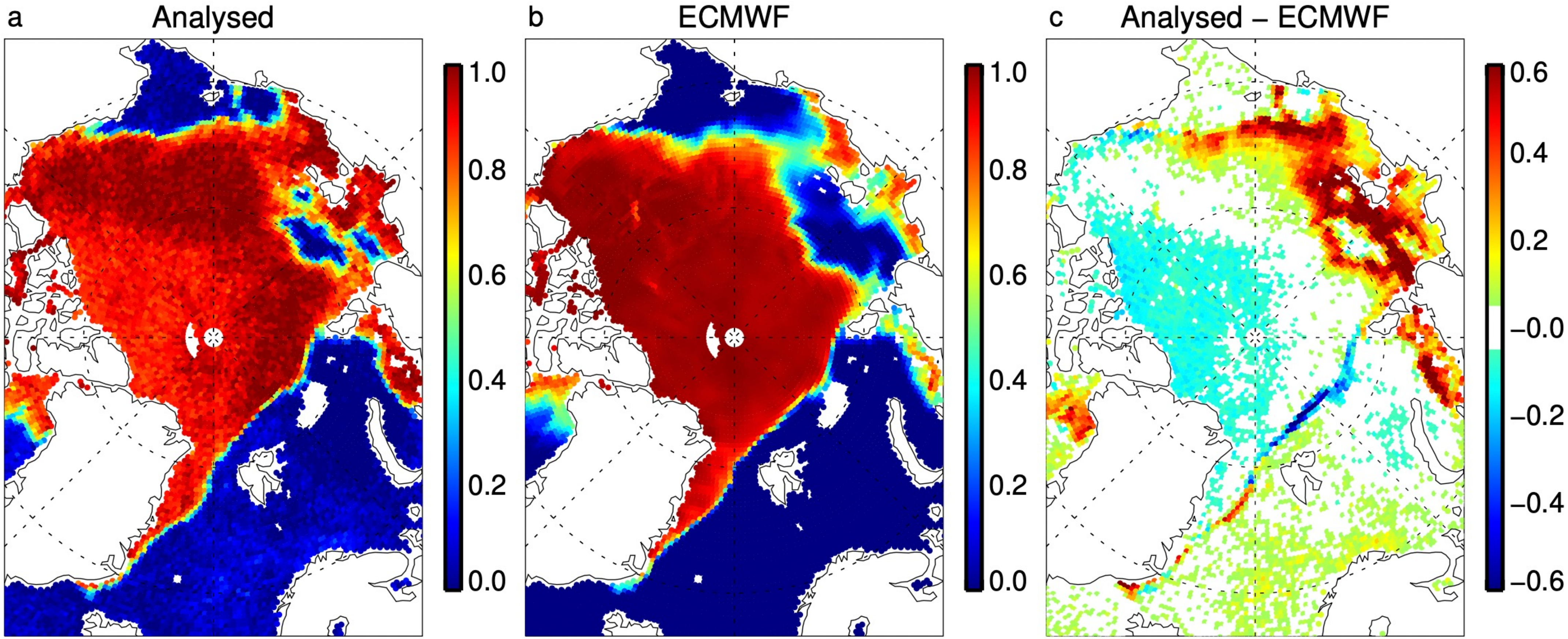
For cycle 49r1 (June 2024?)– assimilation of microwave imagers over sea ice

- Offline hybrid machine learning – data assimilation technique to create a surface emissivity model for sea ice, driven by a set of “empirical state” variables describing unknown aspects of the sea ice surface (grain size, ice age, wetness, etc.)

