Importance of Remote Sensing Observation in Reanalysis Data

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OUTLINE:

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- Introduction: Reanalysis and their importance
- Use of Reanalysis data in Machine Learning.
- CARRA2 Reanalysis
- Importance and Use of Satellite Observations.
- Error Statistics of Clear-sky Microwave and Infrared Radiances in Observation Space.
- Error Statistics are derived from a separate run and analysis valid on January 2023.
- Summary and Conclusion.

Reanalysis

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Meteorological reanalyses provide the most accurate estimate of the atmospheric state by combining NWP systems with historical observational data for any location and time period.

The use of reanalysis data in climate studies and machine learning has grown rapidly, despite known biases in both model and observations.

Modern reanalyses are better at correcting these biases thanks to the increased availability of high-quality observations, improved forecast models, and advances in data assimilation techniques.

Reanalysis and Machine Learning:

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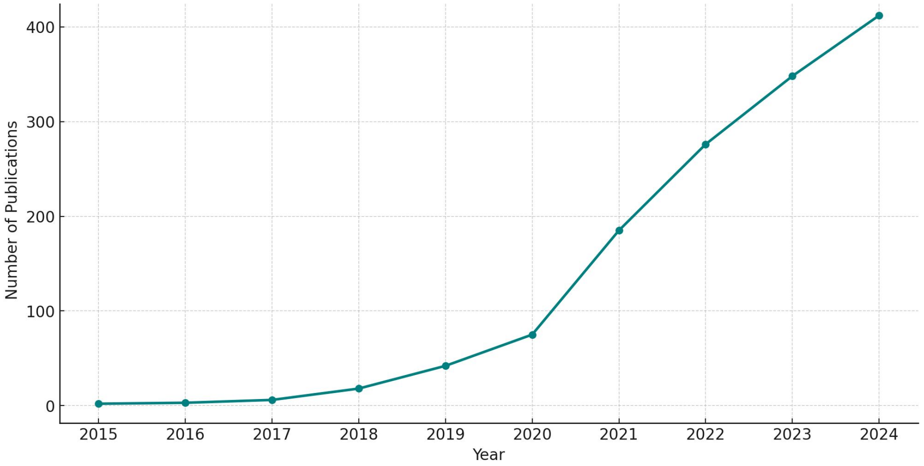
Reanalysis datasets are widely used in Machine Learning because they provide large-scale, consistent weather, and long-term climate records.

- High-Quality Training Data.
- Benchmarking & Model Validation.
- Downscaling & Bias Correction.
- Learn observation operators.

Publication using machine learning and ERA5 reanalysis data (2015-2024)



ERA5 – ECMWF (31 km).
https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview

CERRA - Copernicus European Regional Reanalysis, (5.5 km). (Martin Ridal et al. https://doi.org/10.1002/qj.4764)

CARRA- Copernicus Arctic Regional Reanalysis (2.5 km)
https://climate.copernicus.eu/copernicus-arctic-regional-reanalysis-service

Before 2018: <10 papers.
2018–2020: ~50–100 papers yearly.
2021–2023: >300 papers yearly.
2024: estimate ~400–500 publications.

@ google scholar

Copernicus Arctic Regional Reanalysis (CARRA2)

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Copernicus Arctic Regional Reanalysis Second Generation (CARRA2) a reanalysis product that extends to a larger area to provide pan-Arctic coverage.

Model: Harmonie-AROME, Horizontal Resolution: 2.5 km, Grid Points: 2880x2880, Vertical levels : 65
Data Assimilation: 3D-VAR for upper air observation assimilation from both in-situ and satellite sensors.

Ensemble Prediction System (EPS) for B-Matrix:

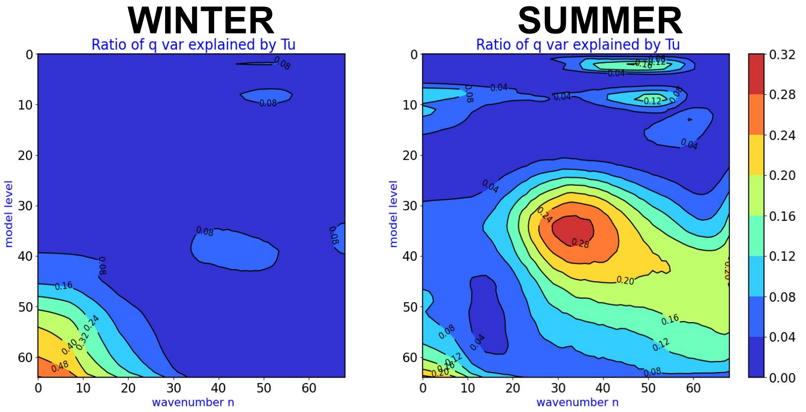
- 9-member and a control.
- IC/BCs use members of an **ERA5 EDA** 10-ensemble members.

Cost Function:

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}_b) + \frac{1}{2}(\mathbf{y} - \mathbf{h}(\mathbf{x}))^T \mathbf{R}^{-1}(\mathbf{y} - \mathbf{h}(\mathbf{x}))$$

$$\mathbf{B} = \begin{pmatrix} \langle \varepsilon_1^2 \rangle & \langle \varepsilon_1 \varepsilon_2 \rangle & \cdots \\ \langle \varepsilon_2 \varepsilon_3 \rangle & \langle \varepsilon_2^2 \rangle & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

STATIC



Percentage of the variance of specific humidity that is explained by unbalance temperature (Tu) as a function of height and wave number.

Conventional Assimilated Observation

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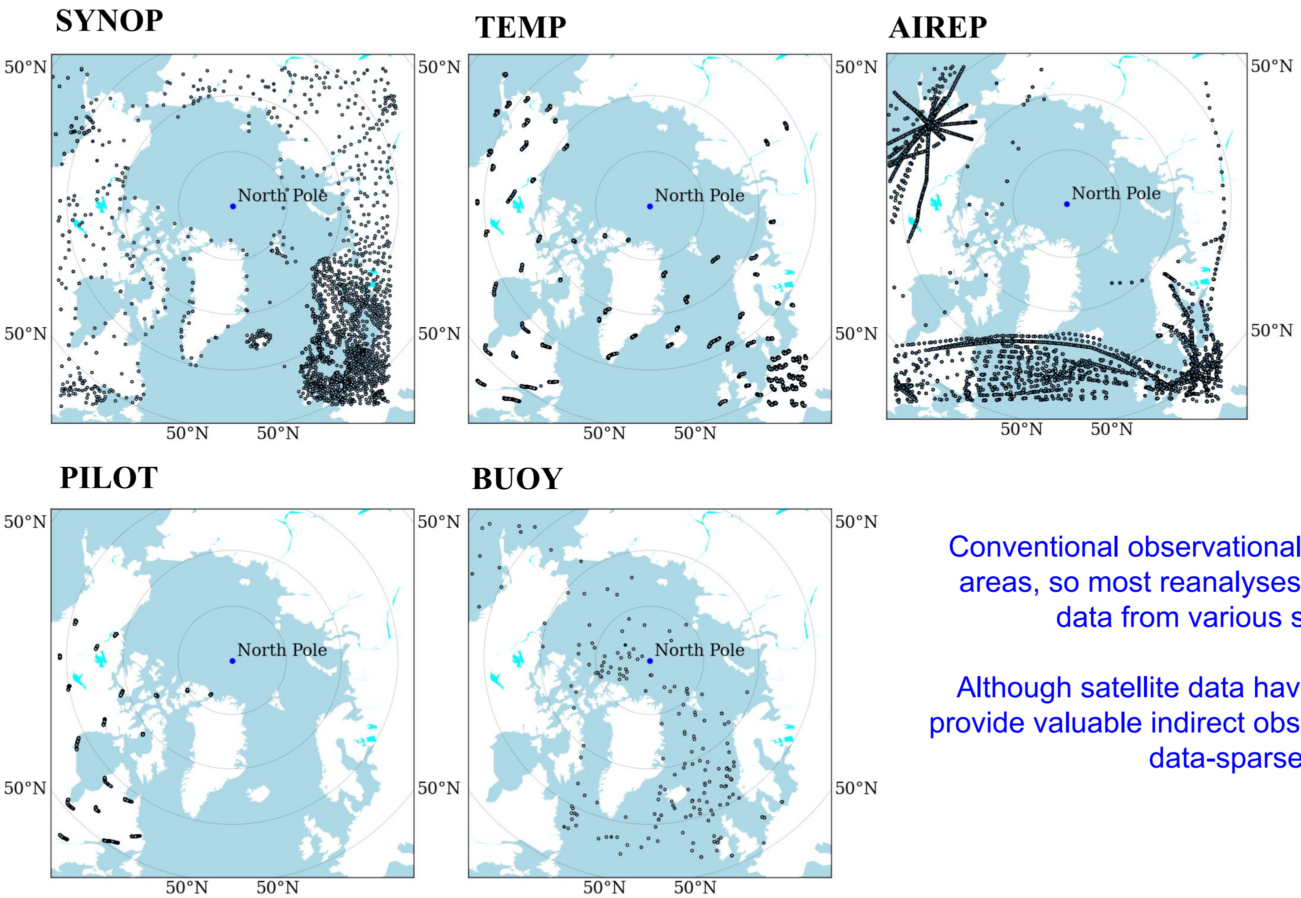
Valid on 20230111 at 00 UTC



Conventional observationals are sparse over ocean areas, so most reanalyses rely on remote sensing data from various satellite sensors.

