

# On the use of horizontal tropospheric gradients in the AROME model

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# Outline

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- On the use of horizontal tropospheric gradients
  - Context and motivation
  - Observation operator
  - Observation quality control
- Experiments and Results
  - Single observation experiment
  - Experiment configuration
  - Scores against the ECMWF analyses
  - Validation against precipitation
- Conclusion and further works on gradients

# Context & motivation

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- ❑ GNSS signals experience tropospheric delays driven by pressure, temperature, and water vapor — containing valuable information for NWP
  - ❑ The Zenith Total Delay (ZTD) represents the integrated atmospheric effect in the vertical direction and is the core GNSS meteorological observable
  - ❑ ZTD assimilation has demonstrated consistent positive impact on NWP forecasts (Poli et al., 2007; Mahfouf et al., 2014; Bennitt & Jupp, 2012)
  - ❑ However, ZTD assumes horizontal homogeneity — missing the azimuthal variability of water vapor
- Tropospheric gradients  $G_N$  and  $G_E$  are introduced to capture this horizontal asymmetry

# Horizontal tropospheric gradients

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□ Horizontal gradients  $G_N$  (North–South) and  $G_E$  (East–West) capture the azimuthal variability of the tropospheric delay

□ The STD incorporates gradients as a first-order correction to the isotropic ZTD

$$\text{STD}(\text{el}, \text{Az}) = \mathbf{m}(\text{el}) \cdot \text{ZTD} + \mathbf{m}_g(\text{el}) \cdot (\mathbf{G}_N \cos \text{Az} + \mathbf{G}_E \sin \text{Az})$$

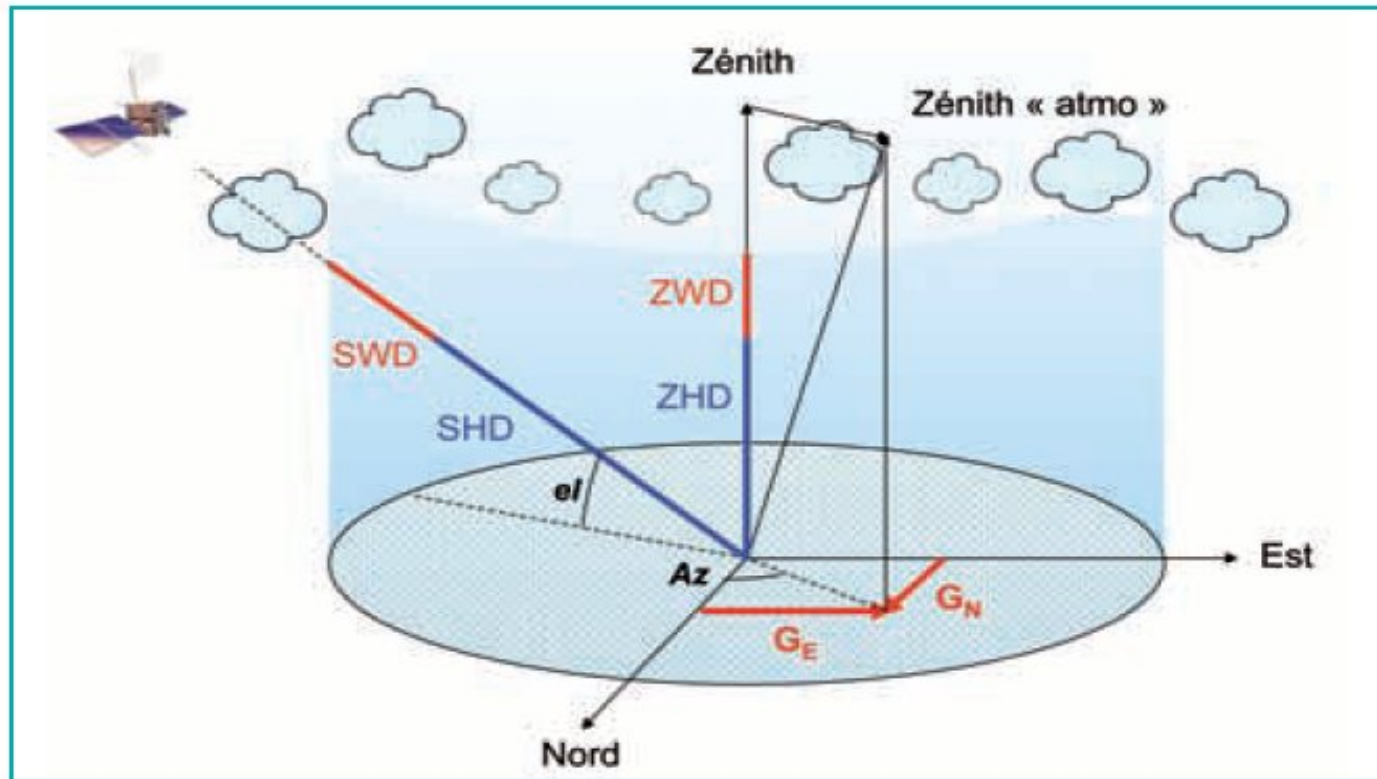
□ Gradients are co-estimated during GNSS processing at no additional observational cost