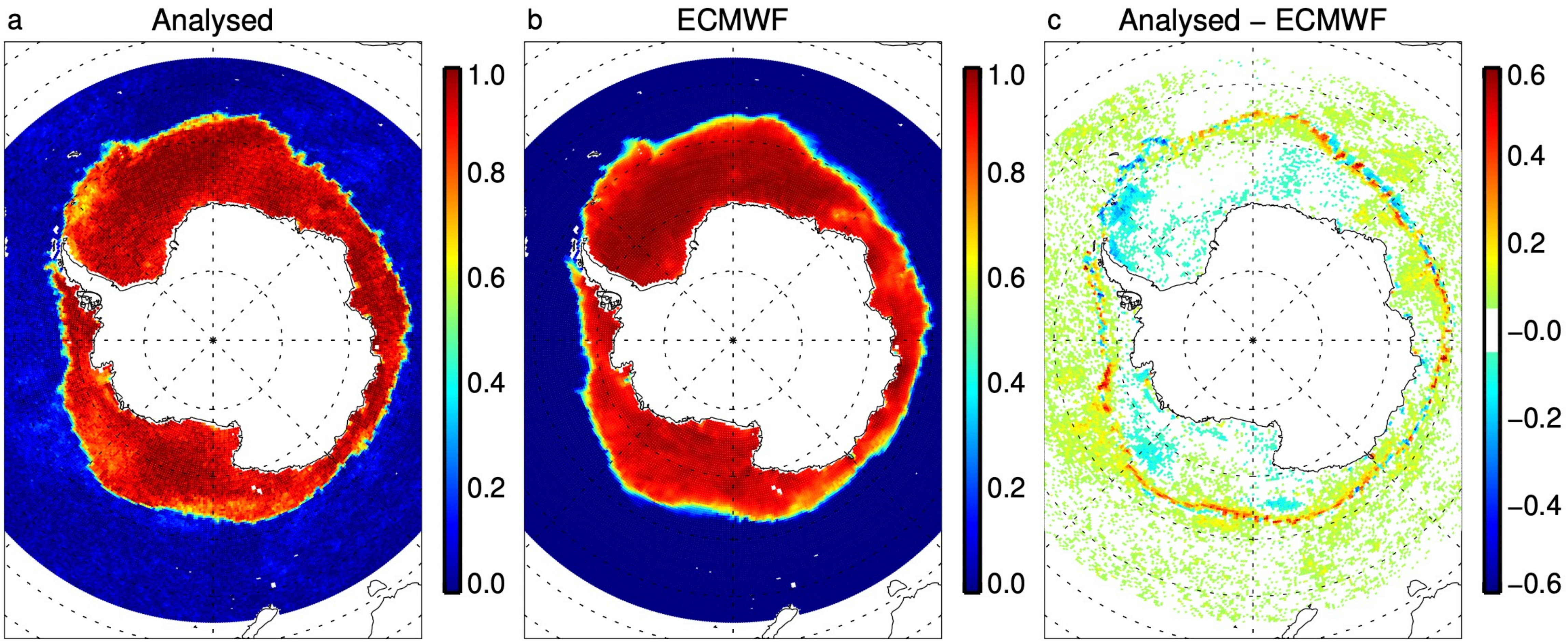
- In ECMWF 4D-Var – use the empirical surface emissivity model with an observation space “sink variable” to estimate the sea ice fraction and the empirical state.
  - Water vapour, cloud and precipitation signal above the sea ice is also used
  - Significant improvement in southern ocean forecasts (T, wind) from being able to assimilate observations over ocean but in close proximity to sea ice

