Royal Netherlands Meteorological Institute
Ministry of Infrastructure and Water Management

The EUMETSAT Network of Satellite Application Facilities

NWP SAF
Numerical Weather Prediction

Transformed retrievals

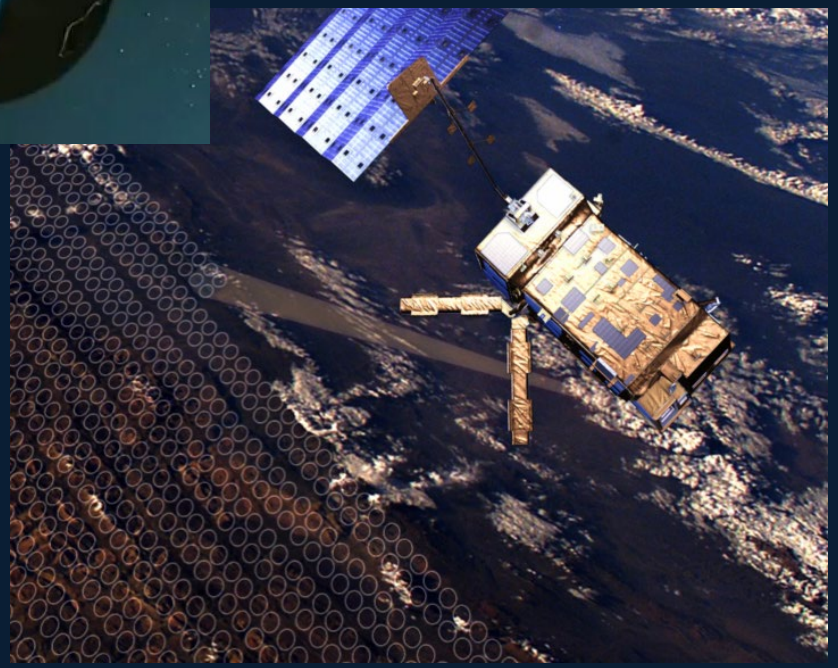
Assimilation of externally generated transformed retrievals from IASI in Harmonie-AROME 4D-Var

Erik Dedding, KNMI

Infrared **A**tmospheric **S**ounding **I**nterferometer

Photo: ©ESA
GIF: ©EUMETSAT

IASI



- Metop constellation (Polar orbit)

- 645 cm^{-1} – 2760 cm^{-1}
- 8461 channels
- Low noise characteristics (first two bands)

- Swath - 2200 km
- Footprint - 12 km

Currently, we do **NOT** use all available information

- Error correlations (spatial, temporal, interchannel)
- Sensitivity to clouds
- Sensitivity to atmospheric gases
- Data volume -> Too many channels → Transformed Retrievals

Photo: ©ESA
GIF: ©EUMETSAT

Project outline

- Project initiated between KNMI and Met Office regarding **transformed retrievals**, sponsored by NWP SAF

- To corroborate the benefits of assimilating transformed retrievals from IASI in HARMONIE-AROME 4D-Var.

➔ Transformed Retrieval observations provided by Met Office (Levens & Migliorini, 2024)

- Refactoring of Met Office code to generate transformed retrievals to embed in the NWP SAF 1D-Var package.

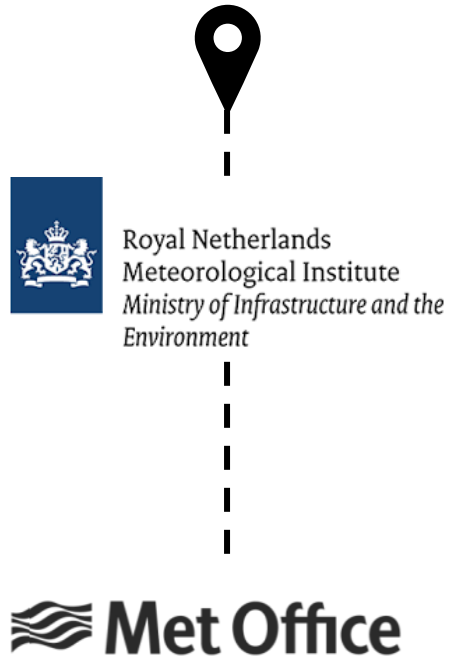


Figure: ©EUMETSAT

Content

The EUMETSAT Network of Satellite Application Facilities

NWP SAF
Numerical Weather Prediction

Transformed retrievals. What and why?

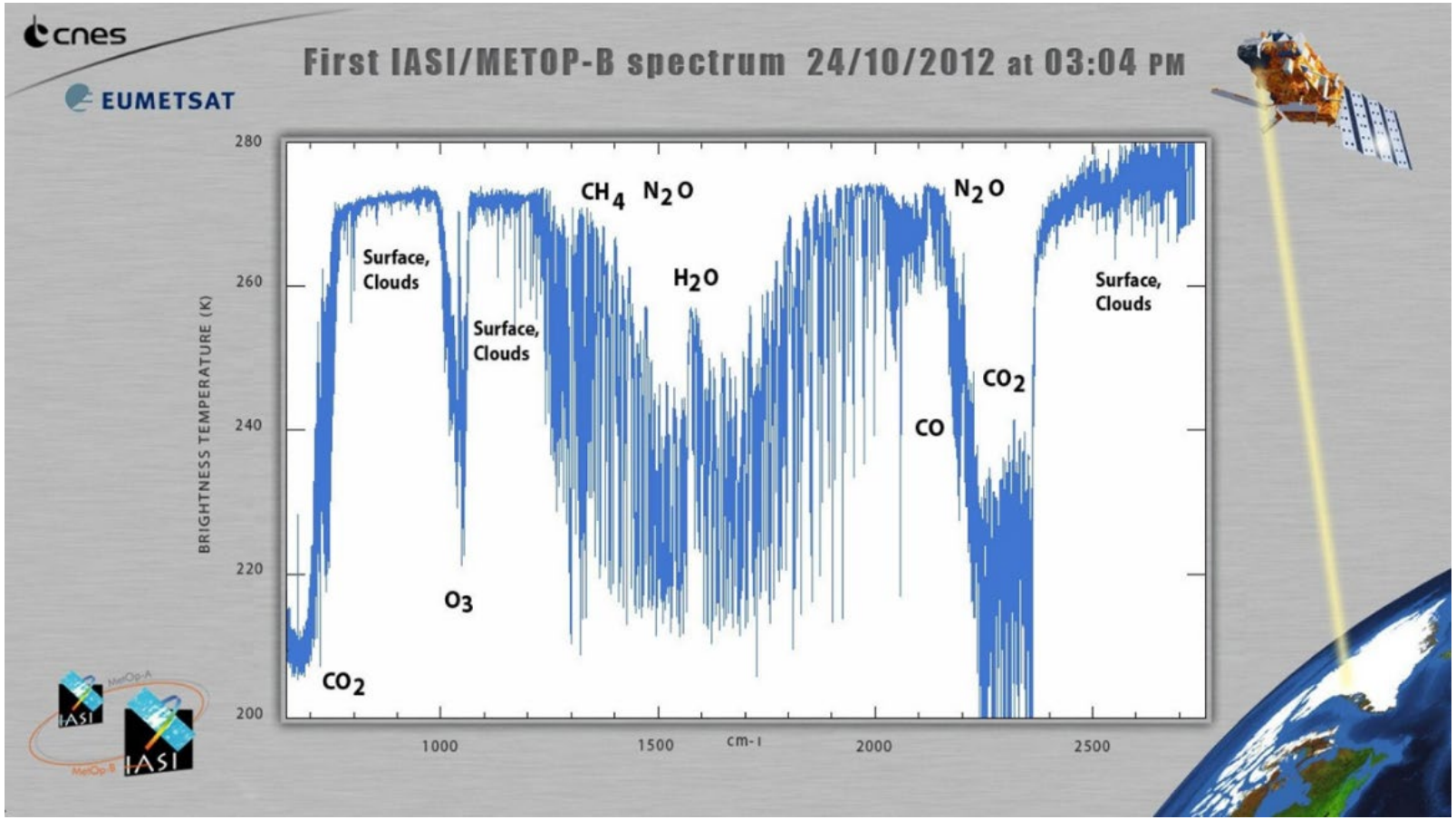
Extending the NWP SAF 1D-Var package

Assimilation of transformed retrievals

Results

Conclusion

What are Transformed Retrievals?
(short version)



$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^{\mathrm{T}}\mathrm{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}\left(\boldsymbol{y}-\mathcal{H}(\mathbf{x})\right)^{\mathrm{T}}\mathrm{R}^{-1}(\boldsymbol{y}-\mathcal{H}(\mathbf{x}))$$

Figure: ©EUMETSAT
Retrieval plot: ©Salonen et al., (2024)

What are Transformed Retrievals?
(short version)

- One-dimensional variational assimilation (1D-Var)

$$\mathbf{y}_{rad} \xrightarrow{\text{1D-Var}} \mathbf{y}_{ret} = \{T(\mathbf{z}), q(\mathbf{z})\}$$

- Then:
  1. Linearise: $\hat{\mathbf{y}} \equiv \mathbf{y}_{rad} - \mathcal{H}(\mathbf{x}^{\mathrm{a}}) - \hat{\mathbf{H}}\mathbf{x}^{a}$
  2. Normalise: $\hat{\mathbf{y}}' = \mathrm{R}^{-\frac{1}{2}}\hat{y}; \quad \hat{\mathbf{H}}' = \mathrm{R}^{-\frac{1}{2}}\hat{\mathbf{H}}; \quad \boldsymbol{\epsilon}' = \mathrm{R}^{-\frac{1}{2}}\boldsymbol{\epsilon}^{\mathrm{o}}$
- Observation equation

$$\hat{\mathbf{y}}' \simeq \hat{\mathbf{H}}'\mathbf{x}^{\mathrm{t}} + \boldsymbol{\epsilon}',$$
$$\text{with} \quad \mathrm{cov}(\boldsymbol{\epsilon}') = \mathbf{I}_{\mathrm{m}} \Rightarrow \mathrm{R} = \mathbf{I}_{\mathrm{m}}$$

- Signal-to-noise matrix

$$S = \mathrm{R}^{-\frac{1}{2}}\mathbf{H}\mathrm{B}^{\frac{1}{2}} = \mathrm{U}_r\Lambda_{\mathrm{r}}\mathrm{V}_r$$

- Generate transformed retrievals and operator

$$\mathbf{y}_{TR} \equiv \mathrm{U}_r^{\mathrm{T}}\hat{\mathbf{y}}'; \quad \mathbf{H}_{TR} \equiv \mathrm{U}_r^{\mathrm{T}}\hat{\mathbf{H}}'$$

- System assimilation

$$J_{TR}(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^{\mathrm{T}}\mathrm{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}(\mathbf{y}_{TR} - \mathbf{H}_{TR}\mathbf{x})^{\mathrm{T}}(\mathbf{y}_{TR} - \mathbf{H}_{TR}\mathbf{x})$$