Although satellite data have their own biases, they provide valuable indirect observations that cover many data-sparse regions.

Satellite Radiances in CARRA2

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Instrument	Satellites	Period	More Information (https://space.oscar.wmo.int)
AMSU-A	NOAA 15-19, EOS-Aqua, Metop-A, Metop-B, Metop-C	1999 -	• Advanced Microwave Sounding Unit - A • 15 channels • Resolution: 48 km
ATMS	S-NPP, NOAA-20, NOAA-21	Sep, 2012 -	• Advanced Technology Microwave Sounder • 22 channels • Resolution: 16 km s.s.p. for channels 165-183 GHz, 32 km for channels 50-90 GHz, 75 km for channels 23-32 GHz
IASI	Metop-A, Metop-B, Metop-C	2007 -	• Infrared Atmospheric Sounding Interferometer • 8461 channels • Resolution 4 x 12-km IFOV (sampling distance: 24 km)
CrIS	S-NPP, NOAA-20, NOAA-21	Sep, 2012 -	• Cross-track Infrared Sounder Resolution • 1305 Channels • 3 x 3 14 km IFOV covering a 48 x 48 km^2 cell (average sampling distance: 16 km)
MSU	NOAA-11, NOAA-12, NOAA-14	1991-2007	Microwave Sounding Unit
MWHS-2	FY-3C, FY-3D, FY-3E	Dec, 2015 -	Microwave Humidity Sounder -2
AMSU-B/ MHS	NOAA 16-19, Metop-A, Metop-B, Metop-C	2001 -	Advanced Microwave Sounding Unit - B

Observation data retrieval process for CARRA collects these 6-hour datasets from the archives and combines observation files for intermediate cycles at 03, 09, 15, and 21 UTC. For instance, for the 09 UTC cycle, observations from 06 and 12 UTC are merged.

Personal communication with Per Dahlgren (Met-Norway)

and https://climate.copernicus.eu/copernicus-arctic-regional-reanalysis-service

Advanced Microwave Sounding Unit (AMSU-A)

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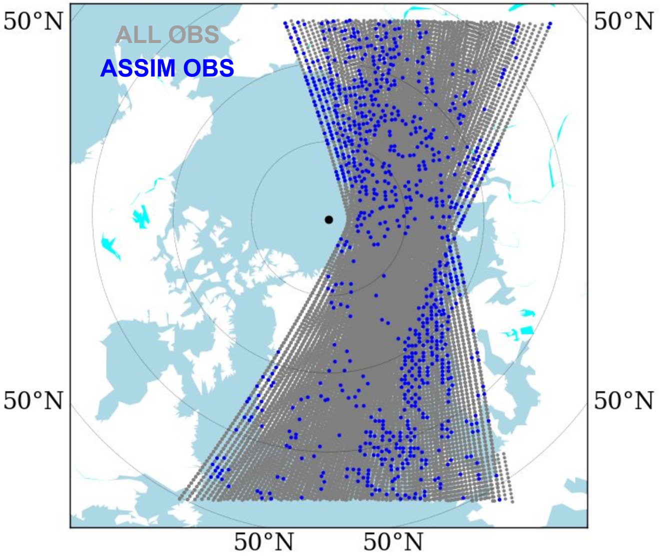
The Advanced Microwave Sounding Unit (AMSU-A), a 15-channel microwave sounder designed primarily to obtain temperature profiles in the upper atmosphere and to provide a cloud-filtering capability for tropospheric temperature observations.

- ➔ 15 channel (AMSU-A) with a frequency range of 15-90 GHz
- ➔ Channel 6, 7, 8, 9 are assimilated.
- ➔ Channel 5 (~53.59 GHz) is more surface sensitive.
- ➔ Near global coverage twice per day.
- ➔ Utilization period 1998-2027.

Channel-6

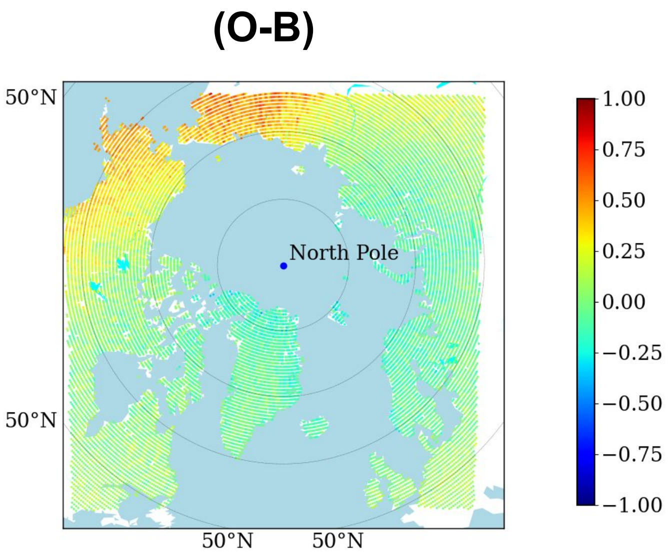
Valid on 2023-01-15 at 12 UTC assimilation cycle

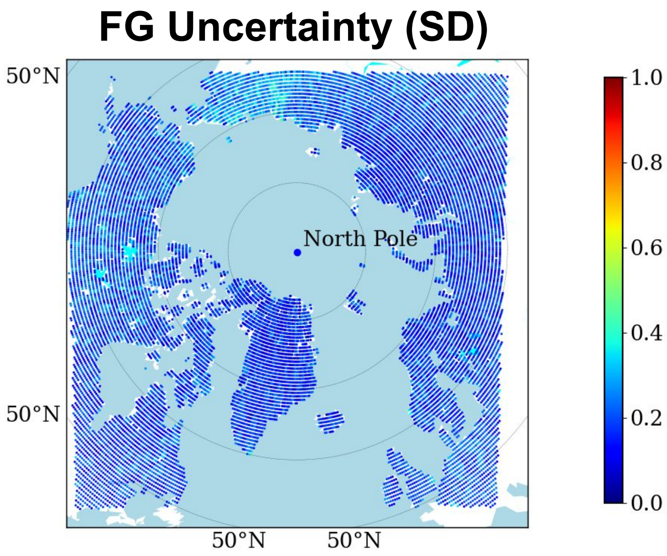


AMSU-A data is assimilated with the dynamic emissivity scheme in screening, which is seen to give more observations through screening and minimization, both over land-ice and sea-ice.

