Sub-Footprint Inhomogeneities and Their Influence on Global-to-Regional NWP Data Assimilation

Lukas Muser, Ch. Köpken-Watts (DWD, Germany)

Accurate data assimilation in NWP requires accurate characterization of both model and observation errors. In this context, observation errors encompass not only instrument uncertainties but also forward operator uncertainties and representativeness errors, e.g., from scale mismatches. As NWP horizontal resolutions increase, model grid cells often become smaller than satellite footprints, allowing multiple grid points within a single field of view (FOV). However, most current assimilation systems simulate radiances from only one model profile, neglecting sub-footprint variability in surface properties (vegetation, soil type, land–sea fraction, skin temperature) and atmospheric conditions (T, humidity, cloud cover, liquid/ice profiles). Quantifying these sub-footprint effects is essential for developing flow- and situation-dependent observation error components.

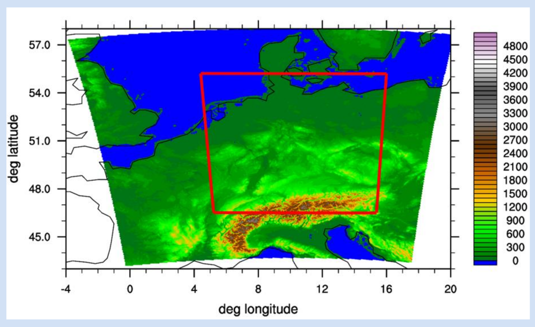
Database

NWP model data are used here, to study the effect of inhomogeneities within satellite footprints (FOVs). Whilst this does not necessarily represent fully the true inhomogeneity, such model background information is available within the data assimilation context and can potentially be used for the setting of a flow dependent observation error component for each observation location.

Global Dataset: ICON DREAM reanalysis
37 days x 4 times = 370 dates over 2024
13 km horizontal grid

Regional Data: ICON D05 deterministic forecast
44 dates (12 UTC) over 2025
500 m horizontal grid

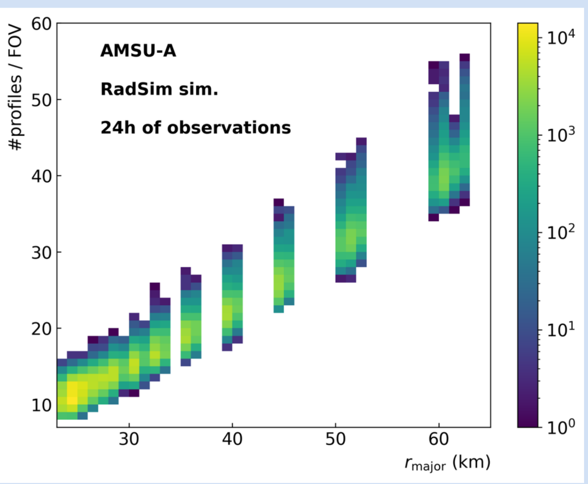
Satellite Inst.:
AMSU-A $r_{maj} \approx 20-60$ km
MHS $r_{maj} \approx 8-20$ km
SEVIRI $r_{maj} \approx 4-6$ km



Approximate location and size of ICON D05 domain

RTTOV v14.1 with RadSim v4.1 used as a forward model

FOV Averaging



Number of ICON (13 km) profiles in one AMSU-A FOV.

Note: No FOV averaging applied in current operational data assimilation!

