Advanced assimilation of satellite observations in a limited-area numerical weather prediction model over the Arctic region

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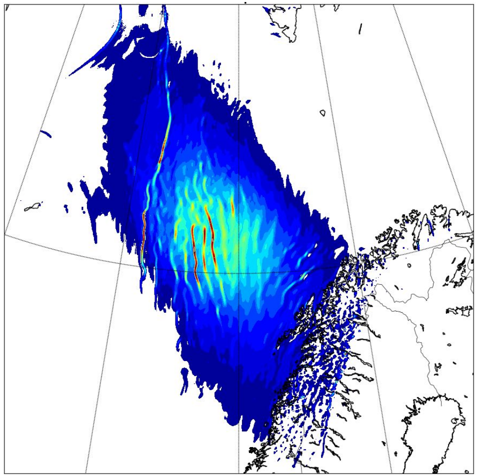
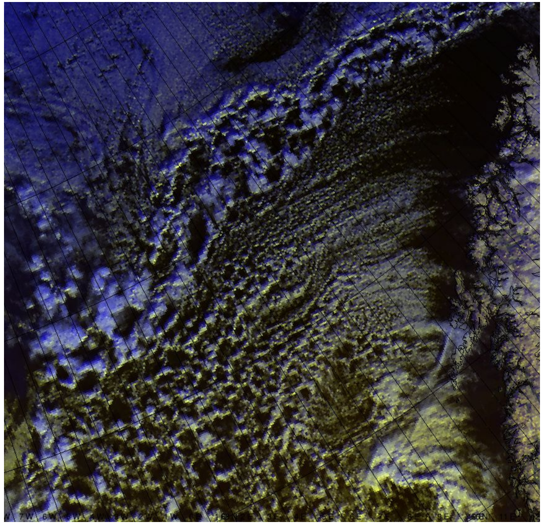
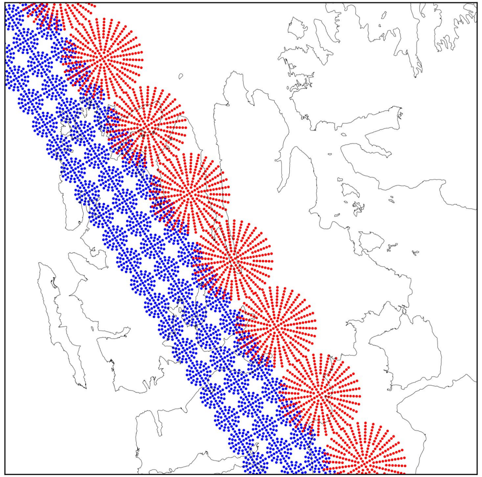






Outline

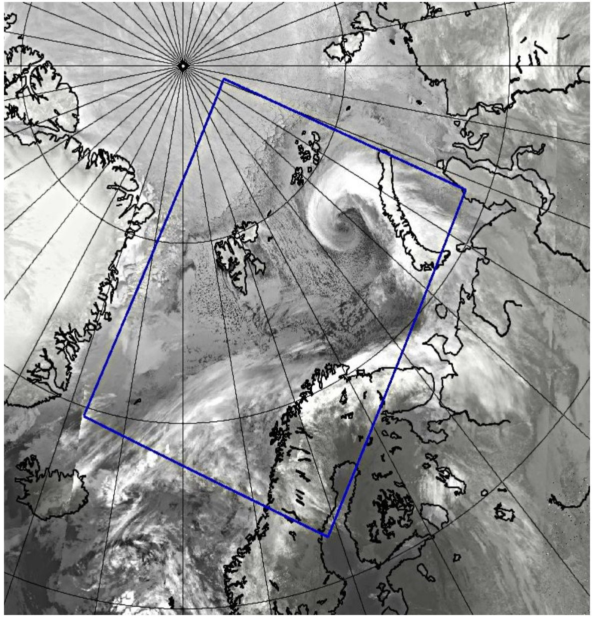
- Motivation, objectives, and background
- Main findings
- Future outlook
- Final remark

Motivation

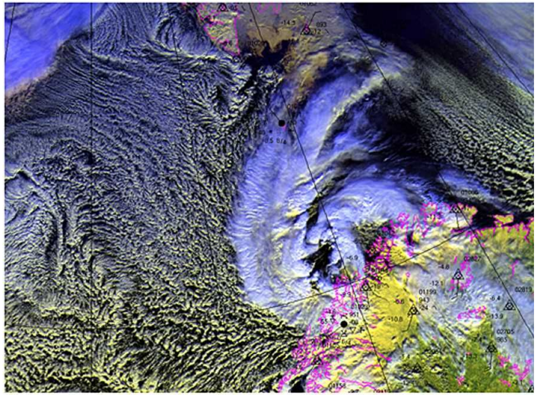
Photo: Eli Anne Ersdal

The numerical weather prediction over high-latitude regions is special and particularly challenging.

Image: U.S. Coast Guard



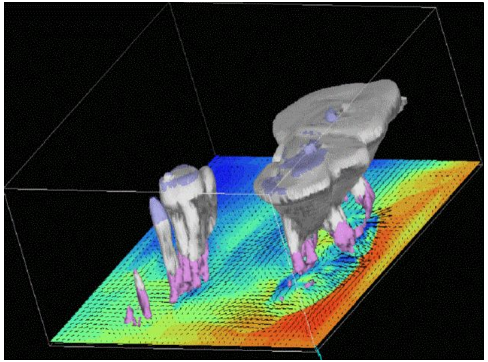
The area of interest (AROME-Arctic domain)



NOAA-19 AVHRR day/night satellite image

Motivation

National Meteorological Institutes (via ACCORD) made successful collaboration in order to develop regional weather prediction models which are portable to any region and applicable with very **high resolution** over a local domain.



AROME modell (image: *Météo-France*)

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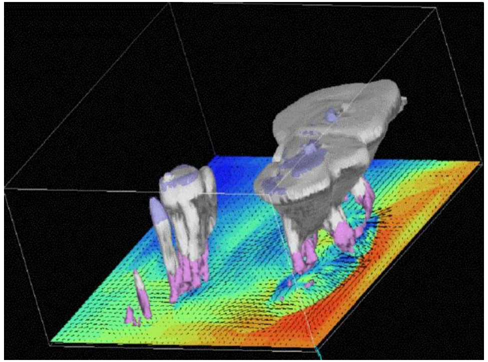
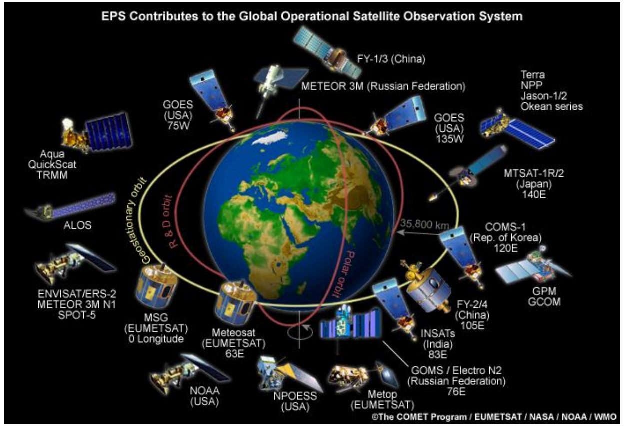


AROME modell (image: *Météo-France)*

In order to keep the model on track with the true atmospheric flow, observations are integrated i.e., assimilated in the numerical models.

Over high-latitude regions, the available conventional observations are sparse, therefore, the **satellite data assimilation** is of high importance.



Motivation

However, **satellite data assimilation** in high-resolution limited-area models **is not optimal** for several reasons

Limited coverage

DA scheme (3D-Var)

Complex bias correction

Point observations

Motivation

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Limited coverage

DA scheme (3D-Var)

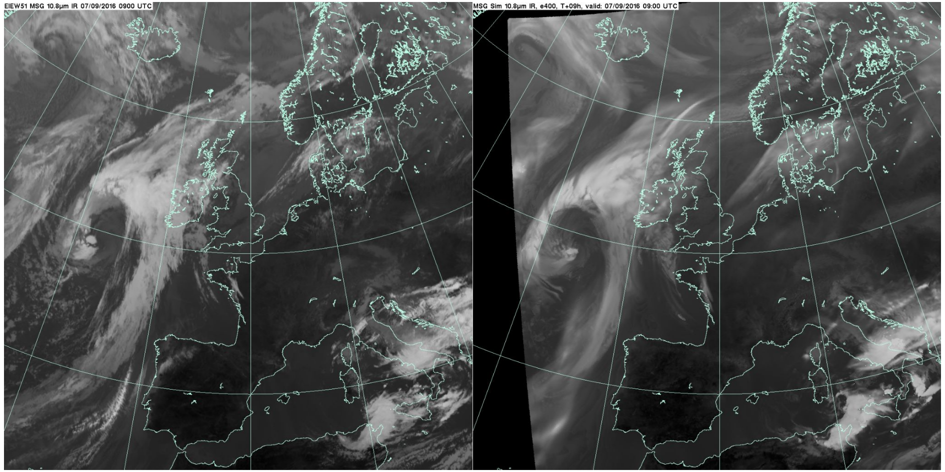
Complex bias correction

Point observations

Motivation

The **representation error** as defined by Janjić *et al.* (2017) consists of error due to unresolved scales and processes, forward model or observation-operator error and pre-processing or quality-control error.