https://climate.copernicus.eu/copernicus-arctic-regional-reanalysis-service

AMSU-A (CH-9) Impact over LAND

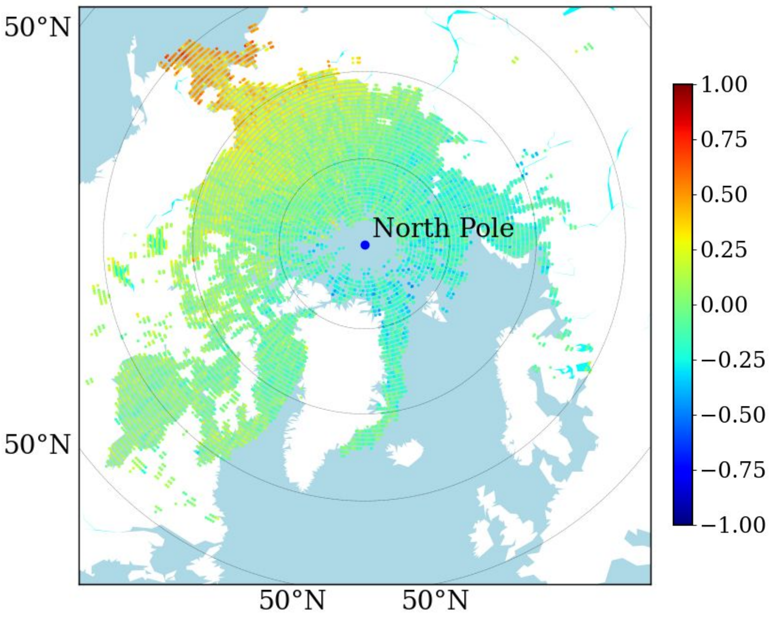




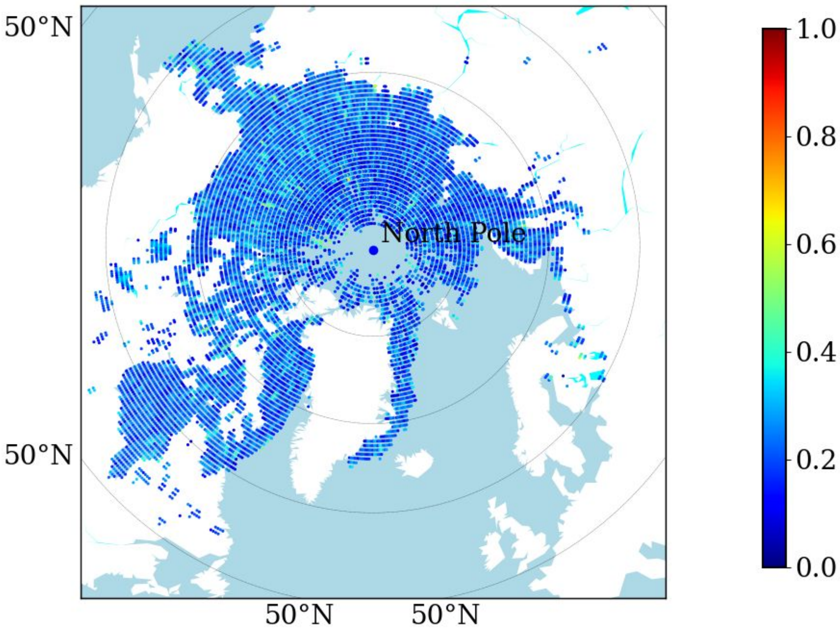
The spatial distribution of the gridded (0.5x0.5) average (O-B) and standard deviation (SD) of error in terms of Brightness Temperature (K) — of AMSU-A **channel-9** is presented. Observations are valid from 5-15, January 2023 and for all 8 assimilation cycle per day.

AMSU-A (CH-9) Impact over SEA-ICE

(O-B)



FG Uncertainty (SD)



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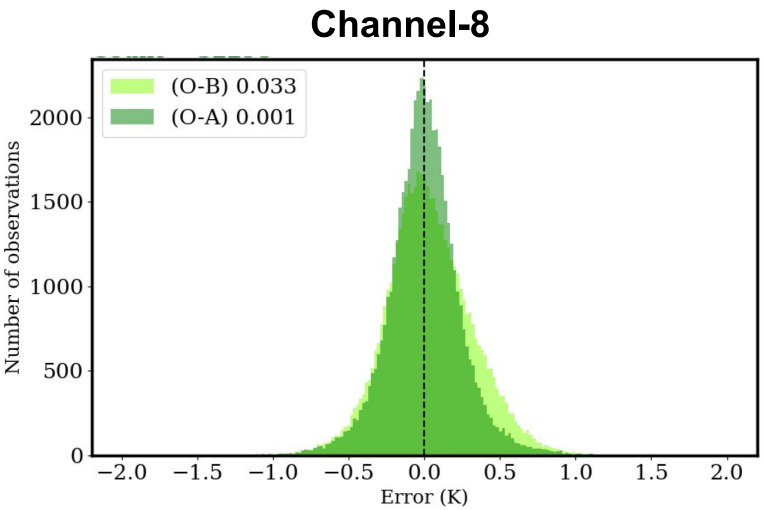
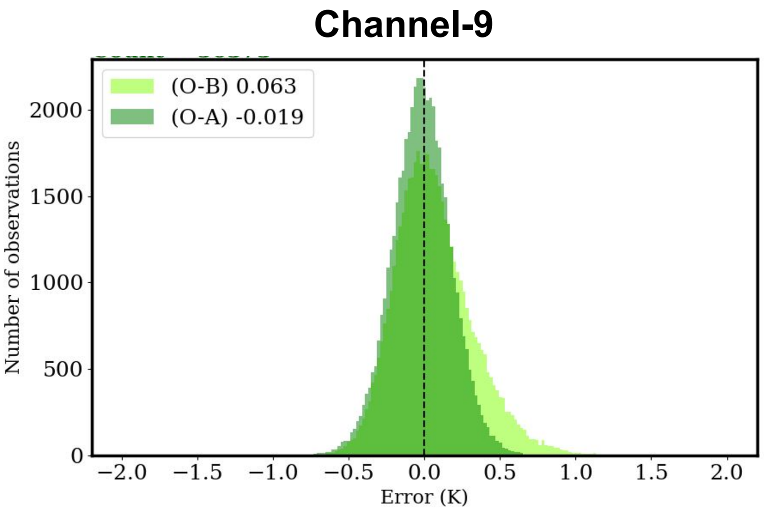
Advanced Microwave Sounding Unit (AMSU-A)





Error histogram of AMSU-A channel-8 and channel-9. Observations are valid from 5-15, January 2023 and for all 8 assimilation cycle per day.

Advanced Microwave Sounding Unit (AMSU-A)

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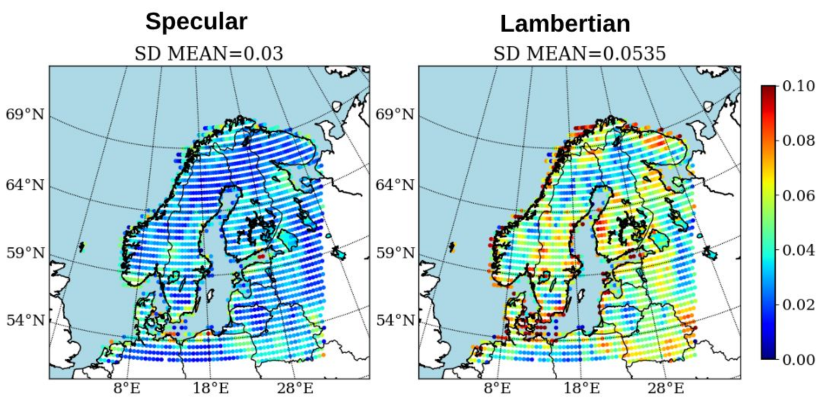
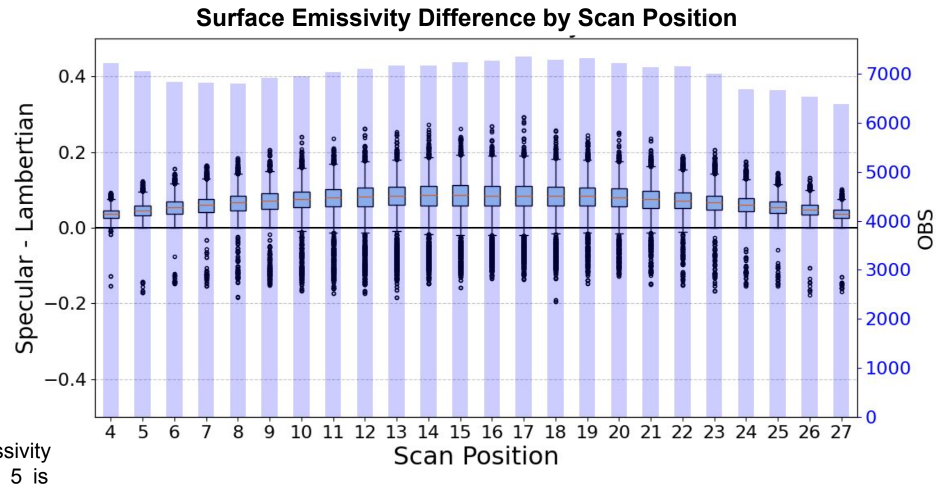
Further efforts are underway to utilize additional Surface-sensitive data.



The spatial distribution of the gridded (0.5x0.5) standard deviation (SD) of retrieved emissivity for two different scenarios—Lambertian and specular reflection—of AMSU-A channel 5 is presented. The image clearly indicates that the uncertainty in emissivity is significantly higher in Lambertian reflection, whereas in specular reflection, the standard deviation (uncertainty spread) is much lower and more uniform.



Differences in surface emissivity calculated using specular and Lambertian experiments for various scan positions during January 2023. AMSU-A Channel-5 is a low-peaking MW, emissivity differ across various surfaces condition and different season. and so the error structure.

