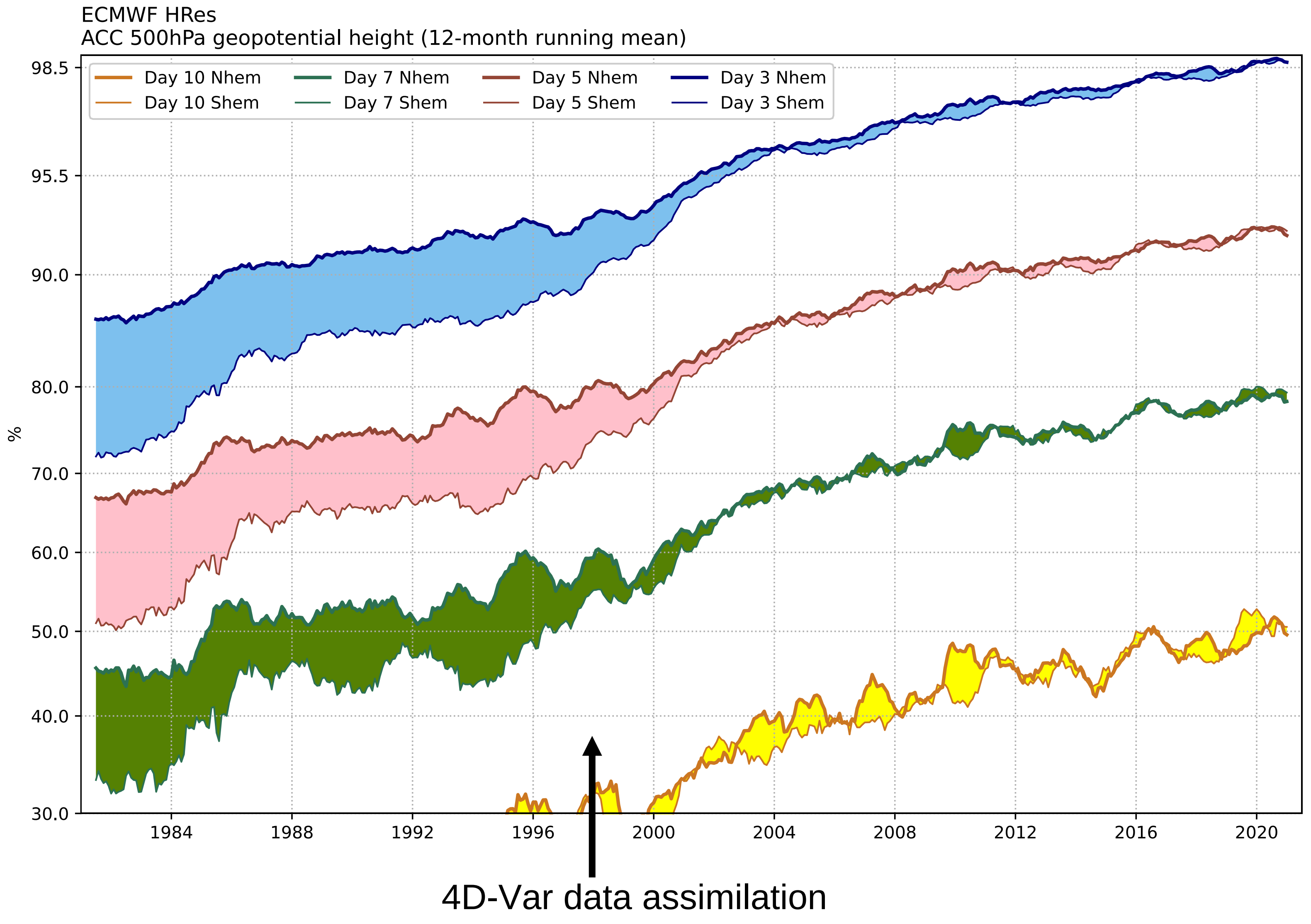
All-surface assimilation: improving the use of satellite data over land, snow and sea-ice surfaces

Alan Geer

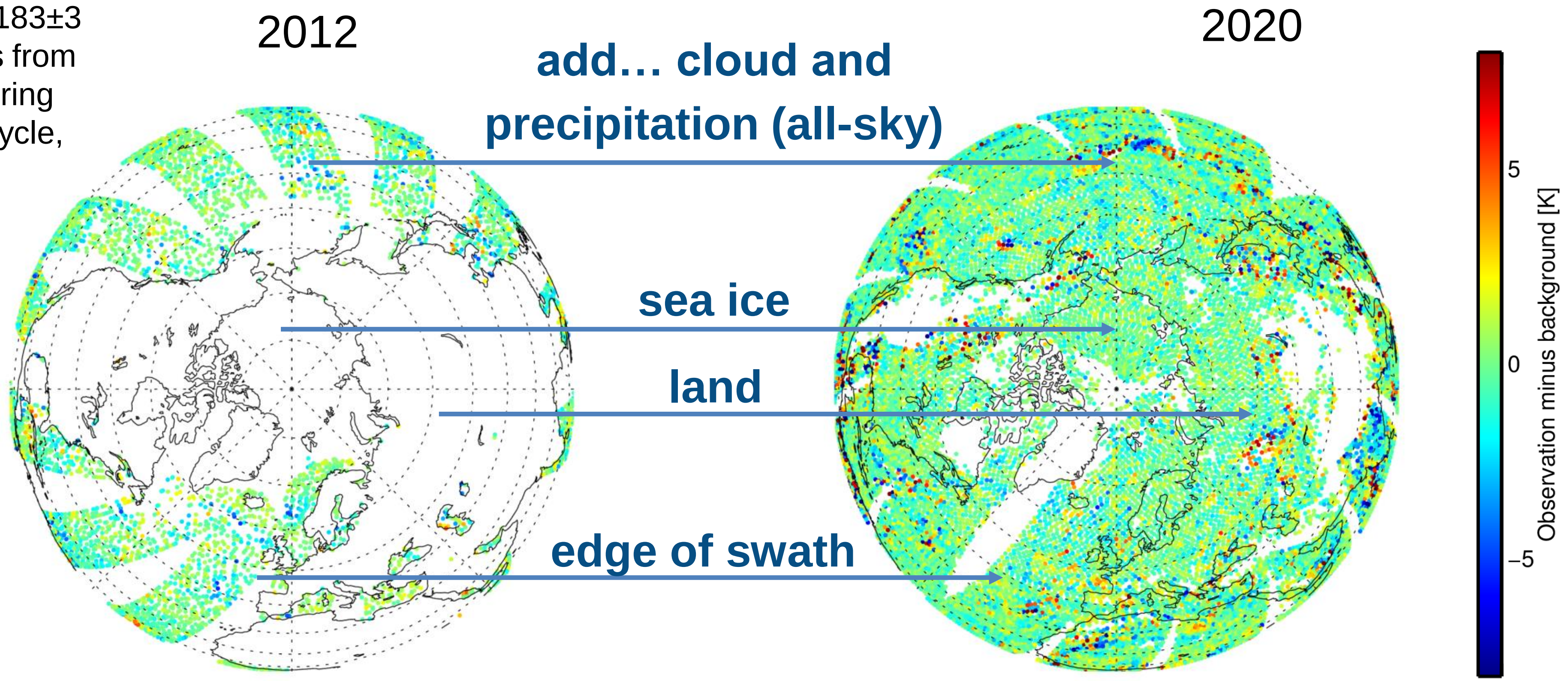
Thanks to: Katrin Lonitz, Niels Bormann, David Duncan

SH versus NH forecast skill gap: learning how to use satellite data (over ocean)



Learning how to use satellite data better: Assimilation of Microwave Humidity Sounder (MHS) radiances for operational weather forecasting at ECMWF

Active channel 4 (183±3 GHz) observations from NOAA-19 MHS during 00 UTC analysis cycle, 1st June

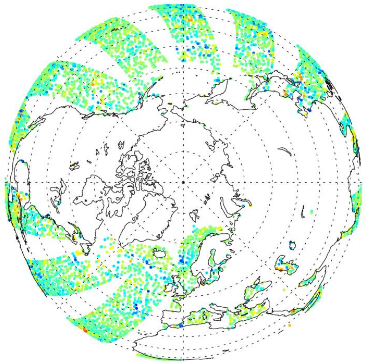


Learning how to use satellite data better: relative contribution to FSOI

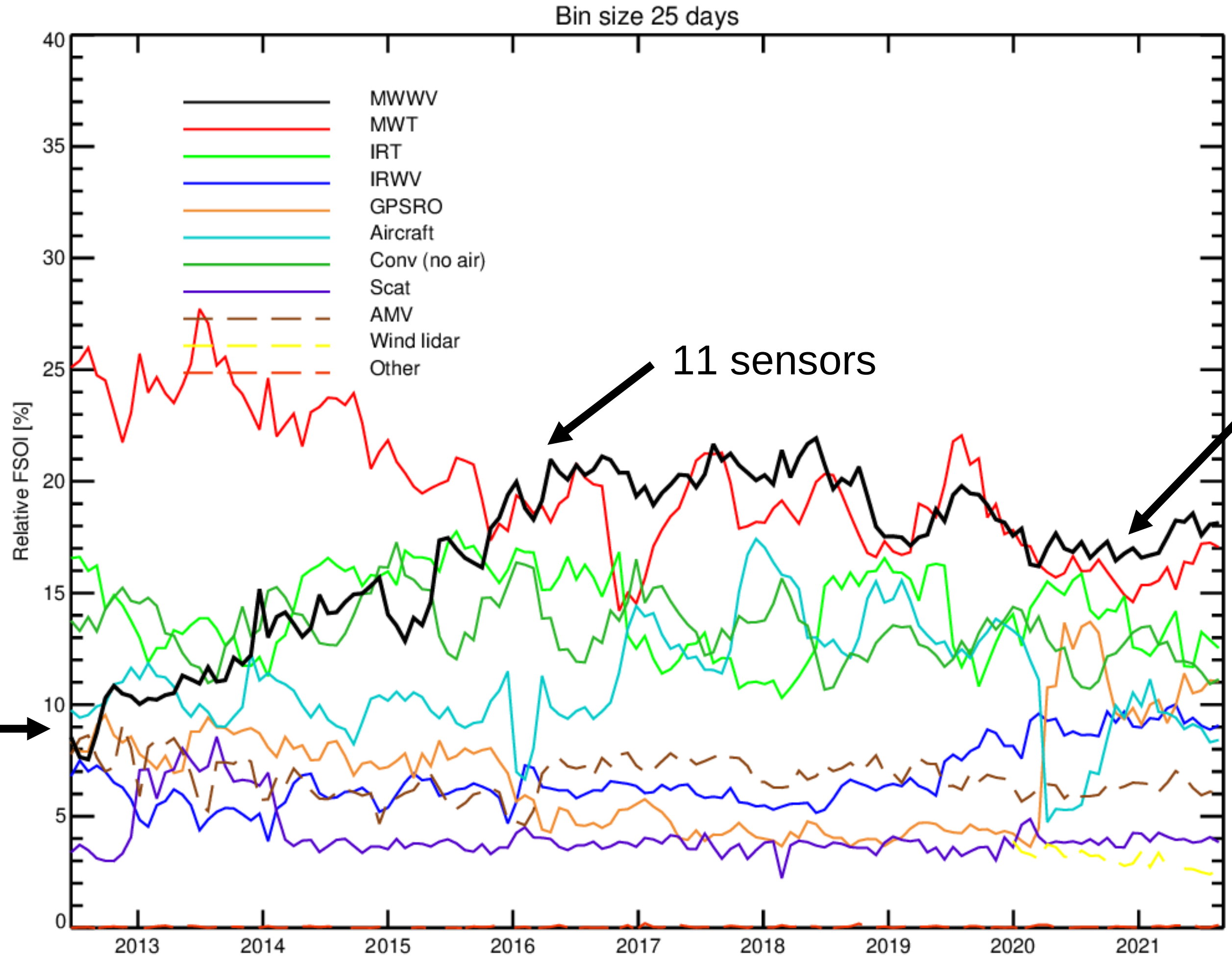
FSOI: see Niels Bormann's presentation

Microwave water vapour radiances (MWWV)

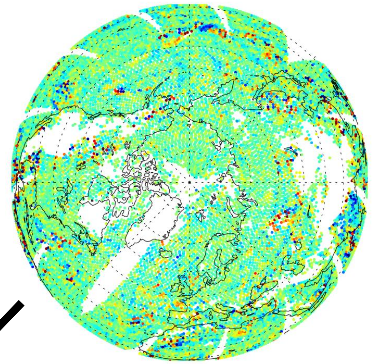
2012



7 sensors



2020

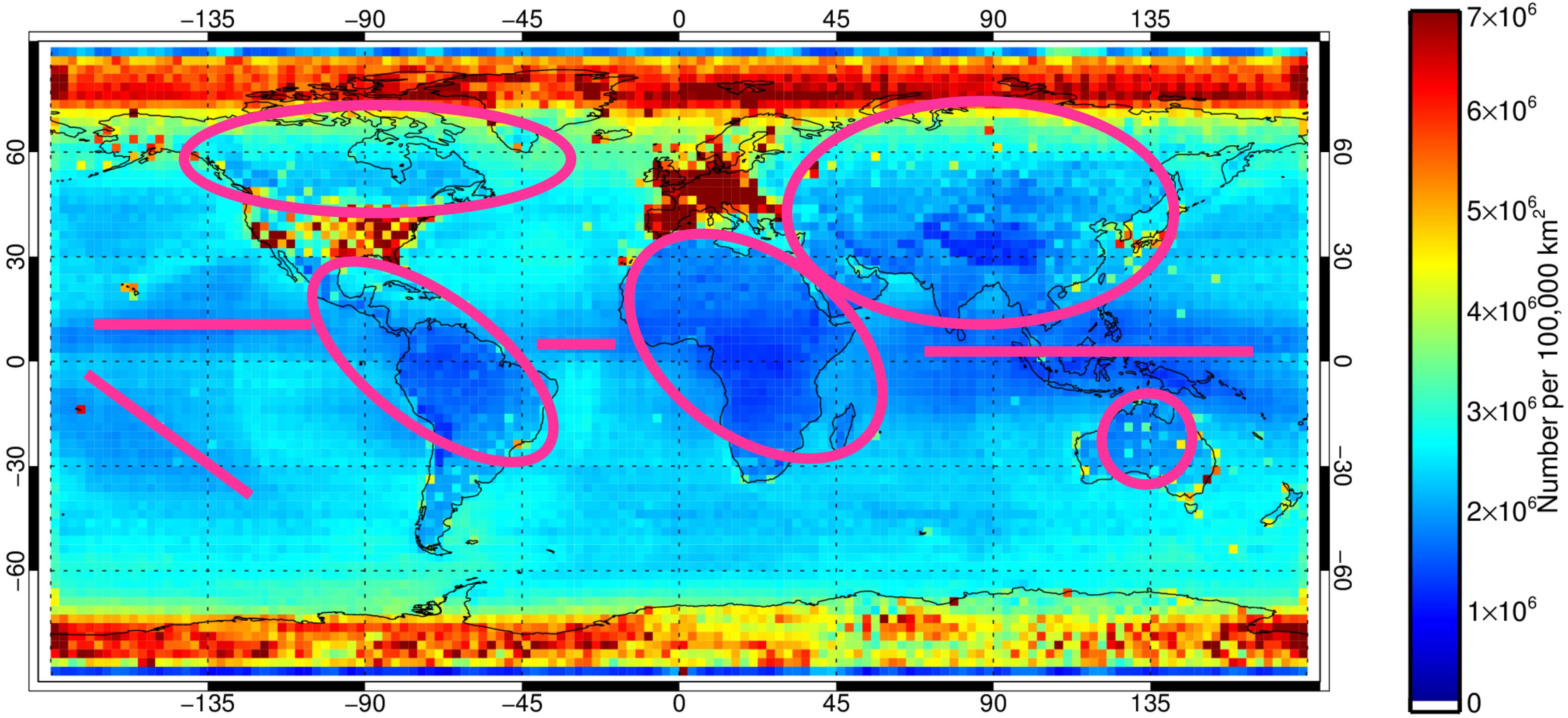


14 sensors

All-surface motivation 1: using the "difficult" observations: big payoffs

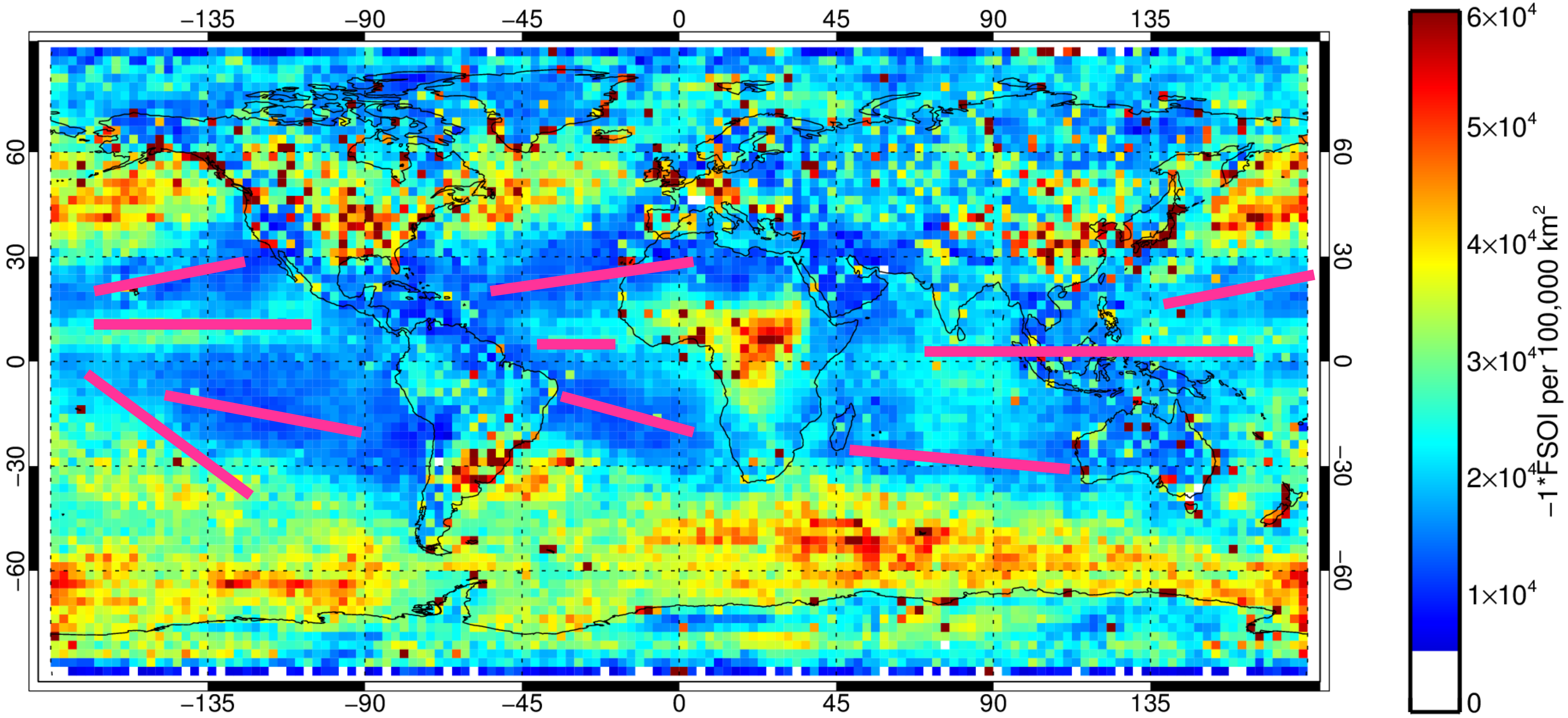
Where are the observation gaps now?