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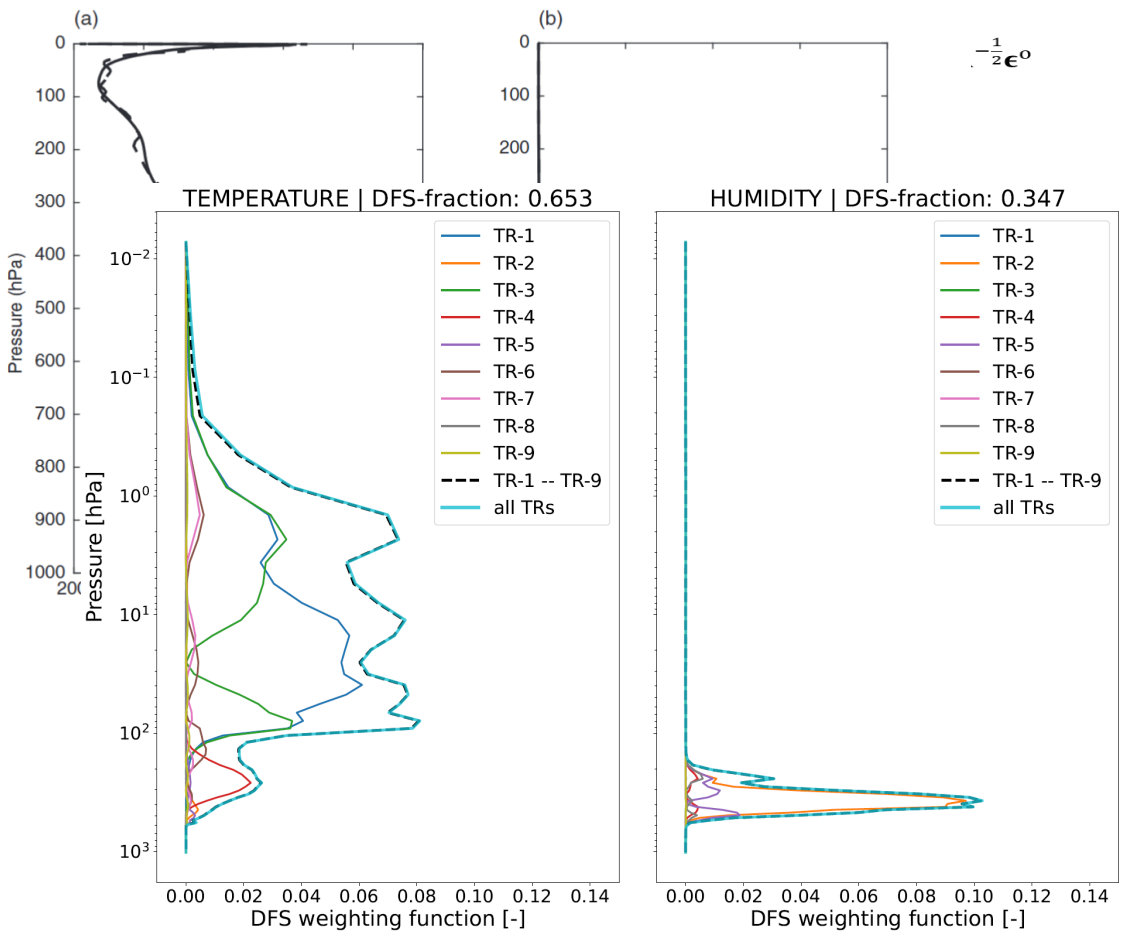

Figure: ©EUMETSAT
Retrieval plot: ©Salonen et al., (2024)

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Migliorini, S. (2012). On the Equivalence between Radiance and Retrieval Assimilation. *Monthly Weather Review*, *140*(1), 258-265. https://doi.org/10.1175/MWR-D-10-05047.1

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Levens, P.J. & Migliorini, S. (2024) Assimilation of Transformed Retrievals from IASI radiances versus direct assimilation of IASI radiances at the Met Office. *Quarterly Journal of the Royal Meteorological Society*, 150(763), 3601–3622. Available from: **https://doi.org/10.1002/qj.4786**

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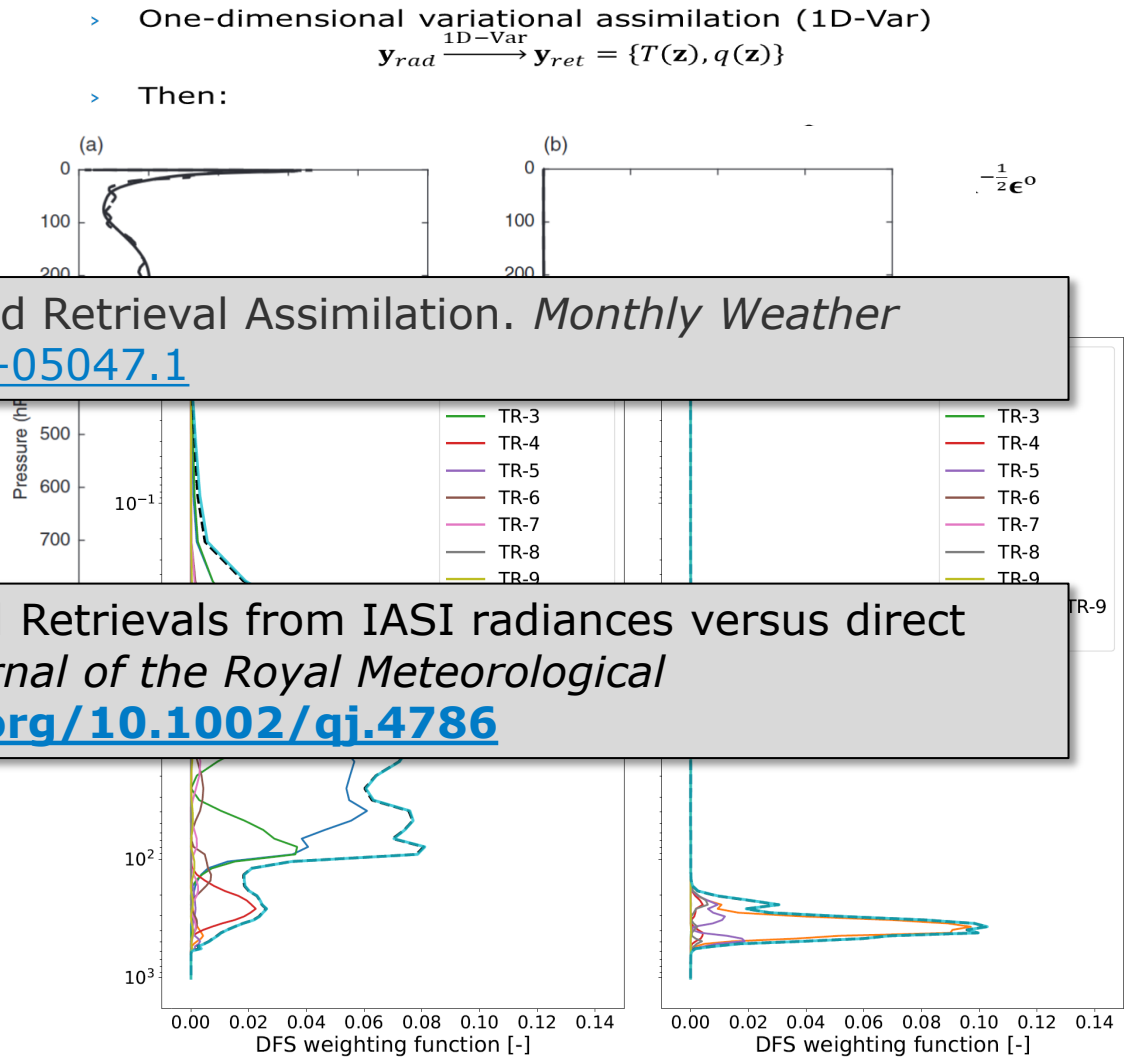
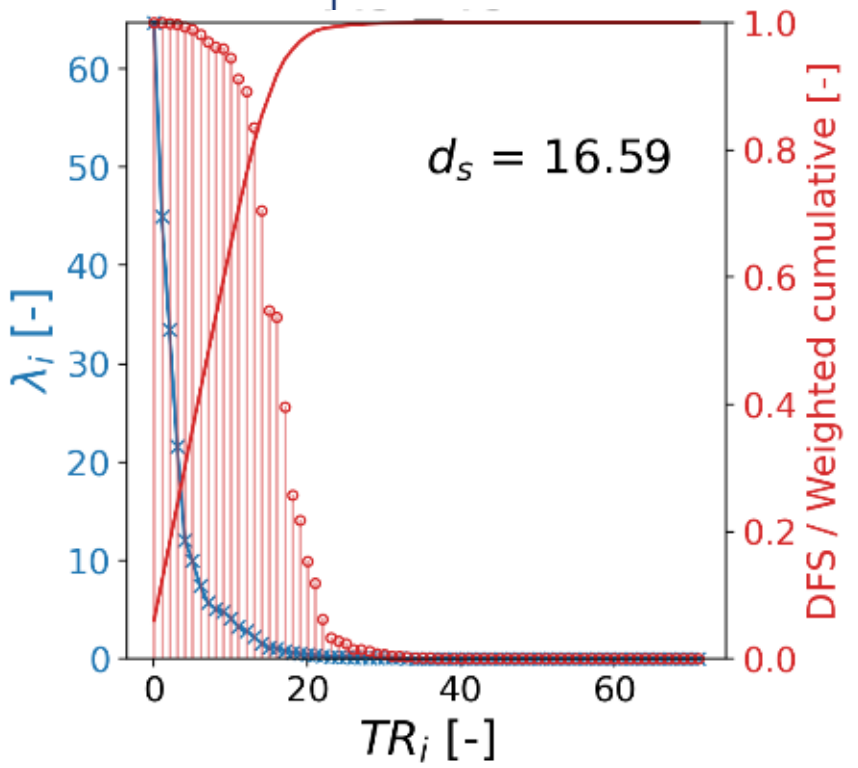


Figure: ©EUMETSAT
Retrieval plot: ©Salonen et al., (2024)

In practice

Example 1

- 313 IASI channels – 43 temperature levels, 28 humidity levels
  - ➔ R=71 transformed retrieval components
  - ➔ Ordered by λ or $d_{s,i}$ (= information content $d_s = \sum_{i=0}^{R} d_{s,i} = \sum_{i=0}^{R} \frac{\lambda^2}{1+\lambda^2}$)
  - ➔ First 22 components yield 99% of total d_s



Example 2

- 123 IASI channels – 70 temperature levels, 70 humidity levels
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  - ➔ Degree of freedom of the signal weighting functions indicate sensitivities to atmospheric variables

In practice

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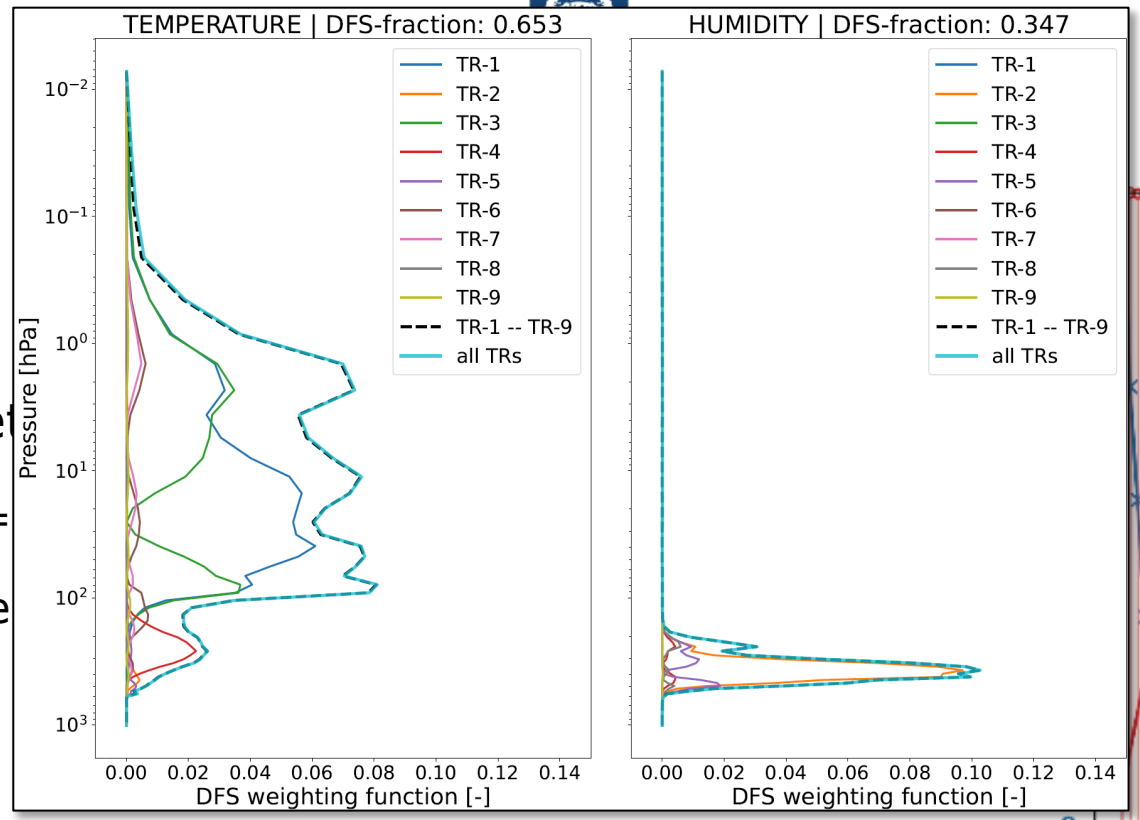