Rapid freeze-up: sea ice fraction - 7th Nov 2020

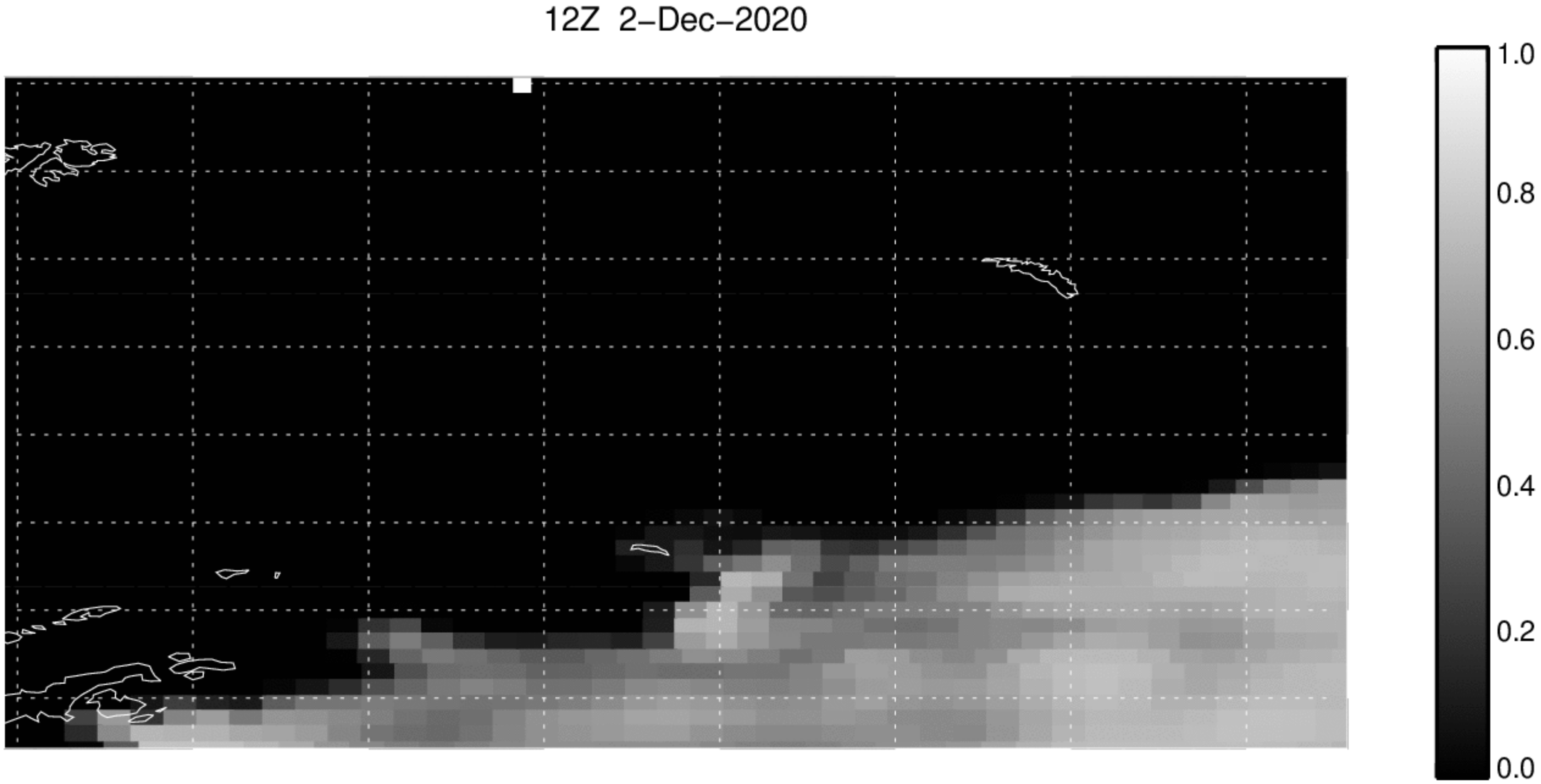
IFS sea-ice patterns do eventually catch up with AMSR2 retrievals after 2-3 days