Observations assimilated in operational 4D-Var: July 2020 – July 2021



Forecast sensitivity to observation impact (T+24): July 2020 – July 2021

All data

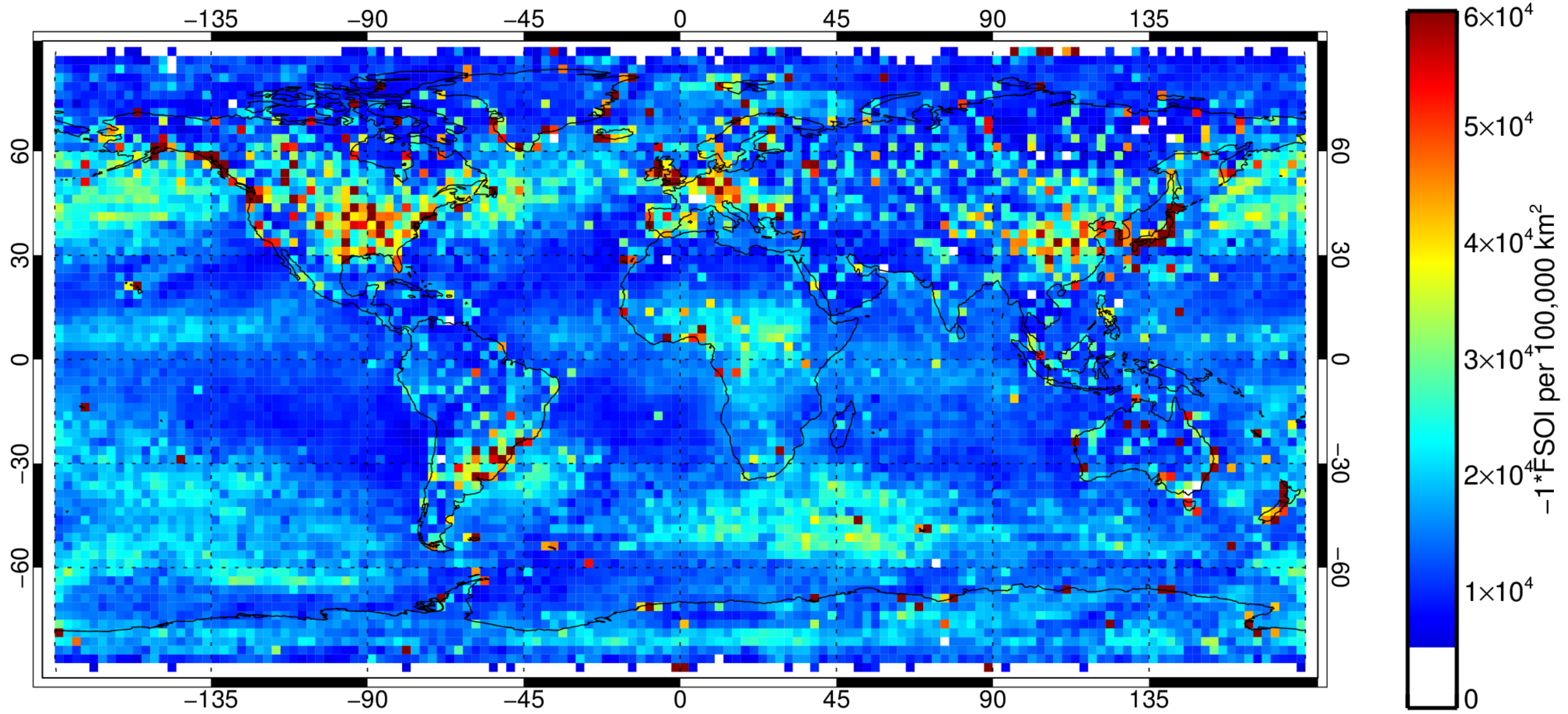


Assumption 1: tropical cloudy areas could benefit from development of all-sky radiances, moist physics and ocean

Assumption 2: subtropical high pressure regions are not that important to forecast skill

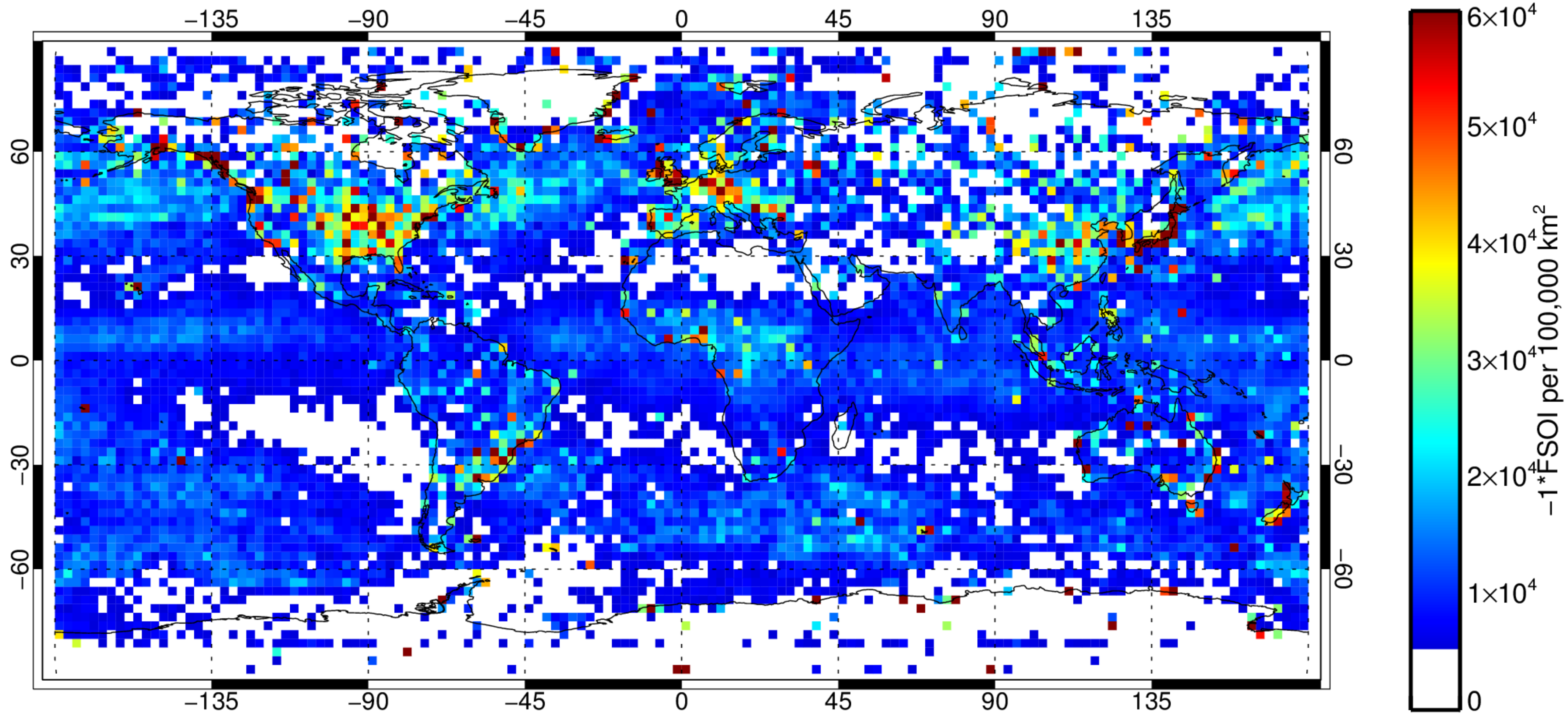
Forecast sensitivity to observation impact (T+24): July 2020 – July 2021

All data minus microwave radiances



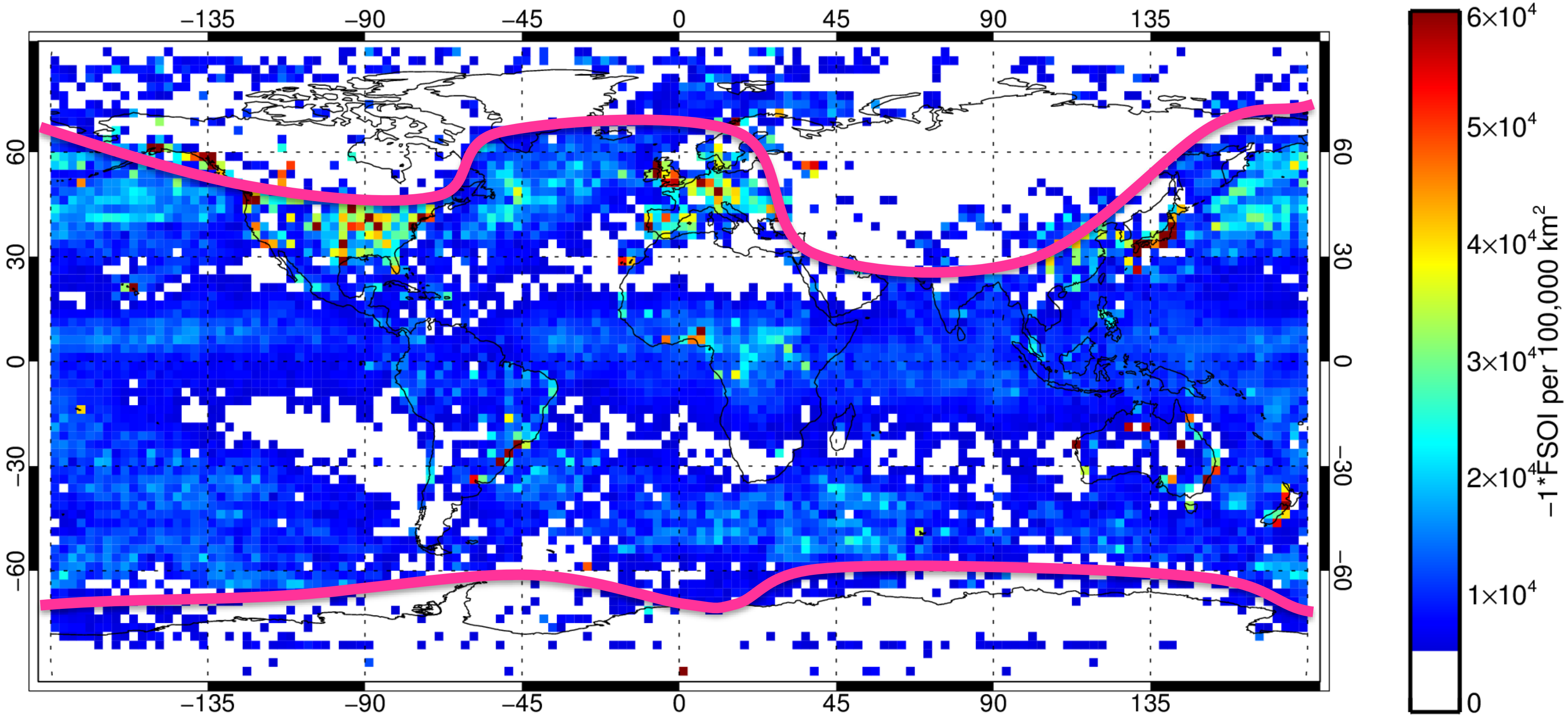
Forecast sensitivity to observation impact (T+24): July 2020 – July 2021

All data minus microwave and infrared radiances



Forecast sensitivity to observation impact (T+24): July 2020 – July 2021

All data minus sondes, synops and microwave and infrared radiances



Assumption 3: strength in depth protects the remaining coloured areas

Ocean, tropics: Buoys, GPSRO, scatterometer, AMVs

Extratropical land: aircraft and profilers

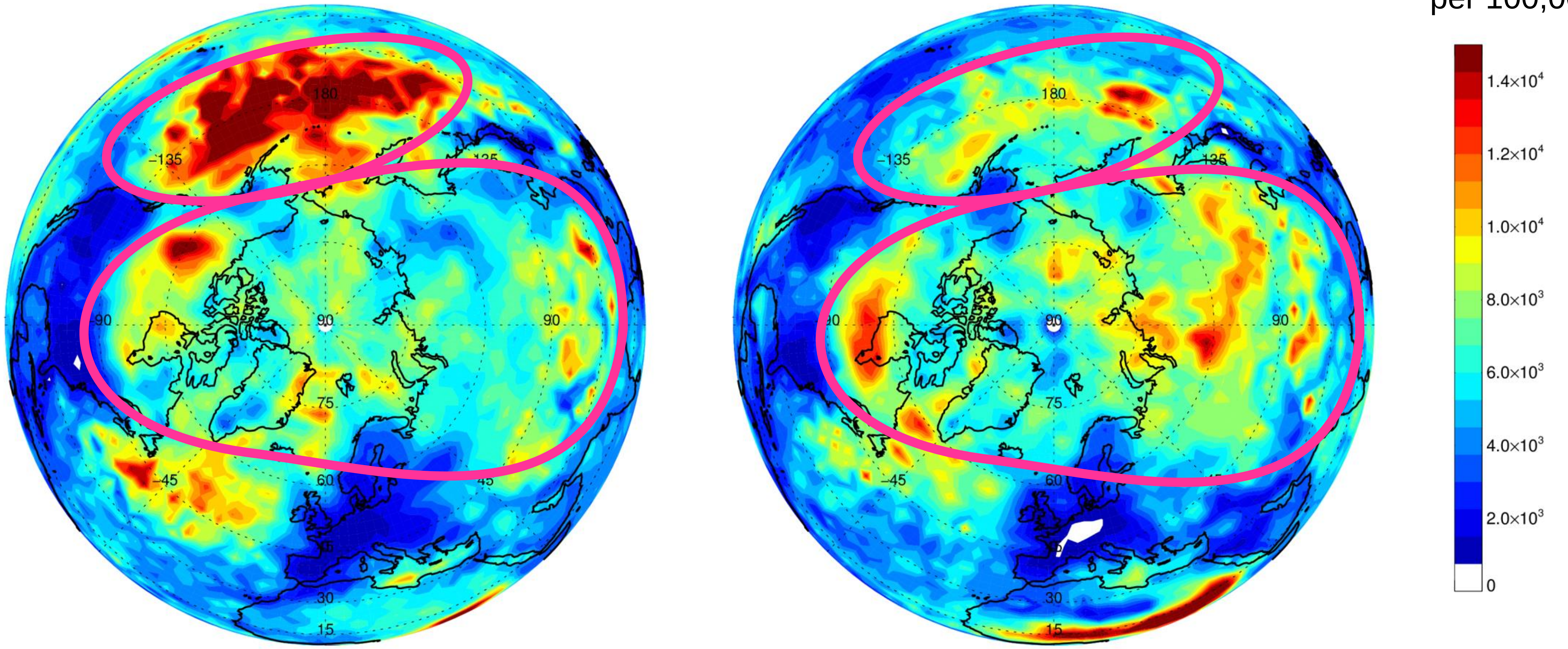
Assumption 4: the regions behind the pink lines are our current observation “deserts” (to be further justified)

Satellite radiances (IR + MW)

-1 x FSOI per 6 months
per 100,000 km^2

“Winter”: November 2020 – April 2021

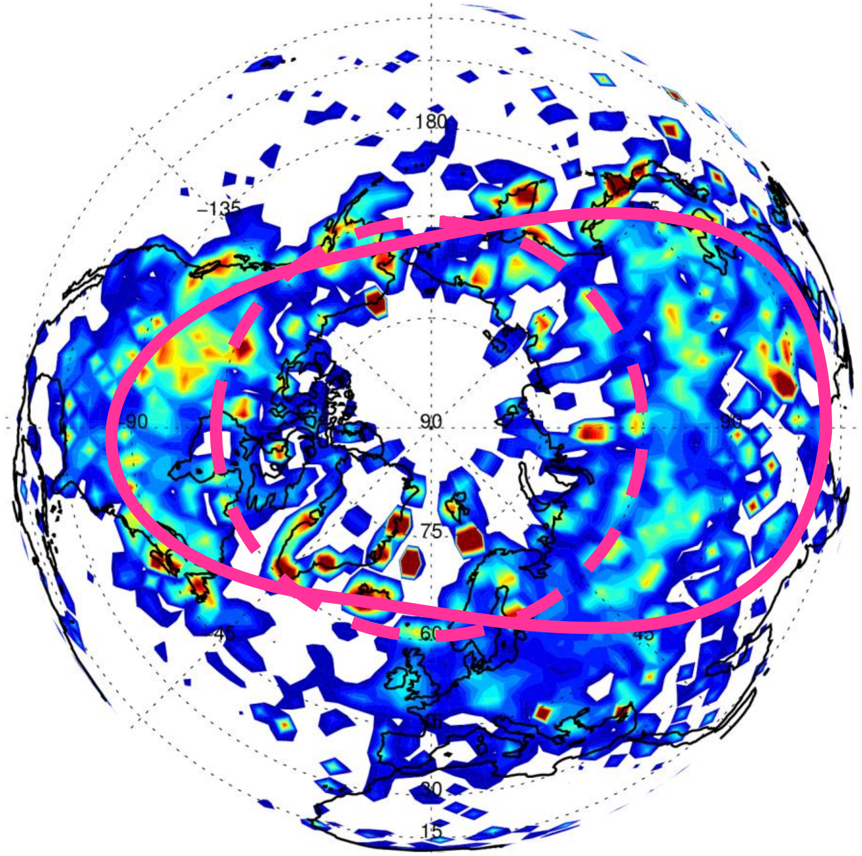
“Summer”: May 2020 – October 2020



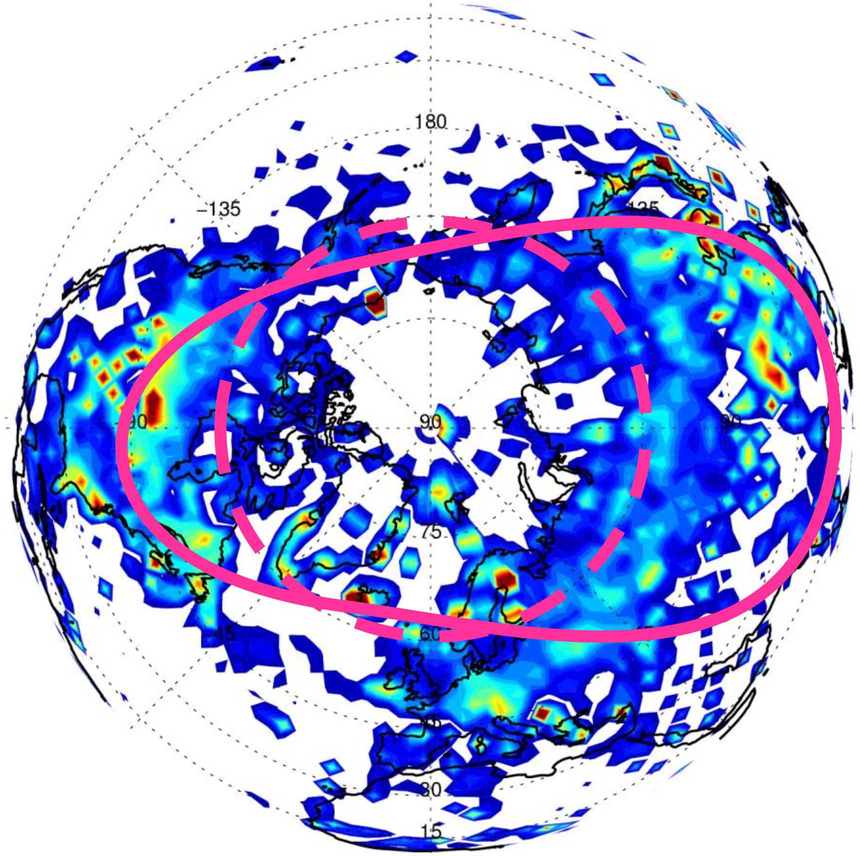
Inside the “dinosaur egg” satellite radiances aren’t used very well, particularly in winter