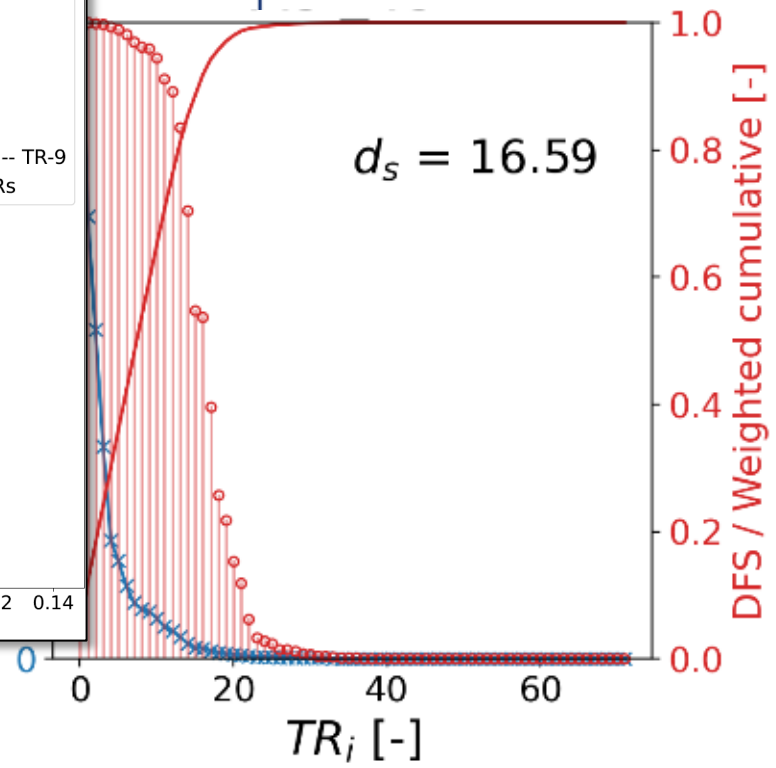

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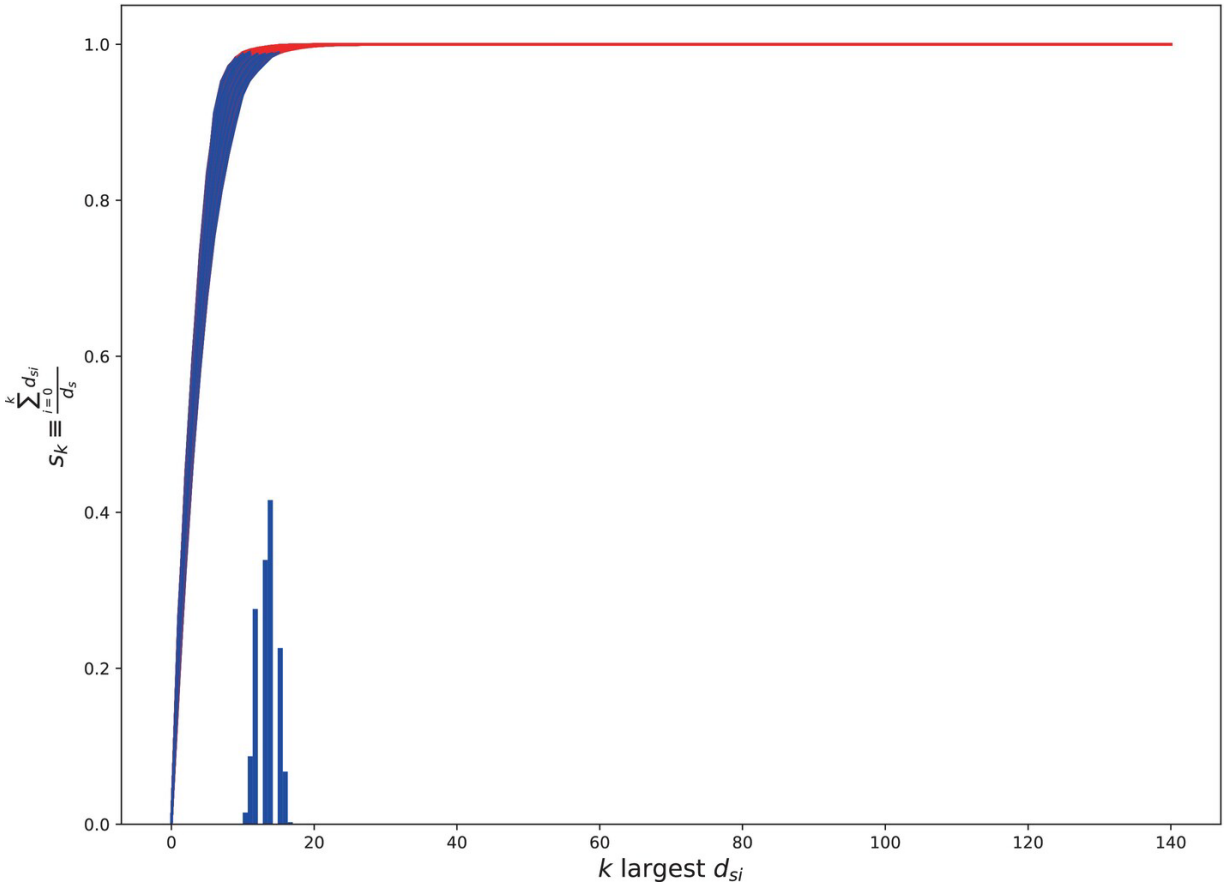
Why would we use Transformed Retrievals?



- Equivalent to assimilation of level 1 radiances
  - No introduction of model bias.

Migliorini, S. (2012). On the Equivalence between Radiance and Retrieval Assimilation

Levens, P.J. & Migliorini, S. (2024) Assimilation of Transformed Retrievals from IASI radiances versus direct assimilation of IASI radiances at the Met Office

- Compress the information content of many channels
  - Number of **assimilated quantities** per observation reduced to number of effective **degrees of freedom** in observation.
- Allow larger information content
- Simplified radiative transfer computations (complex offline)

IASI-NG

MTG-IRS

BUT

- **Similar background must be used in 1D-Var and system assimilation for equivalency**

Plot: Levens & Migliorini (2024)

NWP SAF 1D-Var software package

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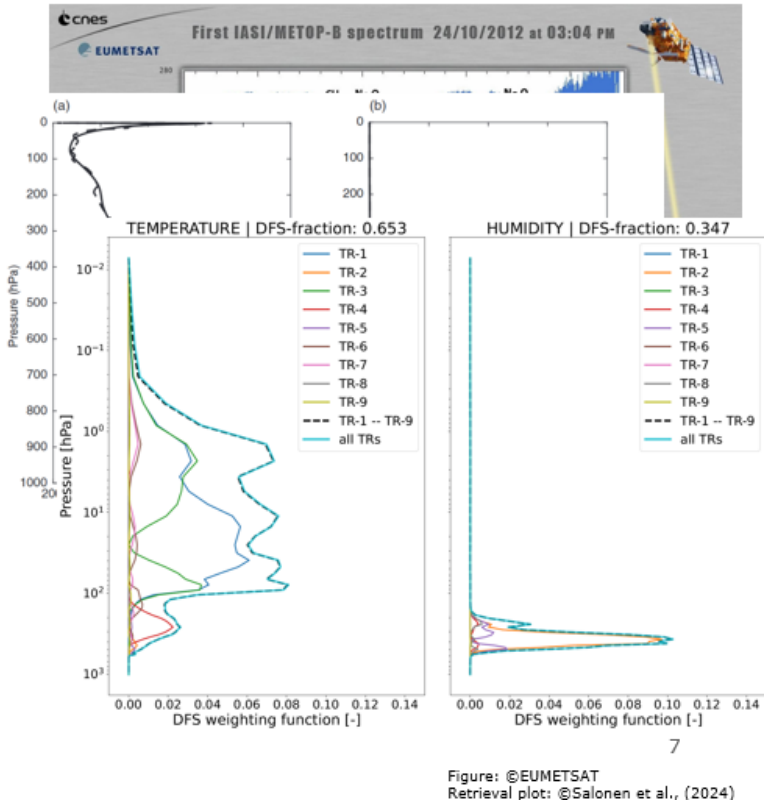

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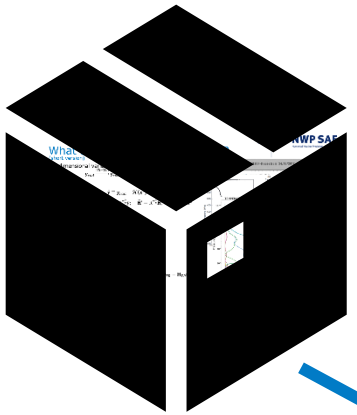
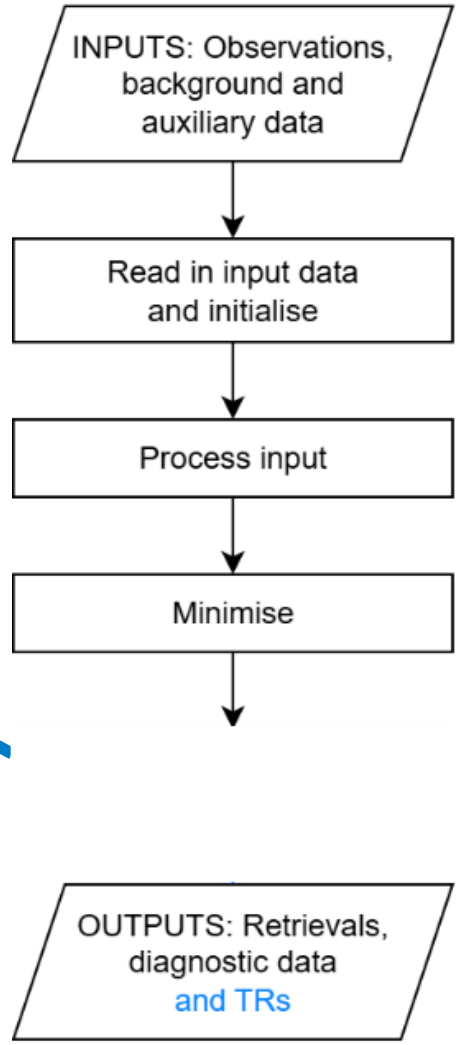
Figure: ©EUMETSAT
Retrieval plot: ©Salonen et al., (2024)