The **unresolved scales** or mismatch between data and model is explained mostly from the global or low-resolution models point of view.

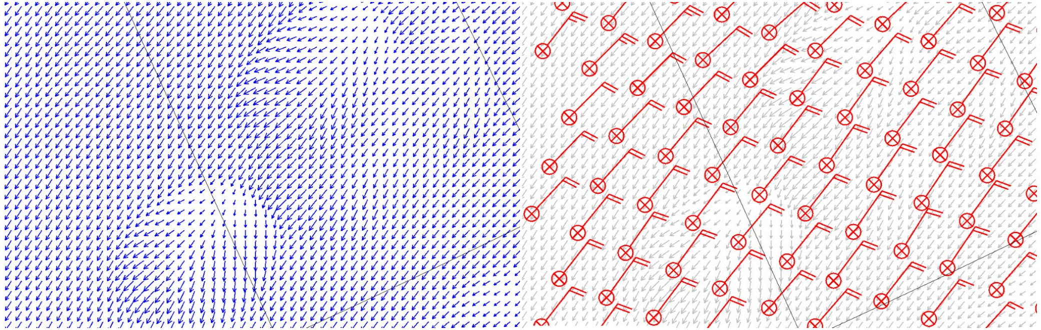


The comparison of observed (left panel) and simulated (right panel) SEVIRI satellite images. The simulated image was derived from the Met Office 4.4km horizontal resolution NWP model over Europe. Figures are taken from the EUMETSAT NWP SAF portal (EUMETSAT, 2016)

Motivation

On the other hand, there is also representation error in high-resolution models and it can be described as an error due to **unobserved scales and processes**.

This error is generally neglected.



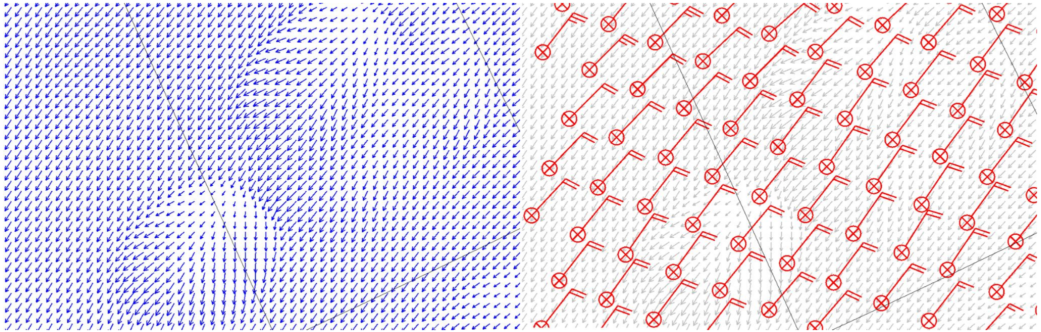
Comparison of AROME-Arctic wind vectors on 2.5 km grid (left panel) and ASCAT Coastal product (right panel) wind barbs with 12.5 km grid for a given case study from paper I.

Motivation

On the other hand, there is also representation error in high-resolution models and it can be described as an error due to **unobserved scales and processes**.

This error is generally neglected.

Assimilating satellite data as point observations is suboptimal because the **satellite footprint** may extend over many grid point of the model.



Comparison of AROME-Arctic wind vectors on 2.5 km grid (left panel) and ASCAT Coastal product (right panel) wind barbs with 12.5 km grid for a given case study from paper I.

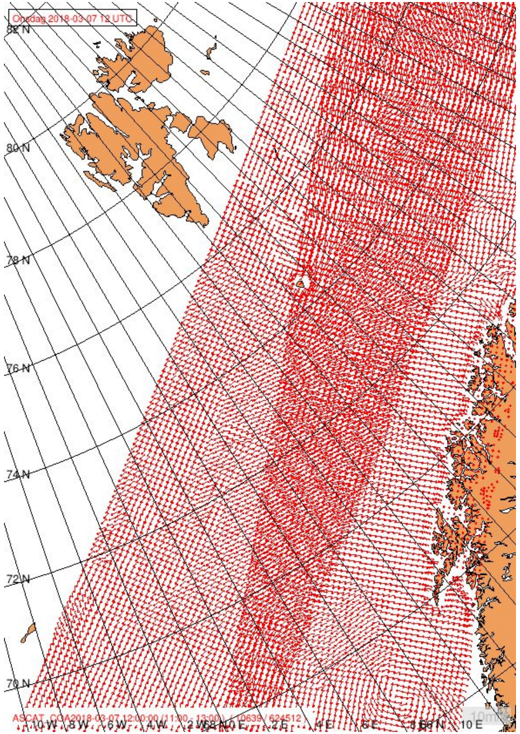
Point observations → ***Footprint operator***

Motivation

Additionally, it is not possible to analyse adequately **small scales over the open ocean** because physical constraints like orography and four-dimensional observations are not available in regional models.

If the mesoscale assimilation system **has not enough constraints**, dynamical model imbalances might appear on the small scales in particular and may interfere with the analysis of the larger scales that can be determined (Stoffelen *et al.*, 2020).

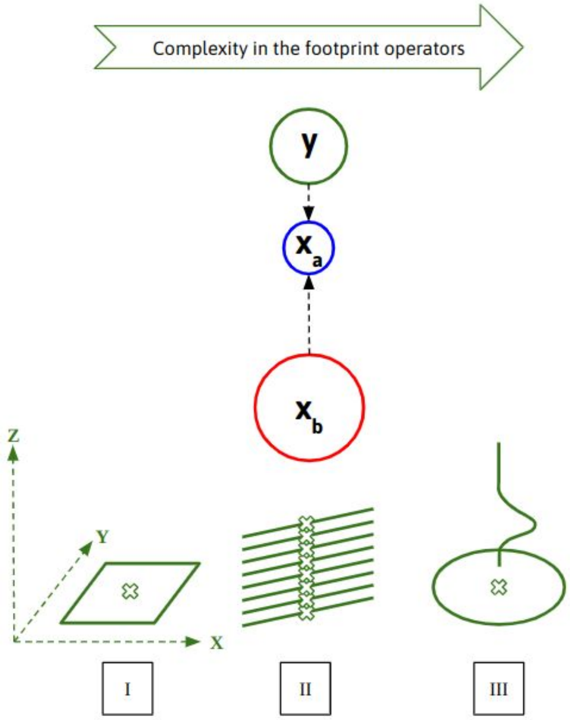
Limited coverage



ASCAT observations inside the AROME-Arctic domain

Objectives: to explore satellite footprint representation

- Investigate **scatterometer ocean surface winds** and a special footprint operator called supermodding;
- Investigate **wind profiles of Aeolus** satellite mission and its proper footprint operator;
- Investigate **microwave satellite radiances** and its complex footprint operator.



Background

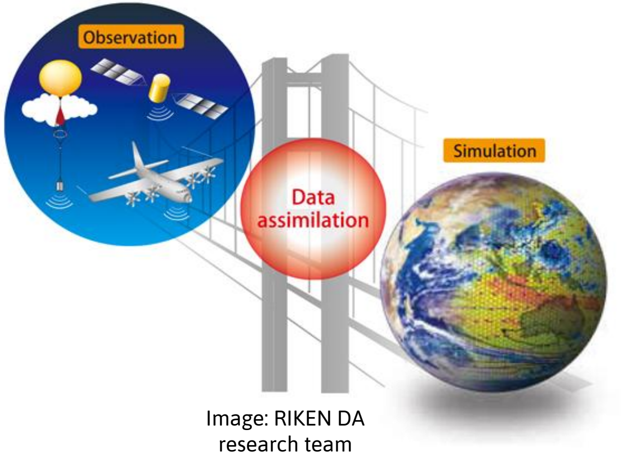


Image: RIKEN DA research team

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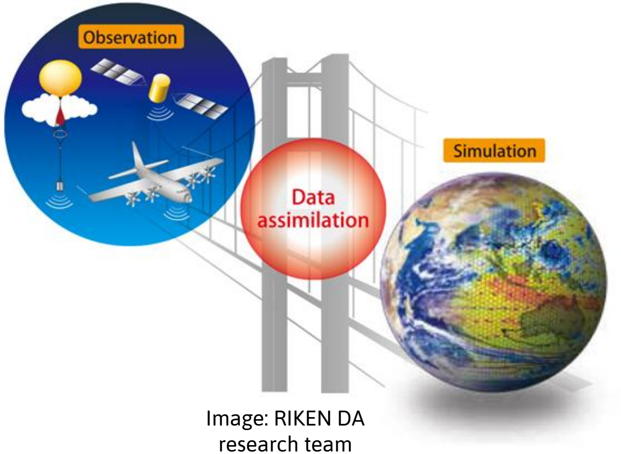