Synop and sonde

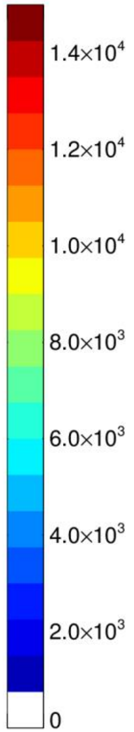
“Winter”: November 2020 – April 2021



“Summer”: May 2020 – October 2020



-1 x FSOI per 6 months
per 100,000 km²



Inside the “dinosaur egg” scattered synops and sondes are doing an outsize job, particularly in winter

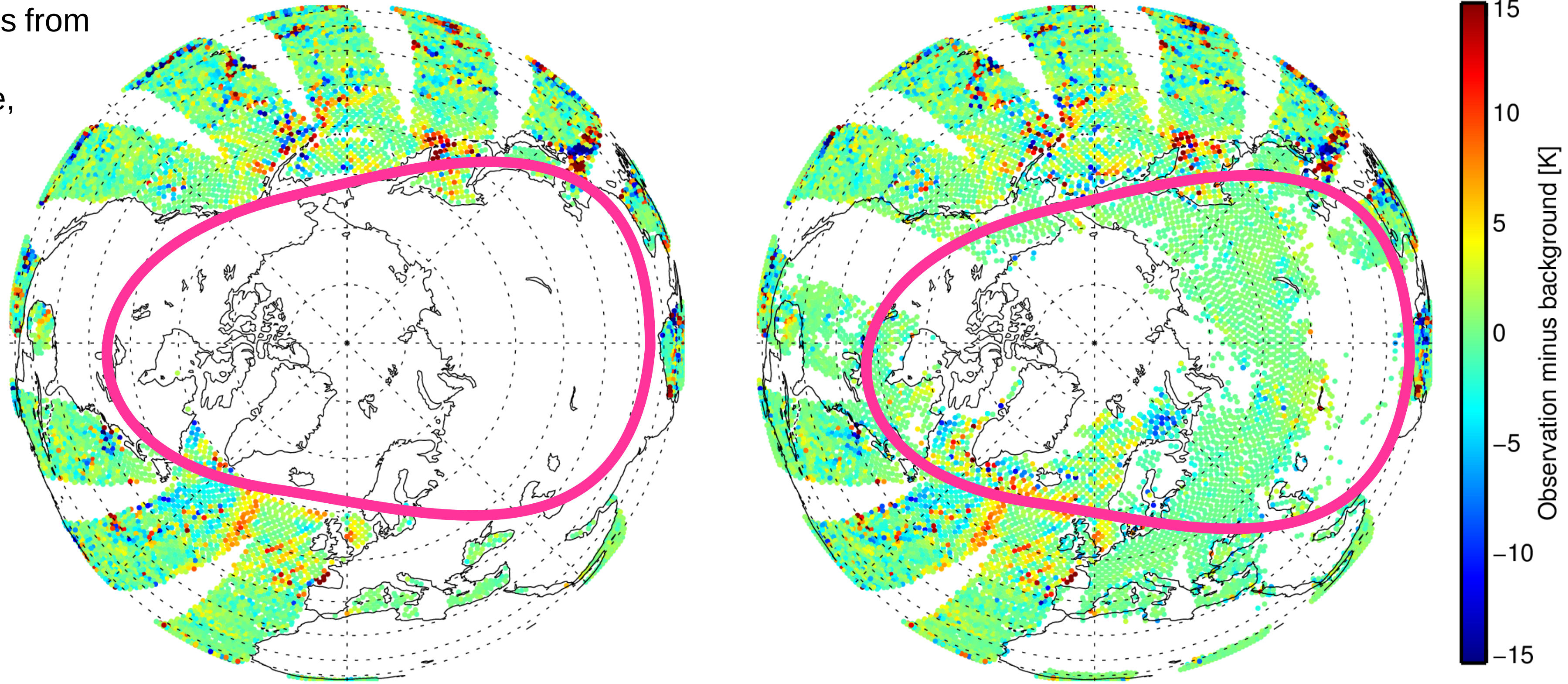
Similar conclusion of APPLICATE results (inc. OSEs) but for >60°N only – Lawrence et al. 2019 https://doi.org/10.1002/qj.3628

Ongoing developments for surface-sensitive microwave channels: cycle 48r1 target

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

now (all-sky but not all-surface)

upgrade



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

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

It’s all about surface radiative transfer

See also talks from Gunnar Spreen, Melody Sandells, Catherine Prigent, Patricia de Rosnay,

ECMWF

It's **all** about surface radiative transfer

See also talks from Gunnar Spreen, Melody Sandells, Catherine Prigent, Patricia de Rosnay

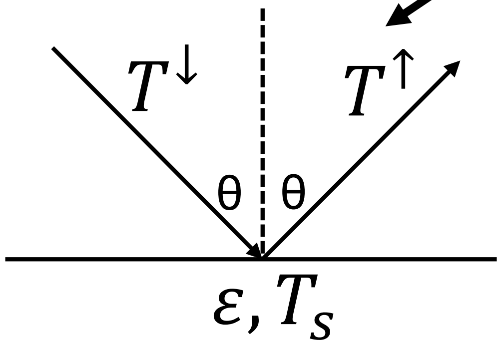
ECMWF

Surface radiative transfer

"Stage 1"

Surface emissivity: **specular** (mirror-like) assumption

Upwelling radiance ("pencil beam") expressed as a brightness temperature



$$T^{\uparrow} = (1 - \varepsilon)T^{\downarrow} + \varepsilon T_s$$

Emissivity

"Skin" (emitting) temperature

$\varepsilon = 0$ — Pure mirror-like reflection

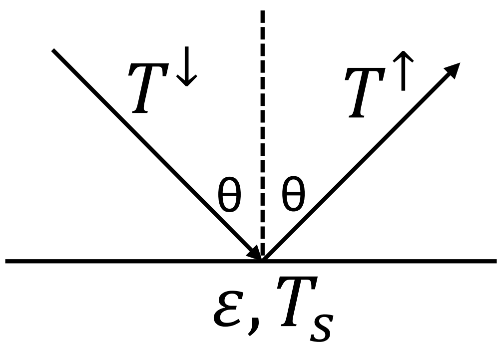
$\varepsilon = 1$ — Blackbody radiation

Dynamic emissivity retrieval: current state of the art in atmospheric DA

See also Catherine Prigent's presentation

In atmospheric DA, dynamic emissivity retrieval is usually done online, prior to 4D-Var (with atlas, e.g. TELSEM2 as backup)

Emssivity retrieved in a window channel is assigned to sounding channels



$$\varepsilon = \frac{(T^{\uparrow} - T^{\downarrow})}{(T_s - T^{\downarrow})}$$

Estimated from observation and background atmospheric profile ($T^{\uparrow}$)

Estimated from background atmospheric profile ($T^{\downarrow}$)

Model background estimate (T_s)

Diurnal cycle of “emissivity”

Night – day ATMS retrieved surface emissivity

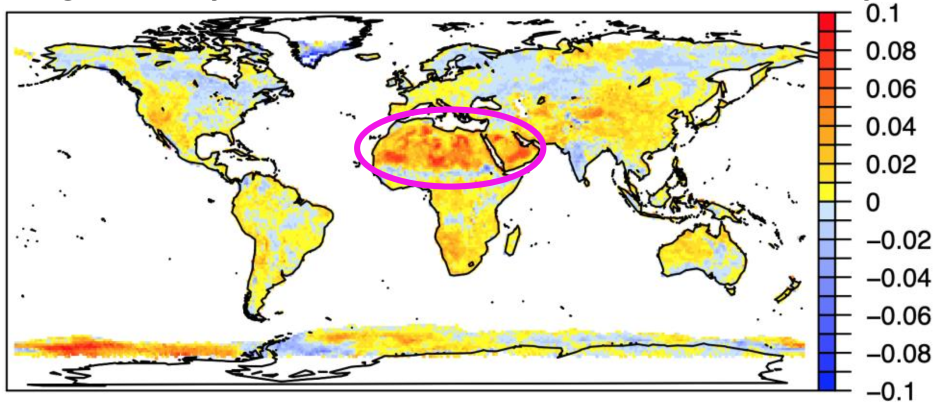
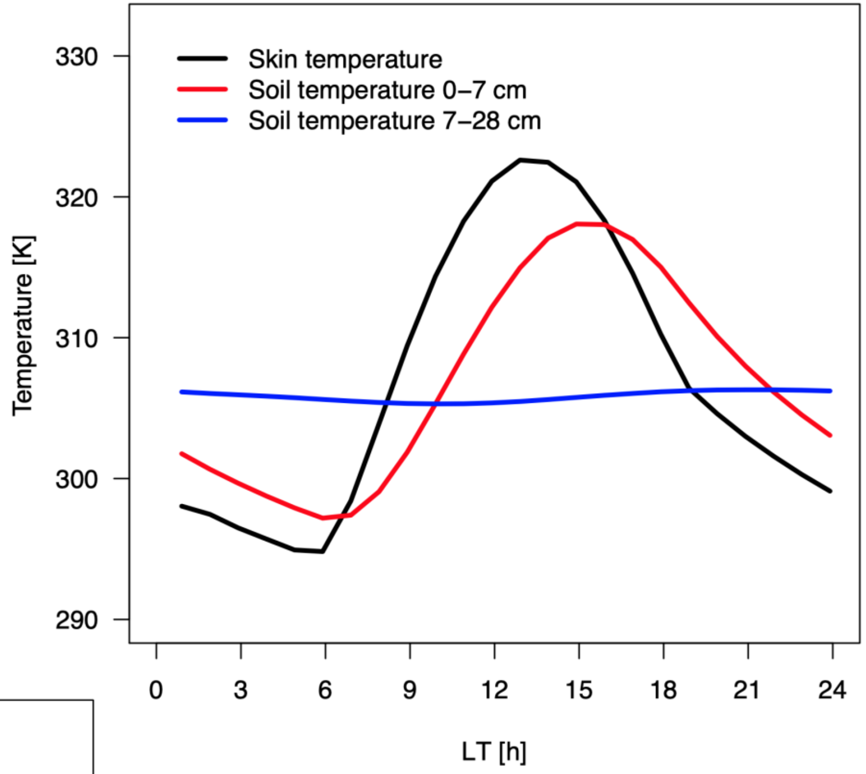
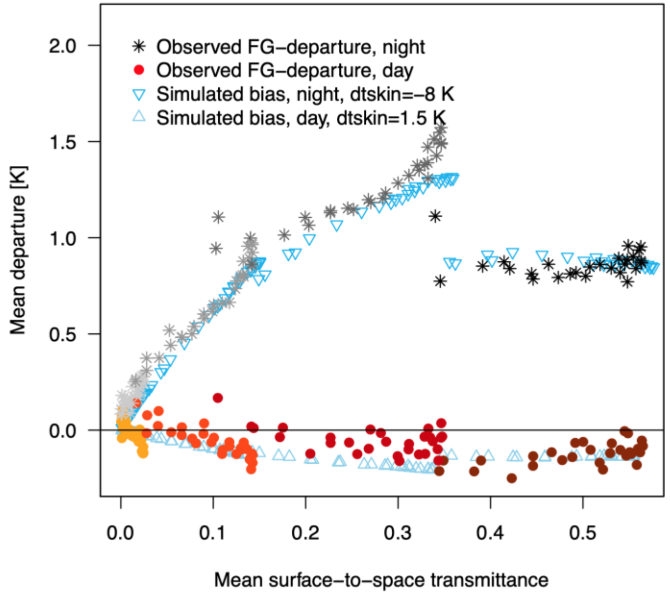
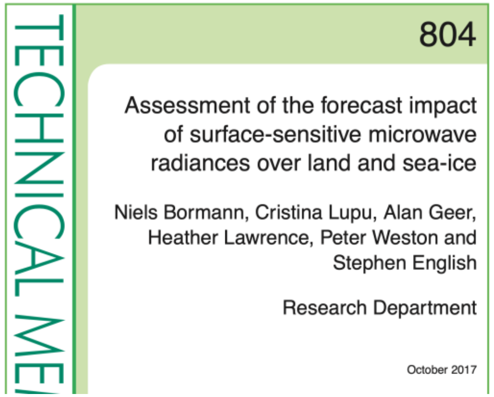


Figure 17: Difference in the mean retrieved surface emissivity at 50.3 GHz between night (1:30) and day (13:30) obtained for ATMS over the period June-August 2014. Data is binned in 1x1° boxes and all emissivity retrievals from observations with a zenith angle less than 20° have been considered, with no attempt to screen for clouds.



2 x 2 degree box,
Eastern Sahara,
June – August 2016




TECHNICAL ME

804

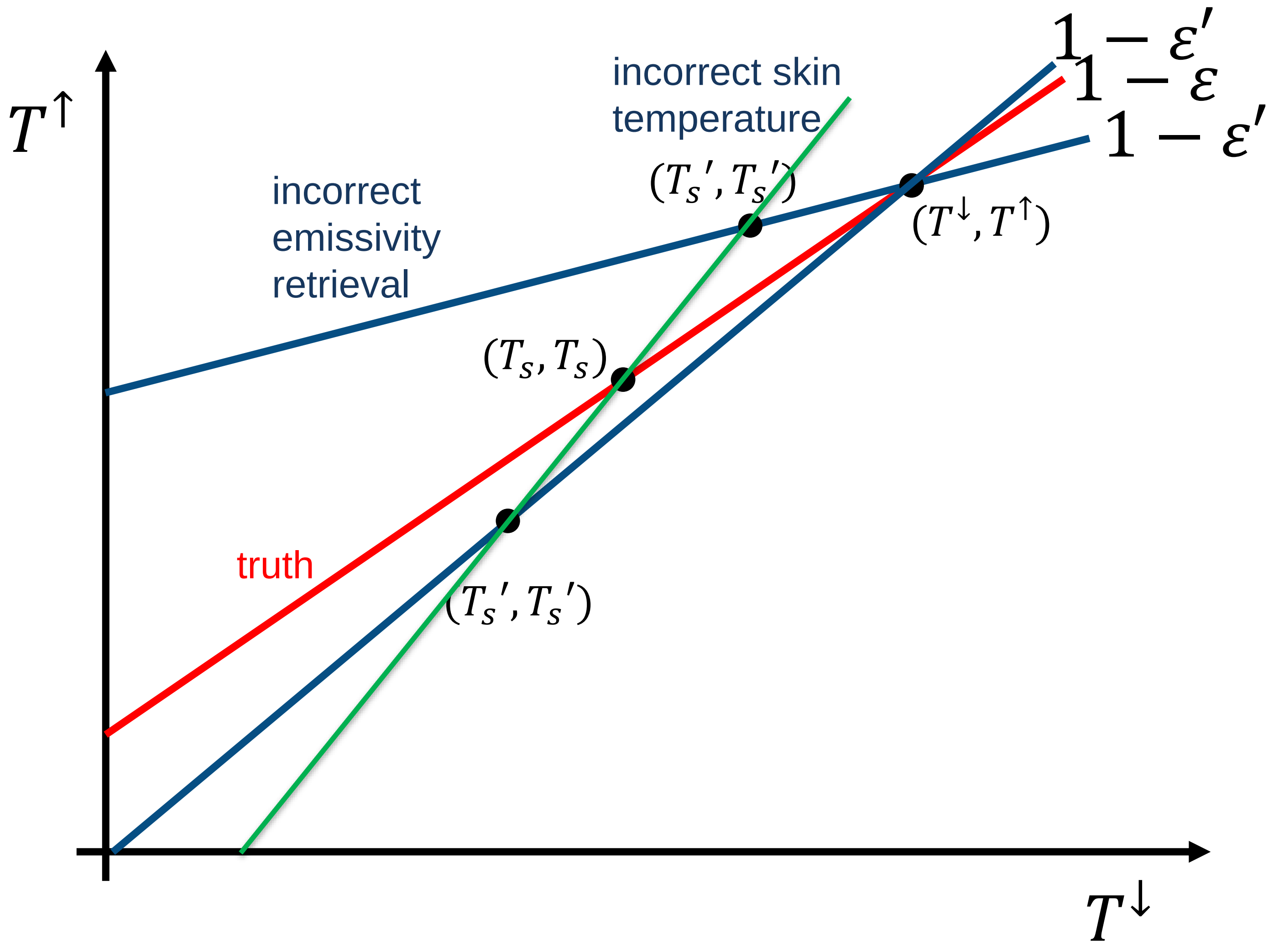
Assessment of the forecast impact of surface-sensitive microwave radiances over land and sea-ice