NWP SAF 1D-Var software package





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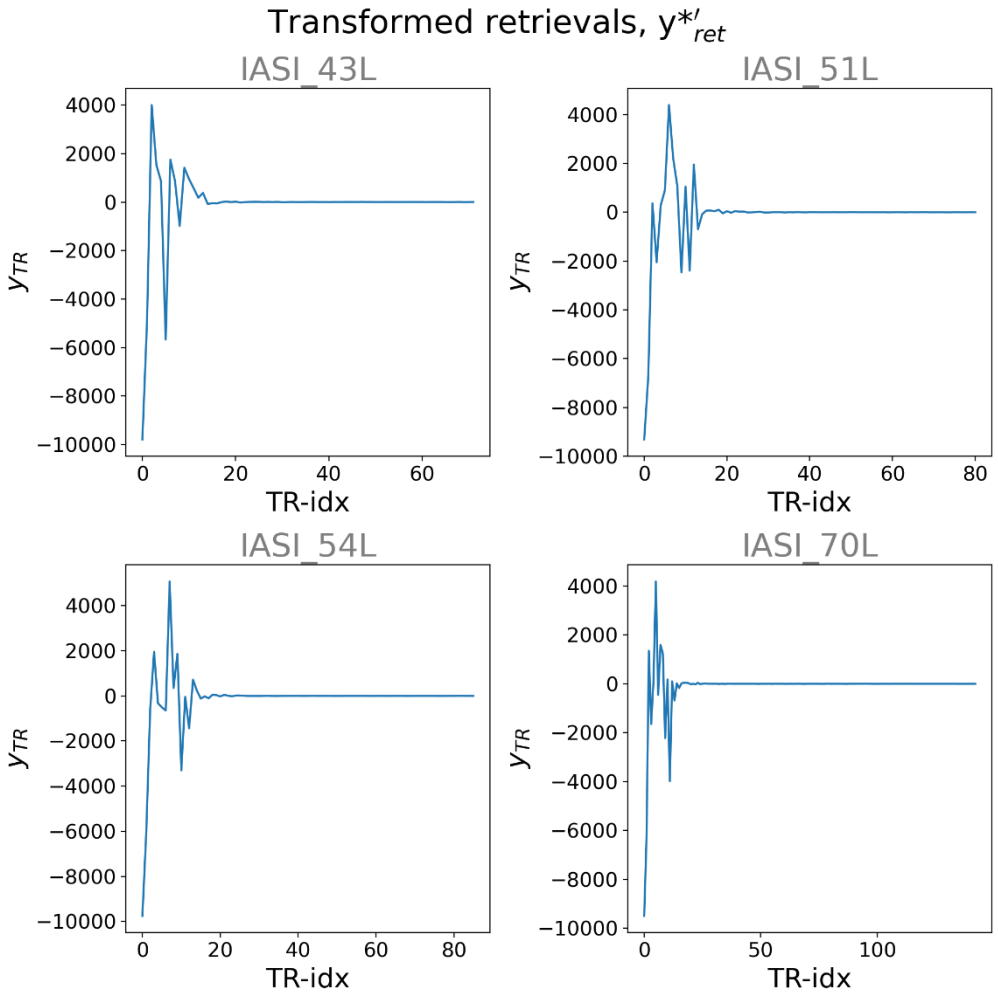
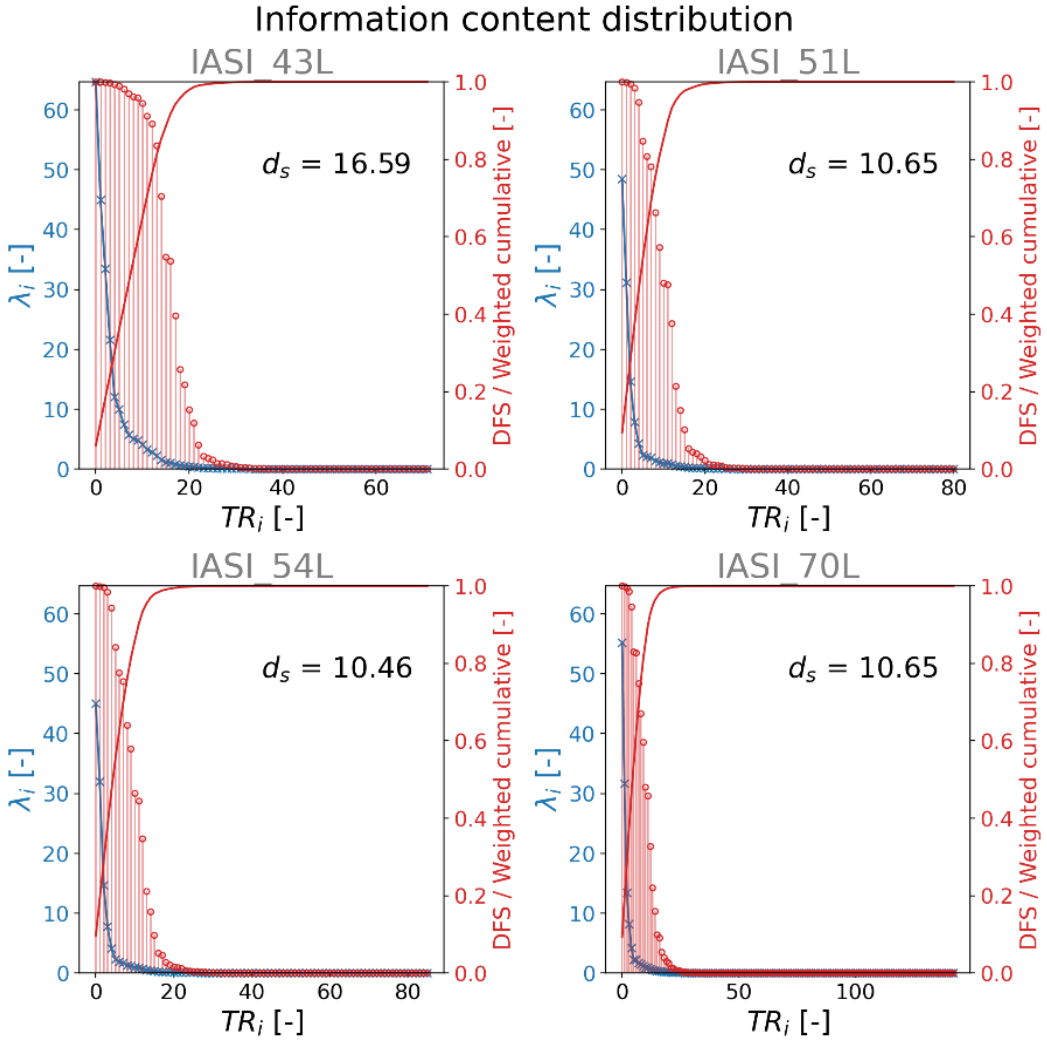
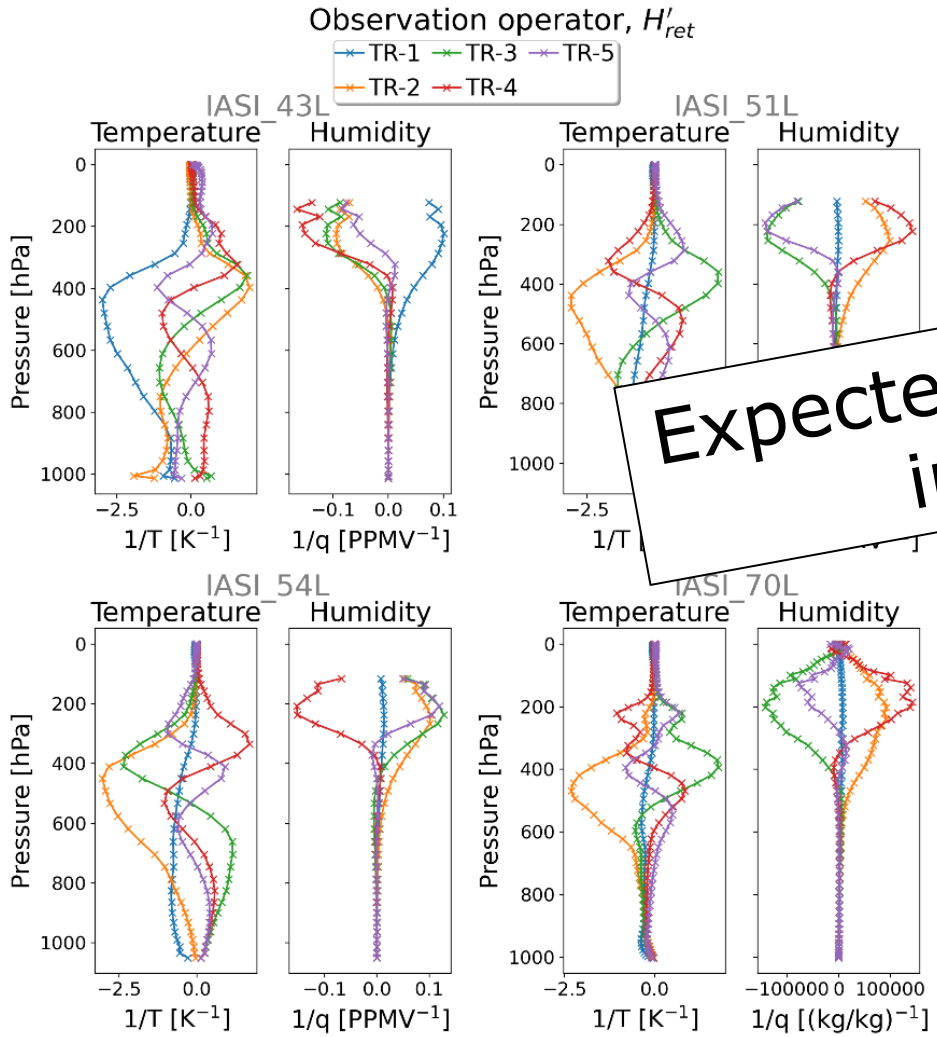
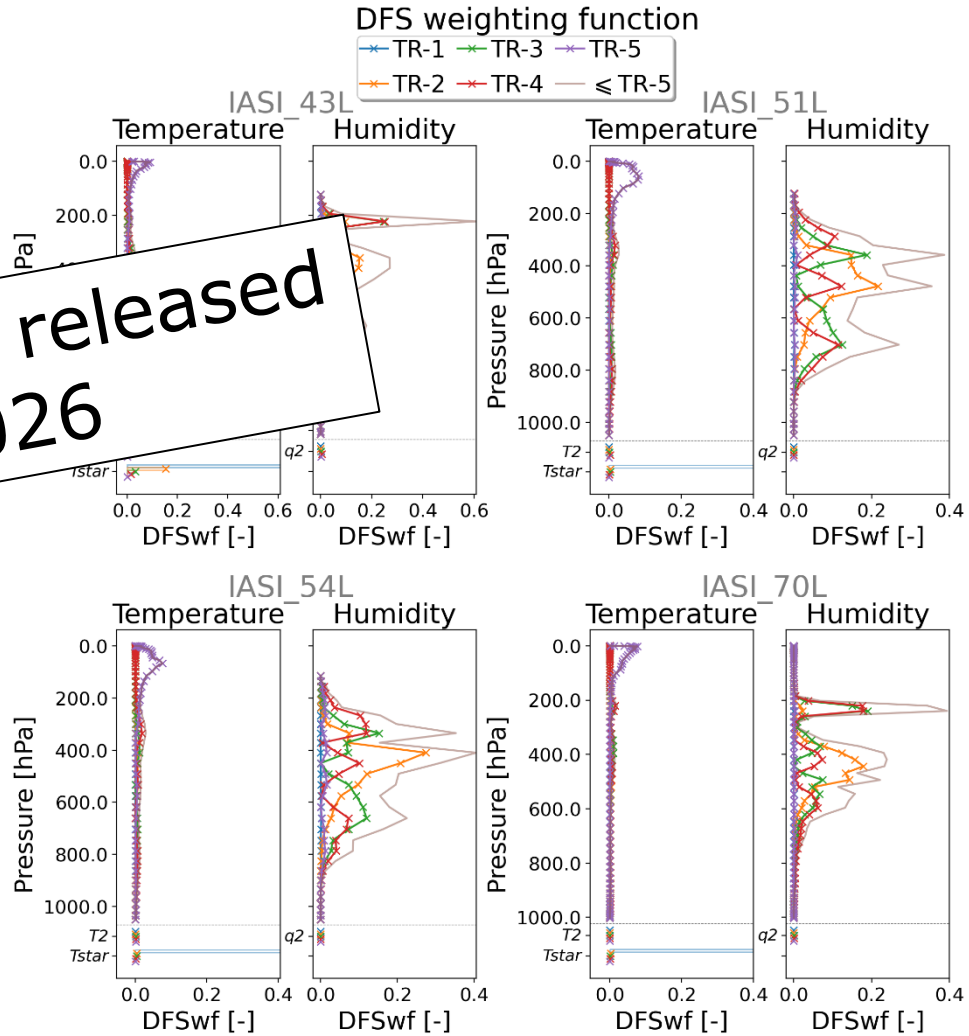




NWP SAF 1D-Var

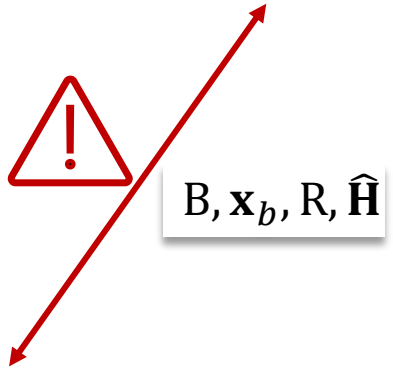




Expected to be released in Q4 2026

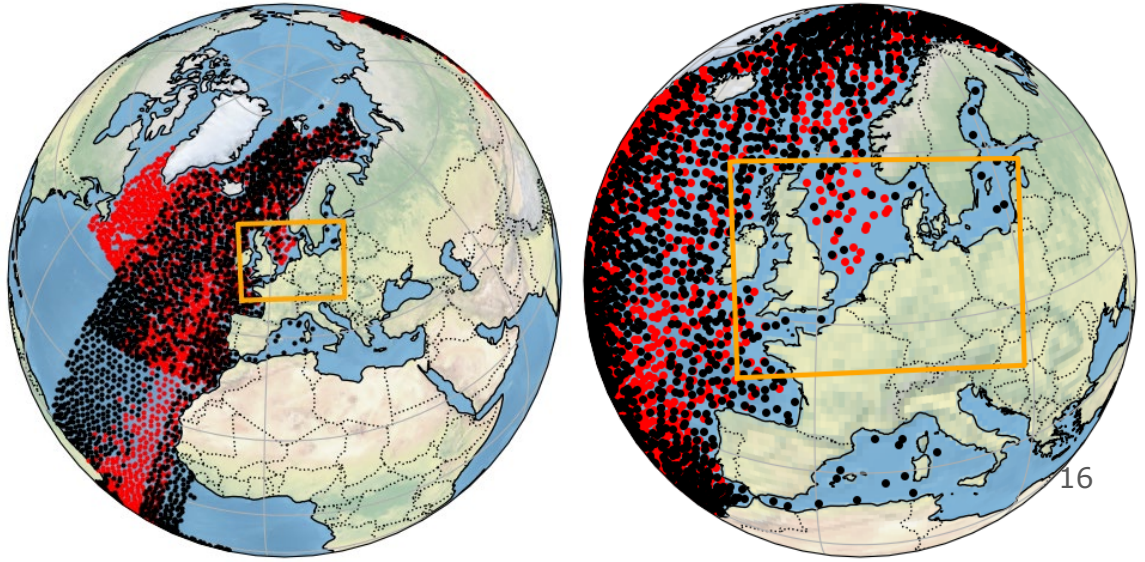
Assimilating externally generated transformed retrievals in Harmonie-AROME 4D-Var