Swapan Mallick, Magnus Lindskog (SMHI) and Stephanie Guedj (MET Norway)

Advanced Technology Microwave Sounder (ATMS)

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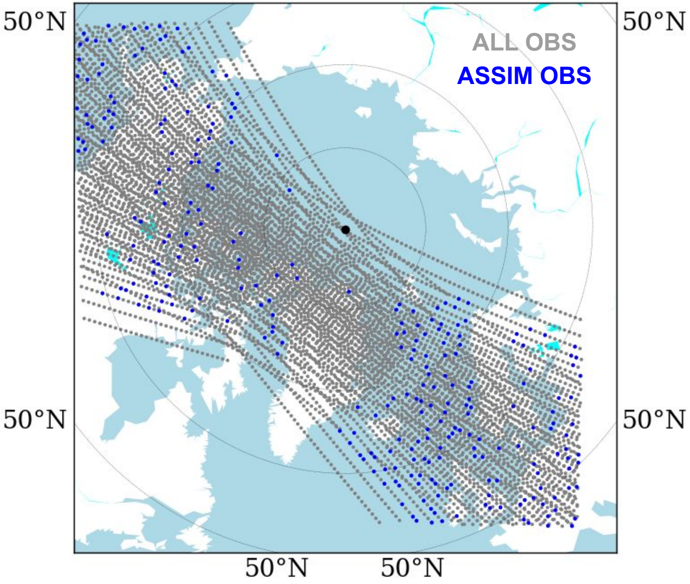
The Advanced Technology Microwave Sounding (ATMS), a 22 channels including the 54 and 183 GHz bands; cross-track scanning, operates in conjunction with the CrIS to profile atmospheric temperature and moisture.

- ➔ Measures microwave radiances at 22 channels (23.8 GHz to 183.3 GHz)
- ➔ Assimilated channels 5-10 and 17-22
- ➔ IFOV size of about 48 km near nadir.
- ➔ Near global coverage twice per day.
- ➔ Utilization period 2012 to 2041.

Channel-6

Valid on 2023-01-15 at 12 UTC assimilation cycle



Advanced Technology Microwave Sounder (ATMS): Impact over Land

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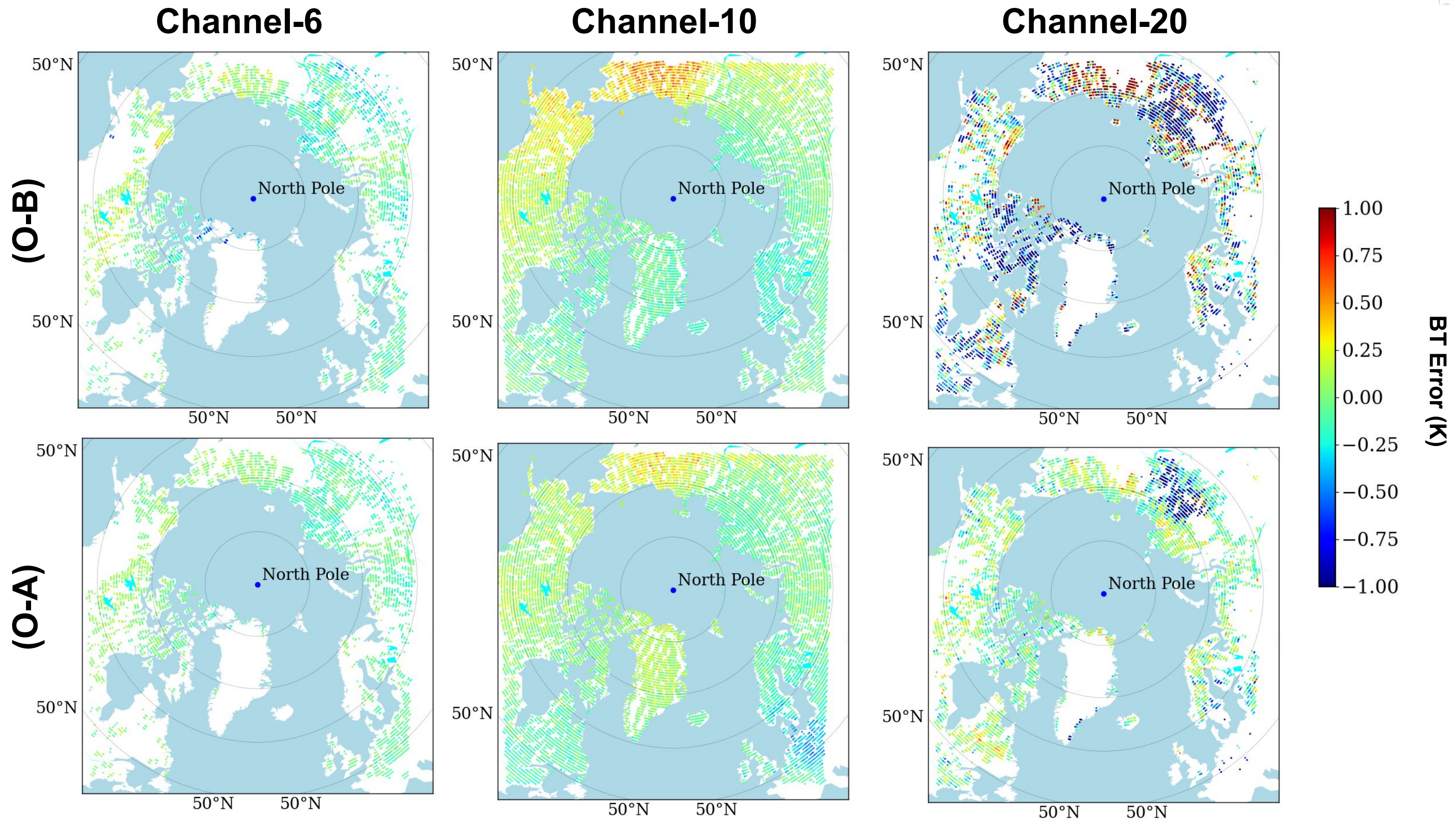

The spatial distribution of the gridded (0.5x0.5) average (O-B) and (O-A) of error in terms of Brightness Temperature (K). Observations are valid from 5-15, January 2023 and for all 8 assimilation cycle per day.

Advanced Technology Microwave Sounder (ATMS): Impact over Sea-ice

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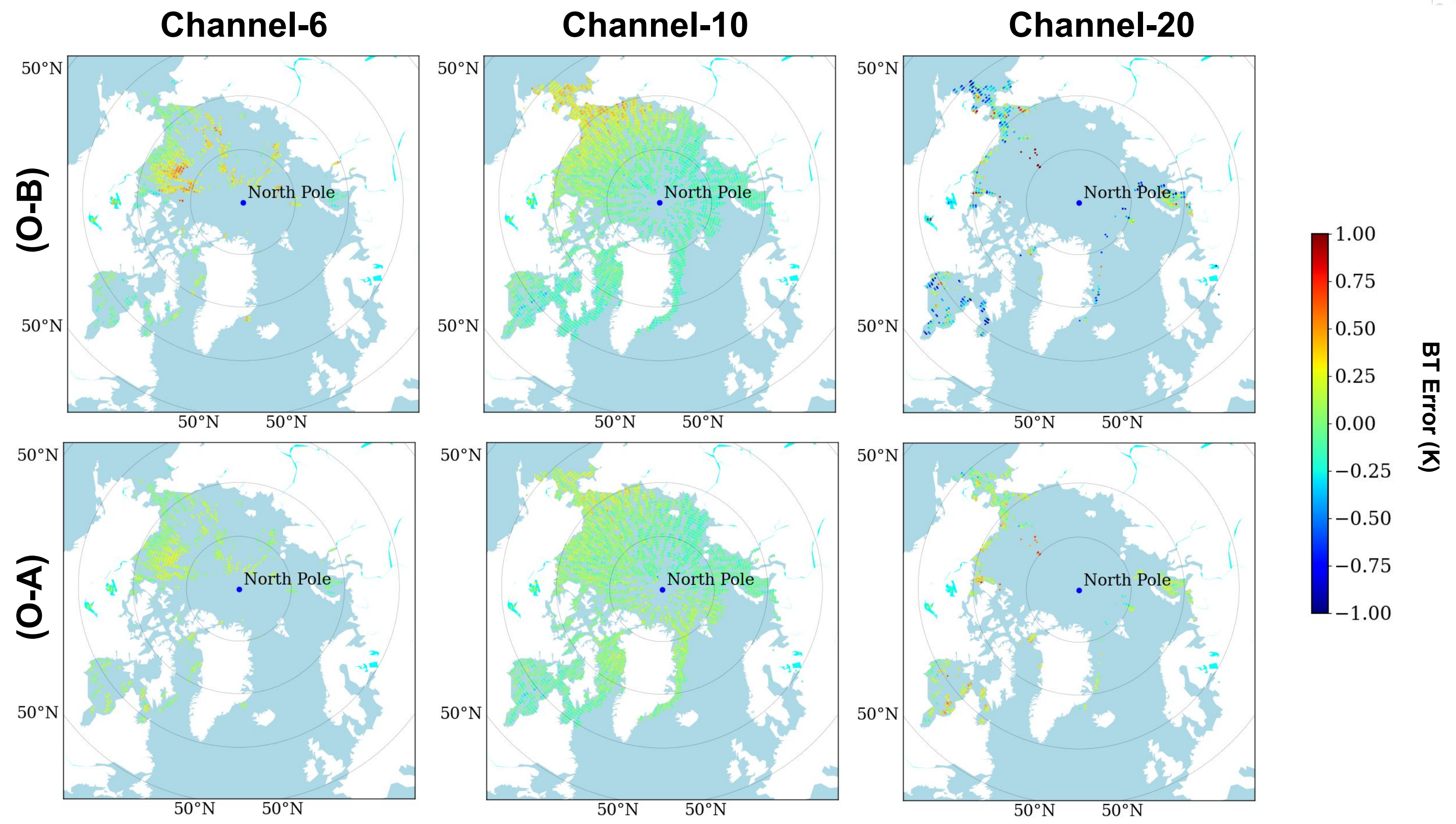
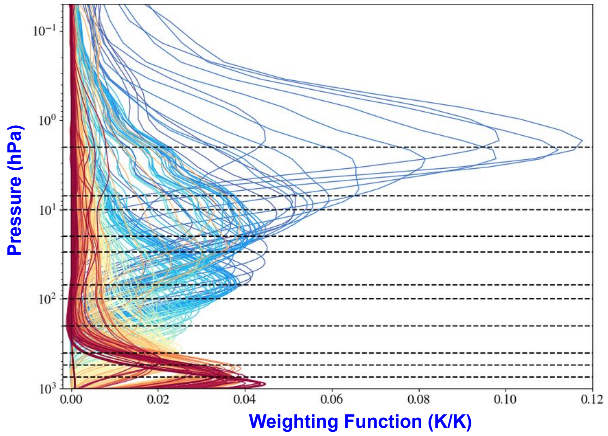