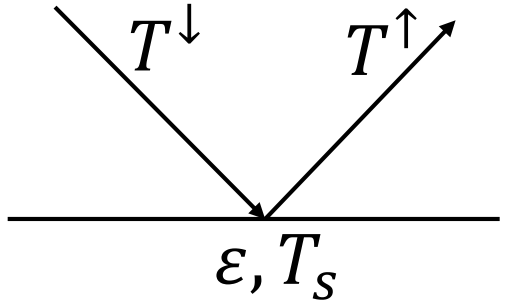
Niels Bormann, Cristina Lupu, Alan Geer, Heather Lawrence, Peter Weston and Stephen English

Research Department

October 2017

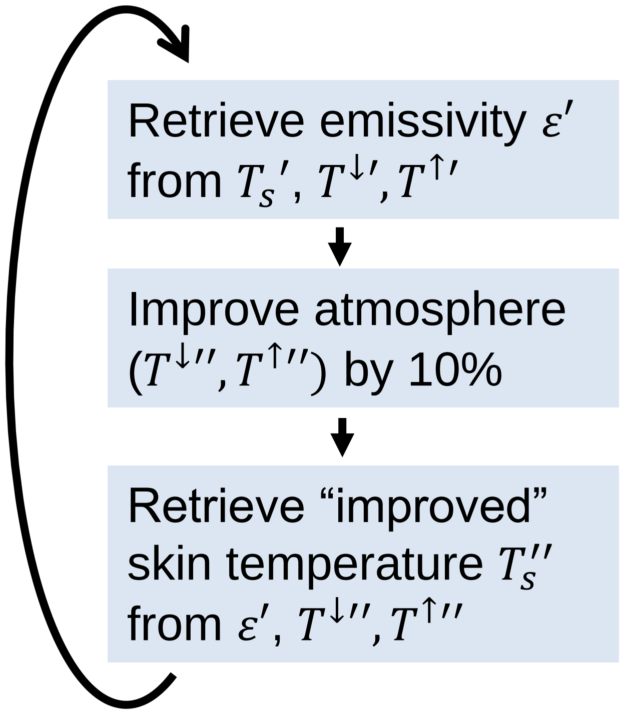
Dynamic emissivity retrievals and incorrect skin temperatures



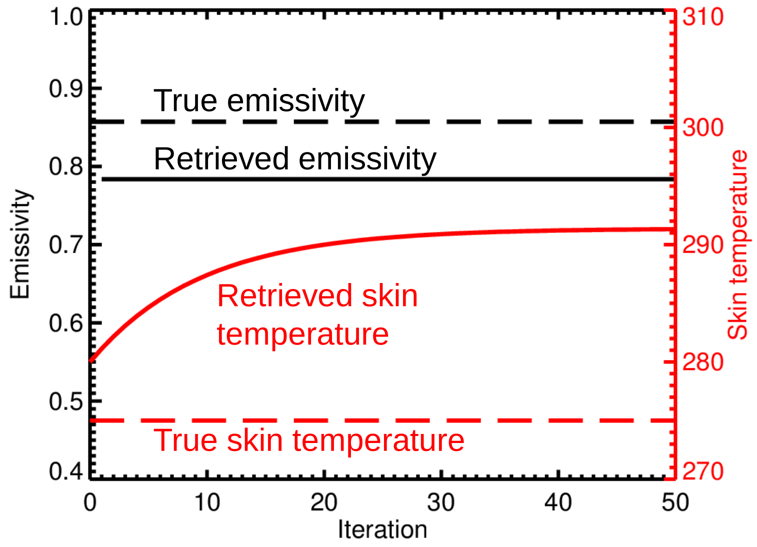


$$T^{\uparrow} = (1-\varepsilon)T^{\downarrow} + \varepsilon T_s$$

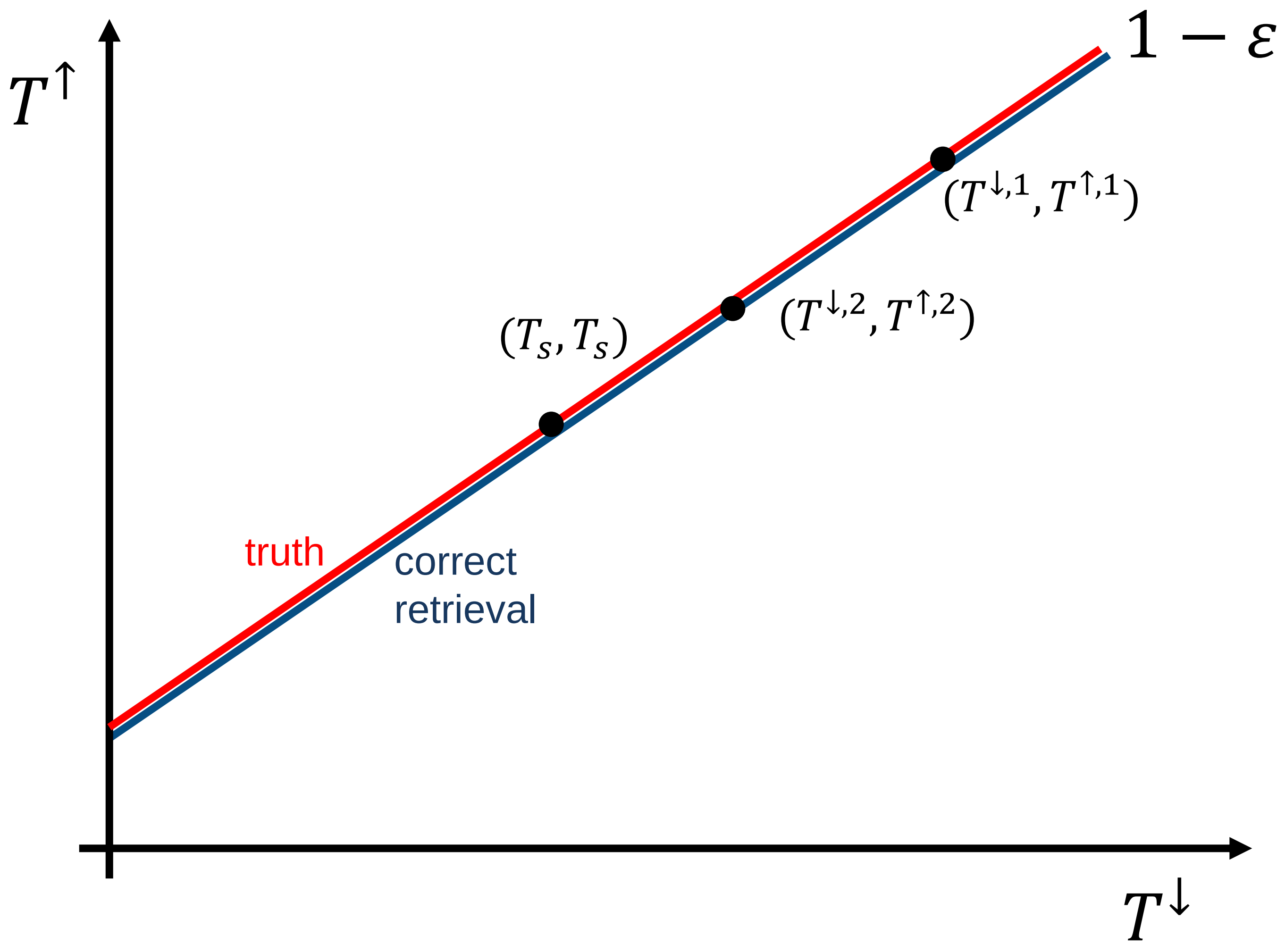
It is impossible to retrieve Ts & emissivity simultaneously from one observation (ill-conditioned)

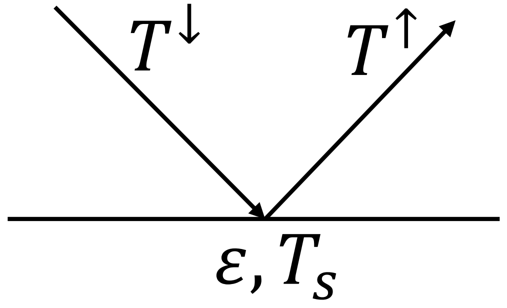


Example where $T_s{}'$, $T^{\downarrow\prime}, T^{\uparrow\prime}$ each start 5 K in error



Multiple observations can constrain emissivity and skin temperature





$$T^{\uparrow} = (1-\varepsilon)T^{\downarrow} + \varepsilon T_s$$

Big assumptions:

- Different atmosphere ($T^{\downarrow}$) – either different channel or different timing of observation
- Constant surface (ε, T_s)

Skin temperature augmented control variable developments (not yet operational)

Skin temperature 2D + diurnal cycle estimated within atmospheric 4D-Var

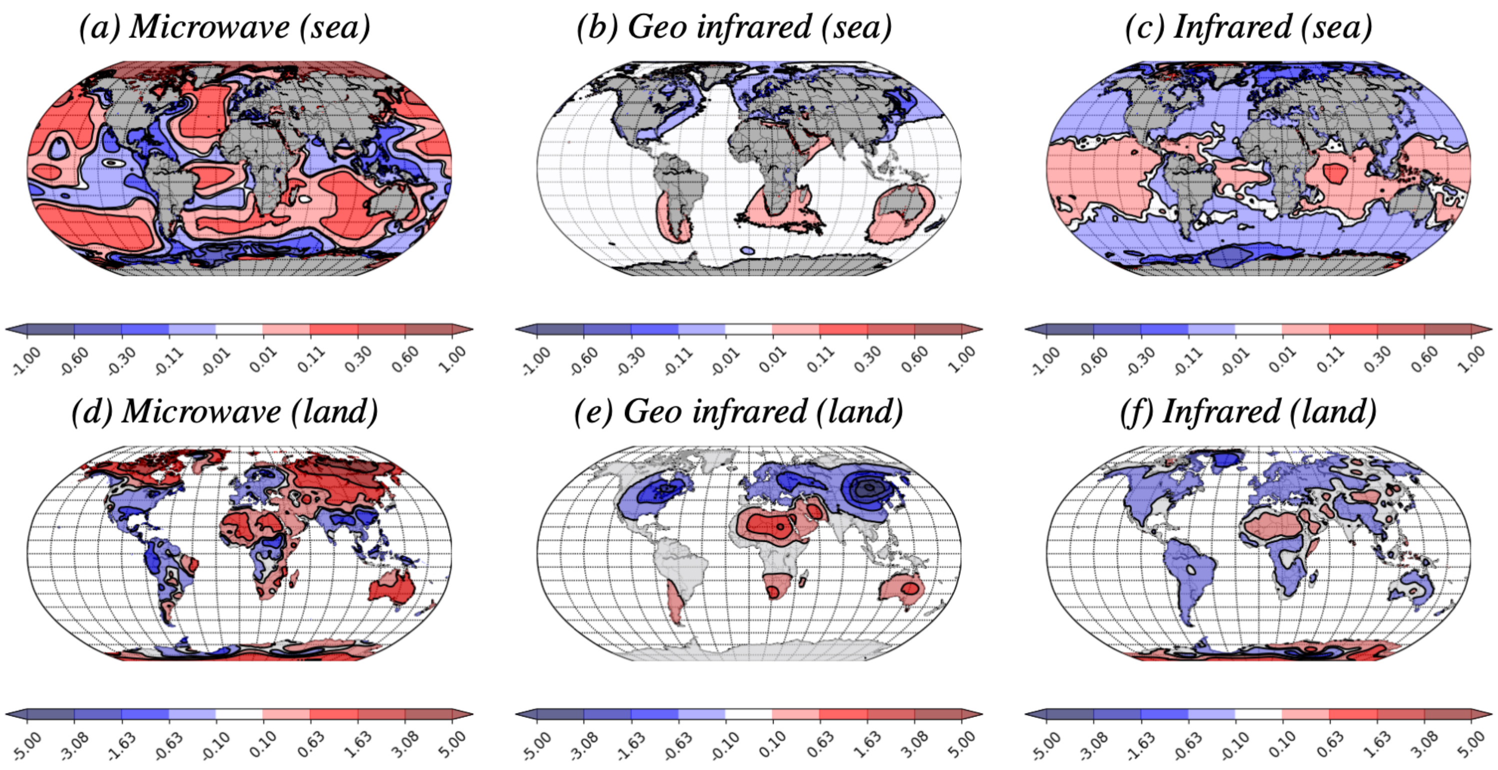
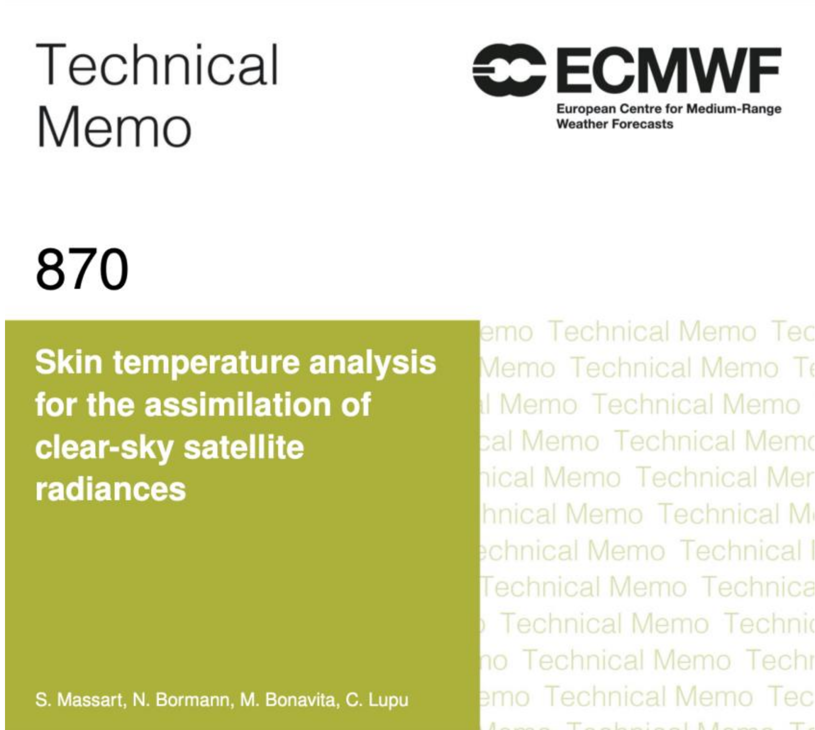
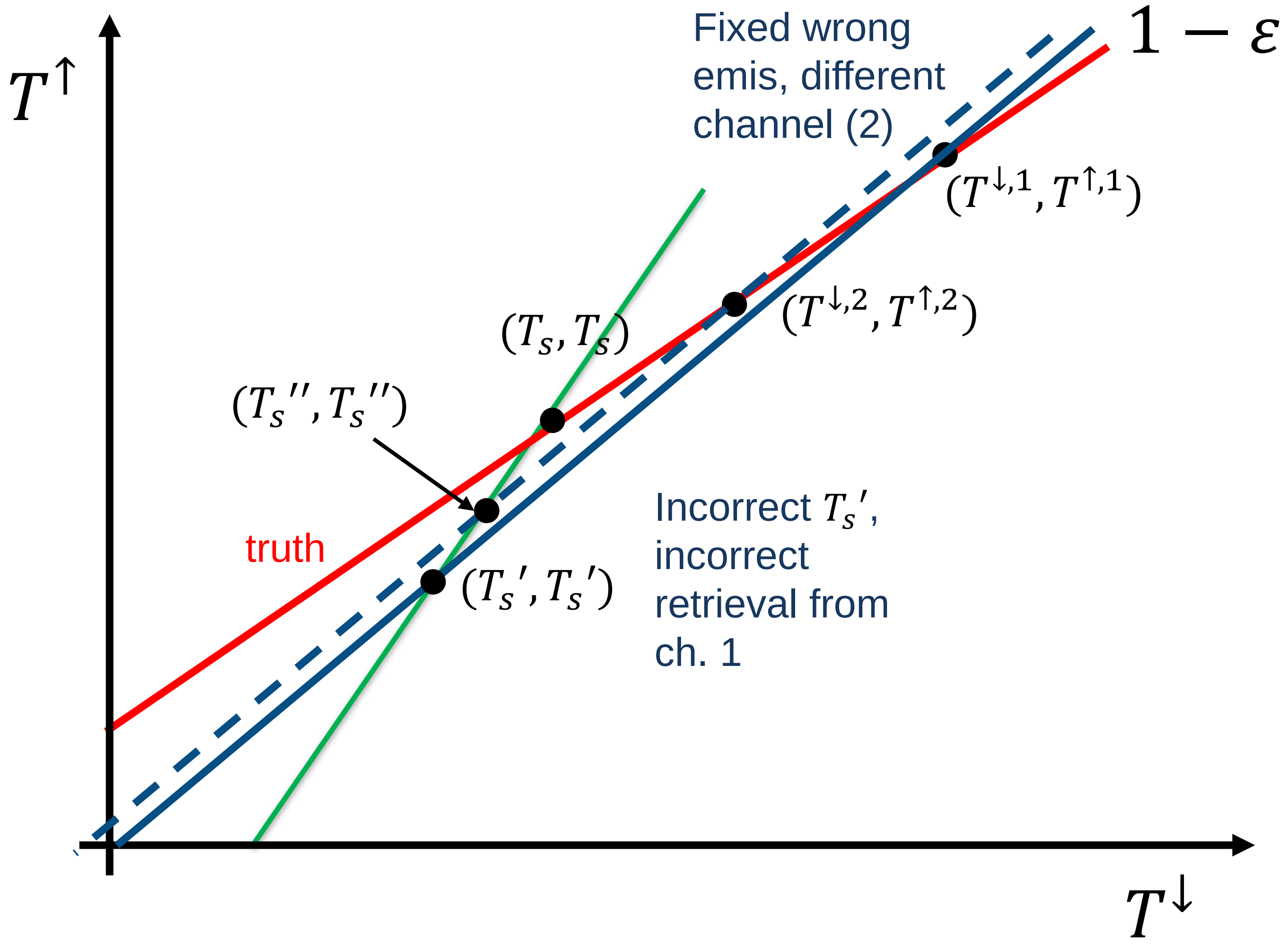
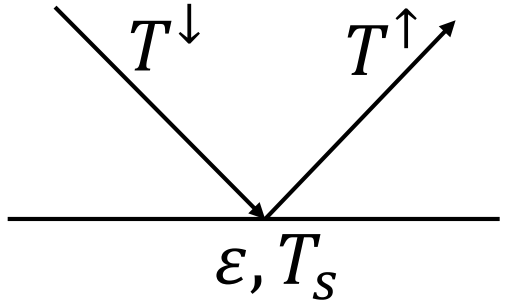


Figure 4: Mean skin temperature increment (in K) for the TOVSCV_2D reference experiment for the month of November 2019 and for the 09Z and 21Z cycles together. Top: over sea. Bottom: over land.