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$$J(\mathbf{x}) = J_b(\mathbf{x}) + J_o(\mathbf{x}) =$$

$$= \frac{1}{2}(\mathbf{x} - \mathbf{x_b})^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x_b}) + \frac{1}{2}(\mathbf{y} - H(\mathbf{x}))^T \mathbf{R}^{-1}(\mathbf{y} - H(\mathbf{x})),$$

$$\mathbf{x_a} = \arg\min J(\mathbf{x})$$

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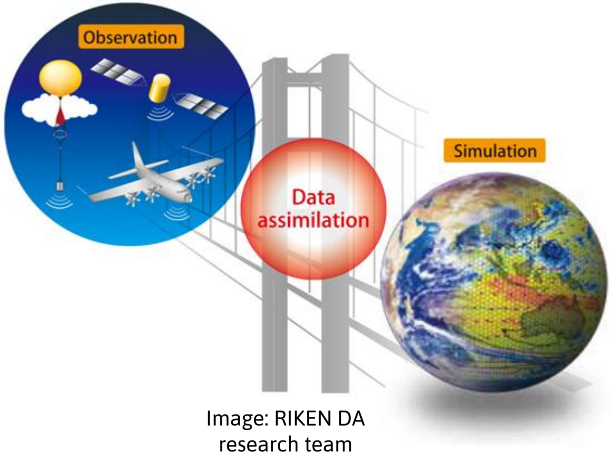

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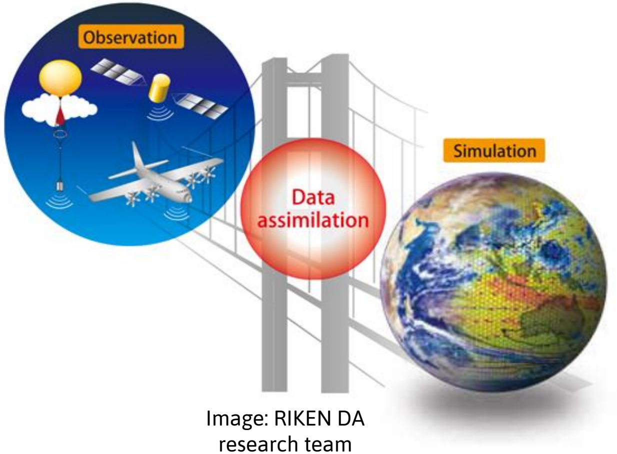
The link between the observation and the model is not trivial.

The observation operator H maps information from state space to observation space.

Background



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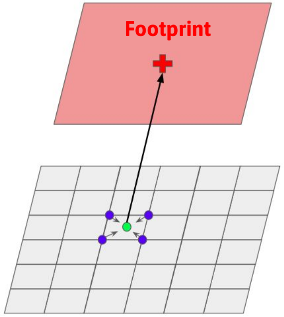

Default assimilation as **Point observation**

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In this forward problem, the observation operator can be the **source** of the representation error

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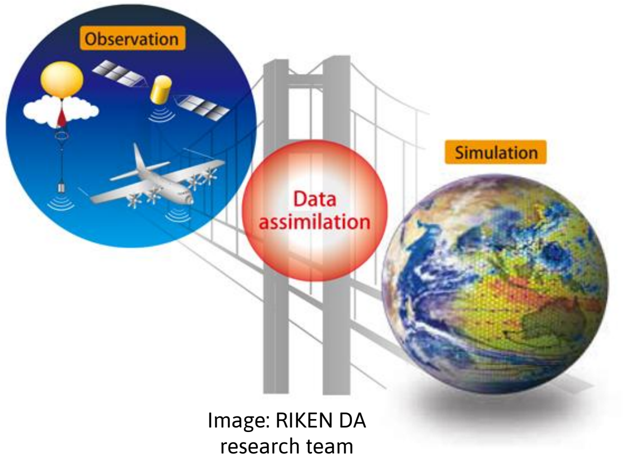

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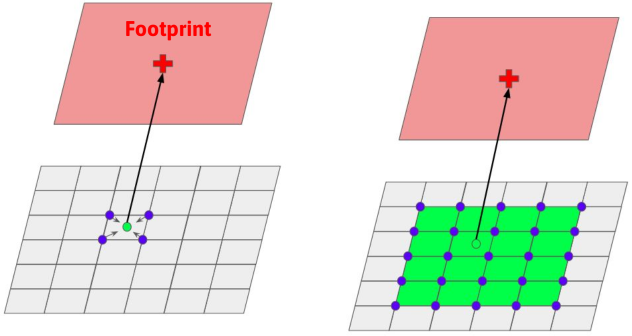

Default assimilation as **Point observation**

Footprint operator

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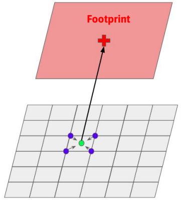
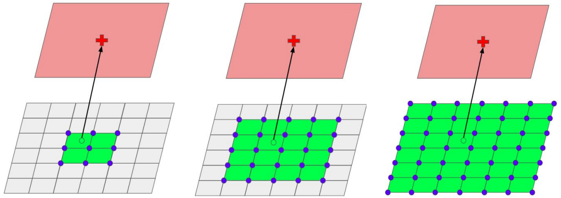
In this forward problem, the observation operator can be the **solution** for the representation error

Footprint operator implementation



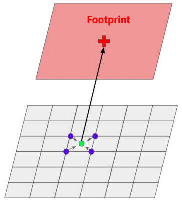
Default assimilation
as **Point observation**

Scatterometer supermodding



Averaging in model space
Supermodding

Footprint operator implementation



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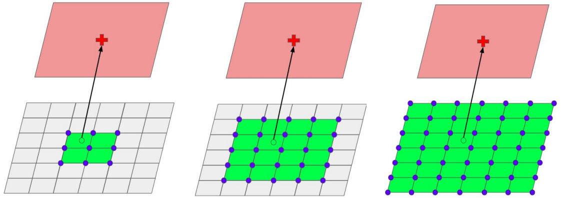
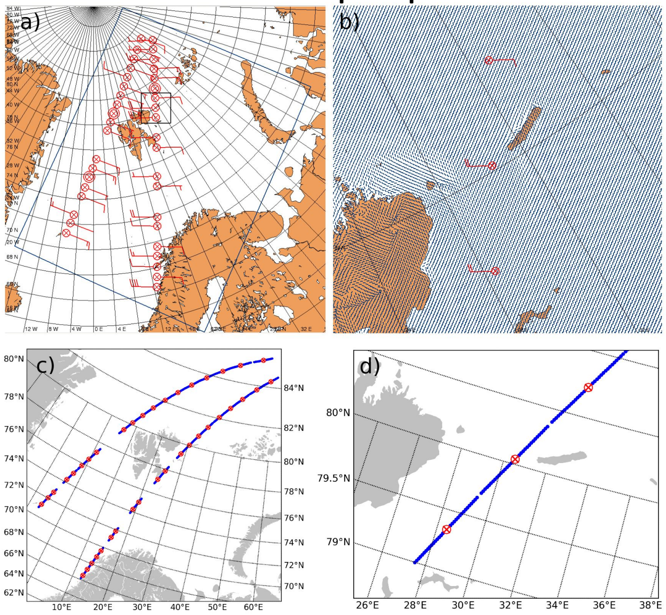


Averaging in model space
Supermodding

Aeolus footprint operator



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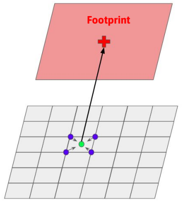

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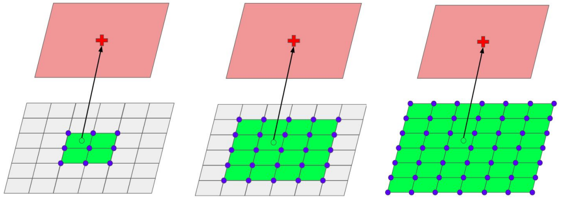
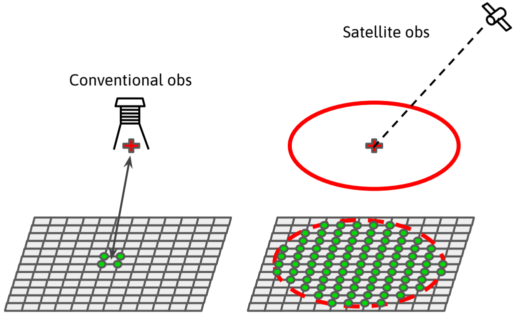