Calculate TOA radiance (RTTOV v14.1) for each ICON profile

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Find neighbouring profiles that lie within FOV

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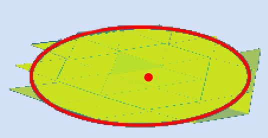
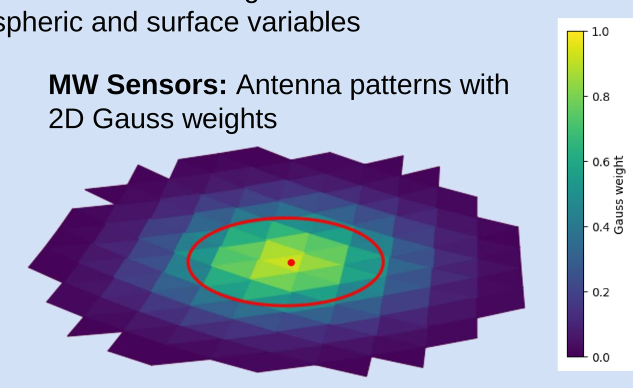
Calculate weighted mean of FOV averaged radiance as well as atmospheric and surface variables

VIS and IR Sensors: no weights



MW Sensors: Antenna patterns with 2D Gauss weights



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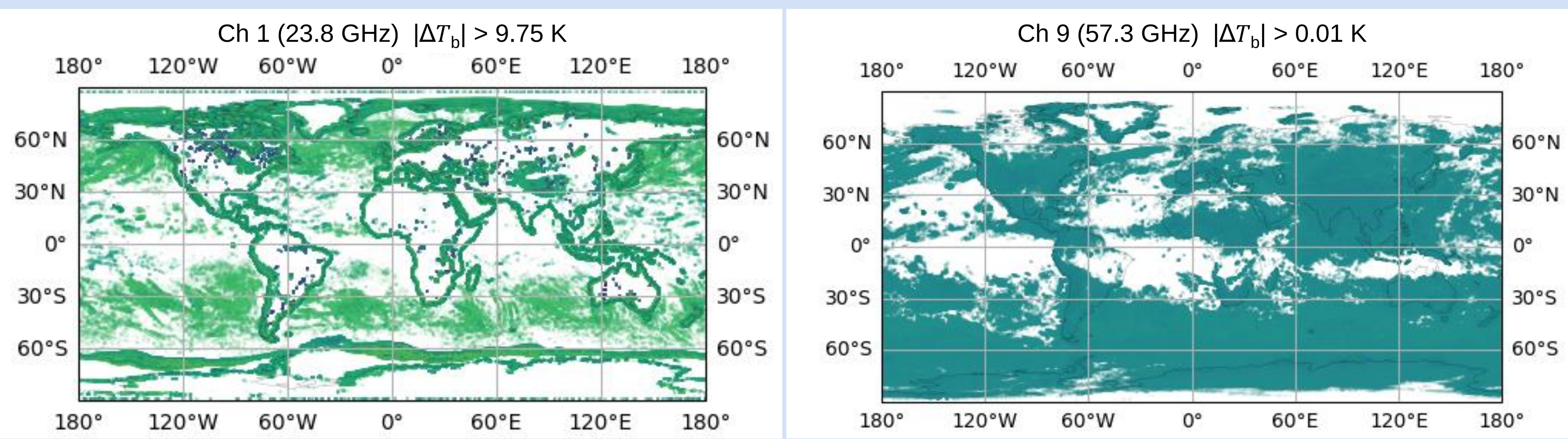
Evaluate $\Delta T_b = T_{b,\text{ single-profile}} - T_{b,\text{ fov avg}}$