- Transformed retrievals ($\mathbf{y}_{TR}$, $\mathbf{H}_{TR}$) generated with Met Office global model
  - 70 pressure levels -> temperature and humidity
  - Up to 175 IASI channels (Met Office global channel set)
  - 1 Month of data for December 2019
  - Thinning applied to transformed retrievals by Met Office
  - Only observations over sea

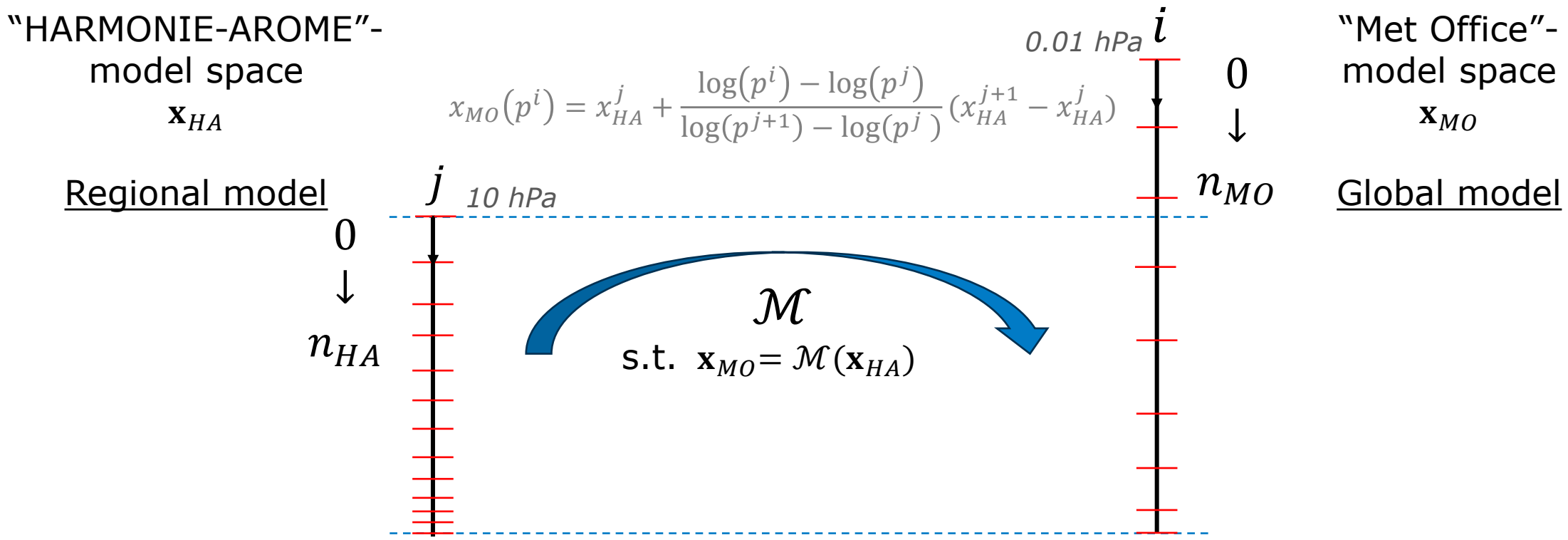


- Assimilated in regional model Harmonie-AROME 4D-Var
  - Domain: Netherlands
  - Using a depleted observation system
  - Compared against level 1 radiance assimilation
  - BUT:
    - Using observations over land and sea
    - Using Harmonie-AROME channel set (171 channels)

Rectified in follow-up assimilation experiment!



Mapping the HARMONIE-AROME state vector



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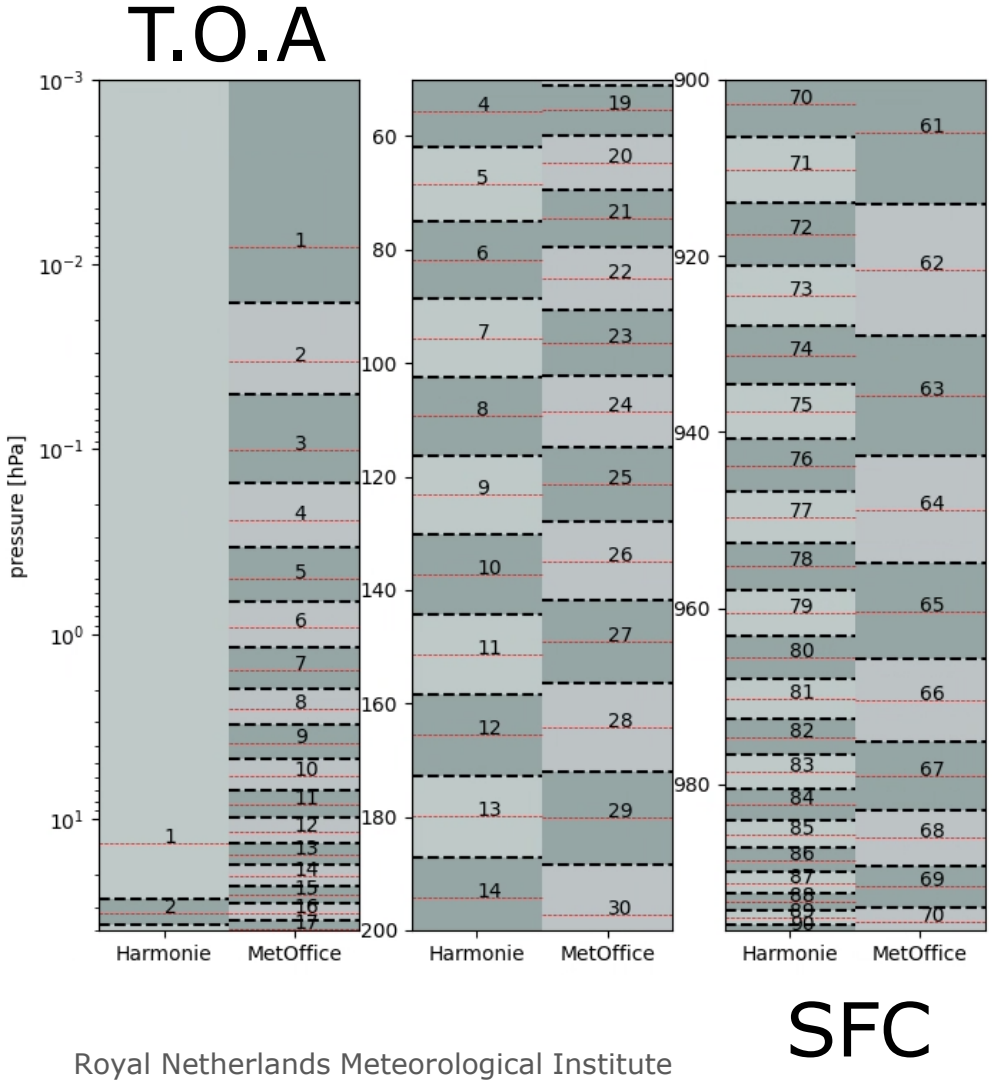
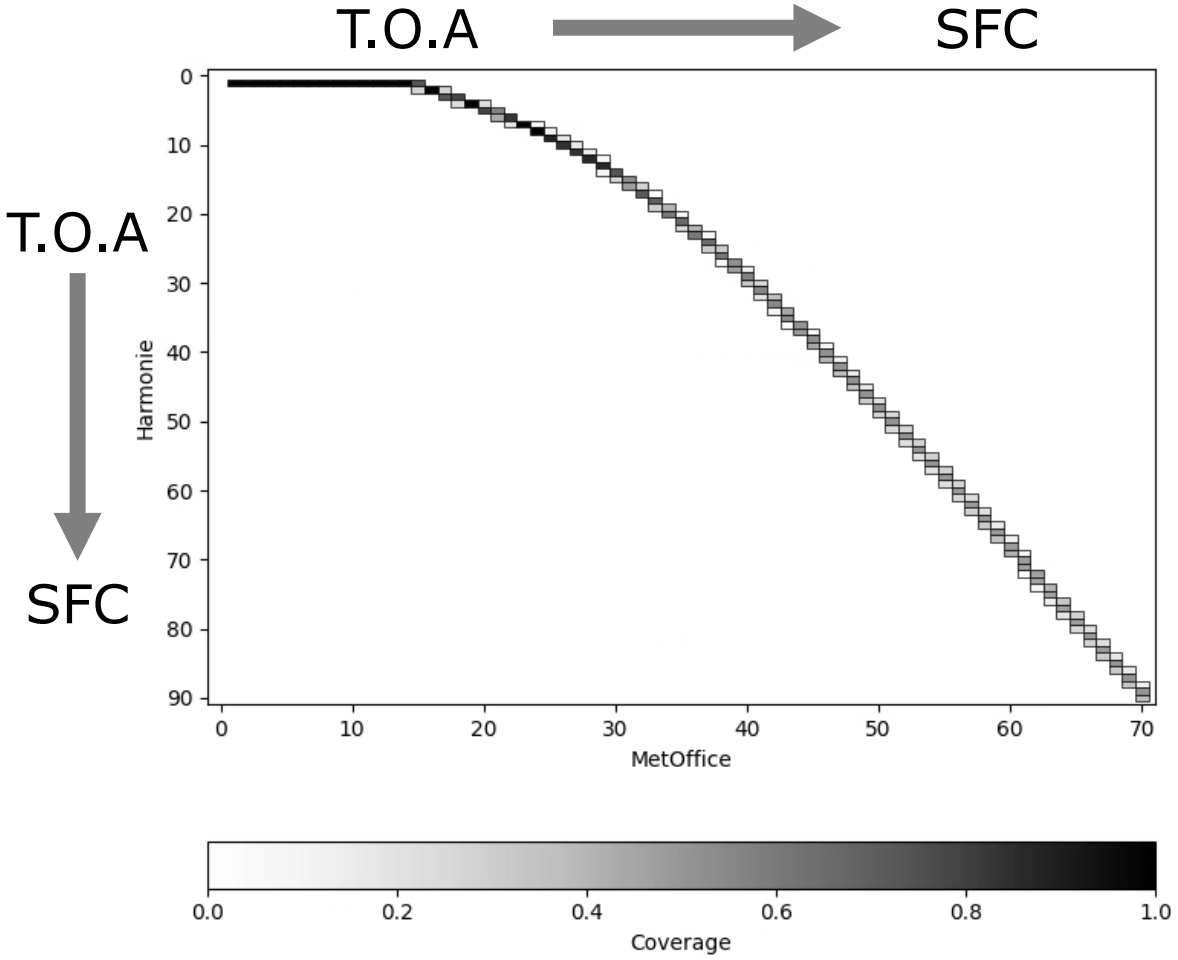




Experiments

	CONV	Transformed Retrievals		L1C Radiances
		λ_r-threshold	Inflate R	
CTRL	☑			

CONV = Radiosondes, Aircraft, Buoys, SYNOP

Experiments

	CONV	Transformed Retrievals		L1C Radiances
		λ_r-threshold	Inflate R	
CTRL	☑			
CTRL + TR	☑	☑		