Averaging in model space
Supermodding

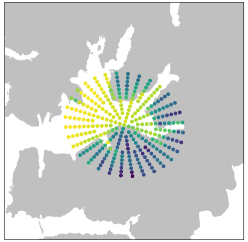
Radiance footprint operator



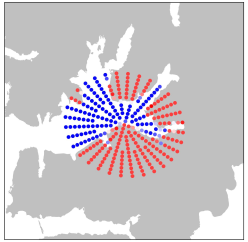
Horizontal interpolation

Averaging in observation space

AMSU-A single obs + footprint

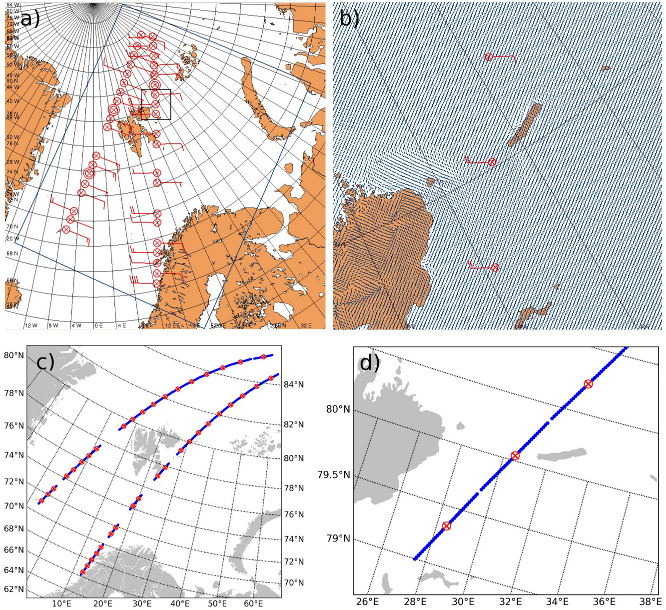


Simulated Tb



Retrieved emissivity

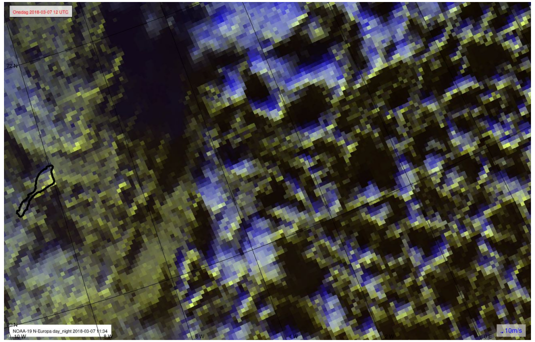
Aeolus footprint operator



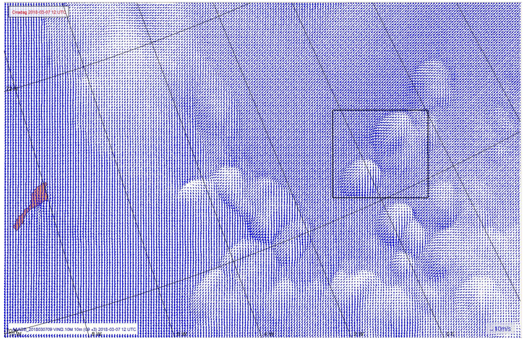
Scatterometer ocean winds and the supermodding operator

Scatterometer supermodding

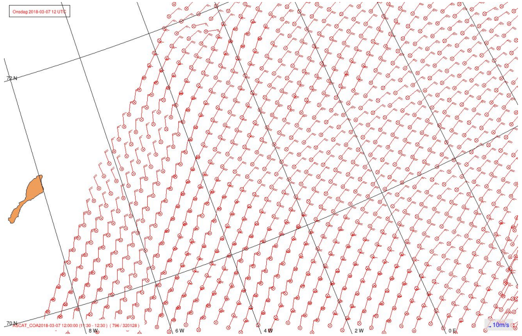
The amplitude of the mesoscale spectrum is reasonably resolved in AROME-Arctic, however, the predicted small-scale phenomena can be out of phase.



AVHRR day/night satellite image



AROME wind vectors



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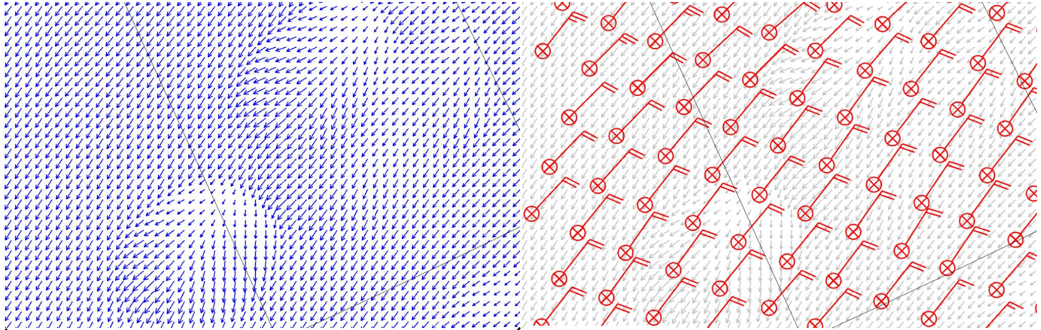
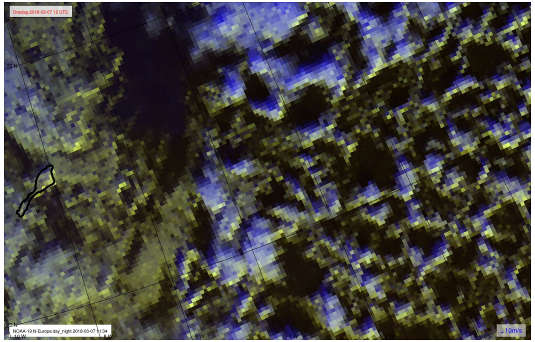


Additionally, the ASCAT winds cannot provide such small-scale information



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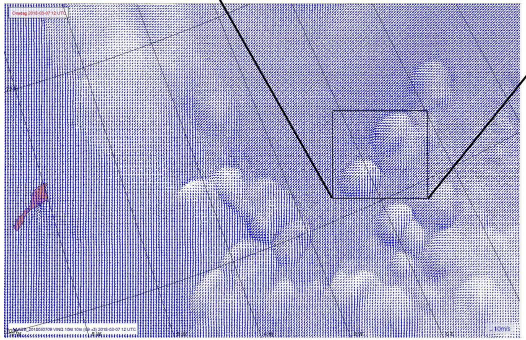

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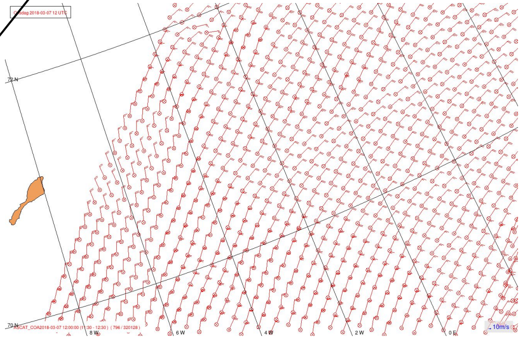

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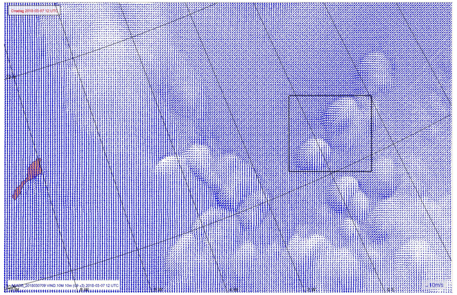

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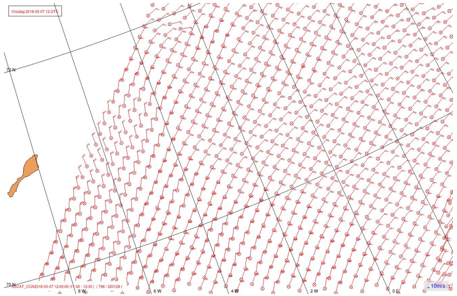

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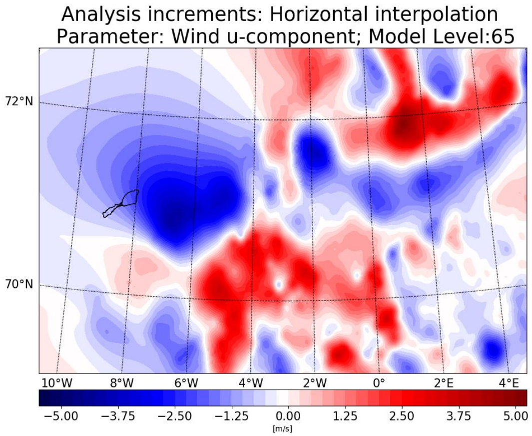
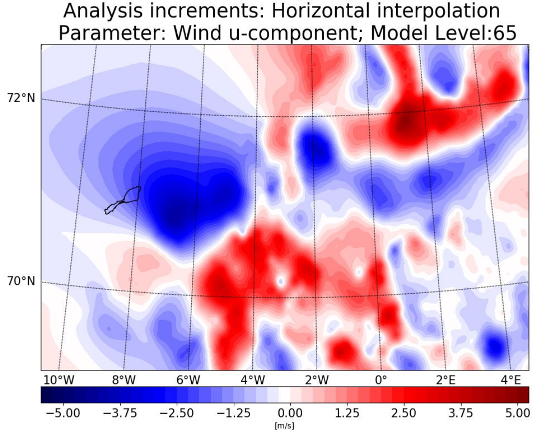


The analysis increments of the default ASCAT assimilation show relatively sharp and localised increments

It means that the coarse-resolution scatterometer observations constrains the smallest scales of the model

Scatterometer supermodding



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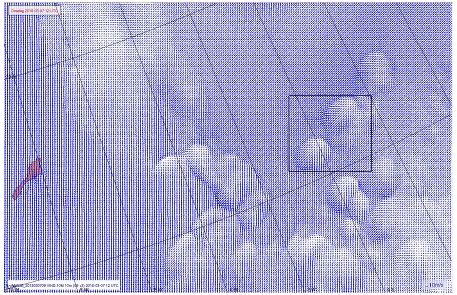

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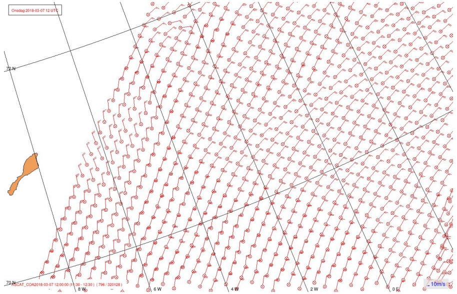
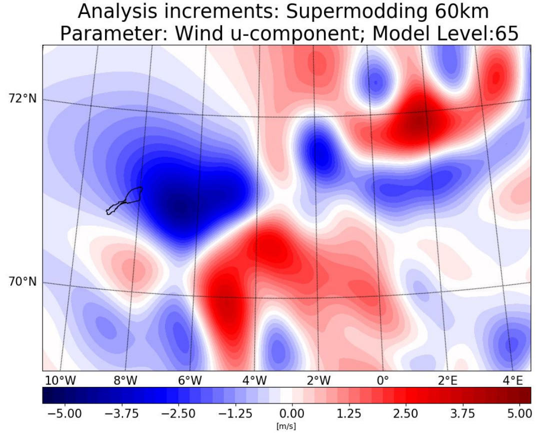


ASCAT wind barbs

However, by the use of supermodding operator, the increments get smoother meaning that the observation has impact on larger scales mostly.