Location of largest $|\Delta T_b|$

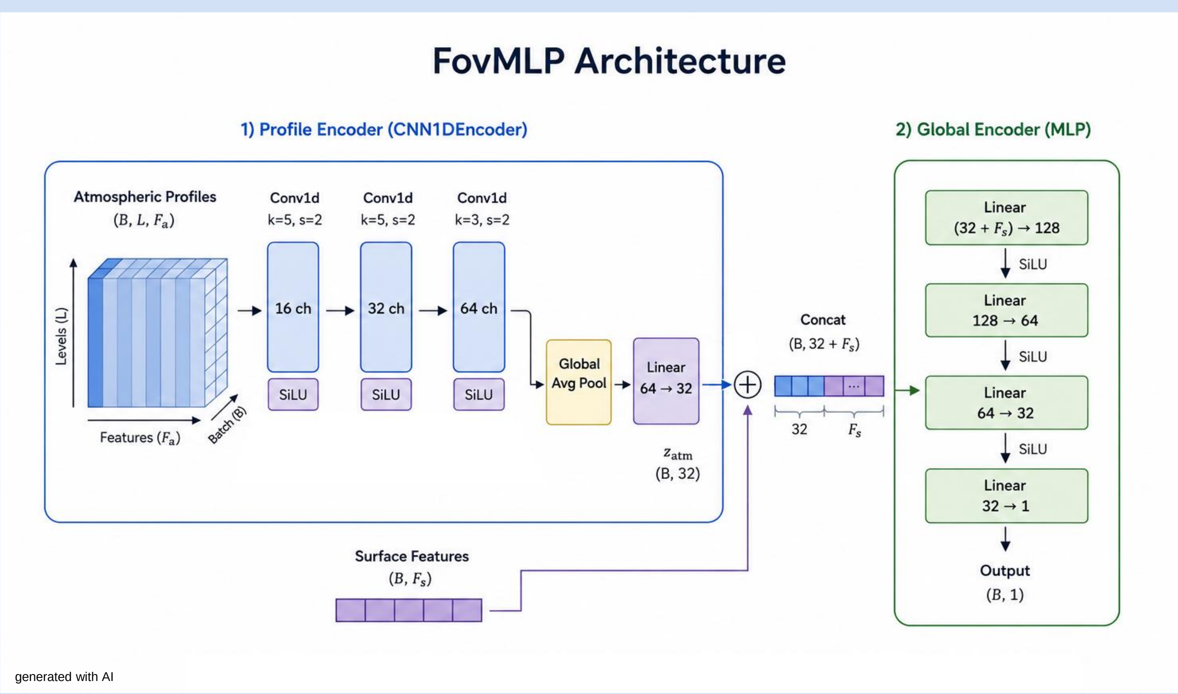


Geographical distribution of $|\Delta T_b|$ that is larger than the 95th percentile. The 95th percentile is calculated for each channel individually.

Window channels: $|\Delta T_b|$ strongly depends on FOV inhomogeneities of surface emissivity and skin temperature.
If sea ice and coast lines are filtered, $|\Delta T_b|$ is more homogeneously distributed, with maximum values mainly over the ocean (*not shown here*).

Atmospheric sounding channels: Sub-satellite footprint inhomogeneities estimated from model fields do not seem to have a large influence on $|\Delta T_b|$. Variations can arise both from temperature and humidity as well as cloud conditions like liquid water, ice, rain or snow.

Outlook: Situation Aware Representativeness Error



Aim: study the use of a ML approach for characterizing the deviation between a FG brightness temperature based on RT simulations using a single profile or all profiles within a FOV.