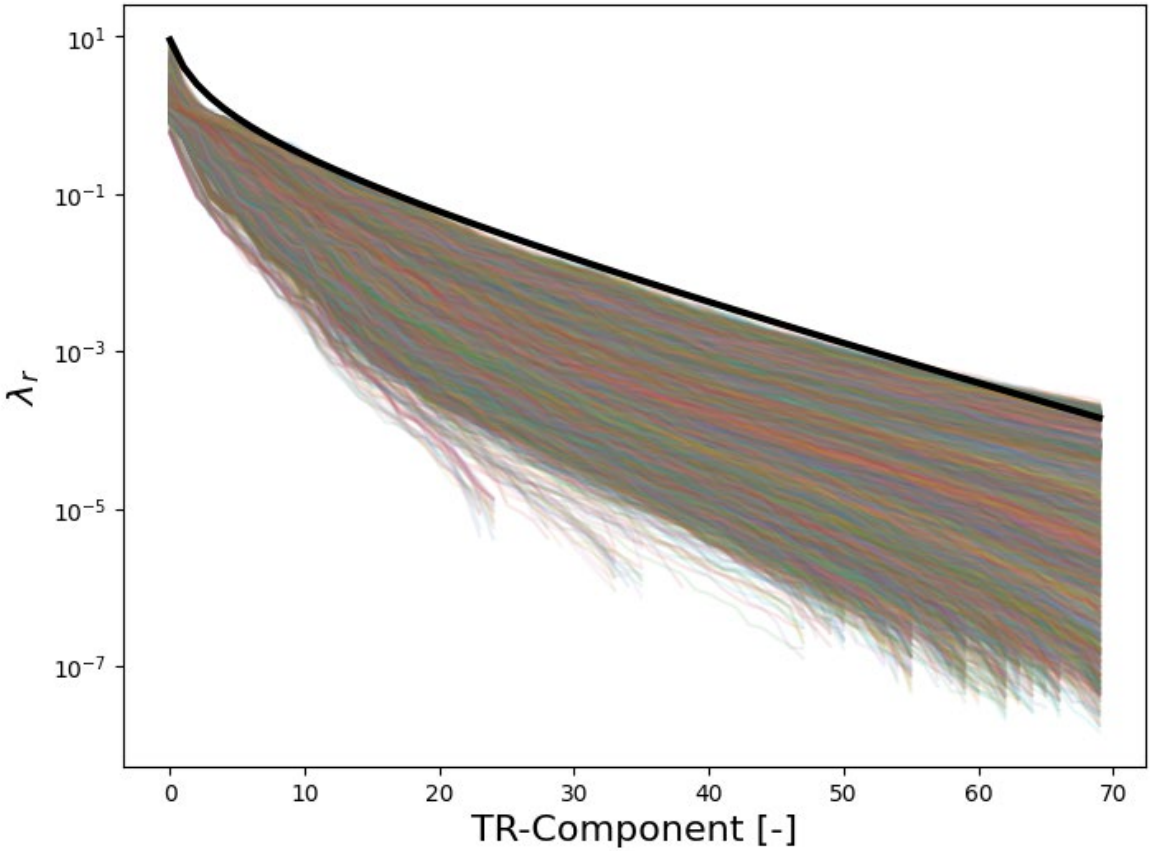
CONV = Radiosondes, Aircraft, Buoys, SYNOP

Inflating R

- Representativeness errors, different backgrounds
- Variance follows $1 + \lambda_r^2$

Migliorini, S. (2012). On the Equivalence between Radiance and Retrieval Assimilation

- Fit top of envelope of singular values



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CTRL + RAD	☑			☑

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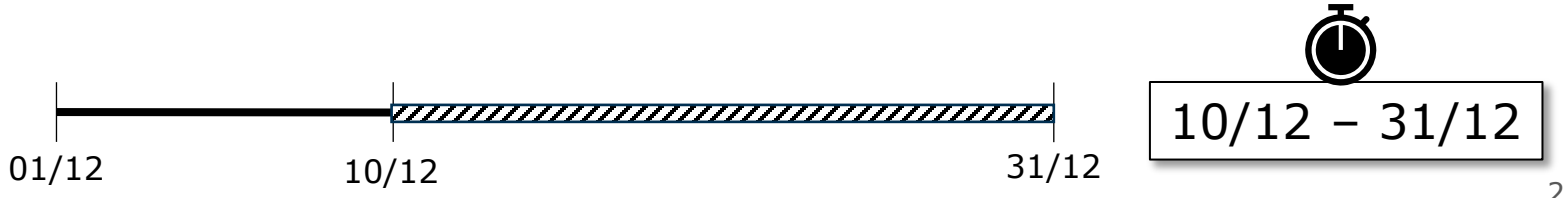
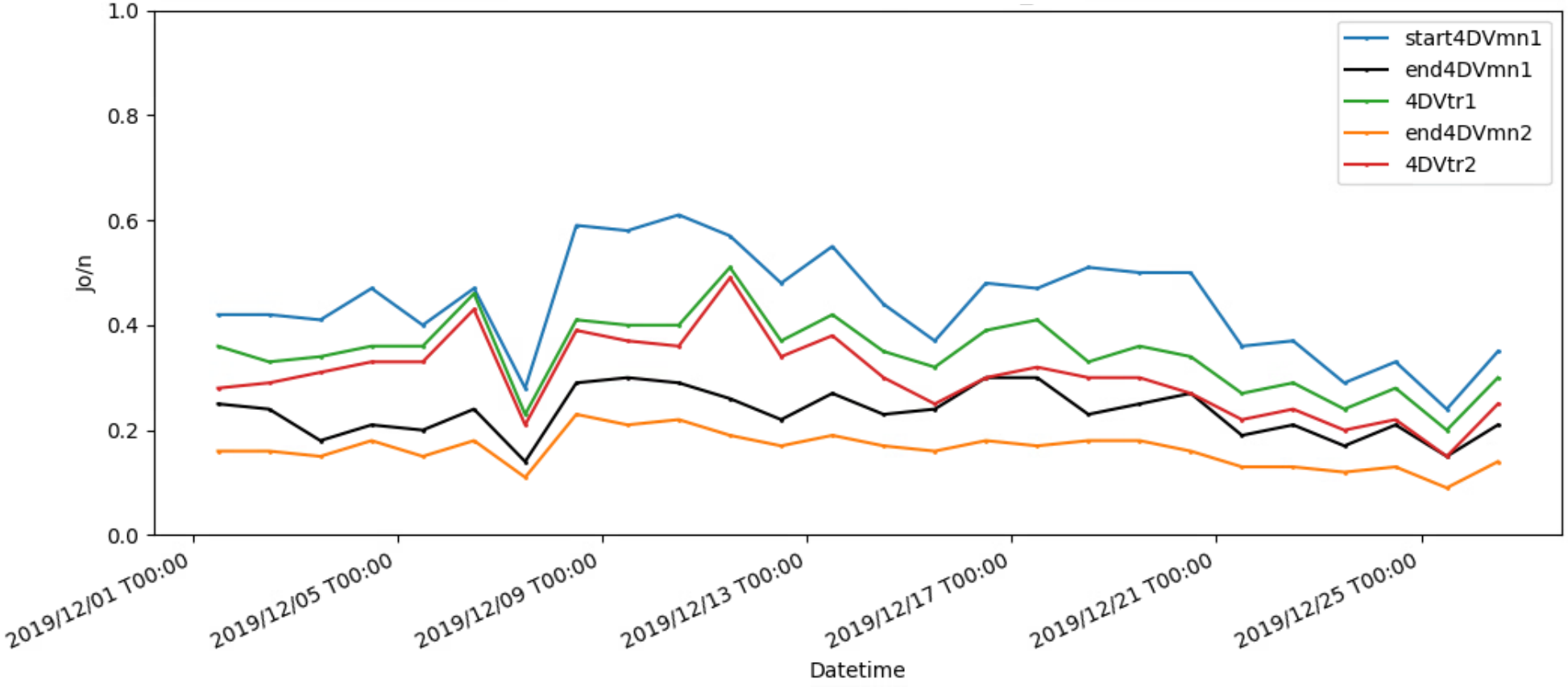


Observation cost function (Jo)

CTRL + RAD



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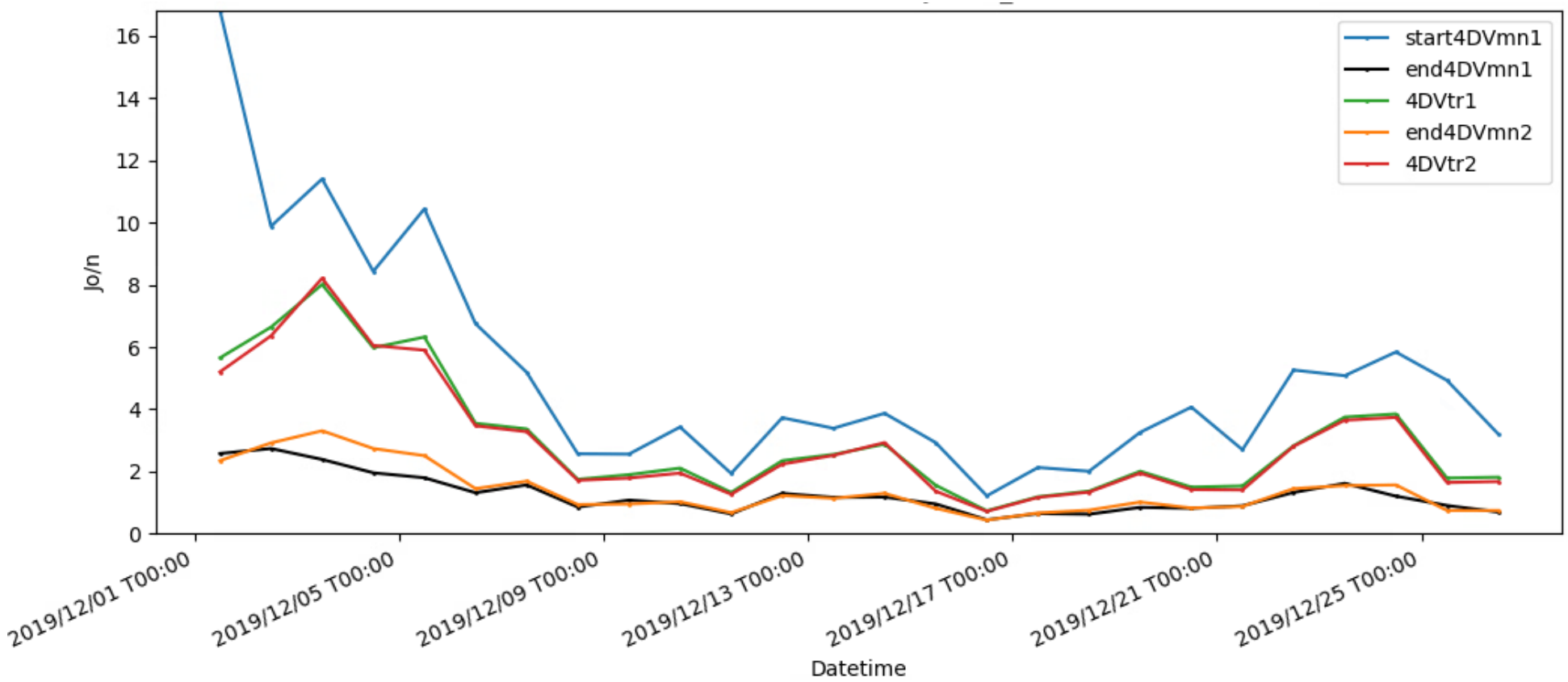

Observation cost function (Jo)