Supermodding with 60 km averaging size.



Scatterometer supermodding

Standard deviation of observation minus background departures (O-B) provide information on the combined observation and background errors.

Scatterometer **supermodding can reduce** the standard deviation of O-B by removing the (background) error variance at small scales. The 30 km supermodding size can provide 4–5% reduction in the standard deviation of O-B and further decrease (up to 8-11%) with larger supermodding sizes.

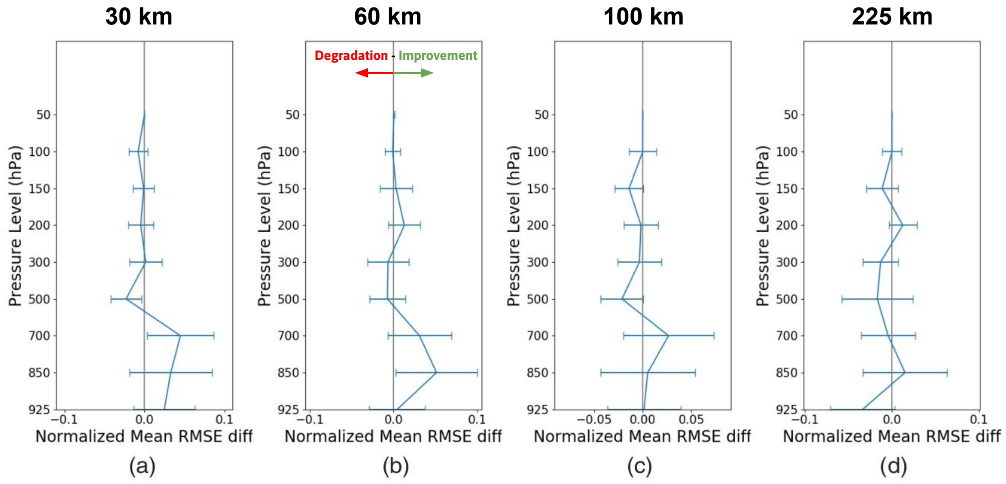
Size (km)	No. of obs.	STDV(d_b^o) for $u_{10\,m}$	STDV(d_a^o) for $u_{10\,m}$	STDV(d_b^o) for $v_{10\,m}$	STDV(d_a^o) for $v_{10\,m}$
Default	34130	2.1460	1.3826	2.3106	1.5335
30	34097	2.0515	1.7110	2.2197	1.8141
60	34002	1.9951	1.8522	2.1479	1.9274
100	33840	1.9880	1.9001	2.0902	1.9596
135	33694	2.0374	1.9457	2.0786	1.9802
175	33564	2.1271	2.0035	2.1125	2.0161
225	33486	2.2809	2.0787	2.1944	2.0660

Scatterometer supermodding

Observing system experiment
1)Default vs Supermodding operator
2)Comparison of different averaging sizes

The use of 30 km supermodding size has mostly positive impact on wind speed and temperature forecasts.

The use of 60 km supermodding showed statistically significant positive impact in wind speed, in temperature, and in geopotential height.



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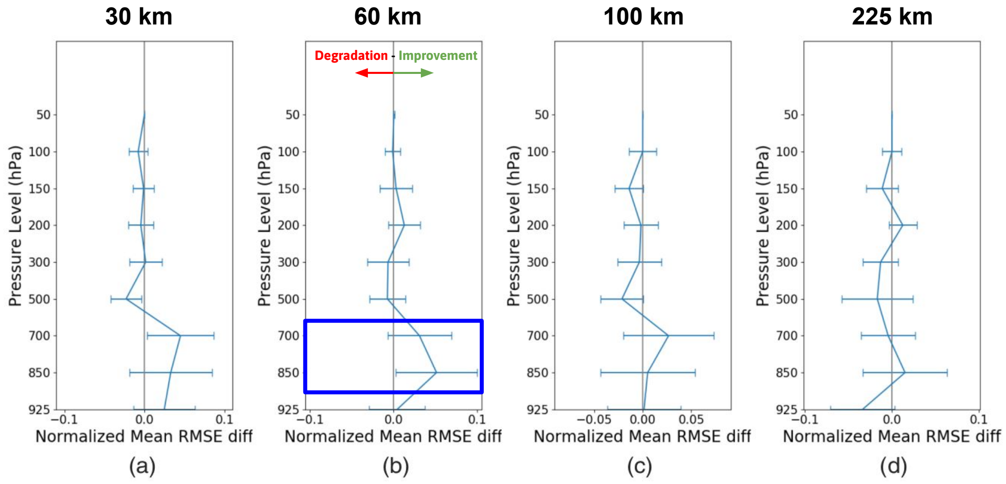
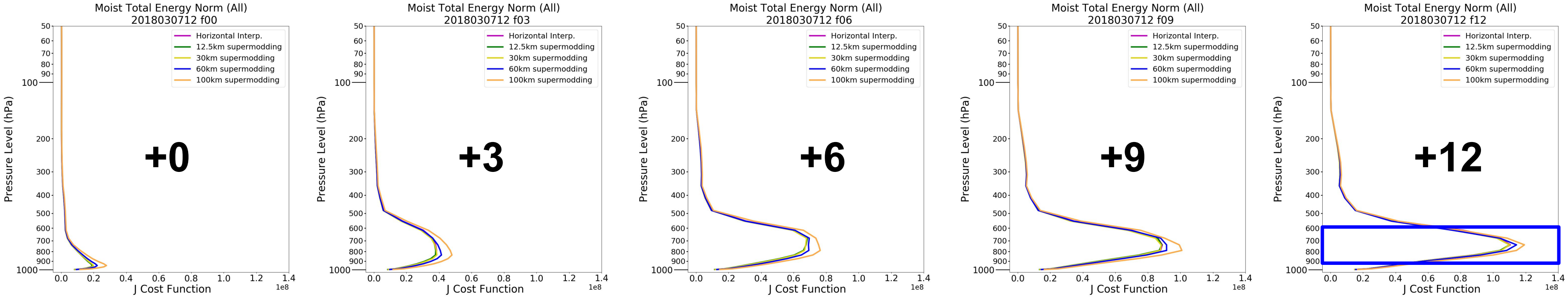
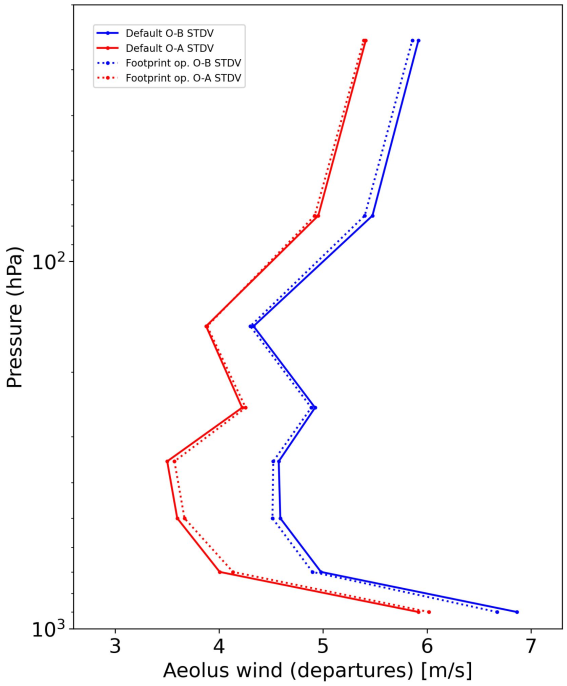




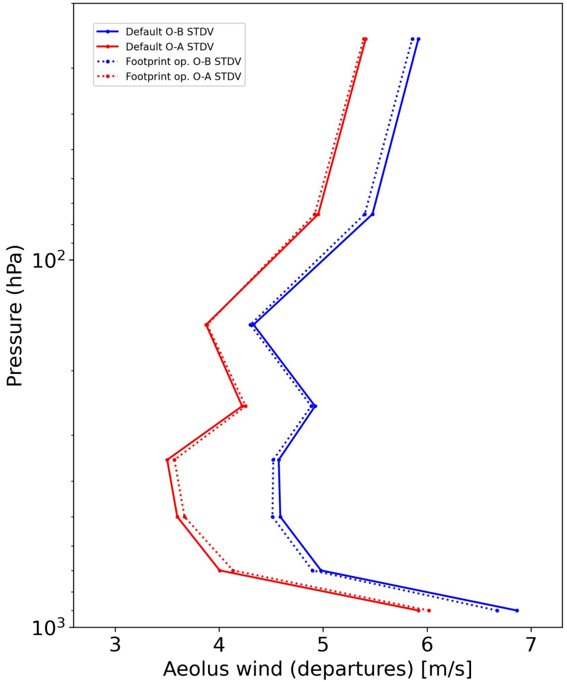
Aeolus wind profiles and the footprint operator