Multiple observations can constrain emissivity and skin temperature

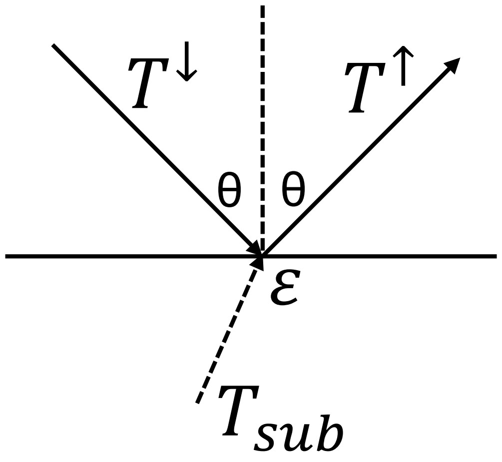




$$T^{\uparrow} = (1-\varepsilon)T^{\downarrow} + \varepsilon T_s$$

Surface emissivity: **specular** assumption with penetration of surface

See also Catherine Prigent's presentation, e.g. desert soils

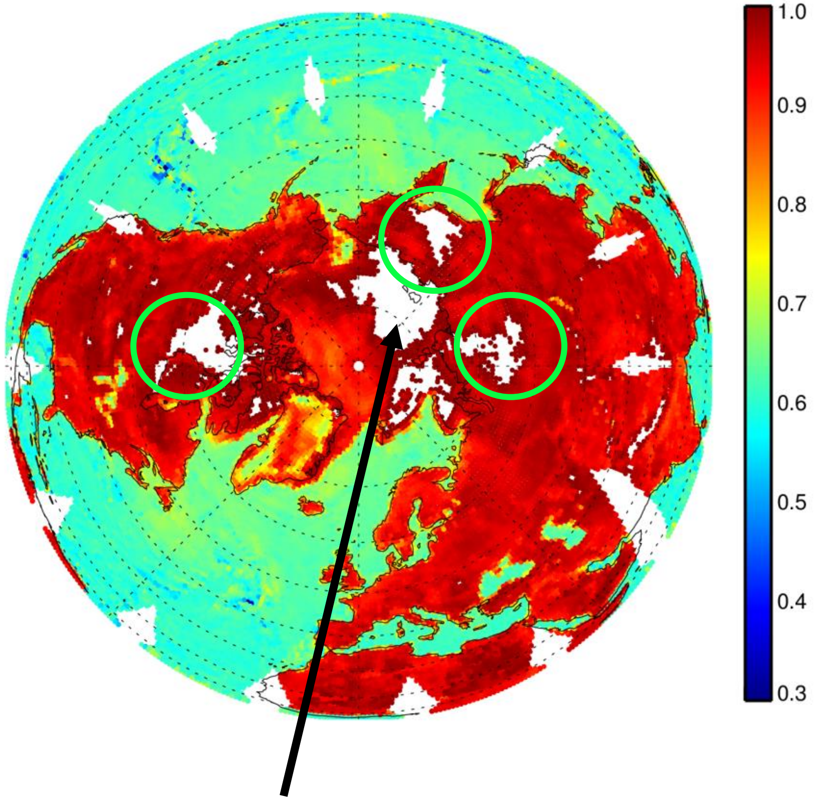


$$T^{\uparrow} = (1 - \varepsilon)T^{\downarrow} + \varepsilon T_{sub}$$

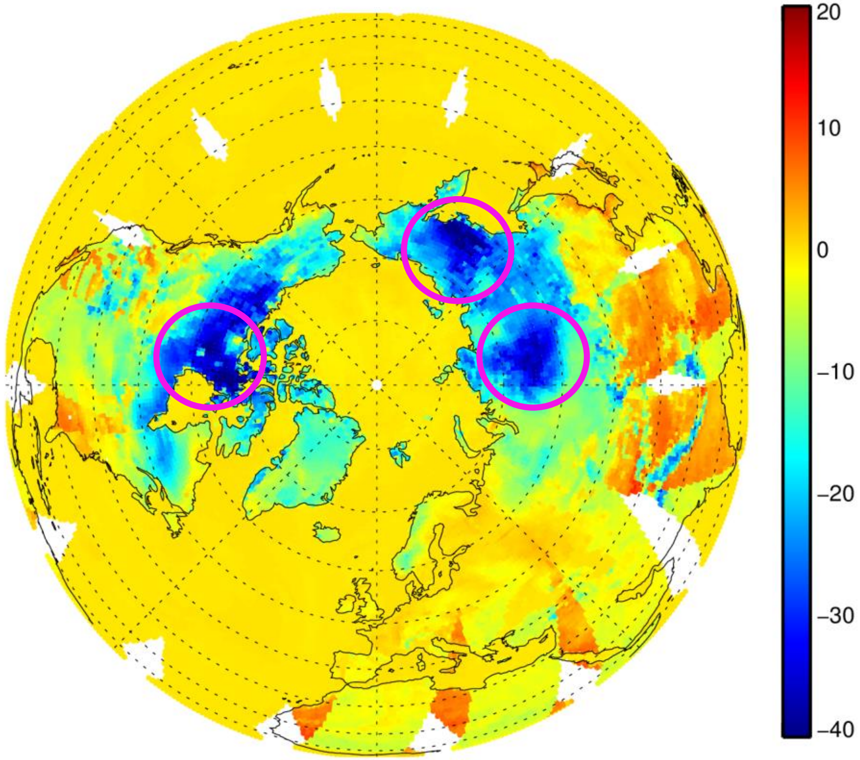
Effective emissivity

Subsurface emitting temperature == effective radiating temperature

Where the dynamic emissivity retrieval breaks down completely



16 Dec 2019
AMSR2 19v
Retrieved emissivity [0-1]



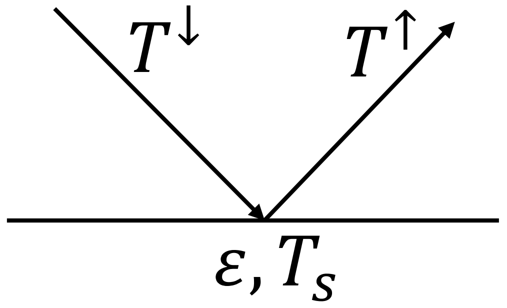
Skin temperature – top layer soil temperature [K]

Similar gaps over sea-ice, due to a similar problem

$$\varepsilon' = \frac{(T^{\uparrow} - T^{\downarrow})}{(T_s{}' - T^{\downarrow})}$$

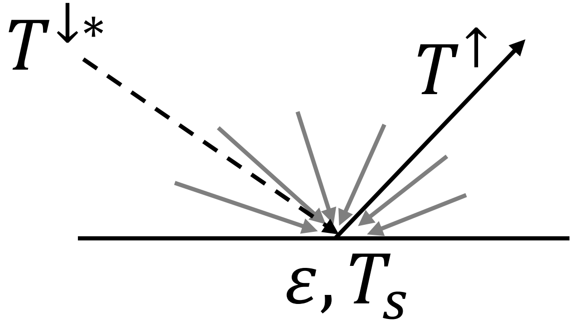
If incorrect $T_s' < T^{\uparrow}$ then retrieved $\varepsilon' > 1$ which is non-physical

Lambertian scattering



$$T^{\uparrow} = (1 - \varepsilon)T^{\downarrow} + \varepsilon T_s$$

Specular



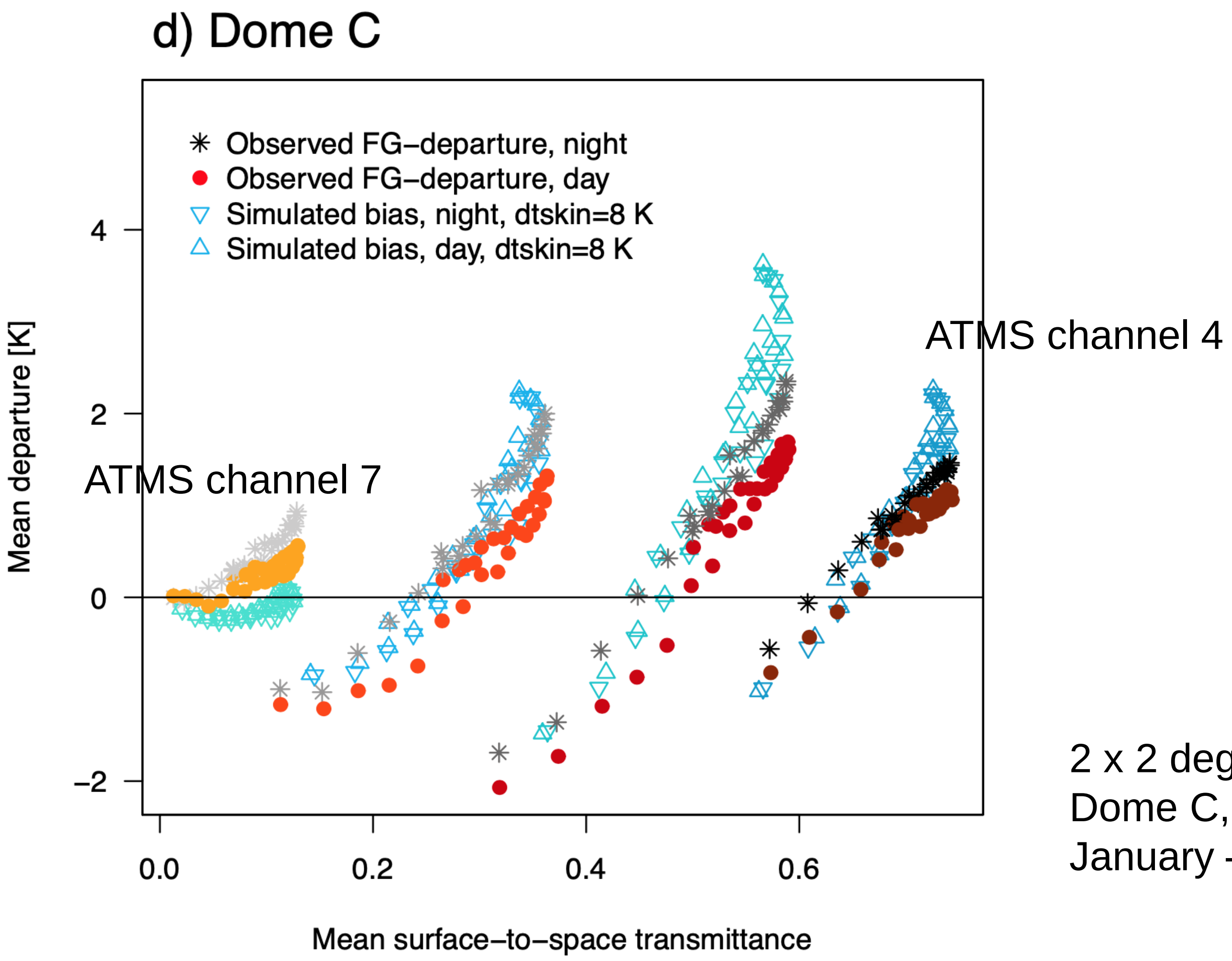
$$T^{\uparrow} = (1 - \varepsilon)T^{\downarrow *} + \varepsilon T_s$$

Lambertian

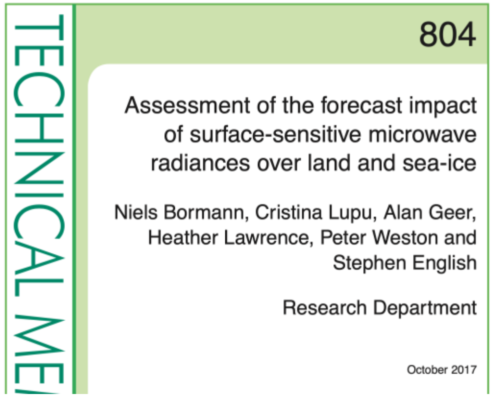
Mätzler (2005): On the determination of surface emissivity from satellite observations, https://doi.org/10.1109/LGRS.2004.842448

Snow and ice surfaces: Lambertian scattering and skin temperature bias

Around 50 GHz, this is a reasonable way to model the snow & ice surfaces



2 x 2 degree box,
Dome C, Antarctica,
January – March 2015



TECHNICAL MEMO

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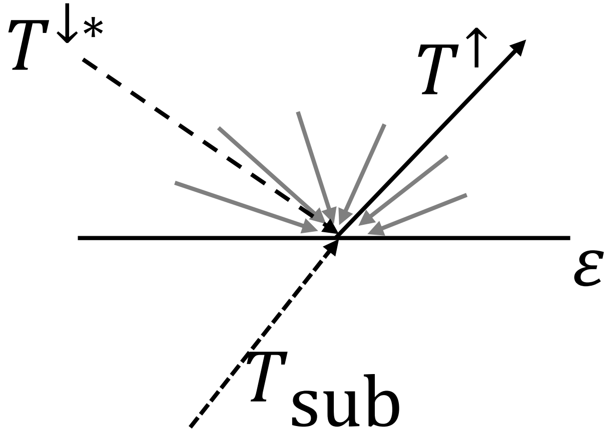
“Variable penetration depth” + Lambertian



$$T^{\uparrow} = (1-\varepsilon)T^{\downarrow *} + \varepsilon T_{\mathrm{sub}}$$

Possible near-future configuration

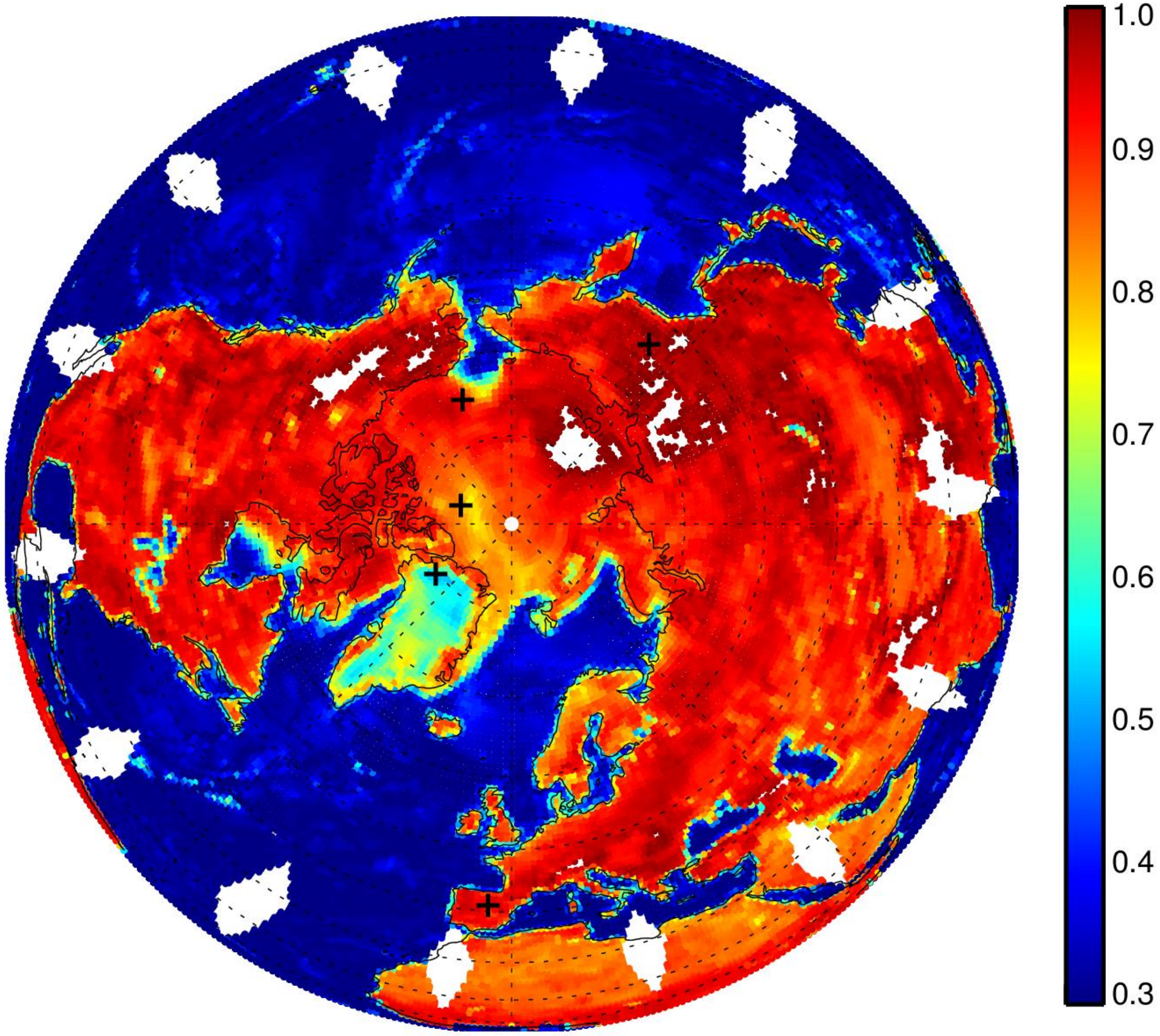
- Variable specular-Lambertian assumption
- Prior to 4D-Var: dynamic emissivity retrieval
- 4D-Var online retrieval of effective radiating temperature (hence some accounting for penetration depth)
- 4D-Var online retrieval of bias correction
- Issues?
  - Non-optimal prior emissivity retrieval
  - Competition between bias correction and “skin” temperature?
- And (in order to make the skin temperature and emissivity retrieval well-conditioned) can we assume radiating temperature and emissivity are constant?
  - between one satellite field of view (FOV) and another?
  - from day to day, hour to hour?
  - from frequency to frequency?