The spatial distribution of the gridded (0.5x0.5) average (O-B) and (O-A) of error in terms of Brightness Temperature (K). Observations are valid from 5-15, January 2023 and for all 8 assimilation cycle per day.

Infrared Atmospheric Sounding Interferometer (IASI)

The Infrared Atmospheric Sounding Interferometer (IASI) is a hyperspectral infrared sounder on the MetOp series of polar-orbiting satellites, used for atmospheric sounding.

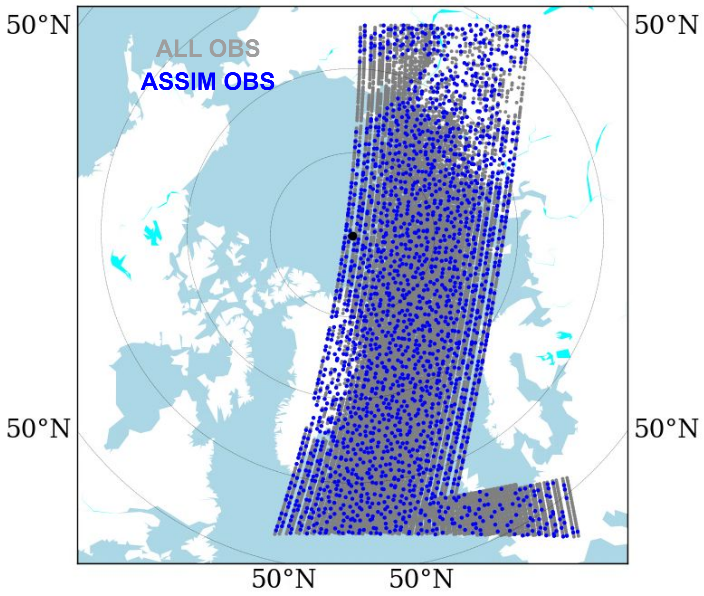
- ➔ **171 (300) channel used for assimilated** (January 2023).
- ➔ Near global coverage twice per day.



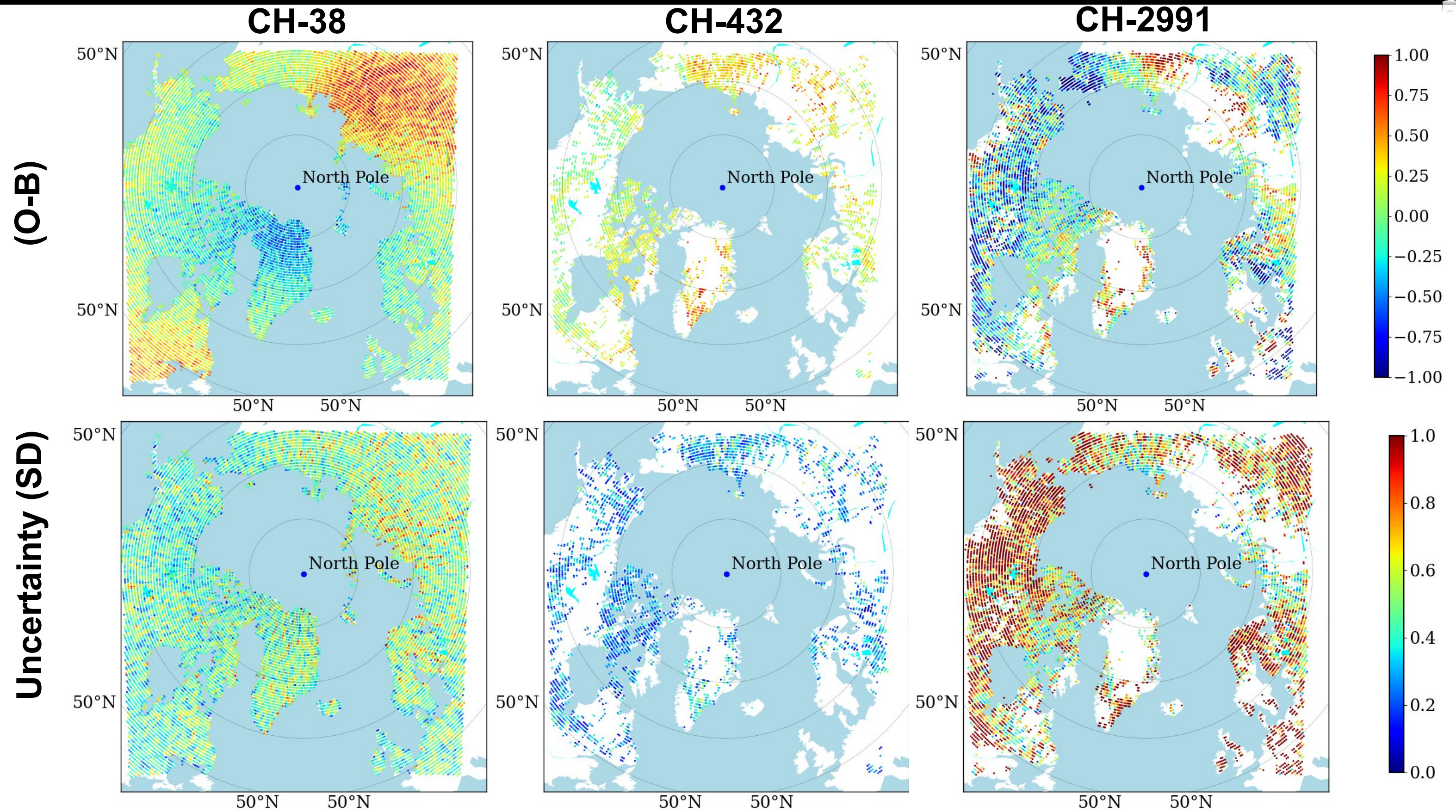
Weighting functions for the 171 selected IASI channels. Dashed horizontal lines represent the 11 pressure levels for which the temperatures are computed. The colours of the weighting functions represent the wavenumbers of the selected channels (blue for the channels around 700 cm−1 , red for the channels around 2200 cm−1).