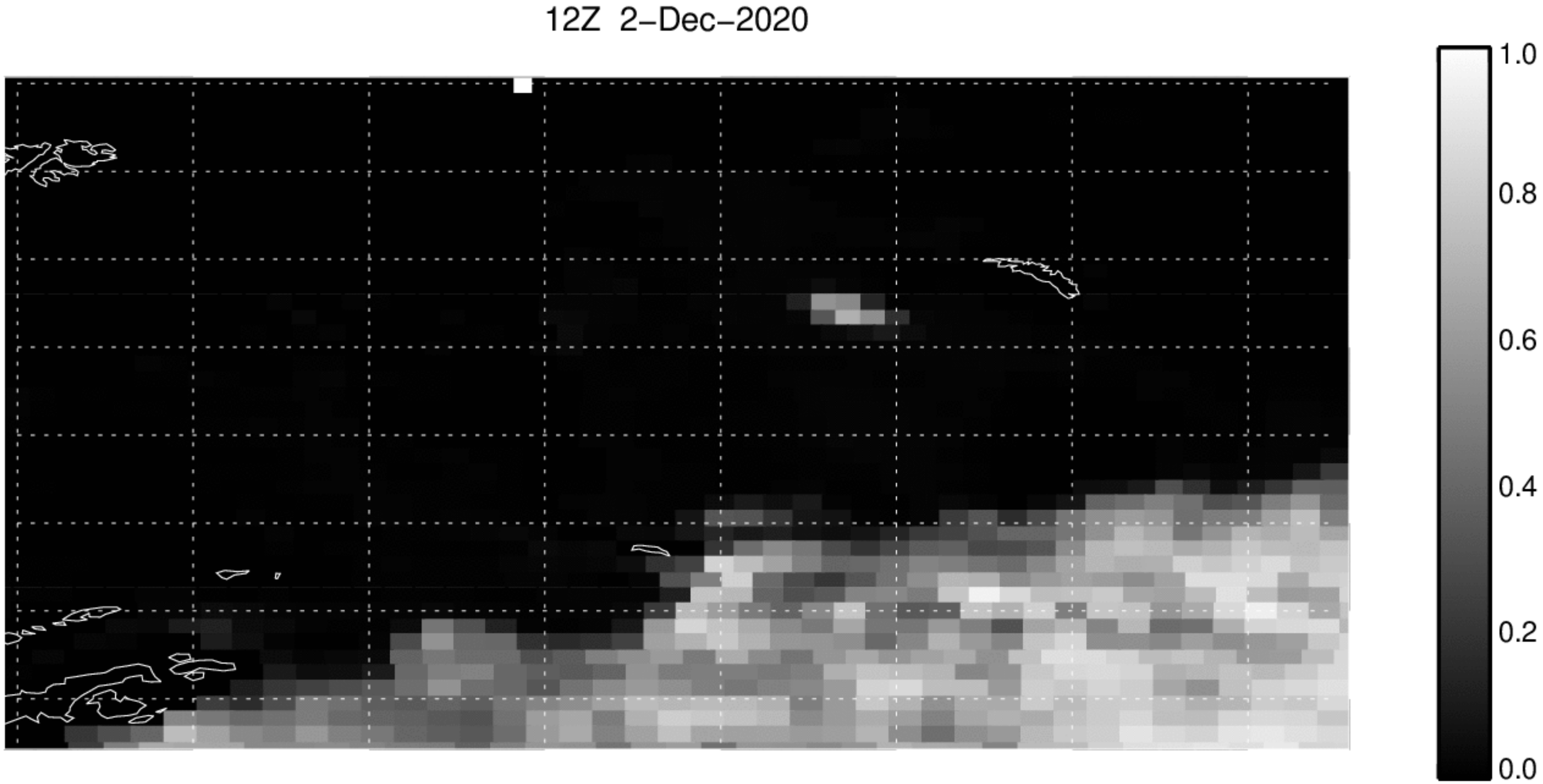
Antarctic example – sea ice fraction 7th August 2020