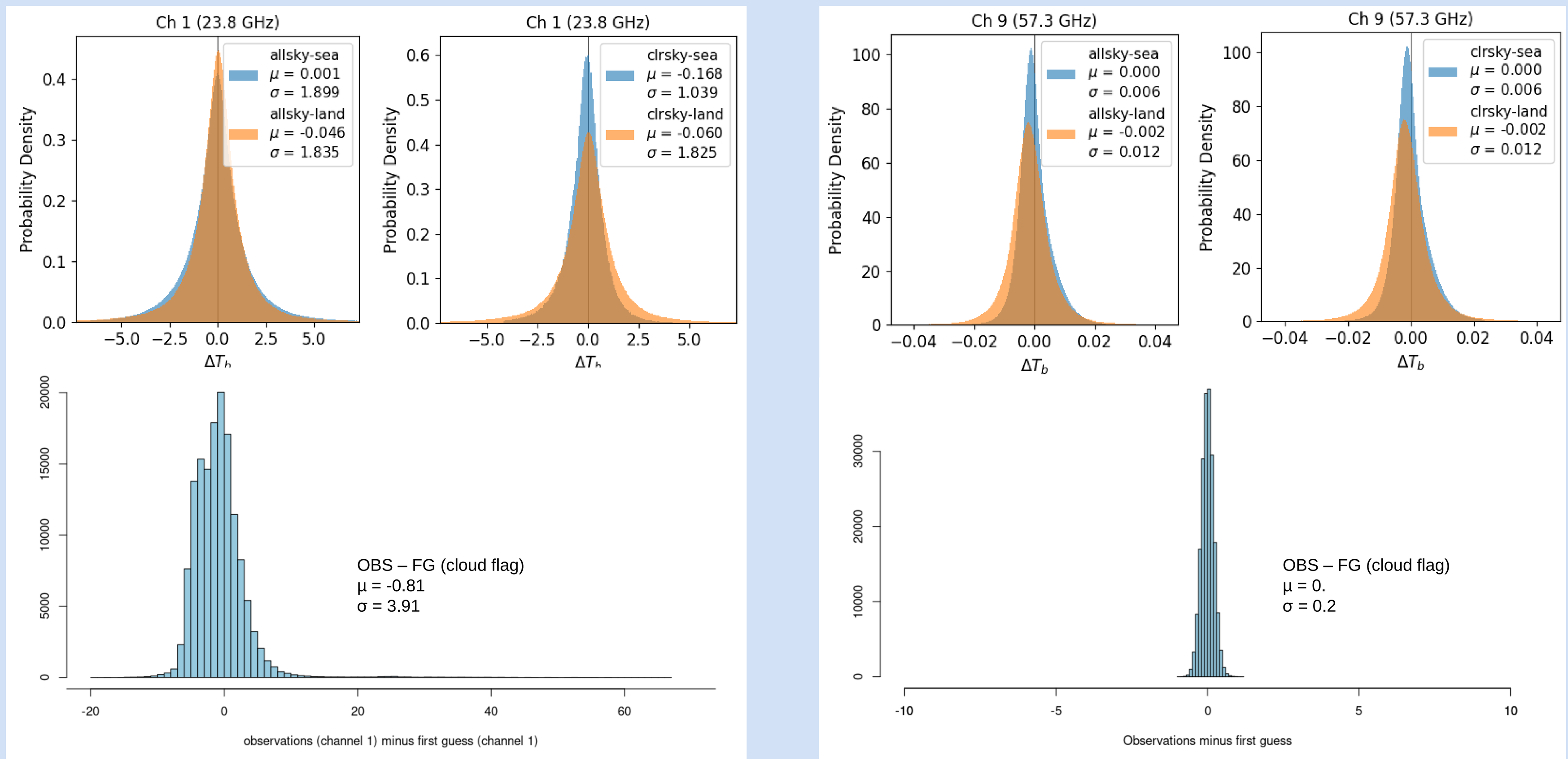
Labels: ΔT_b
Features: The Δ of atmospheric and surface variables that serve as RTTOV inputs between single profile and FOV averaged values (compare with ΔT_b).