Channel-38

Valid on 2015-01-15 at 12 UTC assimilation cycle

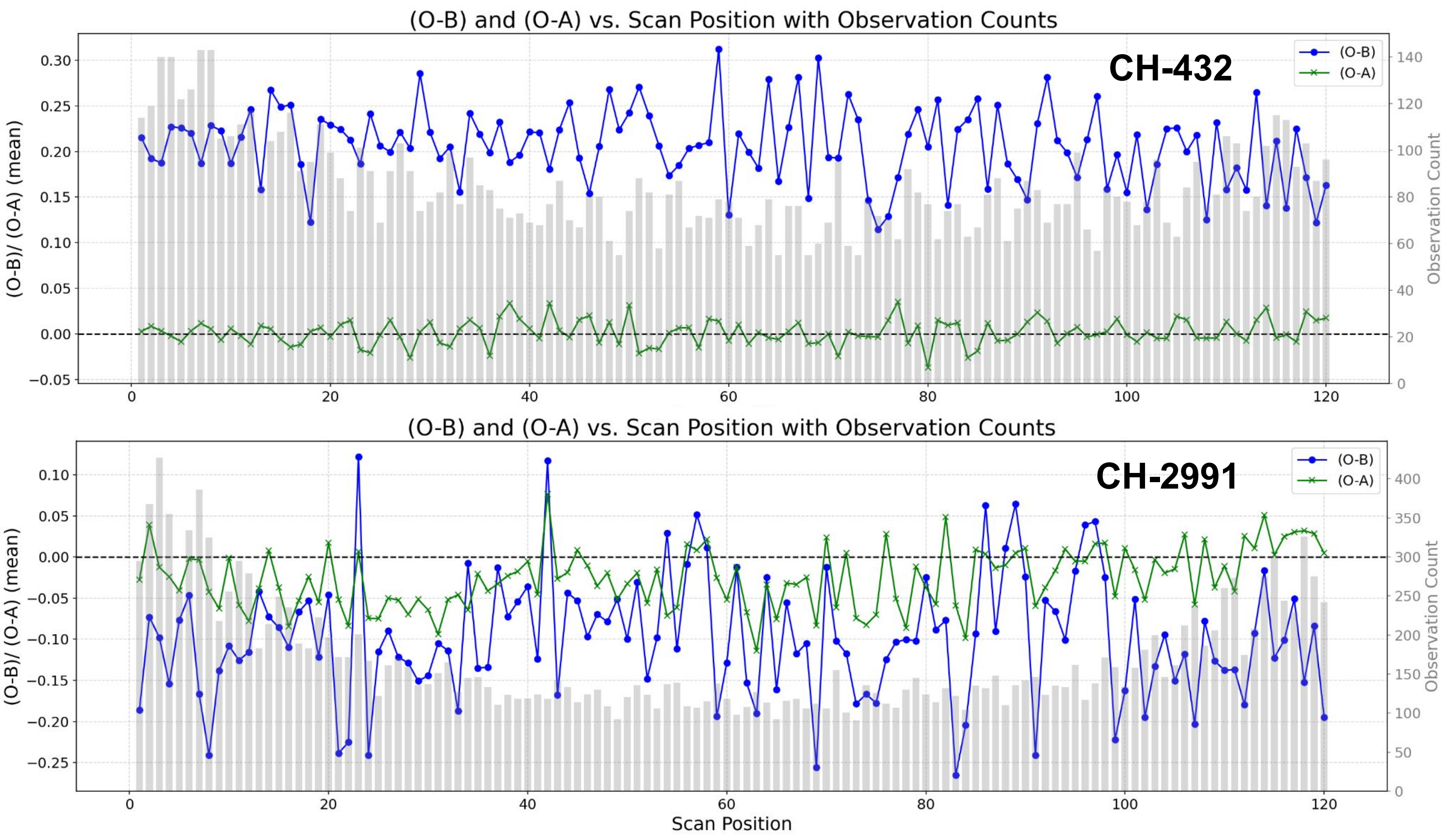


IASI Impact over LAND

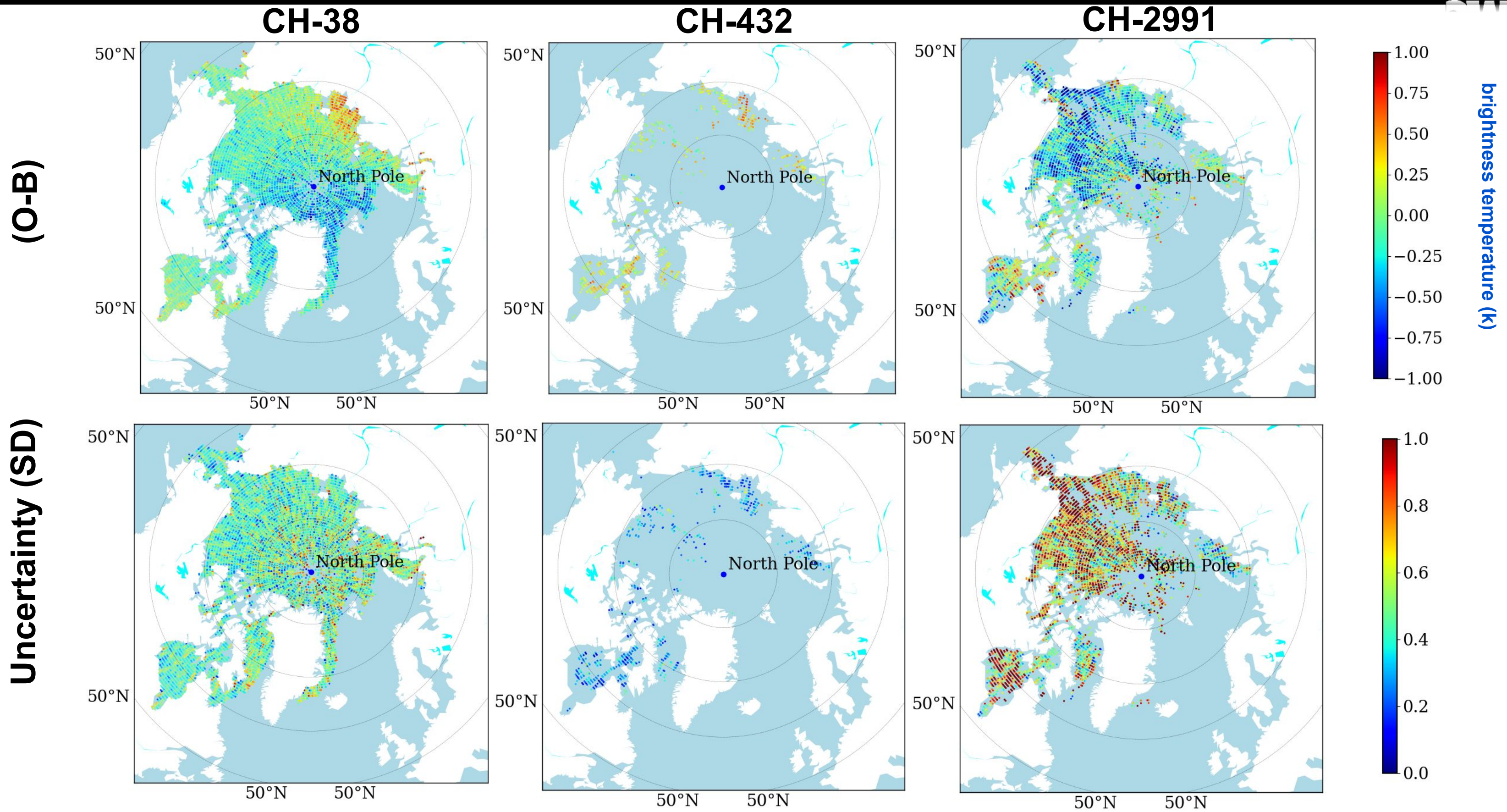


The spatial distribution of the gridded (0.5x0.5) average (O-B) and standard deviation (SD) of error in terms of Brightness Temperature (K) — of IASI channel-38 (higher level), 432 (mid-tropospheric level) and 2991 (near surface level) is presented. Observations are valid from 5-15, January 2023 and for all 8 assimilation cycle per day.

IASI Impact over LAND



IASI Impact over SEA-ICE



The spatial distribution of the gridded (0.5x0.5) average (O-B) and standard deviation (SD) of error in terms of Brightness Temperature (K) — of IASI channel-38 (higher level), 432 (mid-tropospheric level) and 2991 (near surface level) is presented. Observations are valid from 5-15, January 2023 and for all 8 assimilation cycle per day.