Surface radiative transfer

“Stage 2”

ECMWF

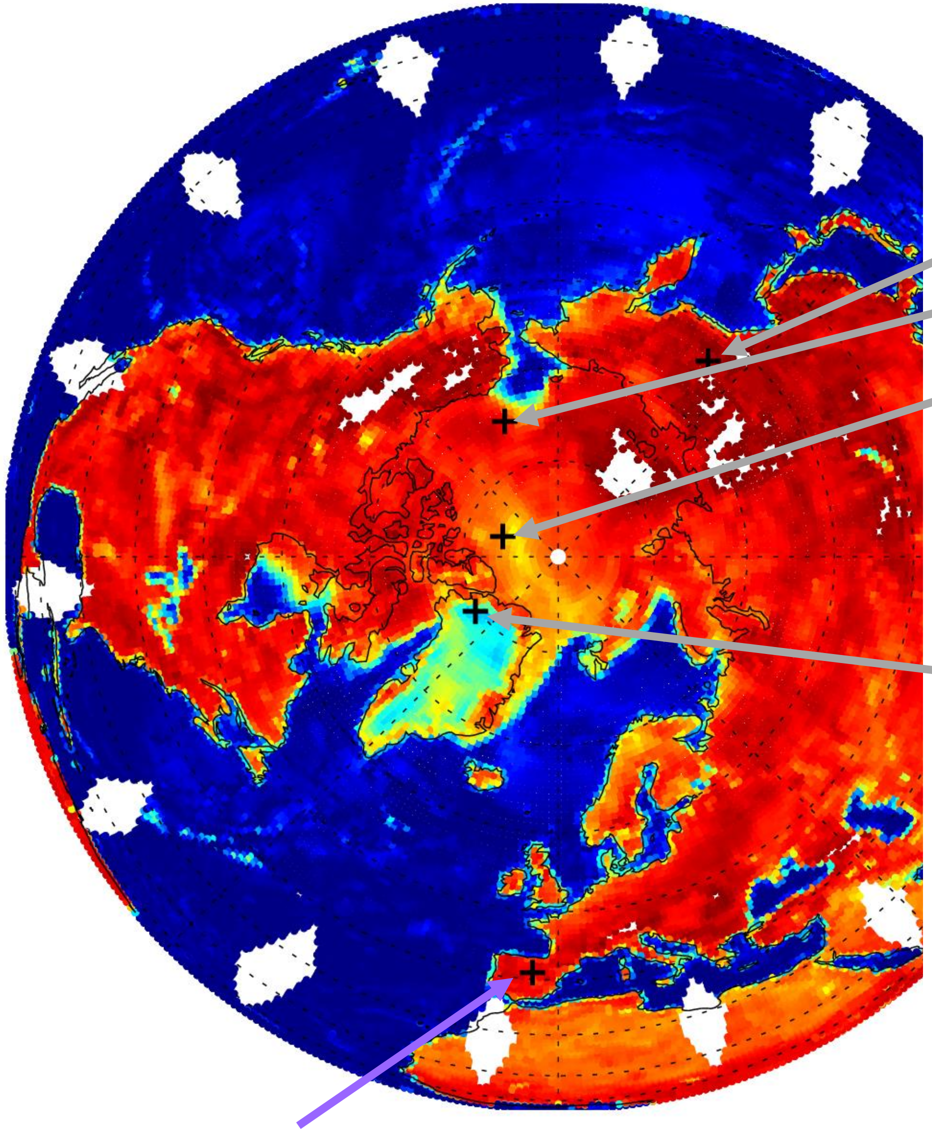
Retrieved surface emissivity from DMSP-F17 SSMIS, 19 GHz, h-polarisation

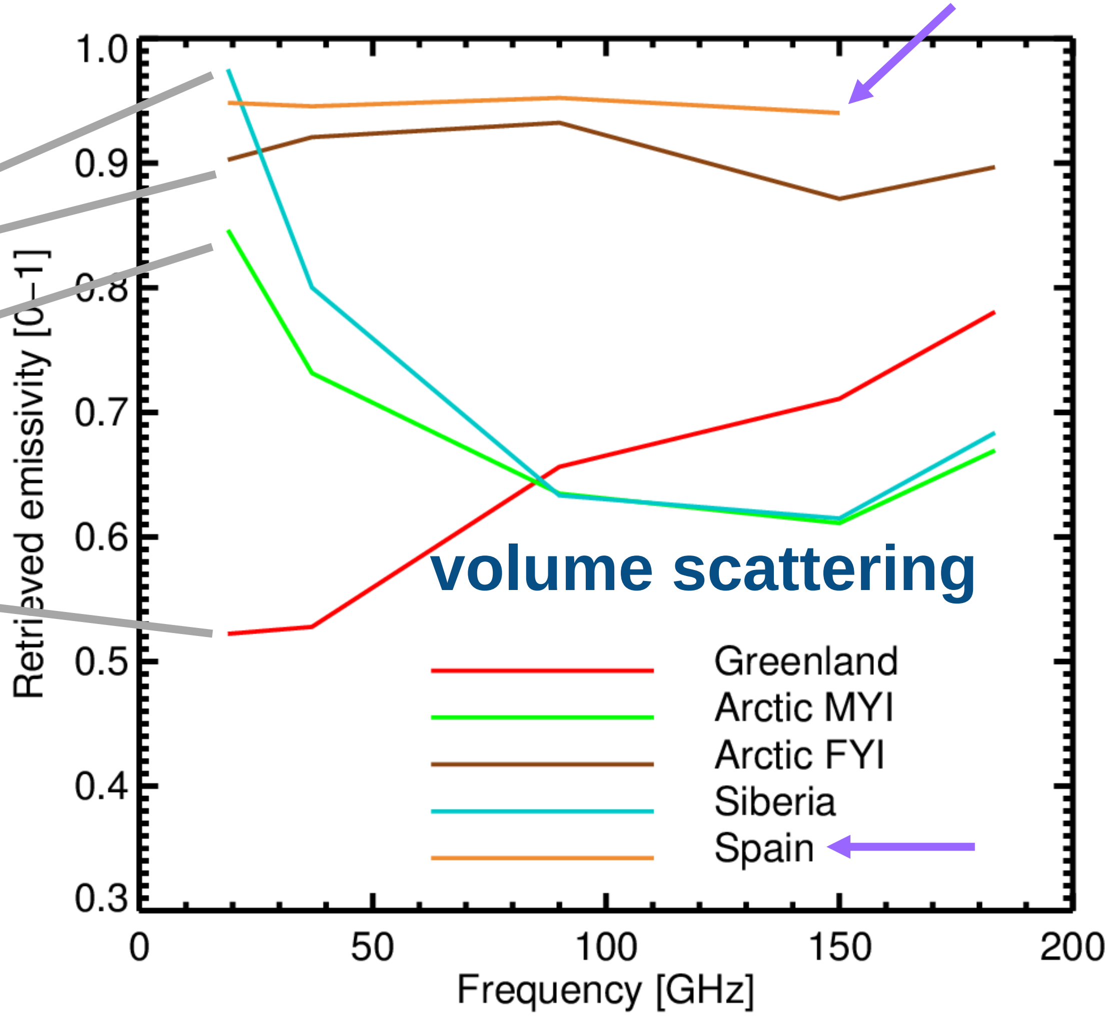


6th Dec 2019

Retrieved using all-sky version of specular dynamic emissivity retrieval (Baordo and Geer, 2016, QJ, https://doi.org/10.1002/qj.2873)

Retrieved surface emissivity from DMSP-F17 SSMIS, 19 GHz, h-polarisation



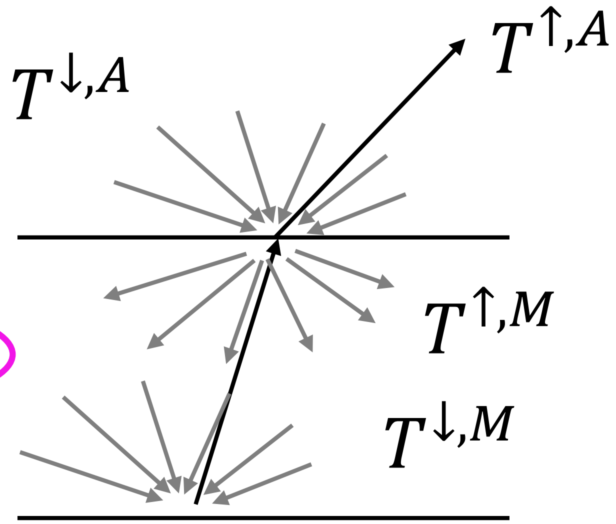


A two-stream slab model for volume-scattering surface media

What's important in a physical model of the surface: optical properties, temperature

ext, ssa, g, T_M

Optical properties: extinction, single scattering albedo, asymmetry parameter
Slab temperature



ε, T_s

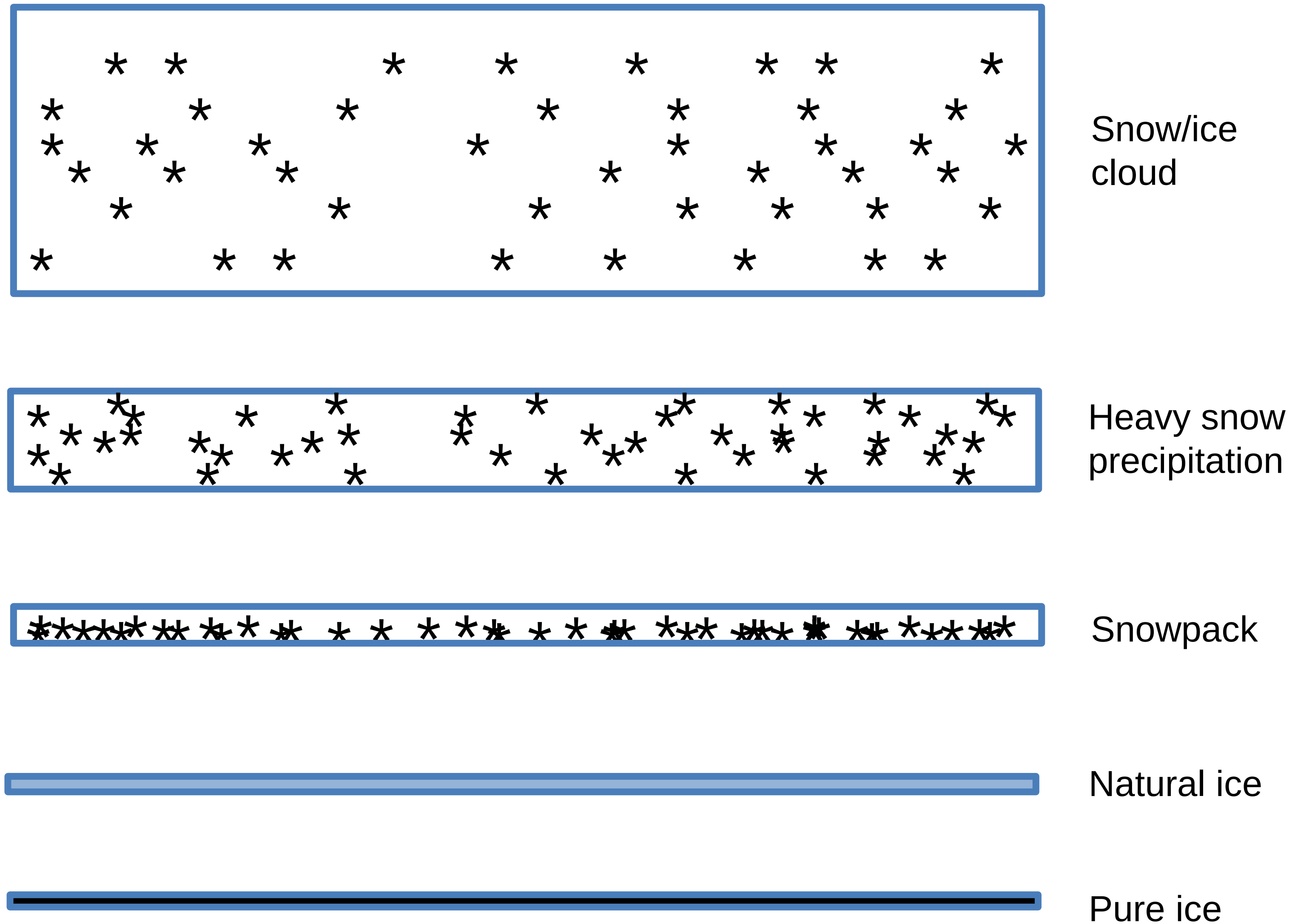
Atmosphere

Dense medium: snow, ice, sand

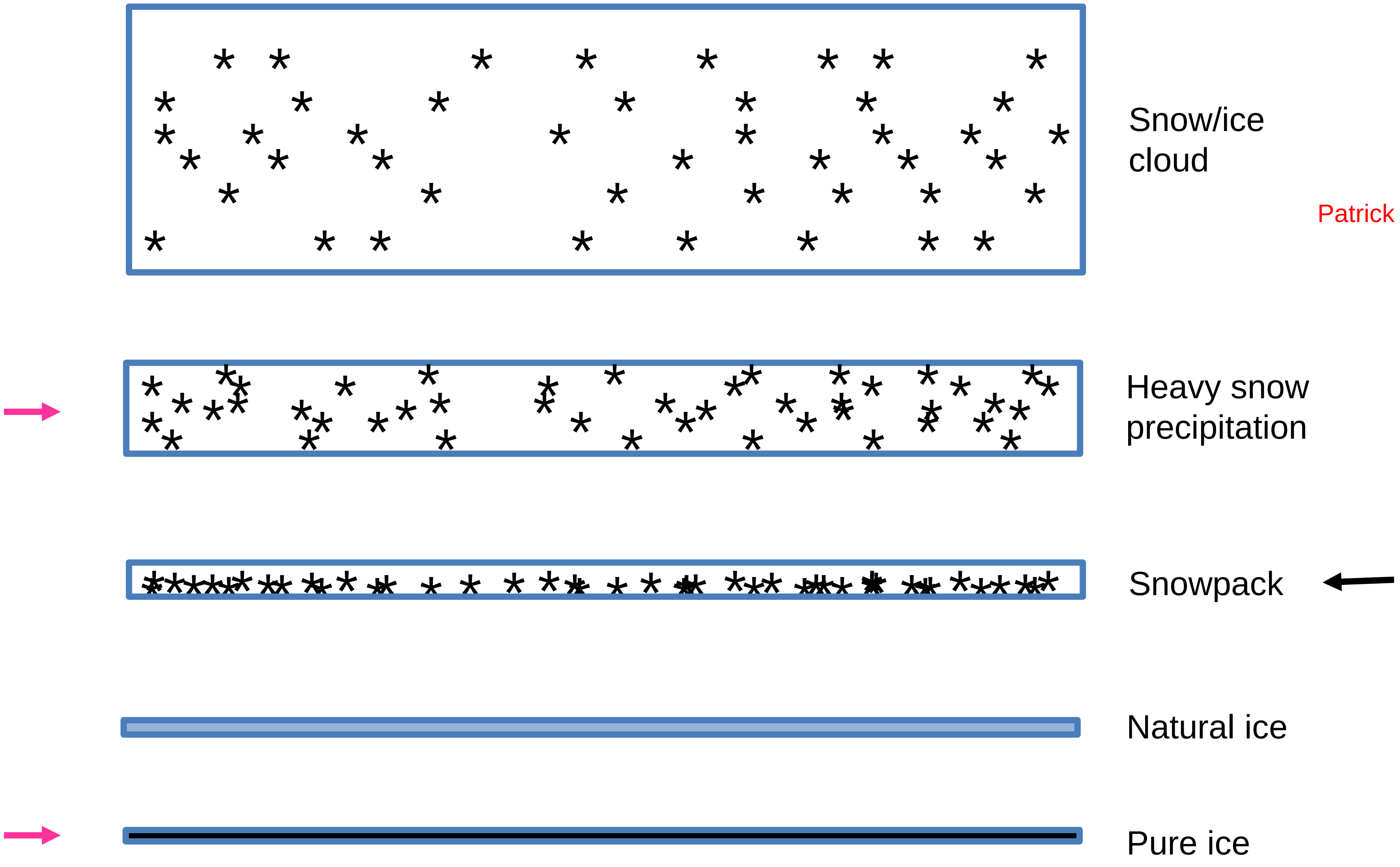
Subsurface: soil, water

Grody (2008, snow, https:/doi.org/10.1029/2007JD009685), Grody and Weng (2008, desert)

From snow cloud to snow pack to ice



From snow cloud to snow pack to ice



State of the art approaches to calculating ext, ssa, g:

Non-interacting non-spherical scatterers (e.g. snow aggregates)

Patrick Eriksson, Philippe Chambon presentations

Dense agglomerations of individual simple scatterers (e.g. ice spheres), interacting, with structure by autocorrelation function:

- Improved Born approximation (IBA)
- Dense media radiative transfer (DMRT)

Melody Sandells presentation

Scattering from air, brine and water bubbles and irregularities

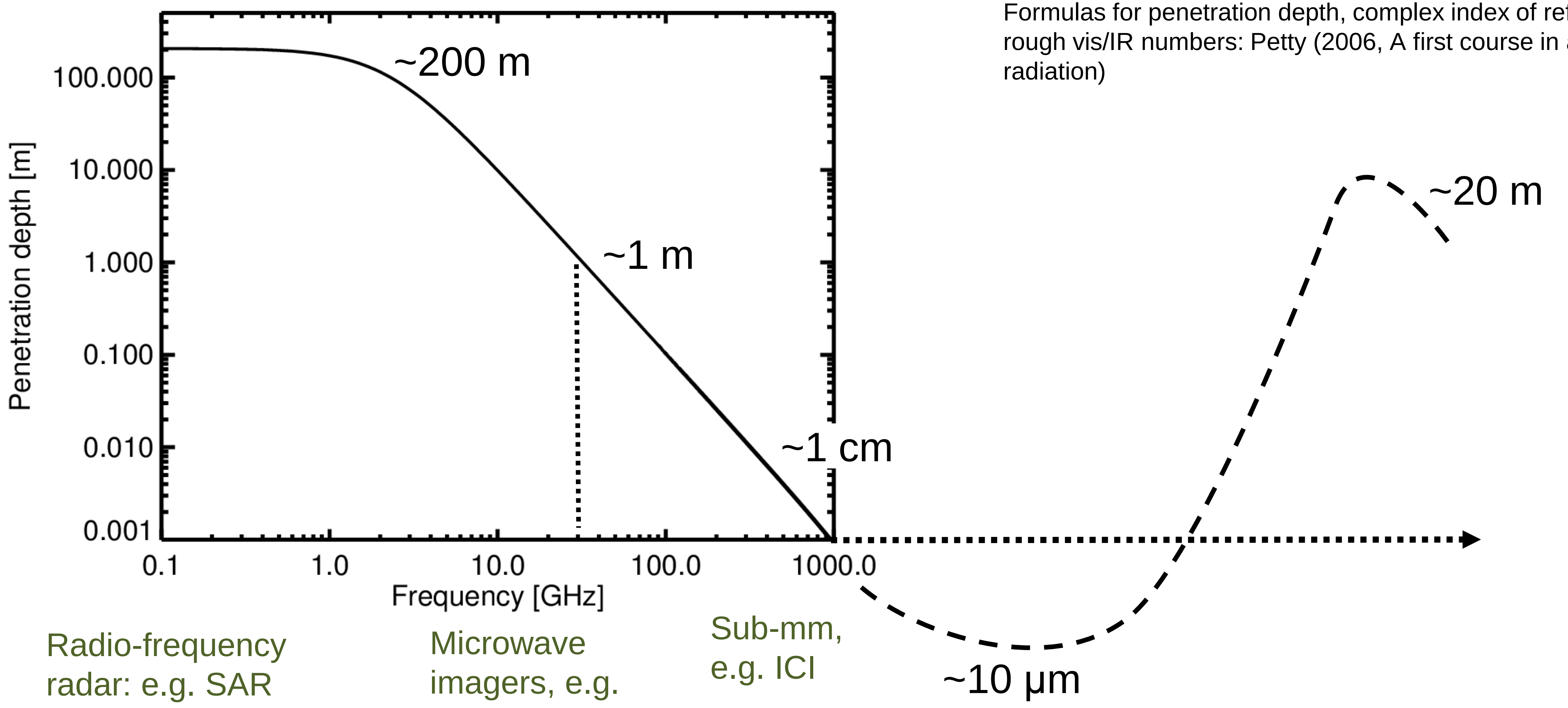
Gunnar Spreen presentation

Absorbing (not scattering)