Aeolus Rayleigh-clear footprint operator



Relatively small but consistent reduction (~1%) in O-B standard deviation was obtained by the use of Aeolus footprint operator - **Aeolus high noise level**

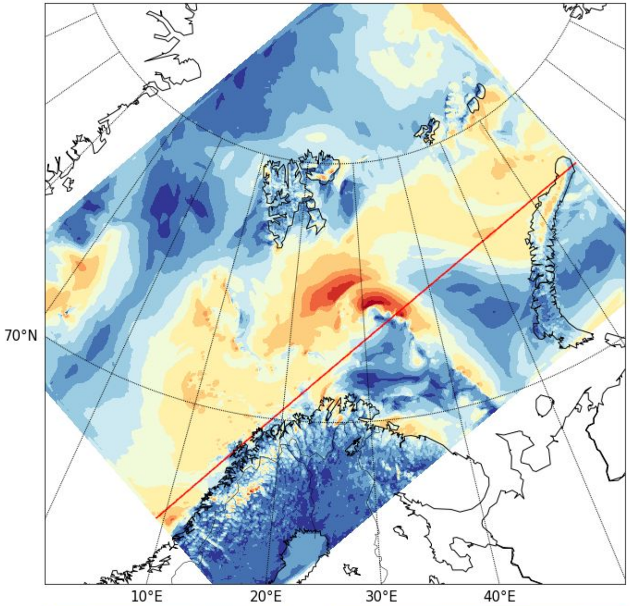
Aeolus Rayleigh-clear footprint operator

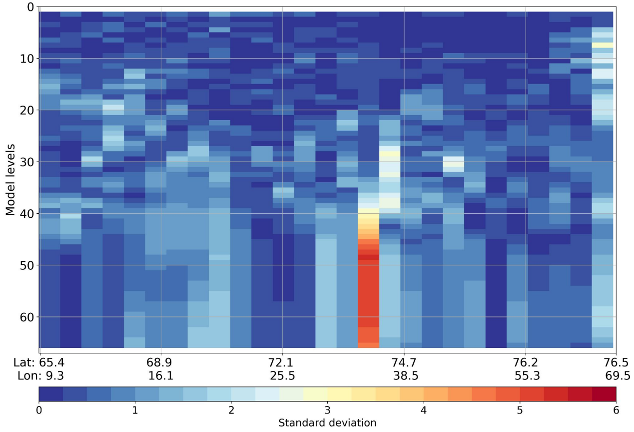


Relatively small but consistent reduction (~1%) in O-B standard deviation was obtained by the use of Aeolus footprint operator - **Aeolus high noise level**

The footprint operator is the most efficient when **the variability in the model field is larger than the observation error (4-5 m/s)**.

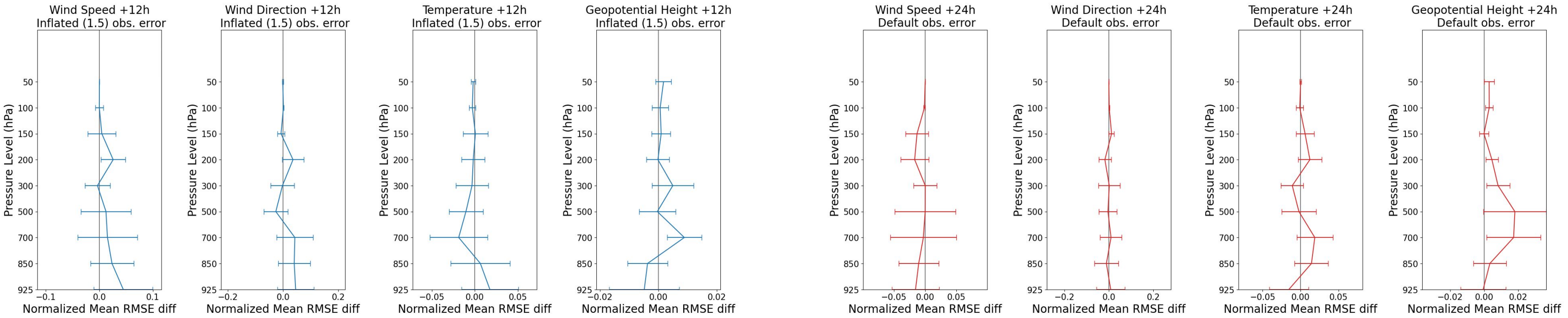
PL case study (25th of November, 2019) and model wind v-component variability along horizontal 87.5 km segments





Aeolus Rayleigh-clear footprint operator

In the case of the Aeolus footprint operator, neutral impact on wind speed and wind direction forecasts, and positive impact on geopotential height forecasts were obtained in the verification scores.



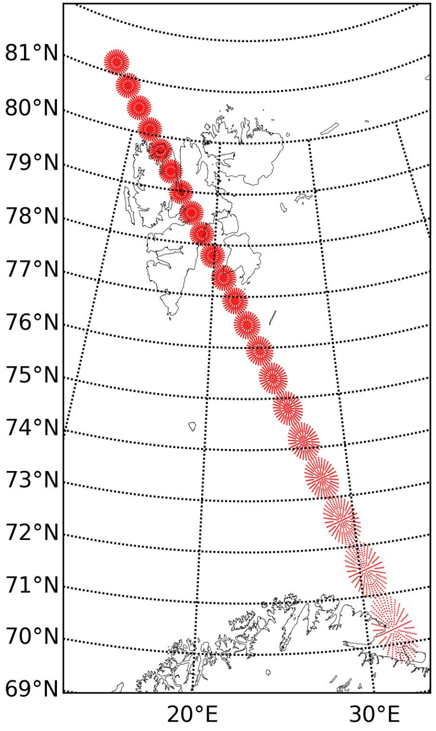
This might be explained by the high noise level of Aeolus Rayleigh-clear (instrument noise is much higher than the representation error).

Microwave cross-track scanning instruments and the footprint operator

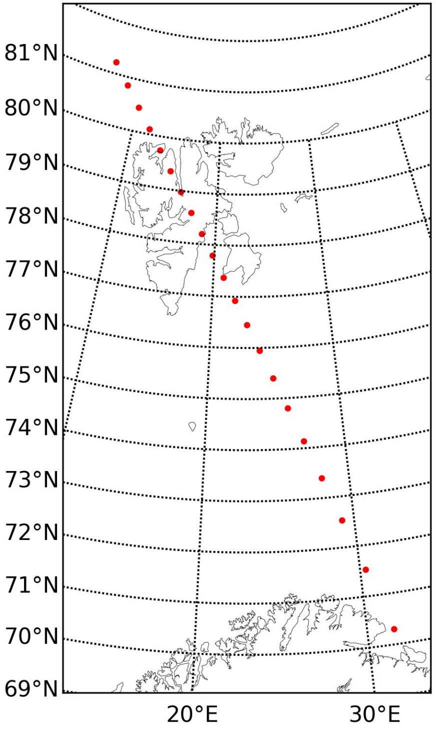
Microwave radiance footprint operator

A prototype implementation for microwave cross-track scanning instruments was explored with AMSU-A and MHS radiances.