IASI Impact over LAND and SEA-ICE

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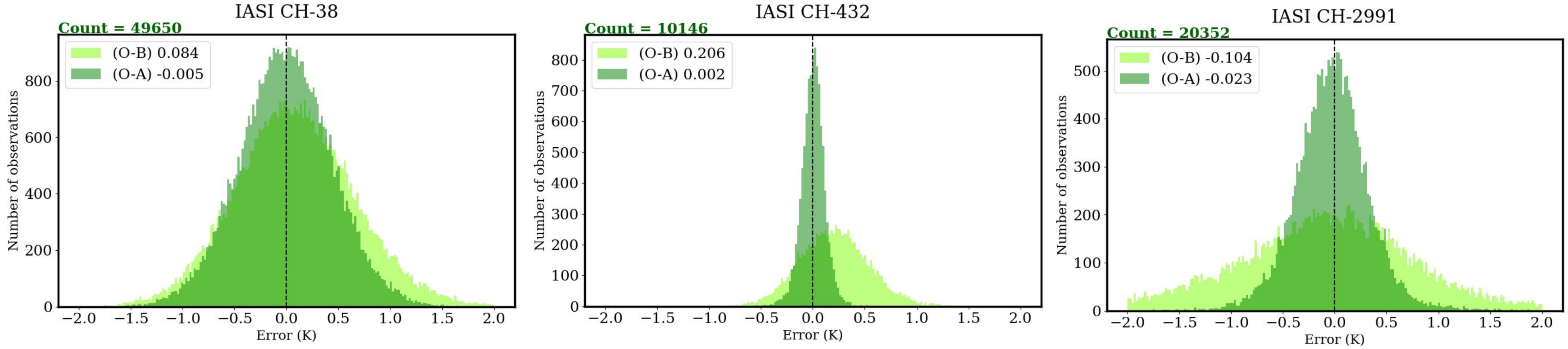
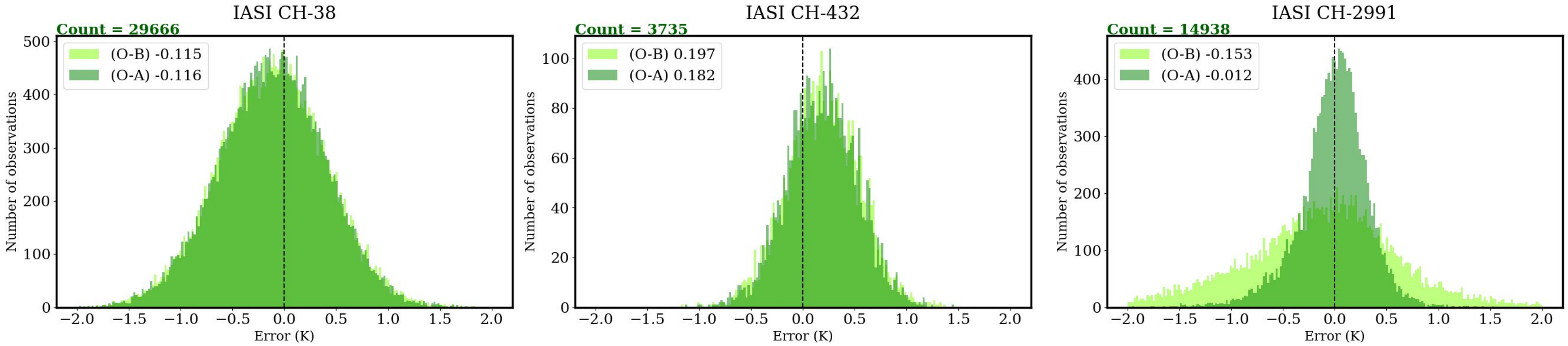
First-guess departure (O-B) and Analysis departure (O-A) of brightness temperature (k)

Over LAND



Over SEA-ICE



IASI Impact over LAND and SEA-ICE

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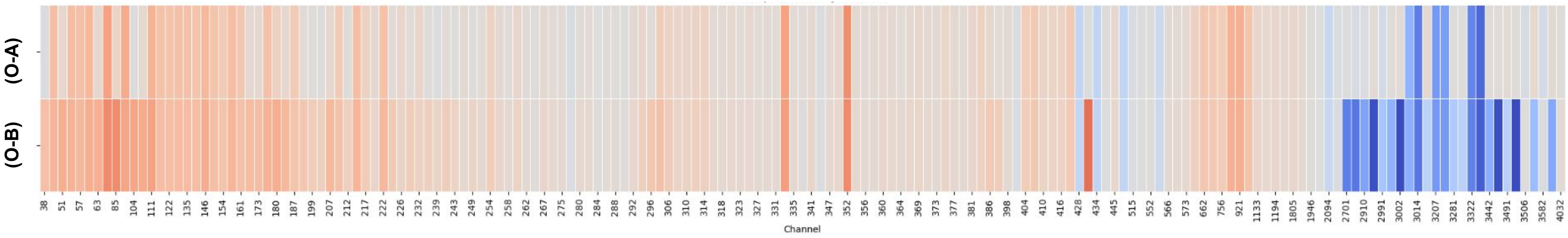
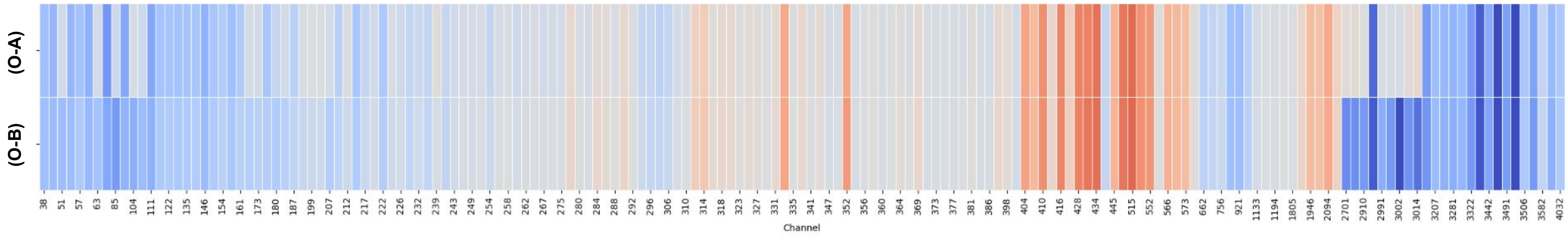
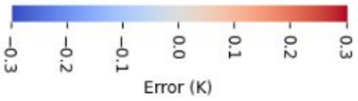
Over LAND



Over SEA-ICE





Error (K) by Channel

IASI Impact (Data Denial Experiments)

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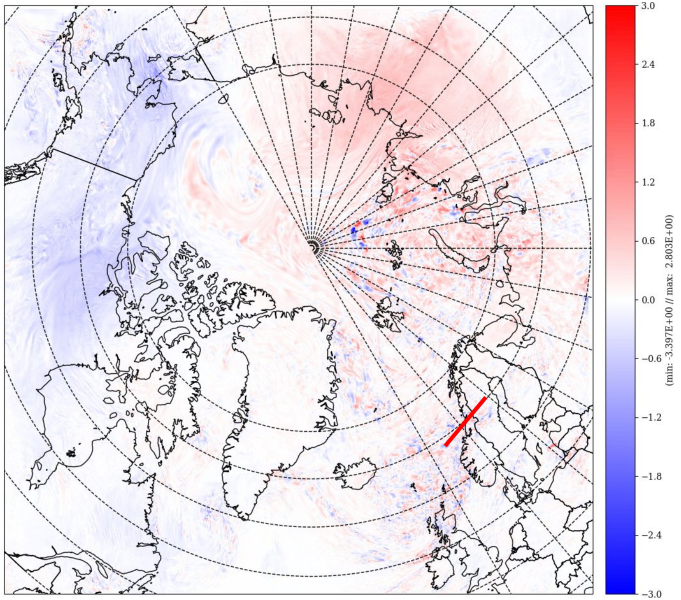
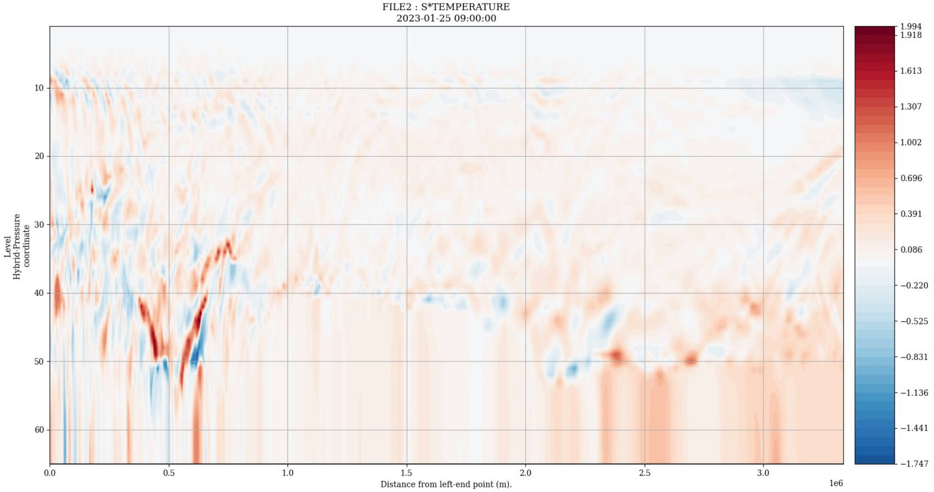
Temperature Difference (CNTL-EXP) at 950 hPa
Valid on 2023-01-25 at 09:00 UTC



Vertical Cross-section of Temperature Difference (CNTL-EXP)
Valid on 2023-01-25 at 09:00 UTC



CNTL : Assimilated all observation
EXP: Without IASI

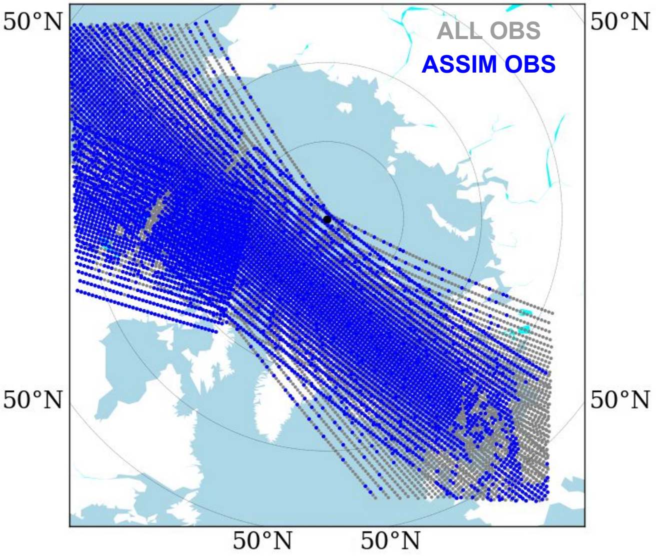
Cross-track Infrared Sounder (CrIS)

The Cross-track Infrared Sounder (CrIS) is the first in a series of advanced operational sounders that provide more accurate, detailed atmospheric temperature and moisture observations for weather and climate applications.