IFS sea ice concentration at AMSR2 locations



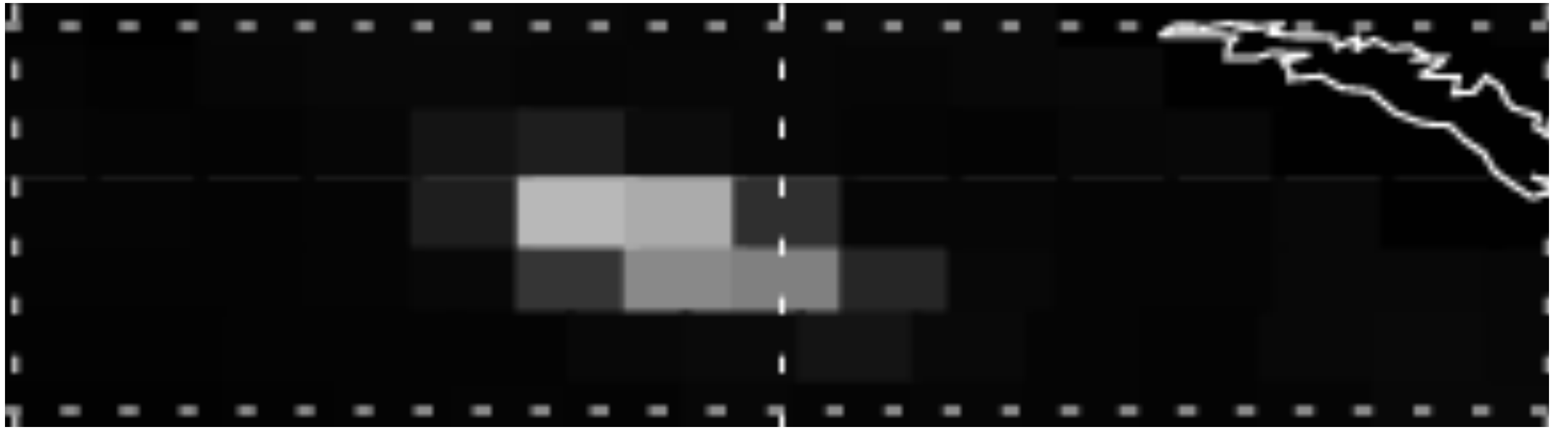
AMSR2 sink variable sea ice concentration



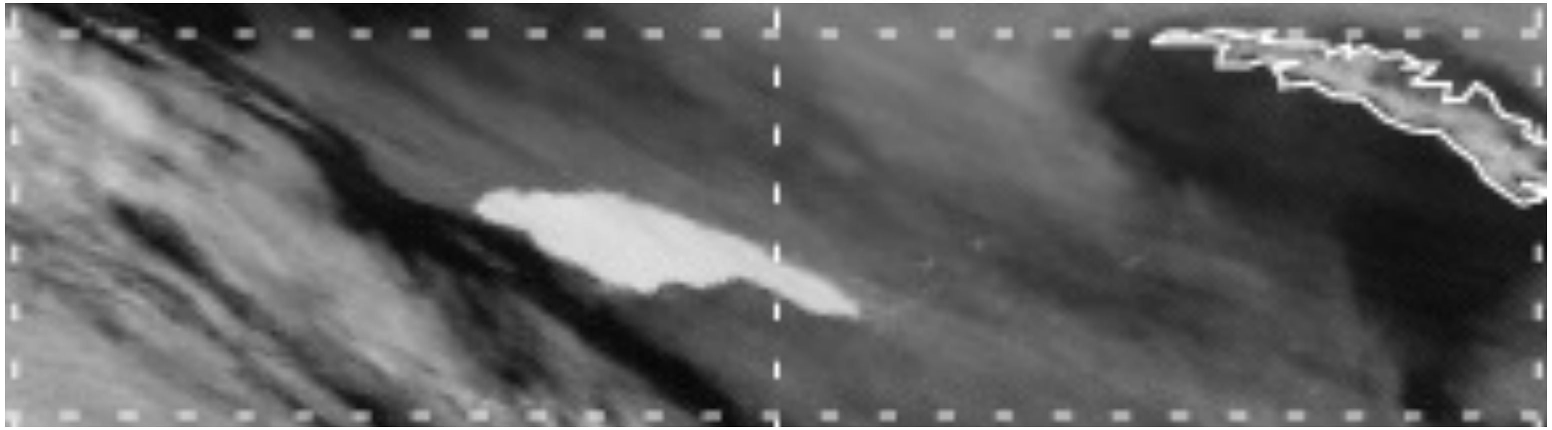
AMSR2 sea ice fraction vs OLCI image: A68A iceberg