Pure solid water ice: penetration depth

Relative permittivity of ice at 263.0 K (up to ~1000 GHz): Mätzler (2006, Microwave dielectric properties of pure ice)

Formulas for penetration depth, complex index of refraction, rough vis/IR numbers: Petty (2006, A first course in atmospheric radiation)



Radio-frequency radar: e.g. SAR

L-band e.g. SMOS

Microwave imagers, e.g. AMSR2

Humidity sounders, e.g. MHS

Sub-mm, e.g. ICI

Hyperspectral infrared., e.g. IASI

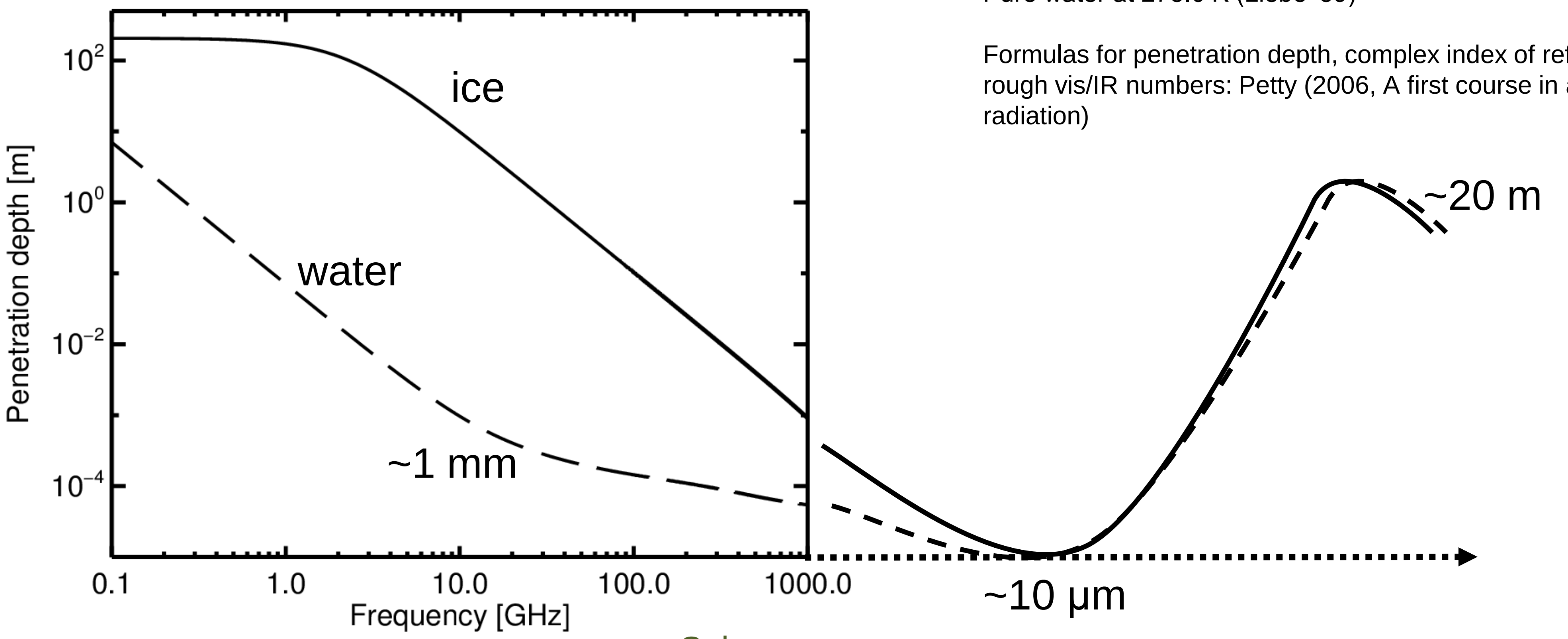
Visible

Water and ice: penetration depth

Relative permittivity of pure ice at 263.0 K (up to ~1000 GHz): Mätzler (2006, Microwave dielectric properties of pure ice)

Pure water at 278.0 K (Liebe '89)

Formulas for penetration depth, complex index of refraction, rough vis/IR numbers: Petty (2006, A first course in atmospheric radiation)



Radio-frequency radar: e.g. SAR

L-band e.g. SMOS

Microwave imagers, e.g. AMSR2

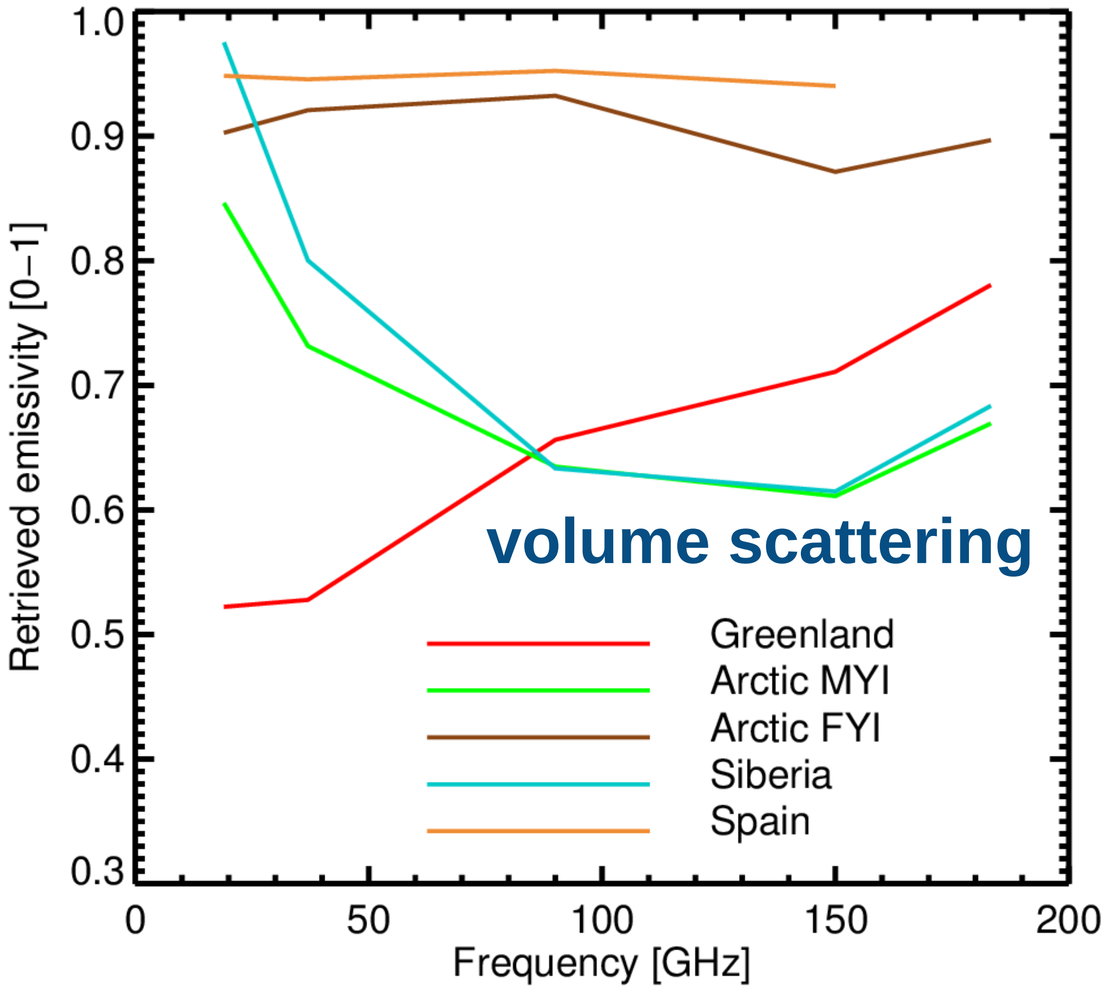
Sub-mm, e.g. ICI

Humidity sounders, e.g. MHS

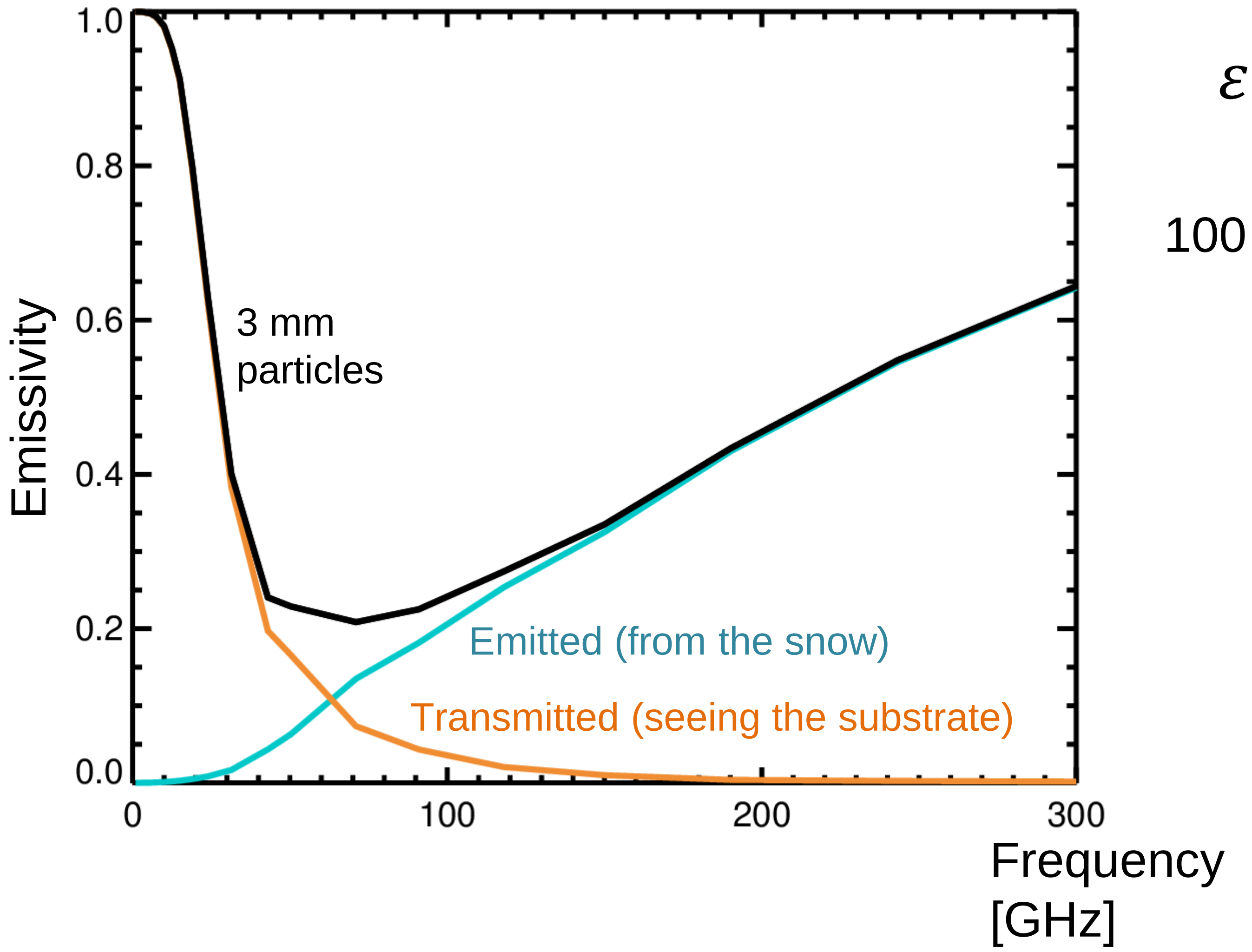
Hyperspectral infrared., e.g. IASI

Visible

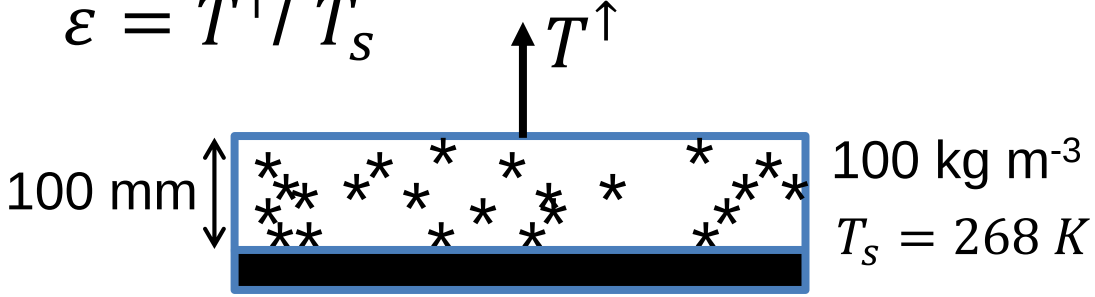
Retrieved surface emissivity spectra from DMSP-F17 SSMIS: h-polarisation



Non-interacting hail particles (a “very thick cloud” approximation)



$$\varepsilon = T^{\uparrow} / T_s$$

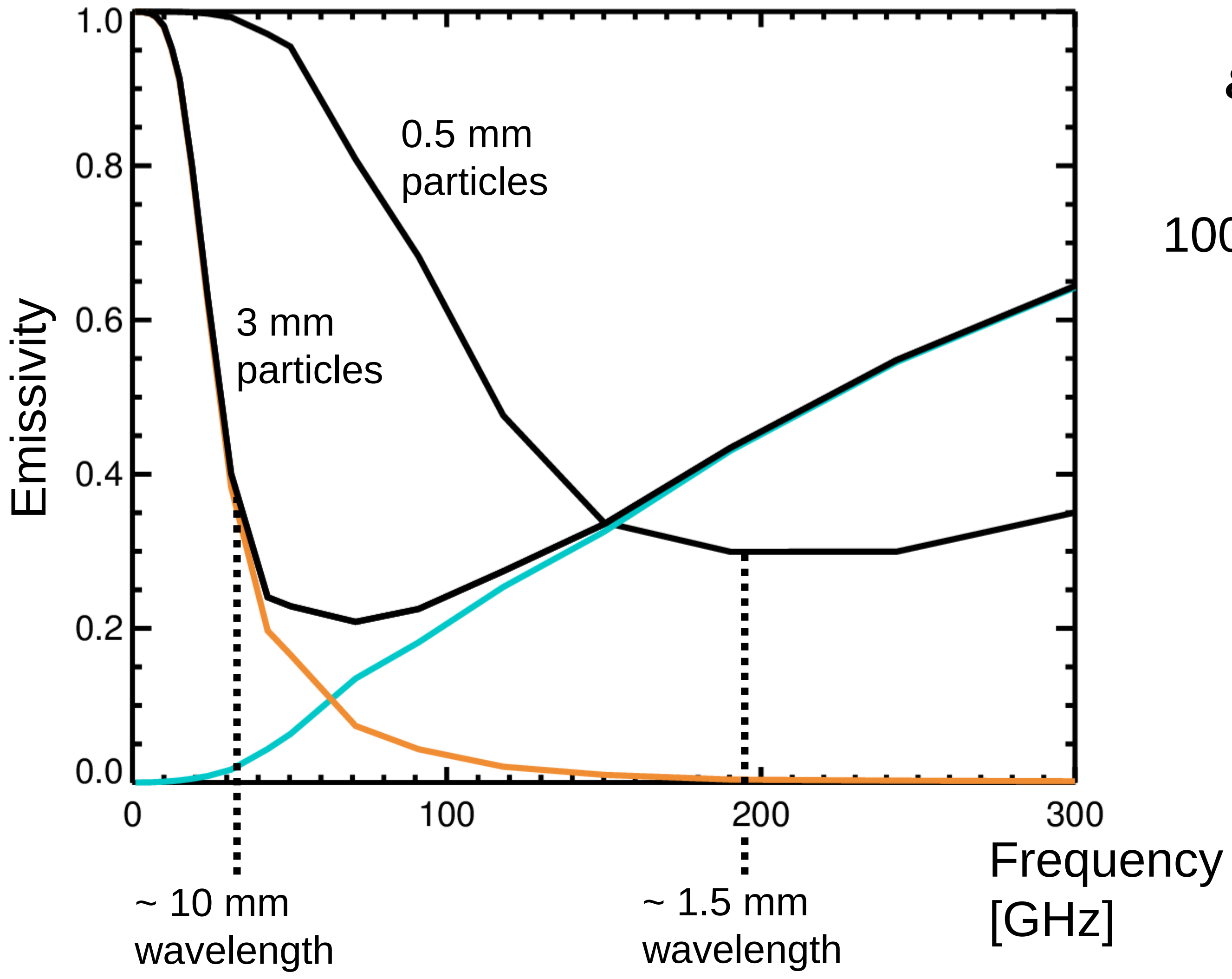


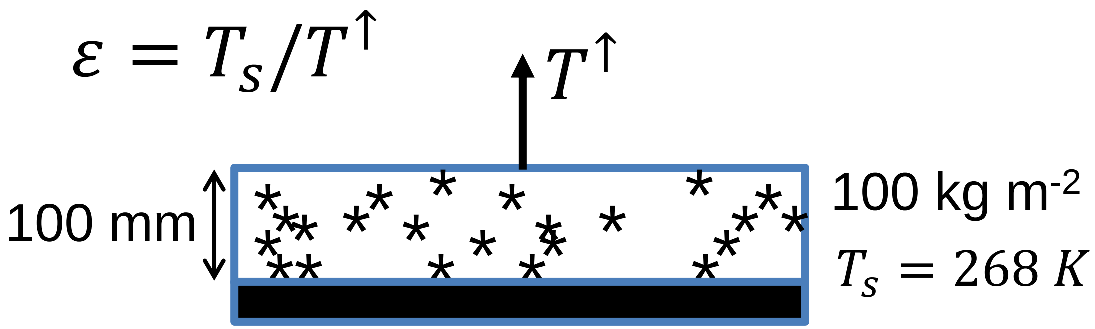
2-stream radiative transfer approximation (as Geer et al., 2021, https://doi.org/10.5194/gmd-2021-73)

Substrate (blackbody) at 268.0 K. No downwelling radiation from the atmosphere.