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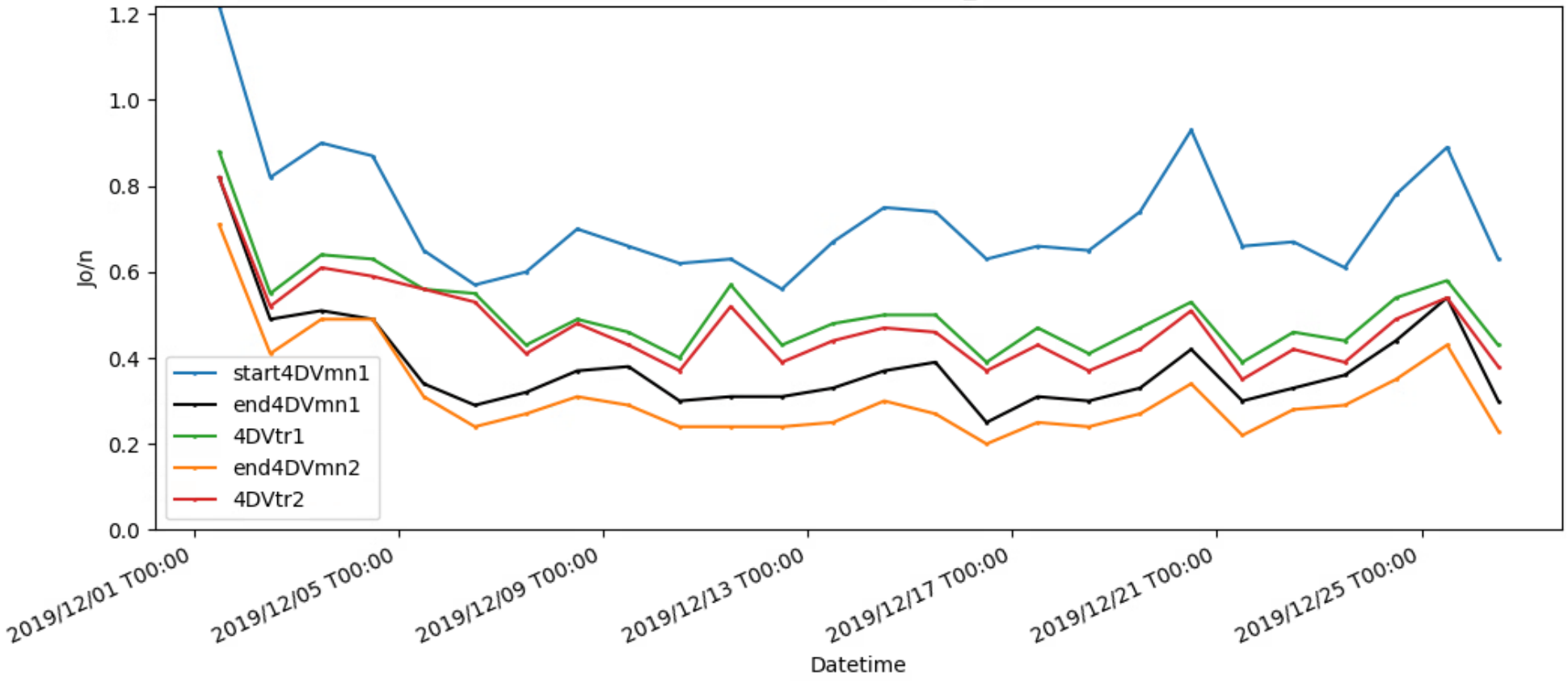
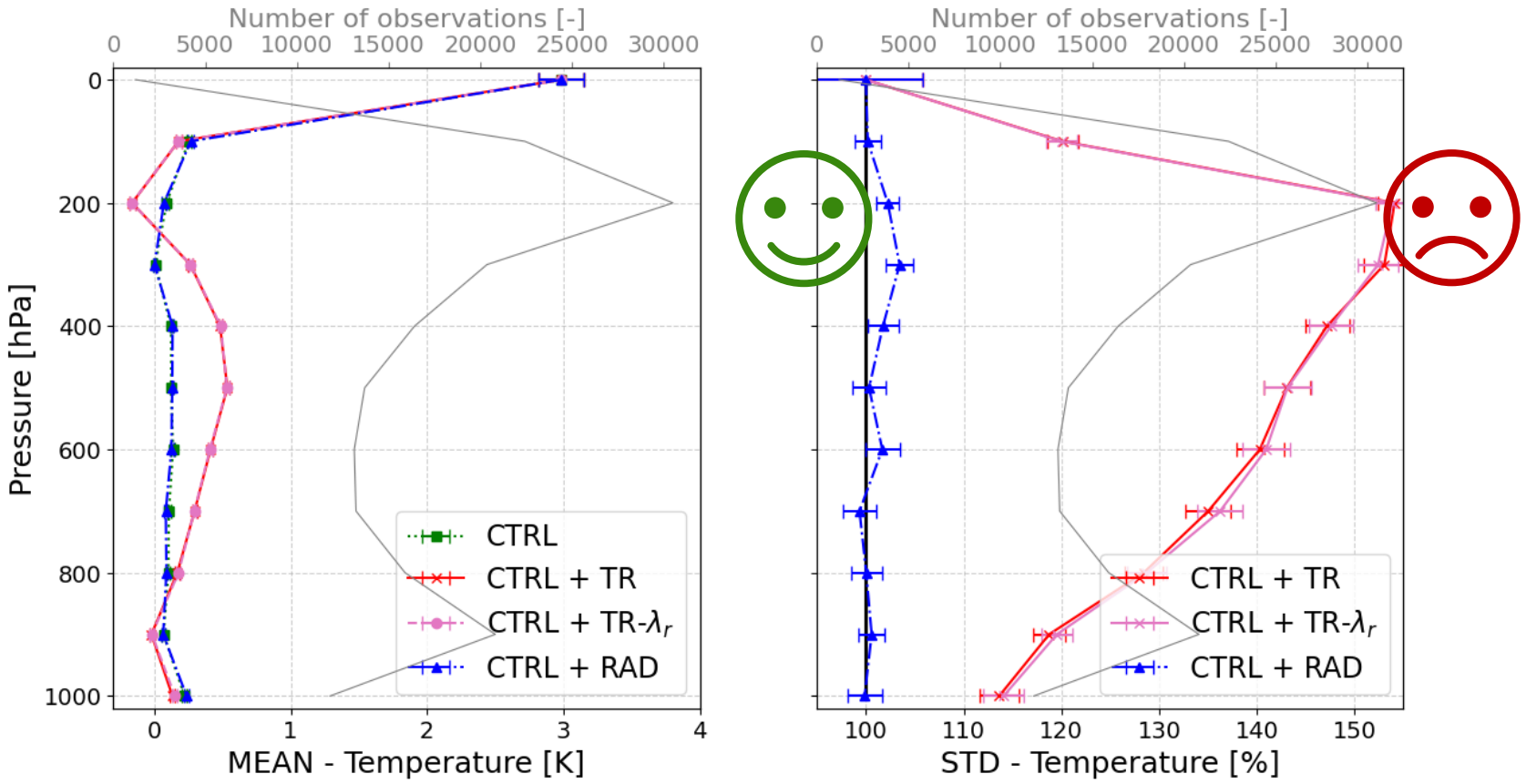


Impact of transformed retrieval observations

Mean

Radiosonde first guess departures - ***Temperature***

Standard deviation



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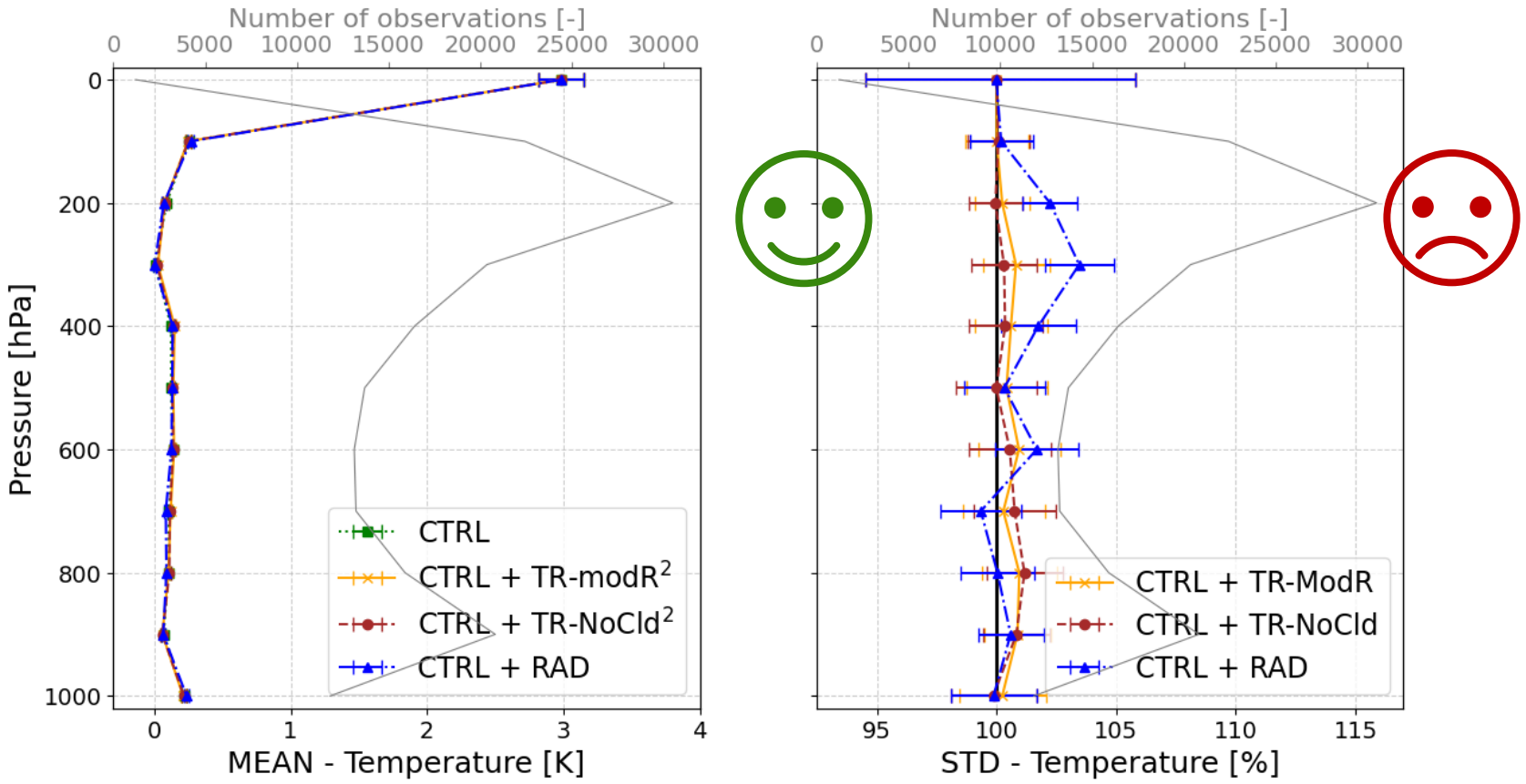
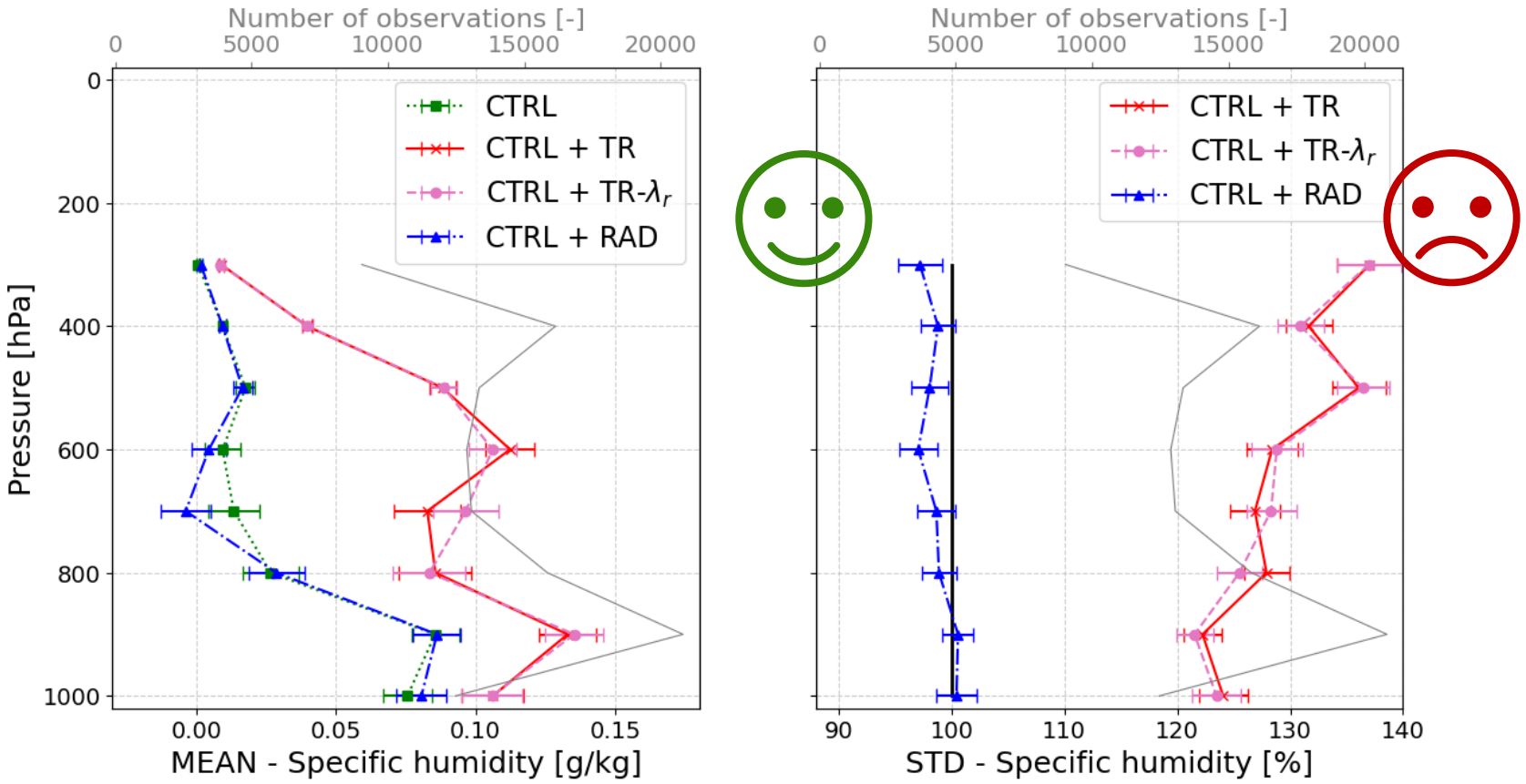