- ➔ **112 channel selected for assimilation (out of 1305)**.
- ➔ Near global coverage twice per day.

Channel-39

Valid on 2015-01-15 at 12 UTC assimilation cycle



CrIS (CH-26) Impact over SEA-ICE

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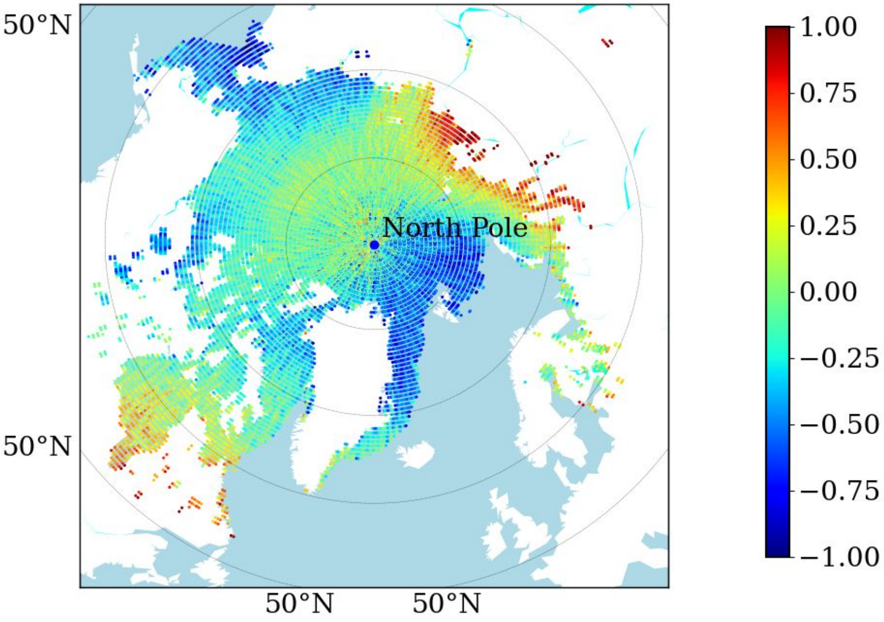
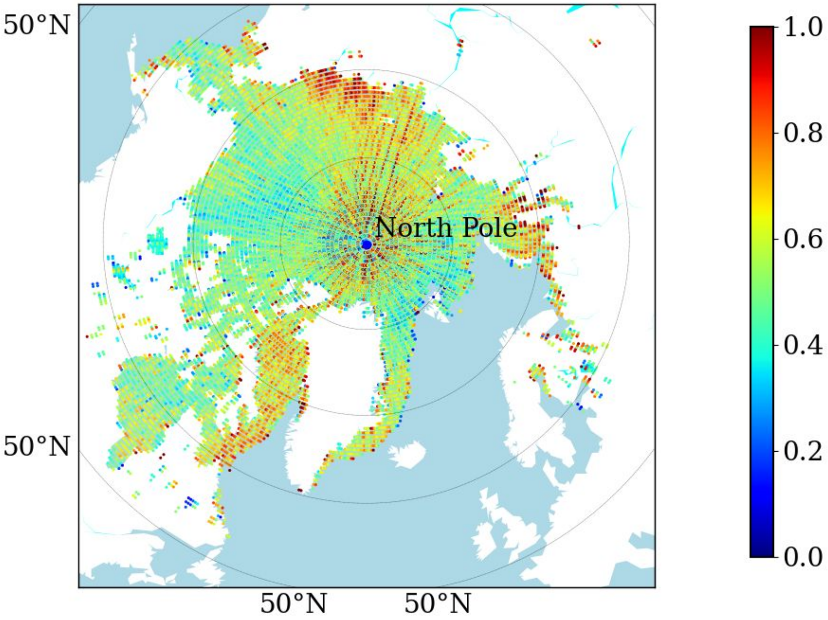
Channel-26 Brightness Temperature Error (in K)

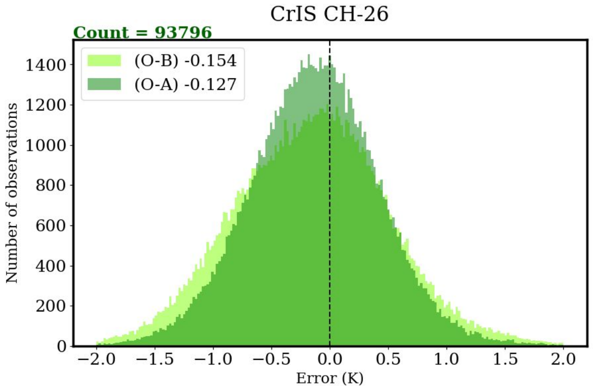
(O-B)

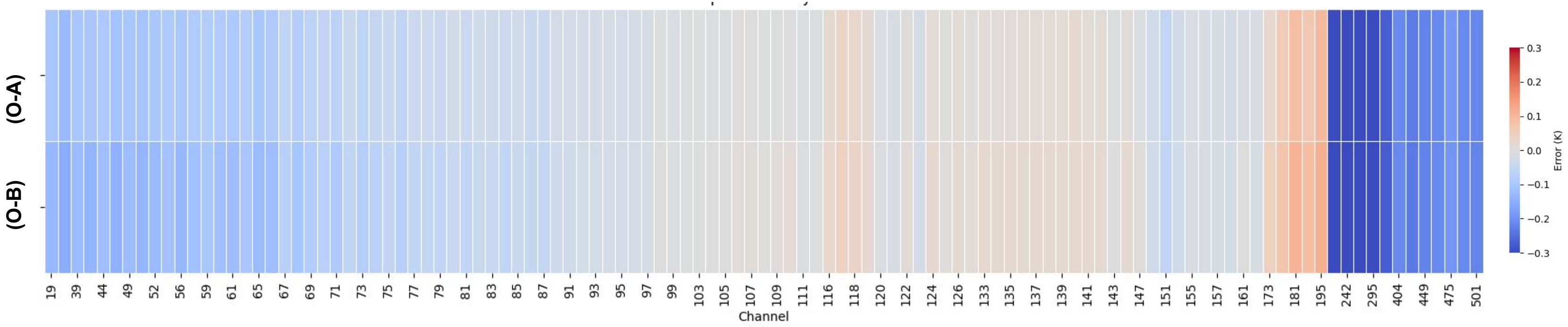


SD



CrIS Impact over SEA-ICE





Error (K) by Channel

Summary and Conclusion

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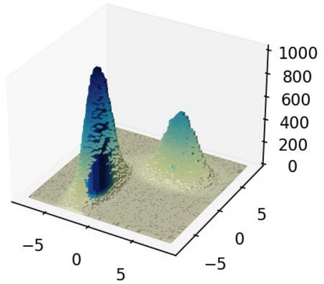
- Assimilation of high-resolution data within reanalysis products holds critical significance in regions with sparse observational coverage and for extracting information at higher atmospheric levels. This process involves several key components, including the assimilation methodology, quality of observations, frequency of assimilation, and the specification of the background error covariance matrix.

- The incorporation of high-quality observational datasets remains fundamental to the ongoing advancement of reanalysis products. However, several challenges persist, such as managing observation errors, implementing data thinning strategies, applying variational bias correction techniques, and selecting appropriate spectral channels.

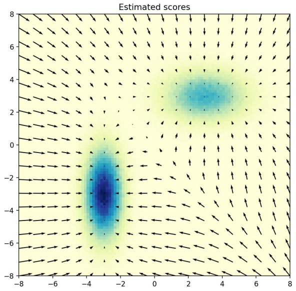
- Furthermore, the utilization of new, higher-resolution satellite datasets, including those obtained from **Arctic Weather Satellite (AWS),** is increasingly instrumental in enhancing both the accuracy of analyses and the skill of forecasts.

- From an ML perspective, a pretrained model that leverages reanalysis data, combined with the assimilation of observations using a **score-based diffusion model**, may further enhance the accuracy of the analysis fields.

Probabilistic Diffusion Model



Score-Based Diffusion Model



Thanks for your Attention !