- Standardised (level wise) with mean and standard deviation

Loss: Weighted Huber Loss to focus more on non zero labels

Distribution of ΔT_b

AMSU-A

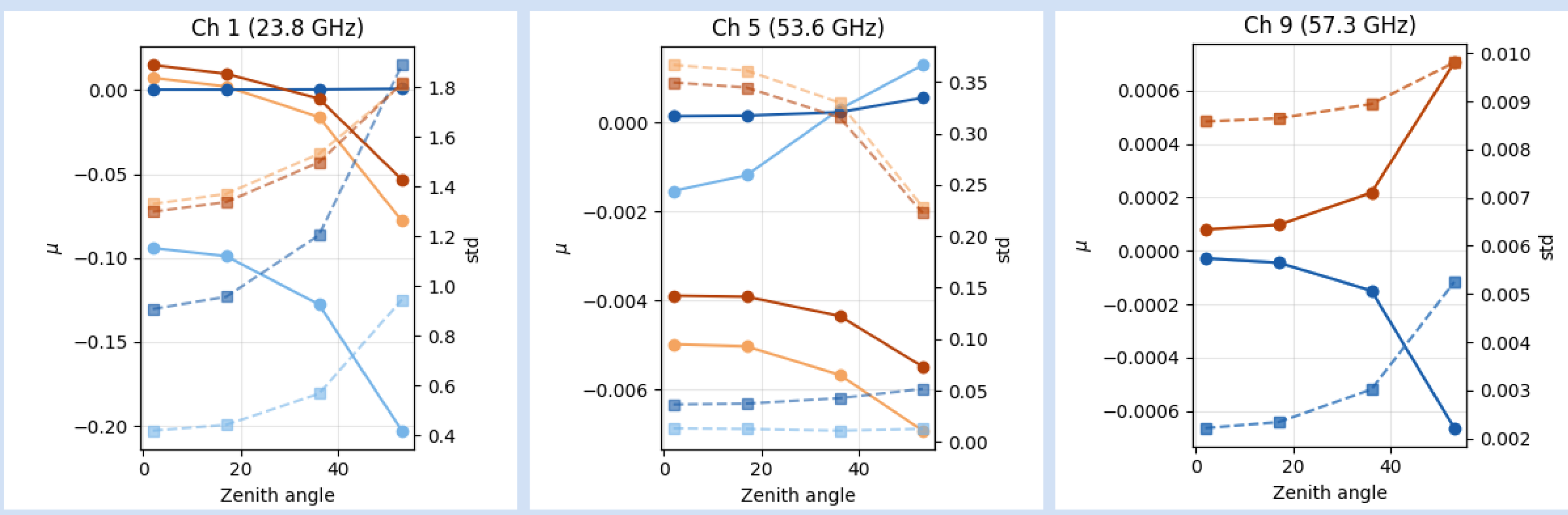


Distribution of ΔT_b for two channels of simulated AMSU-A data under all-sky (left sub-panel) and clear-sky conditions (right sub-panel). The blue histogram shows data for footprints that only contain sea points, the orange histogram for land points. The lower figures show OBS – FG (observation minus first guess) statistics of the operational global data assimilation system of DWD for the channel 1 and 9 of AMSU-A.