Impact of transformed retrieval observations

Mean

Radiosonde first guess departures – ***Specific Humidity***

Standard deviation

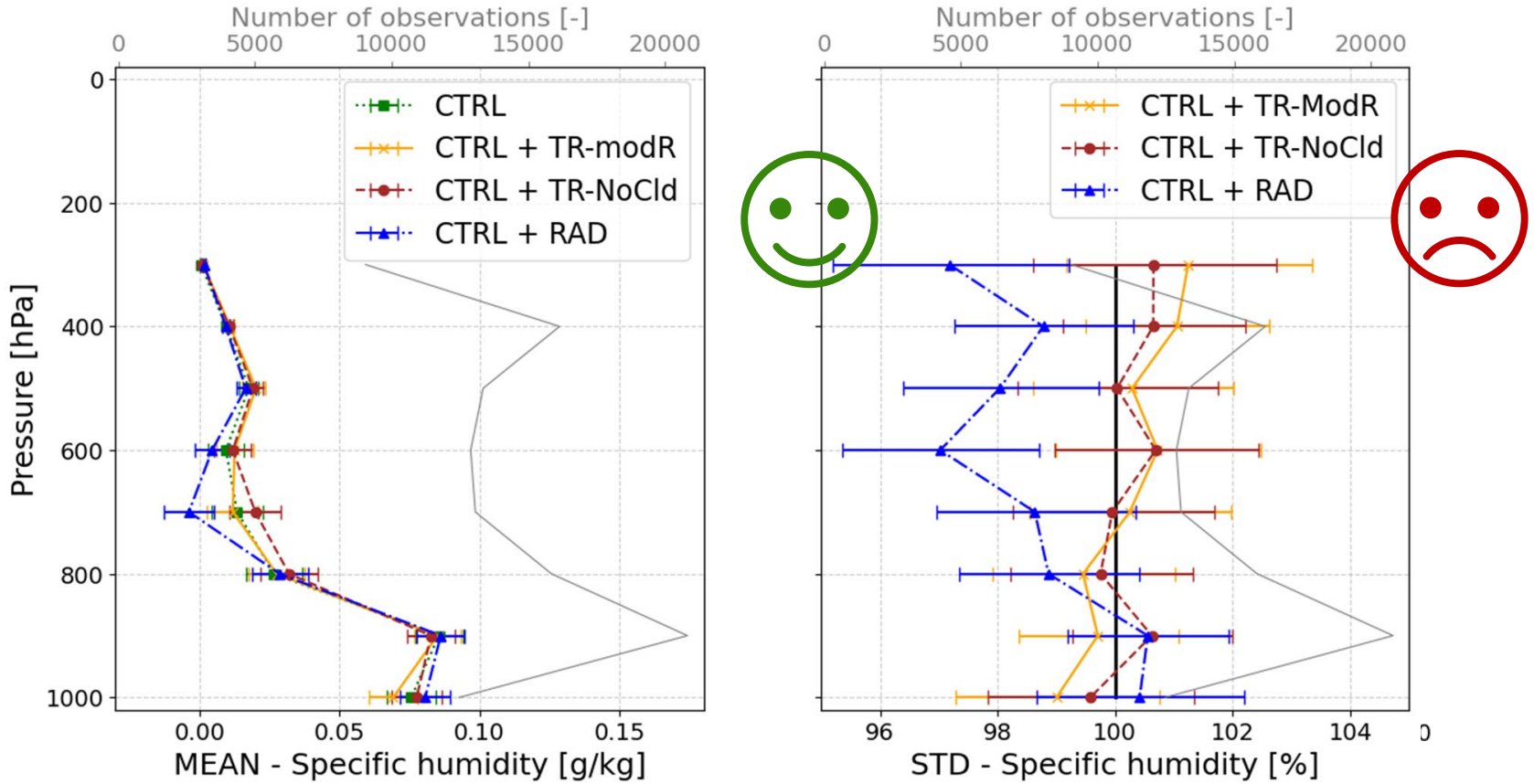


Impact of transformed retrieval observations

Mean

Radiosonde first guess departures - ***Specific Humidity***

Standard deviation



Similar IASI settings

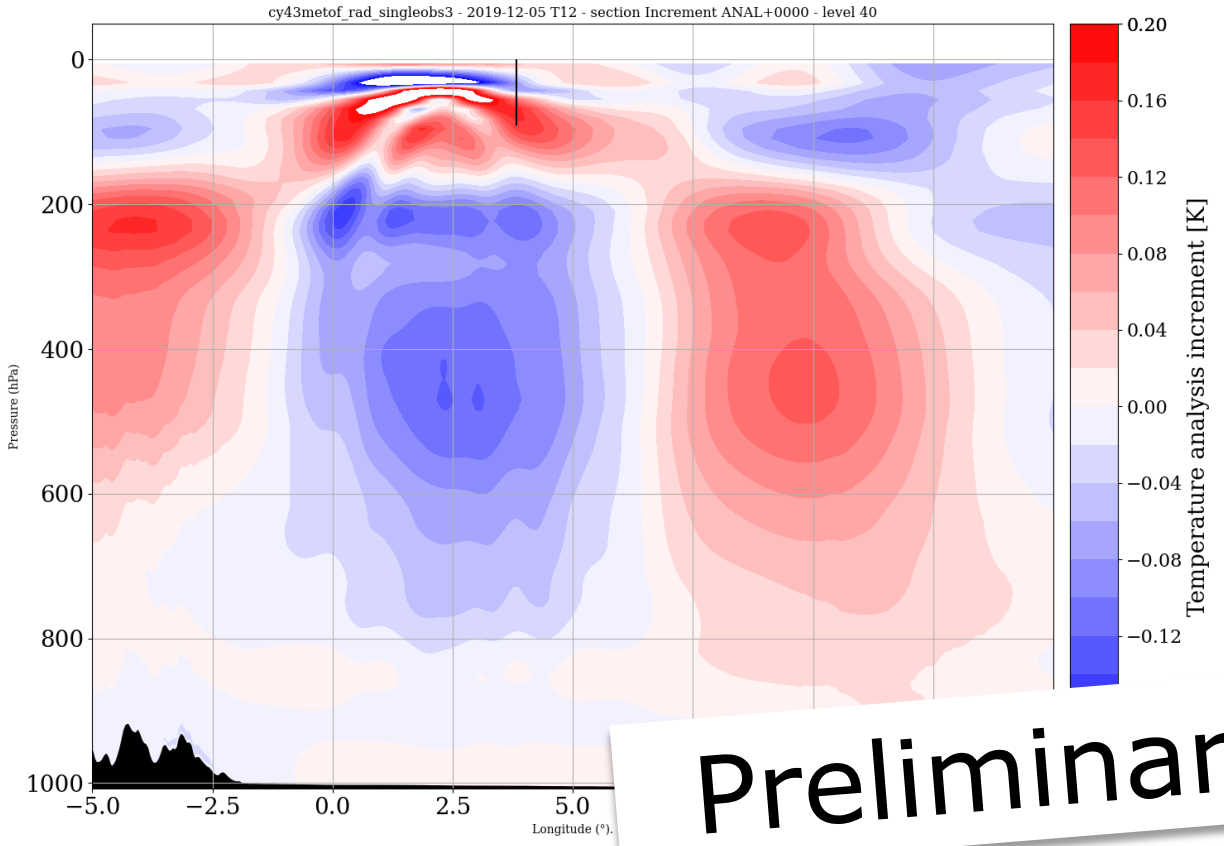
The EUMETSAT Network of Satellite Application Facilities

NWP SAF Numerical Weather Prediction

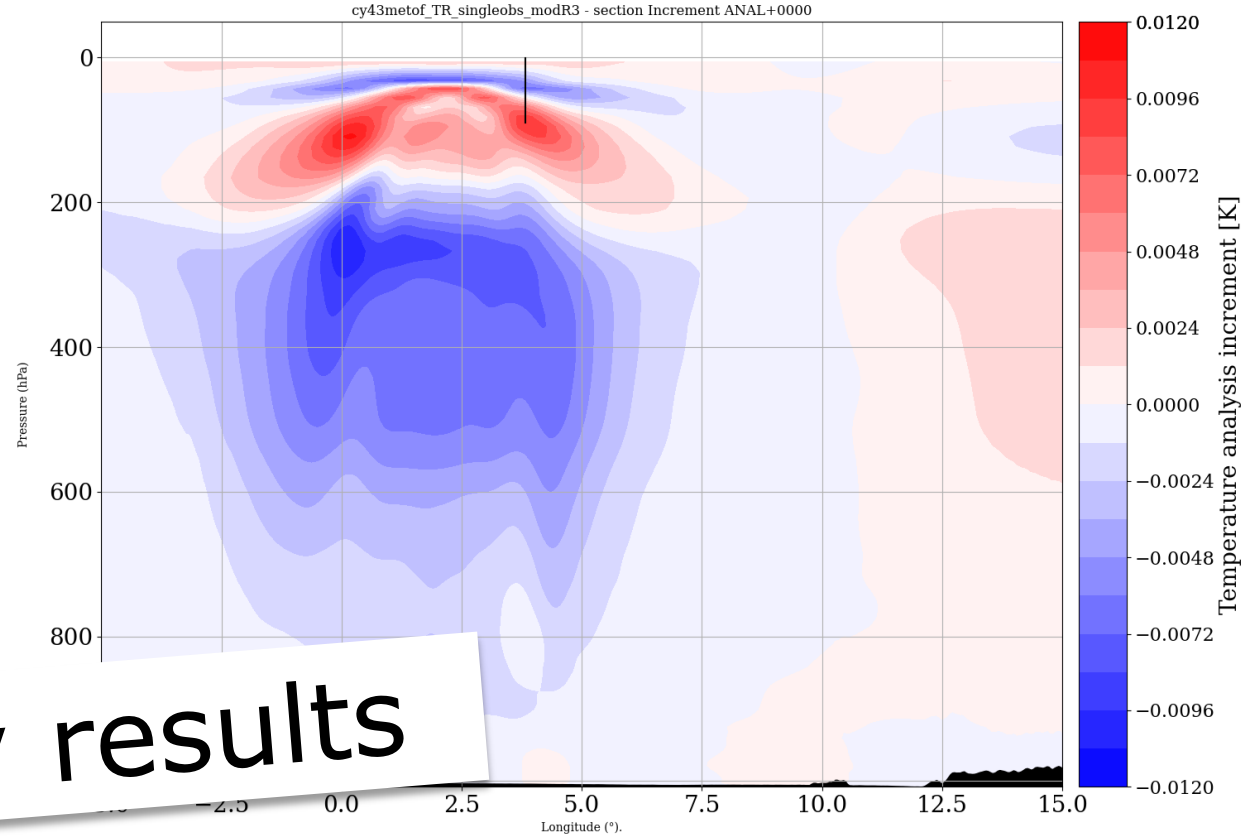
Single observation experiment

2019-12-05 T12

L1c radiance



Transformed retrieval



Preliminary results

Concluding remarks

- Transformed retrievals may offer an alternative to direct radiances assimilation to maximally utilise the information content.
- Extended NWP SAF 1D-Var software package to generate transformed retrievals. Q4 2026!
- Assimilated transformed retrievals generated by Met Office into Harmonie-AROME 4D-Var.
- Assimilation indicates neutral to slightly negative impact from external transformed retrievals. Further research ongoing
- Presence of clouds has big impact on transformed retrievals (IASI !!).

Next steps

- Follow-up assimilation experiment with similar “IASI settings” including single obs experiments.
- Generate transformed retrievals with Harmonie-AROME model.
- Bias correction in a transformed retrieval framework.

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