AMSR2

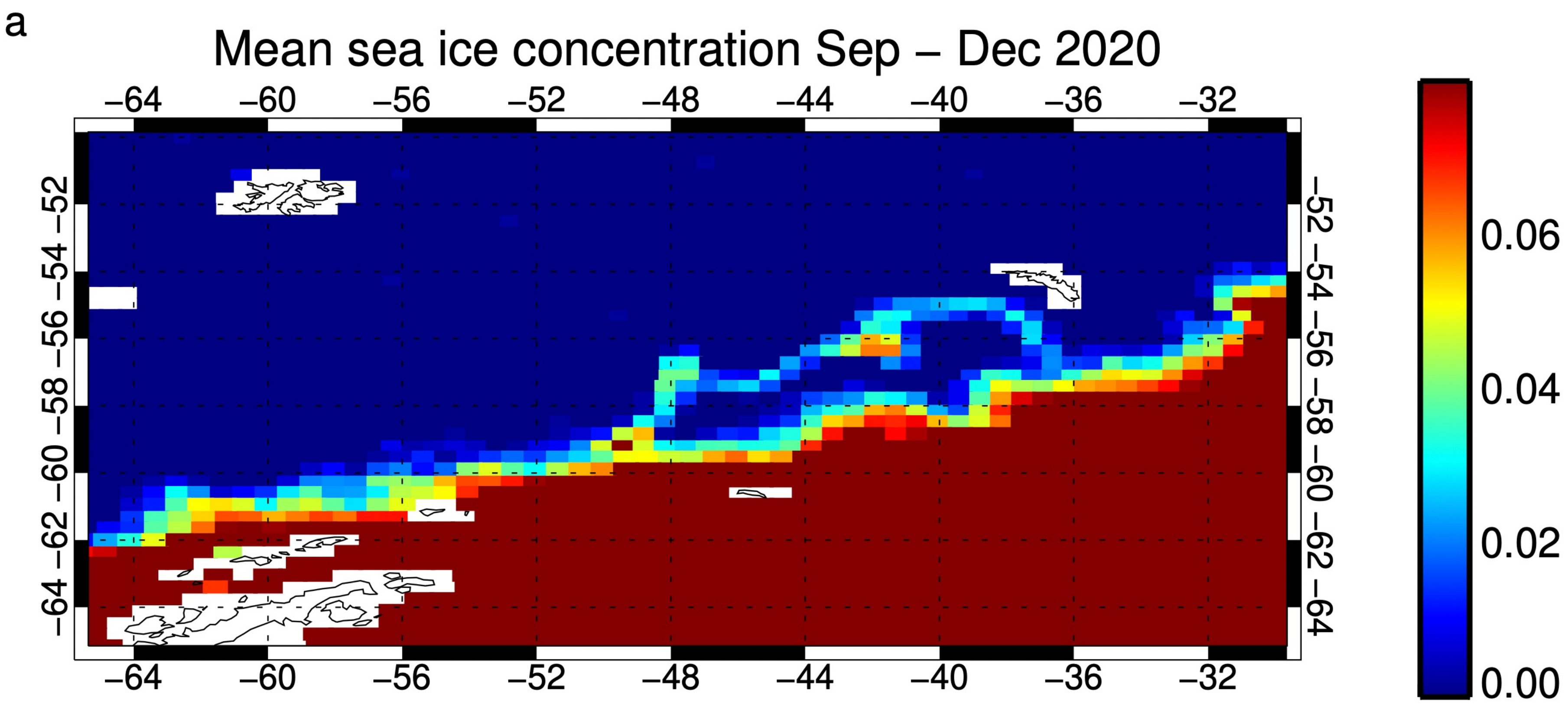
1 pixel ~
40x40 km



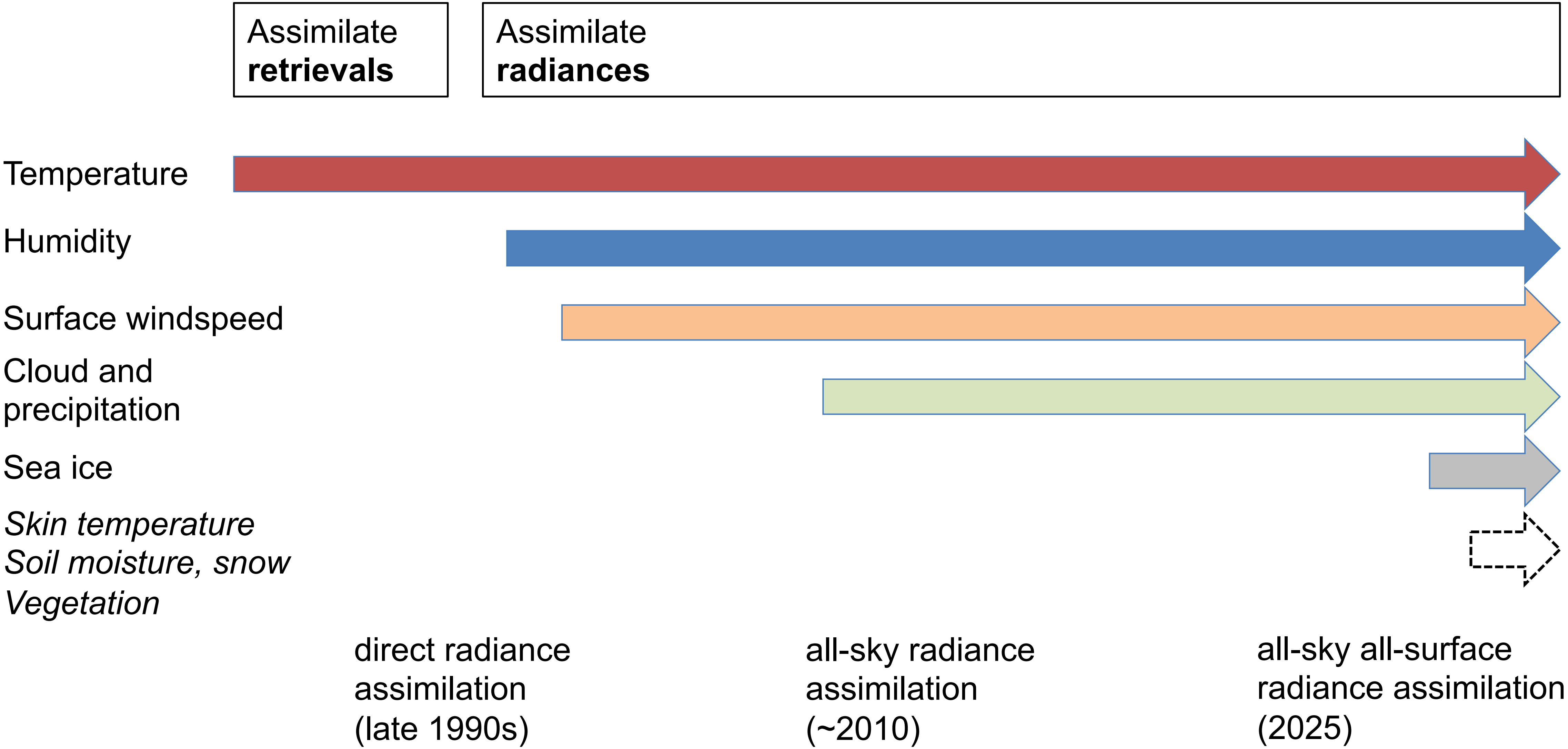
12Z 4th Dec 2020



OLCI channel
10 (681 nm)


a
Mean sea ice concentration Sep – Dec 2020
–64
–60
–56
–52
–48
–44
–40
–36
–32
–52
–54
–56
–58
–60
–62
–64
0.06
0.04
0.02
0.00

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)

Questions?