AMSU-A footprint operator



AMSU-A default obs. operator



Microwave radiance footprint operator

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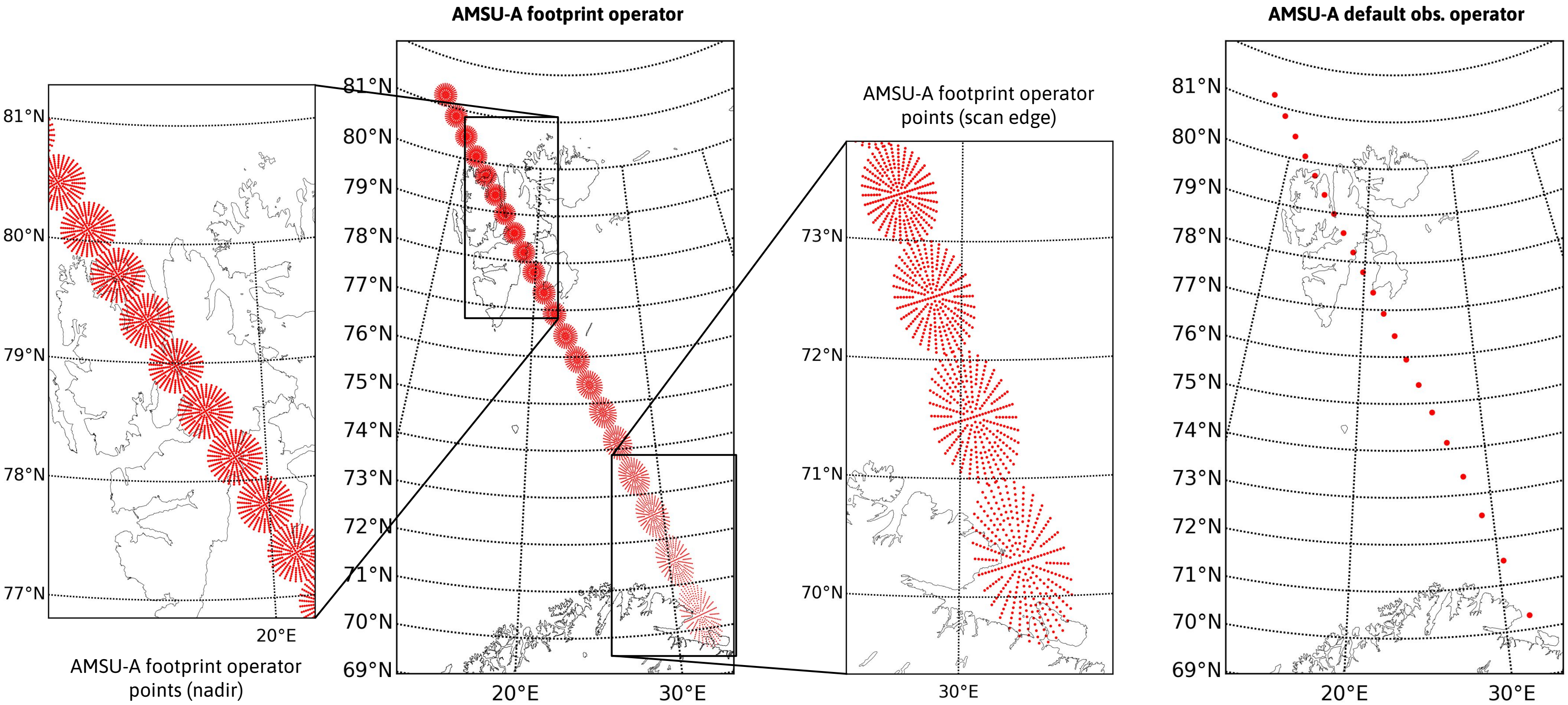
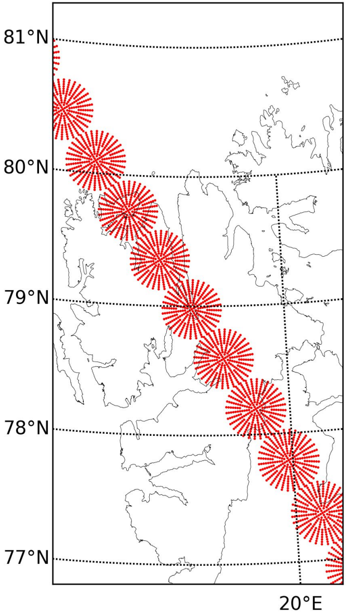
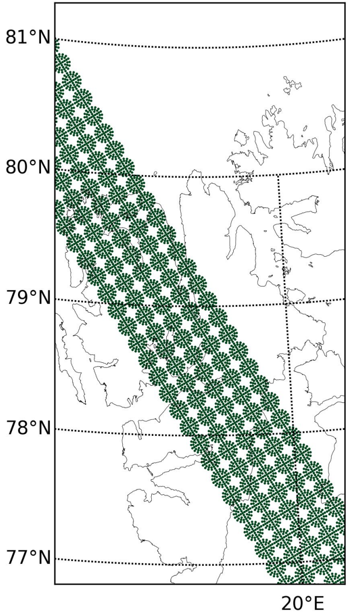


Microwave radiance footprint operator

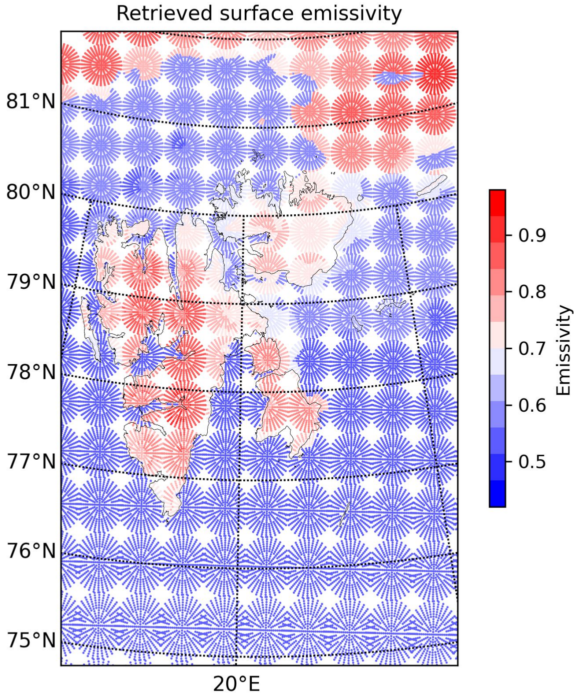
A prototype implementation for microwave cross-track scanning instruments was explored with AMSU-A and MHS radiances.



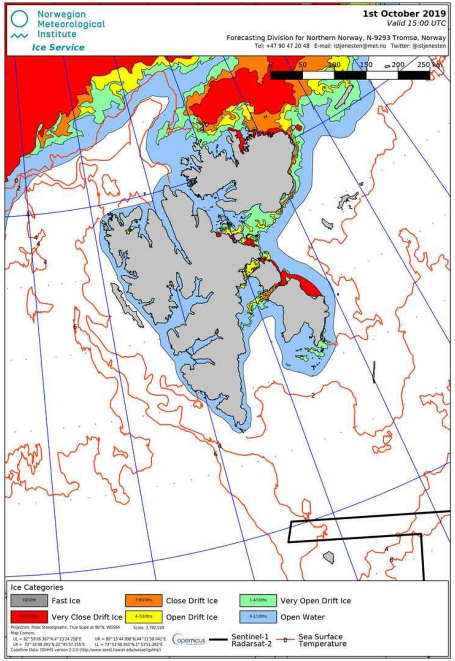
AMSU-A footprint operator points (nadir)



MHS footprint operator points (nadir)



AMSU-A channel 6

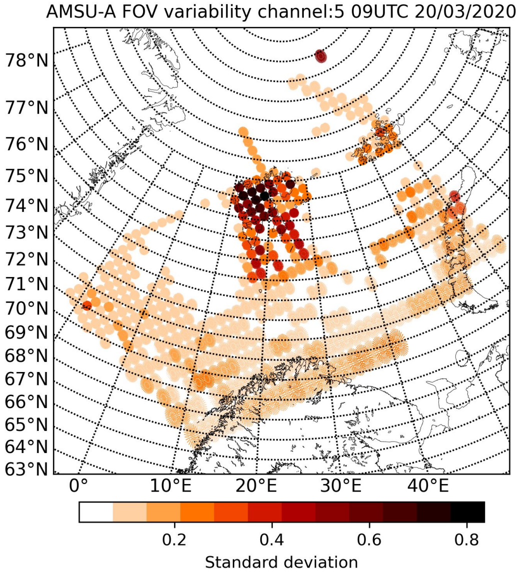


Sea-ice chart of MET Norway

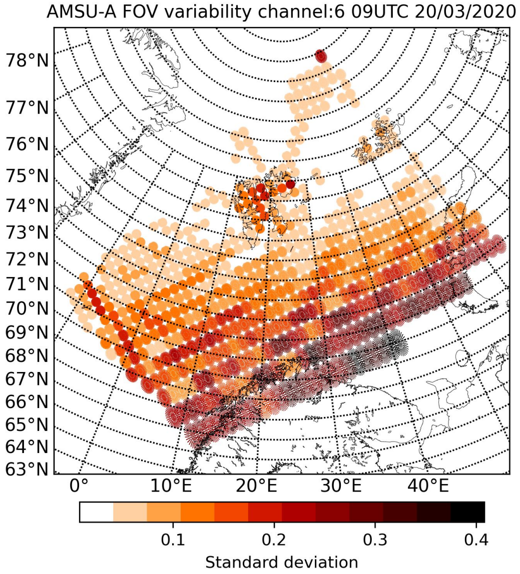
Microwave radiance footprint operator

A case study was carried out to identify areas of the highest sub-footprint variability for both AMSU-A and MHS data.