ARTS scattering database ICON hail particle (Eriksson et al, 2018, https://doi.org/doi: 10.5194/essd-10-1301-2018)

Non-interacting hail particles (a “very thick cloud” approximation)





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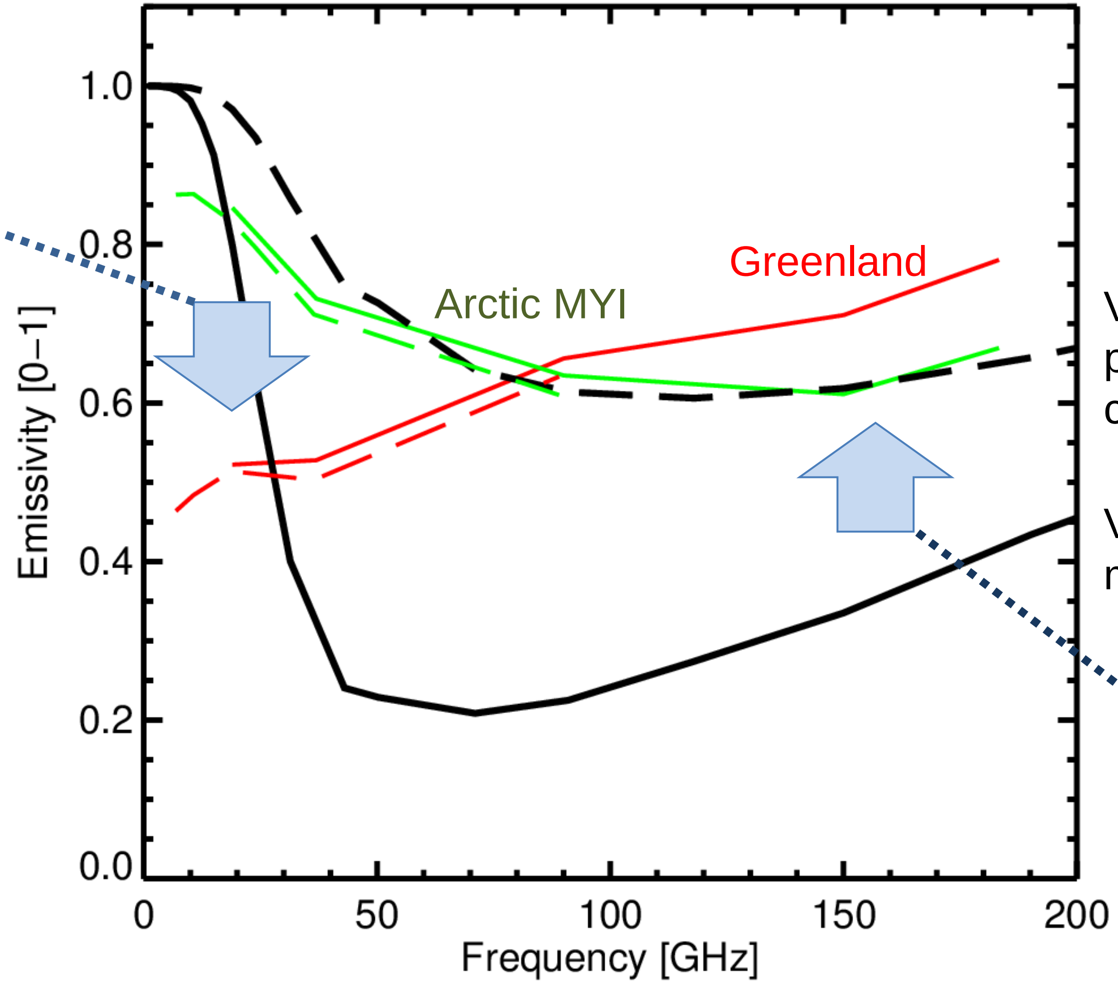
Retrieved surface emissivity spectra from AMSR2, F17 SSMIS, h-polarisation + modelled equivalents

Scattering processes needed on a cm-scale:
- fluctuations in dense media
- reflections from ice layers
- boundary roughness



Very thick cloud: 3 mm hail particles + additional constant absorption

Very thick cloud: 3 mm hail particles

Absorbing processes needed – liquid water? **OR** snowpack temperature much warmer than Tskin

Snow Microwave Radiative Transfer – Picard et al. (2018)

https://doi.org/10.5194/gmd-11-2763-2018

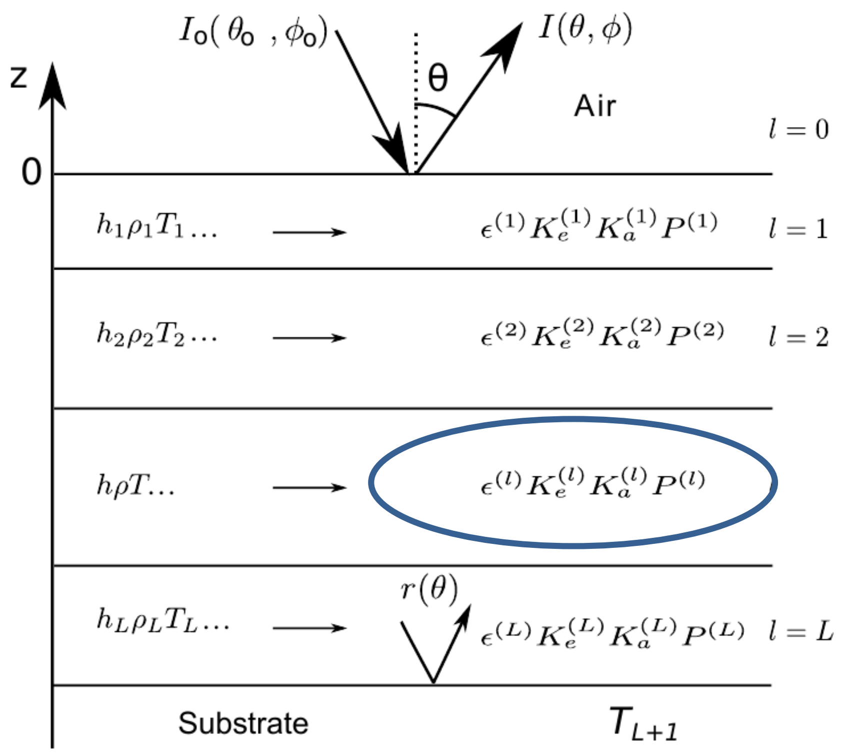


Figure 1. Multilayered medium modeled by SMRT. The incident radiation I_o comes either from a radar beam (active mode) or from the sky (passive mode with atmospheric contribution).

- Discrete ordinate radiative transfer
- Treatment of reflection at layer boundaries
- Flexible model allowing most current theories of snow radiative transfer to be tested.
- Mainly employed at 37 GHz and below so far

The common language: optical properties: extinction, absorption, phase function

Practical “stage 2” surfaces

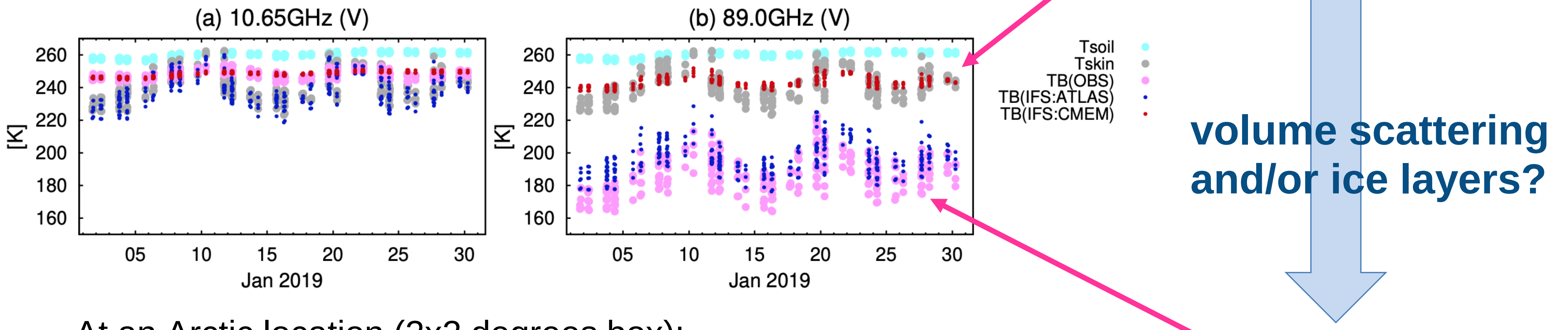
… other processes that need modelling

- Snow and ice:
  - Ice layers, layer reflection/refraction, layer roughness
- Vegetation
  - Full of water = microwave absorption
- Soil
  - Roughness
  - Dielectric model
  - Moisture dependence

See Catherine Prigent and Patricia de Rosnay presentations

Full physical modelling of snow – CMEM + RTTOV

- Hirahara et al. (2020) https://doi.org/10.3390/rs12182946



At an Arctic location (2x2 degrees box): timeseries of modelled and observed brightness temperature

See Patricia de Rosnay's presentation

Why not just run a full physical model for surface radiative transfer?

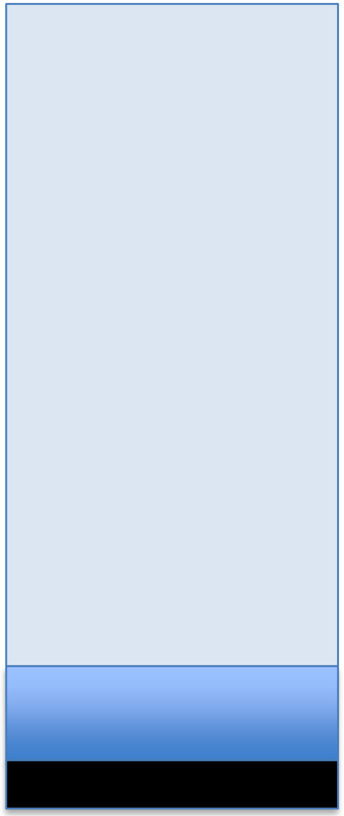
- Current state-of-the-art is broadly only valid up to 20 GHz
  - And even low-frequency surface optical properties are a work in progress
  - (but the results presented by Melody Sandells with SMRT showing good agreement at 89 – 243 GHz could be a game changer)

See Melody Sandells' presentation

- Parameters feeding into the optical properties are extremely heterogeneous both locally and globally, in time and space

- Radiation depends most strongly on quantities that are not forecast or accurately known
  - E.g. radiation-relevant "grain size" of snow (microstructure)

Possible “stage 2” framework for all-surface assimilation of satellite radiances



All-sky, scattering atmosphere

Scattering surface media layer

Non-scattering substrate

No complete physical theory for this?:

- **Semi-empirical models**
- **Fully empirical (ML)**
- **Auxiliary control variables in 4D-Var**

Common language across frequencies and across snow, desert, sea-ice etc.:

- **optical properties**
- **temperature profile**

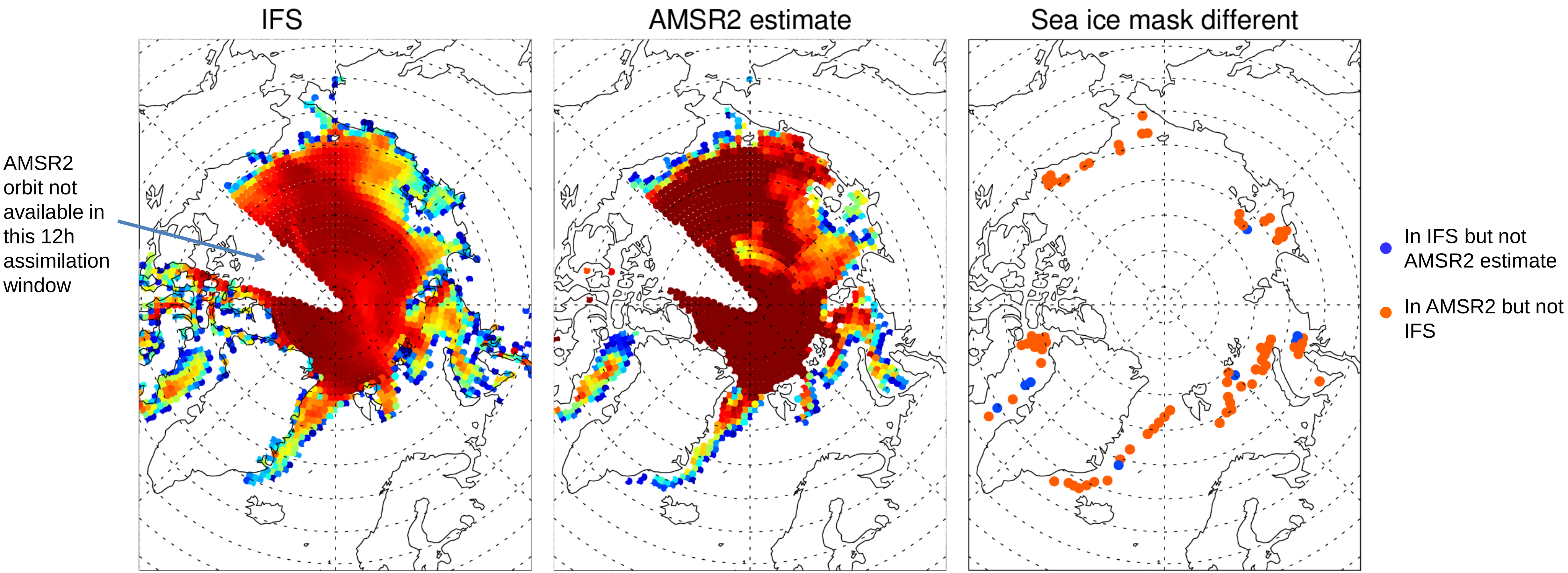
E.g. variables exchanged with surface models:

- **Sea-ice concentration**
- **Temperature profile**

Benefits of doing this

Sea-ice retrieved in atmospheric DA in cycle 48r1 package

Sea-ice fraction (0-1, blue-red), 20th June 2019, *at AMSR2 locations*



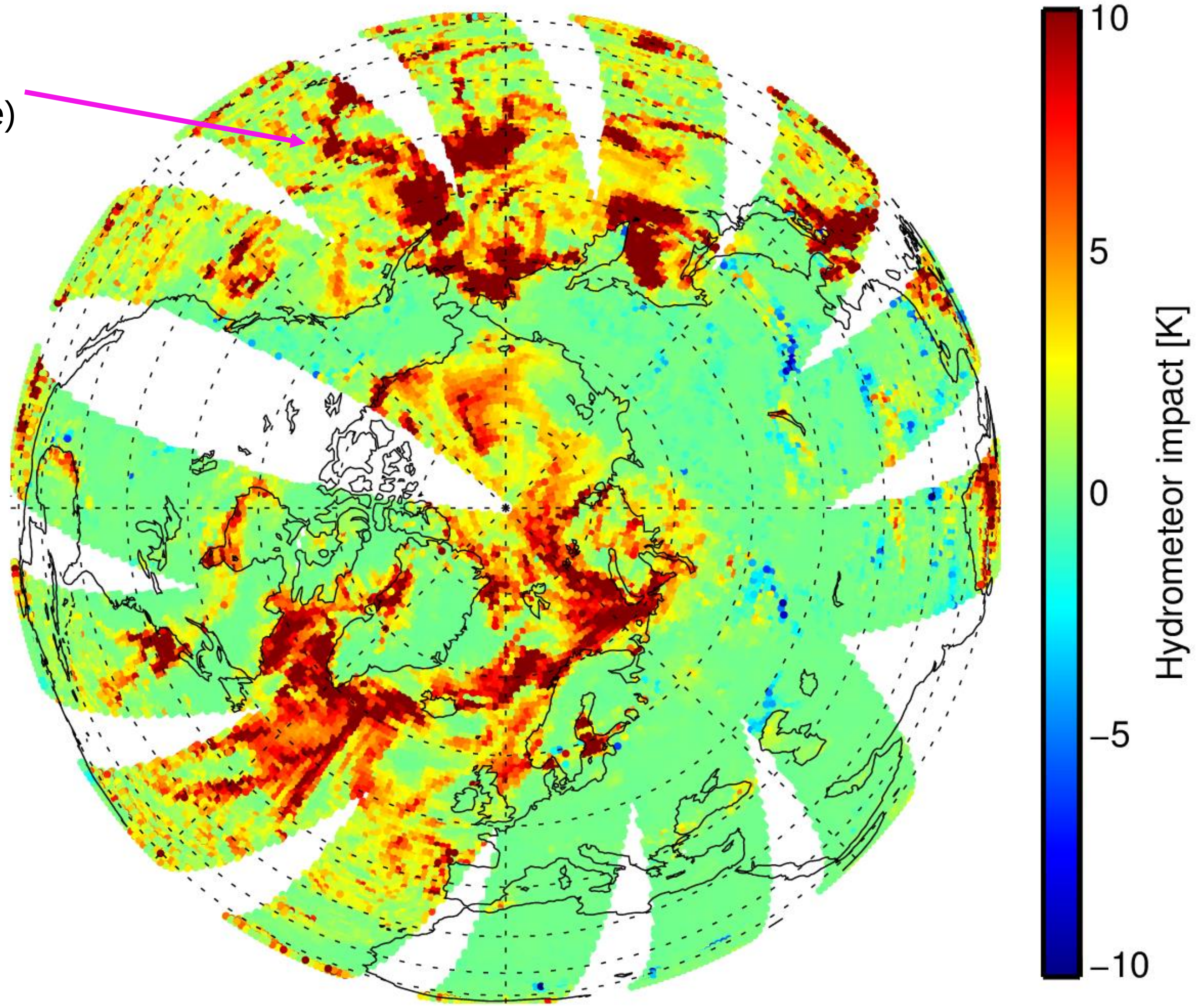
Now based on OSTIA assimilation into OCEAN5 – quite accurate

Simple sea-ice fraction estimate from 10 GHz AMSR2, made as part of atmospheric DA

Difference in sea-ice masks based on 5% fraction

Simulated sensitivity to cloud and precipitation: 36.5 GHz (v-pol)

Hydrometeor impact reaches >30K in precipitation (off-scale)



Simulated all-sky TB minus simulated clear-sky TB at AMSR2 locations (26th June 2019, 00 UTC window)

All-surface radiance assimilation: conclusions

- The dinosaur egg
  – The biggest remaining *geographical* gap for atmospheric data assimilation is the use of satellite radiances that are sensitive to the non-ocean surface: particularly sea-ice, snow, winter, high altitude, but even normal summer vegetation, soil
- To solve the radiative transfer physics problem is to solve the surface problem
  – **Optical properties (and temperature profile)** are the links to the surface schemes (sea-ice, snow, soil etc.)
  – But optical properties depend on microstructural details that vary wildly (time and space) and are not fully represented in forecast models or analyses

parallels to all-sky radiance assimilation →

- Essential supporting technologies:
  – DA, 4D-Var, particularly auxiliary control variables
  – Empirical modelling, e.g. ML (but not where appropriate physics is available)
  – Coupled assimilation
- Benefits:
  – Atmosphere (e.g. low cloud over land)
  – Coupled assimilation (sea-ice, snow, soil-moisture, SST etc.)