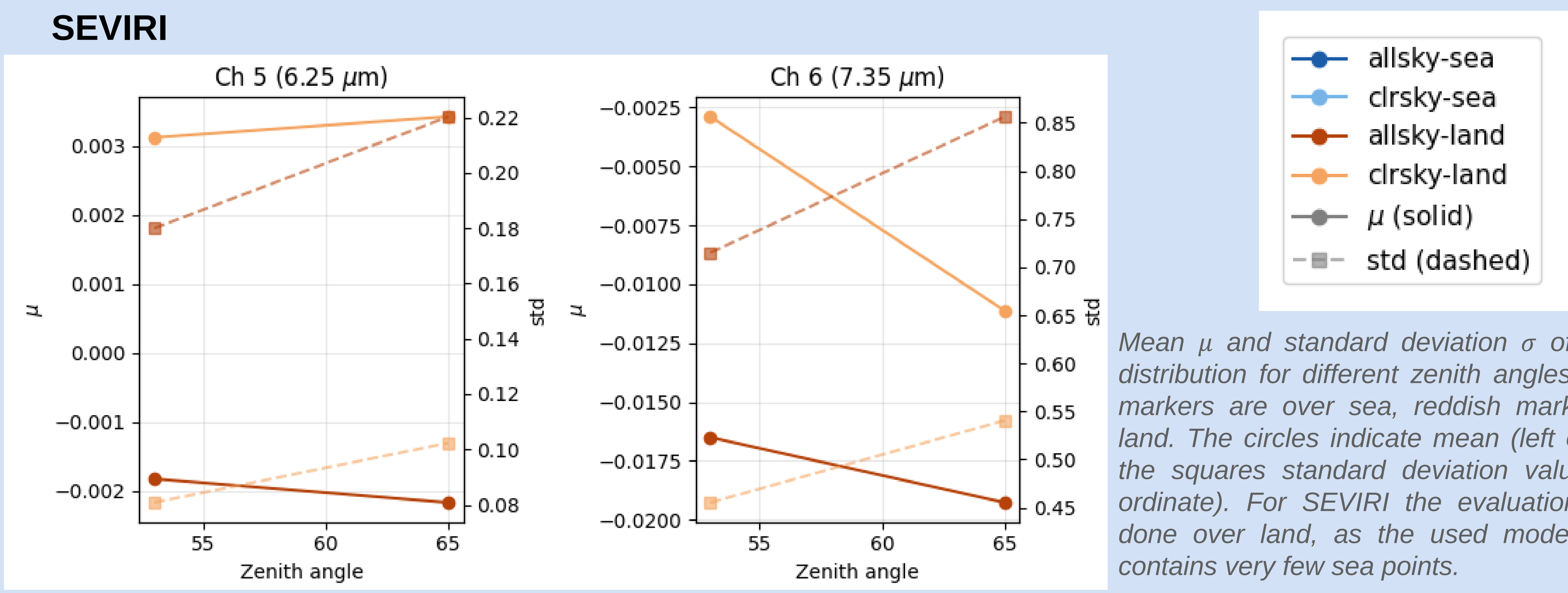
Window channels: Sub-satellite footprint inhomogeneities increase σ of the ΔT_b distribution mainly over sea. Differences in ΔT_b due to sub-satellite footprint inhomogeneities are at the same order of magnitude as OBS – FG errors.

Atmospheric sounding channels: Almost no difference between all-sky and clear-sky. Differences in ΔT_b due to sub-satellite footprint inhomogeneities (when estimated based on model fields) are significantly smaller than OBS – FG errors.

AMSU-A



SEVIRI



Mean μ and standard deviation σ of the ΔT_b distribution for different zenith angles. Blueish markers are over sea, reddish markers over land. The circles indicate mean (left ordinate), the squares standard deviation values (right ordinate). For SEVIRI the evaluation is only done over land, as the used model domain contains very few sea points.

The **mean** μ of the ΔT_b distribution is usually close to 0. Hence, neglecting sub-footprint inhomogeneities does not introduce a systematic bias. The same behaviour is seen for SEVIRI and MHS channels (*not shown here*). An exception are the clear-sky conditions over sea for surface sensitive MW channels. In this case, neglecting sub-footprint inhomogeneities introduces a cold bias in the order of $0.1-1$ K. Additionally, there is a tendency of the bias to increase in magnitude with an increasing zenith angle for all instruments and channels.

The **standard deviation** σ of the ΔT_b distribution for MW instruments is typically largest for surface sensitive channels, but reduces significantly for atmospheric sounding channels. Systematically, σ is larger over land for almost all MW channels. Similar to μ, the σ value tends to increase with increasing zenith angle. An exception are AMSU-A channels 4 to 7. The increased length of the radiation path due to increased zenith angle shifts the sounding height to higher altitudes, hence, less surface influence and different atmospheric conditions.
Sub-footprint inhomogeneities in cloud variables only seem to play a role over sea for some MW channels (AMSU-A ch 1, 2, 3, 15 and MHS ch 1, 2, 5), however, VIS and IR also show a strong effect over land with a large difference in σ between all-sky and clear-sky conditions.

Based on the evaluated NWP model data:

- Negligible representativeness error for AMSU-A temperature sounding channels which have no or only little surface sensitivity
- Largest $|\Delta T_b|$ for surface sensitive channels
- Sub-footprint inhomogeneities in cloud variables mainly play a role in VIS and IR channels as well as surface sensitive MW channels

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Dr. Lukas Muser
EUMETSAT Research Fellow
DWD, Germany
Lukas.muser@dwd.de