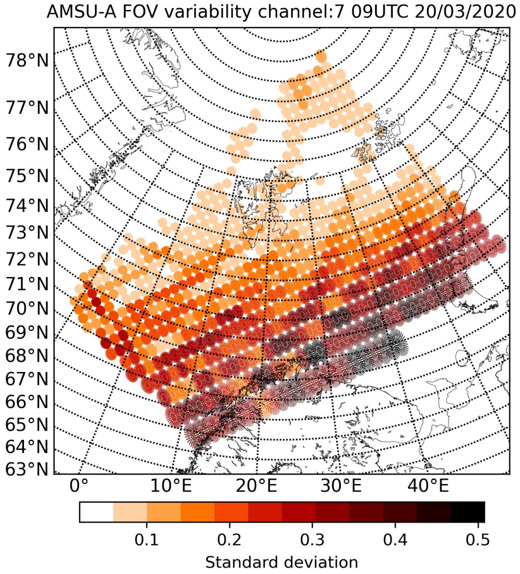
AMSU-A channel 5



AMSU-A channel 6



AMSU-A channel 7

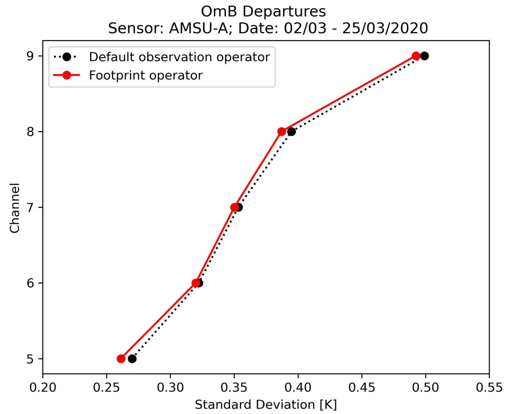


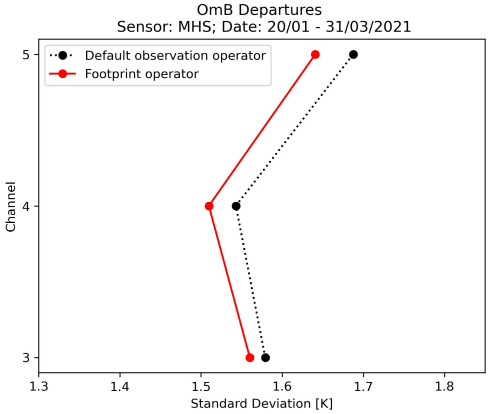
Microwave radiance footprint operator

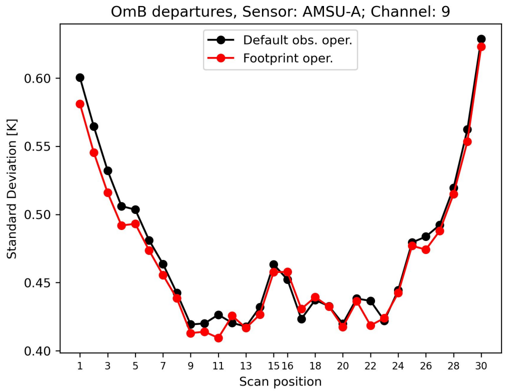
The microwave radiance footprint operator provides consistent reduction in O-B standard deviations similarly to previous studies.

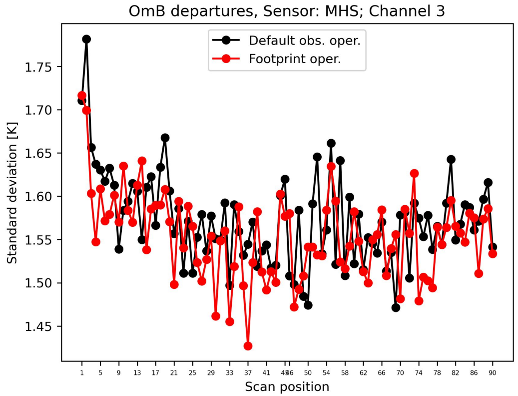
However, the computational costs are increased significantly, therefore optimisation becomes essential.

Assimilation setup	Minim runtime performance	Relative increase
Default operator AMSU-A	363 seconds	-
Footprint AMSU-A (301 FOPs)	638 seconds	75.7%
Default operator MHS	342 seconds	-
Footprint MHS (45 FOPs)	419 seconds	22.5%









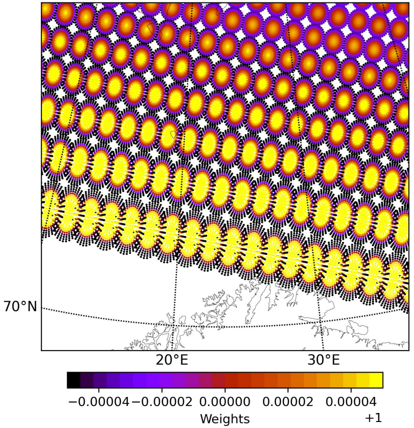
Future outlook

Future outlook

- In a high-resolution state-of-the-art assimilation system, advanced solutions like superobbing or footprint operators are required to reduce representation error.

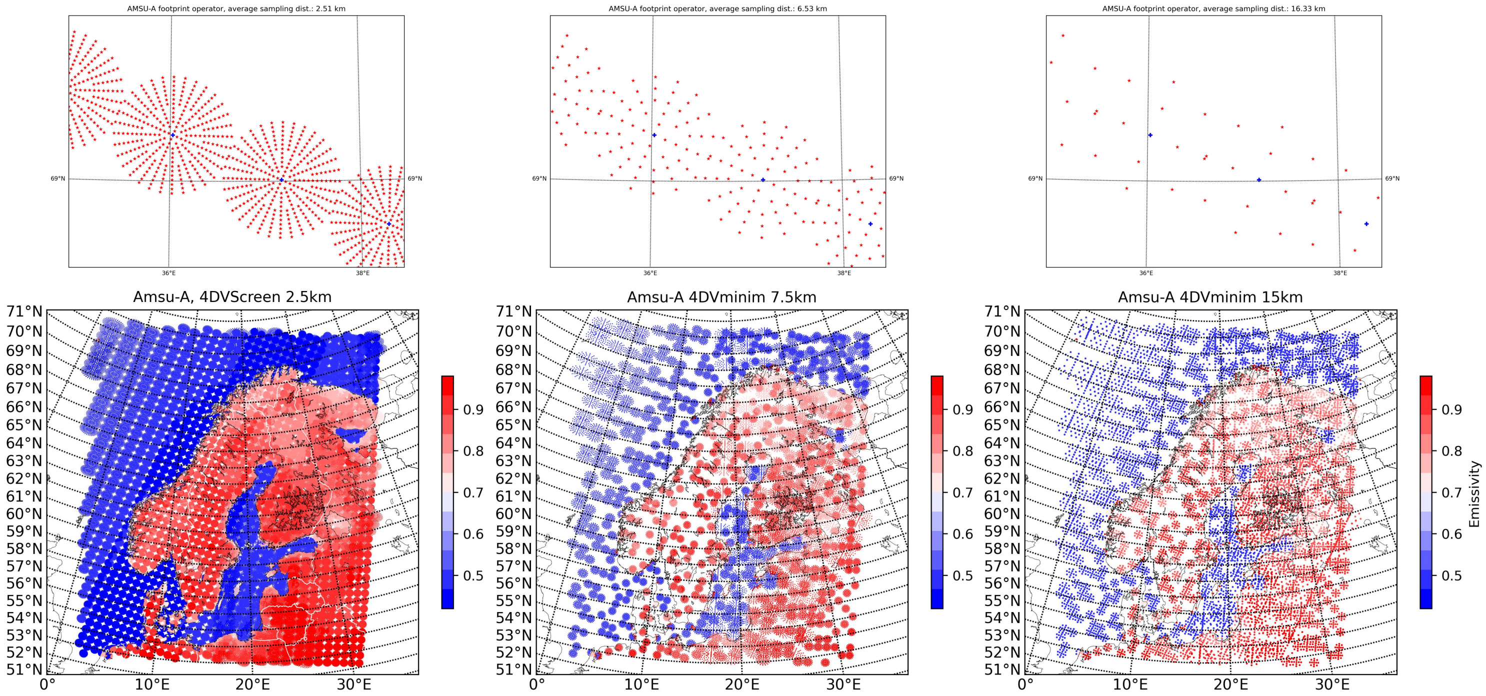
- Future developments of radiance footprint operator: to take into account the radiance **antenna pattern**, the representation of **effective field-of-view** (swept by the antenna beam), and to study future micro-satellites (AWS, Sterna).

- Another area of application can be to use the supermodding operator in **ensemble prediction systems** in order to account for uncertainties and to **generate perturbations** in the ensemble data assimilation (EDA) procedure. By the use of the supermodding operator, one can design the observation operator for the ensemble system which aims to quantify the uncertainties incorporated in the unobserved scales and processes in data assimilation.



Future outlook

- Test thoroughly the developed footprint operator with more advanced assimilation schemes (hourly RUC or time-consistent 4D-Var, 4D-EnVar).



Final remark

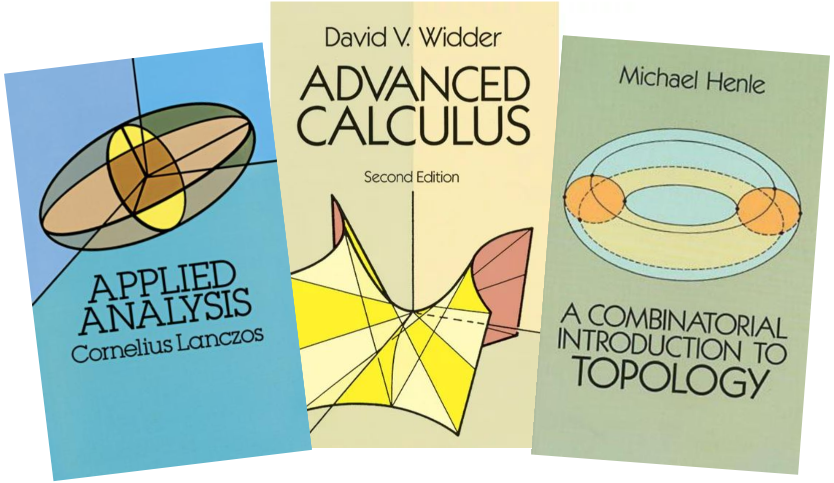
Ex libris Dezső Dévényi

I didn't have a chance to know Dezső Dévényi in person.

However, his scientific books filled up the office where we have been working and I started as a newcomer.

For example, many books from Dover Publications

I hardly understood the title of his books and I felt much respect towards his knowledge and legacy.



Acknowledgments

Thanks for the colleagues in the NWP group at OMSZ

Thanks for the selection committee

Thank you for your attention.

Questions?