□ ZTD  $\sim 2.5$  m vs. tropospheric gradients  $\sim$  few millimetres — small but physically meaningful signal

□ Gradients are more pronounced during meteorological fronts and convective systems (Kacmarik et al., 2019; Nahmani et al., 2019)

□ Strong correlations between gradients, precipitation and moisture flux over Morocco (Koulali et al., 2012)

# Horizontal tropospheric gradients



$$G_N = 10^{-6} \int_0^{\infty} z \left[ \frac{\partial N(z)}{\partial y} \right] dz$$

North-south tropospheric  
gradient

$$G_E = 10^{-6} \int_0^{\infty} z \left[ \frac{\partial N(z)}{\partial x} \right] dz$$

East-west tropospheric  
gradient

# Horizontal tropospheric gradients

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## Step #1

- Code the obs operator + TL + AD (done in cy41)
- Validate the tangent linear and the adjoint (done in cy41)
- Tune the direct observation operator (partially done in cy41)

## Step #2

- Build or get a set of observations in bufr format
- Phase and validate the code in cy46

## Step #3

- Observation quality control
- Tune the direct observation operator
- Data assimilation experiments

## Step #4

- q Phase and validate the code in cy48
- q Data assimilation experiments with Arome 3DVar and 3DEnVar (and 4DEnVar if the code is phased in cy49)

# Observation operator for tropospheric gradients

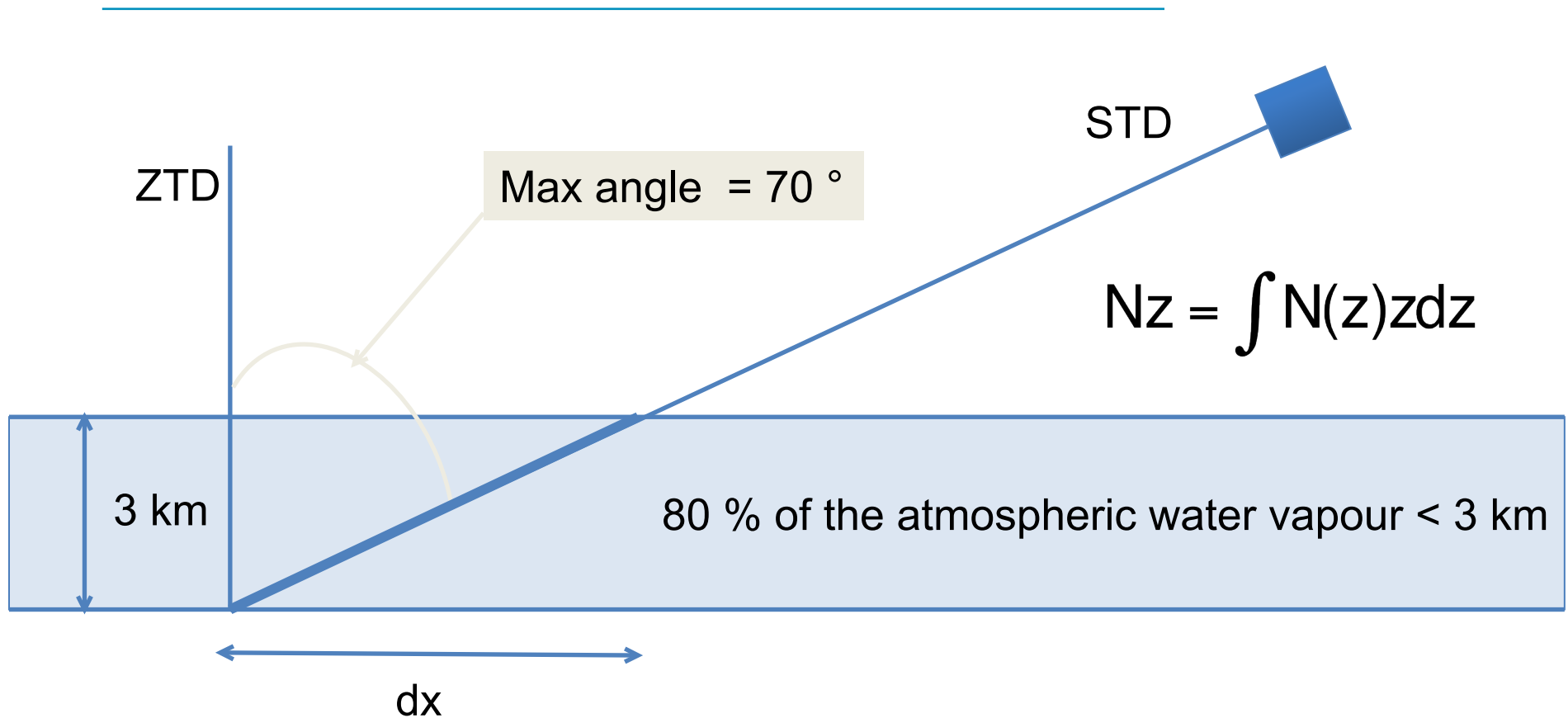
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- ❑ The observation operator computes  $G_N$  and  $G_E$  through vertical numerical integration of the horizontal refractivity gradients:

$$G_N = 10^{-6} \int z \frac{\partial N}{\partial y} dz \quad G_E = 10^{-6} \int z \frac{\partial N}{\partial x} dz$$

- ❑ The horizontal refractivity gradients  $\frac{\partial N}{\partial y}$  and  $\frac{\partial N}{\partial x}$  are estimated at each vertical level using a finite difference scheme between two surrounding profiles to the north/south and east/west respectively
- ❑ The Linear Horizontal Gradient (LHG) assumption is adopted — the refractivity is assumed to vary linearly in the horizontal direction between the surrounding profiles
- ❑ Similarly to the ZTD operator, the gradient components are obtained through numerical integration over height
- ❑ The 2D GOMs enable the **horizontal interpolation** of model profiles at each observation point, making the computation of simulated ZTD gradients possible within the observation operator

# Horizontal tropospheric gradients

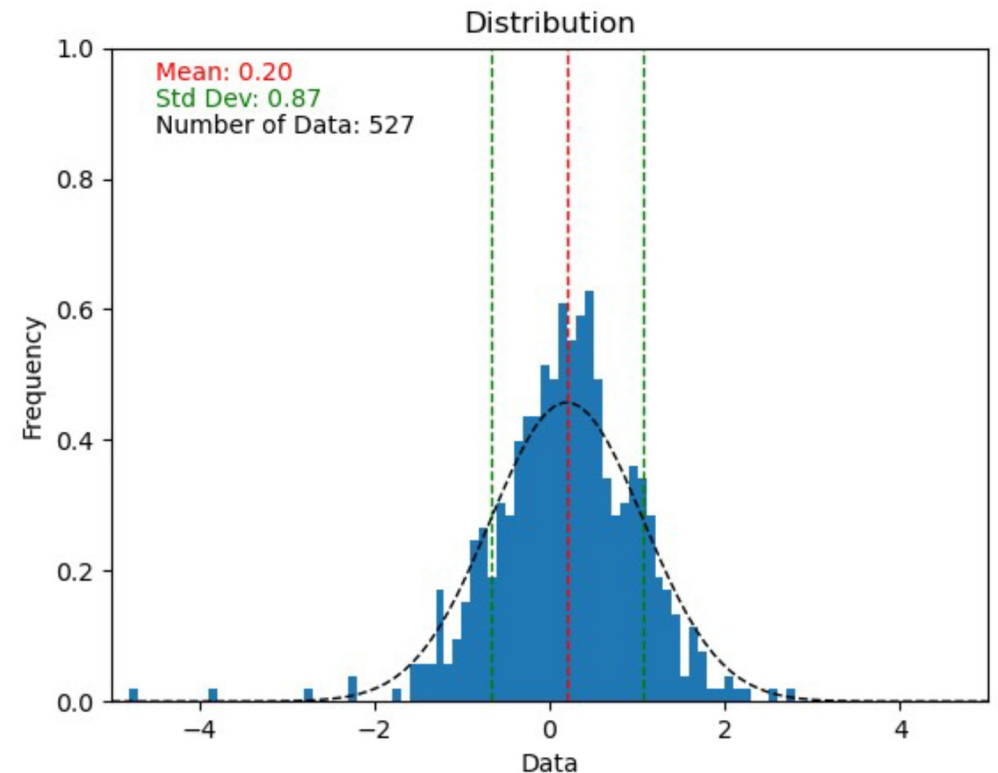
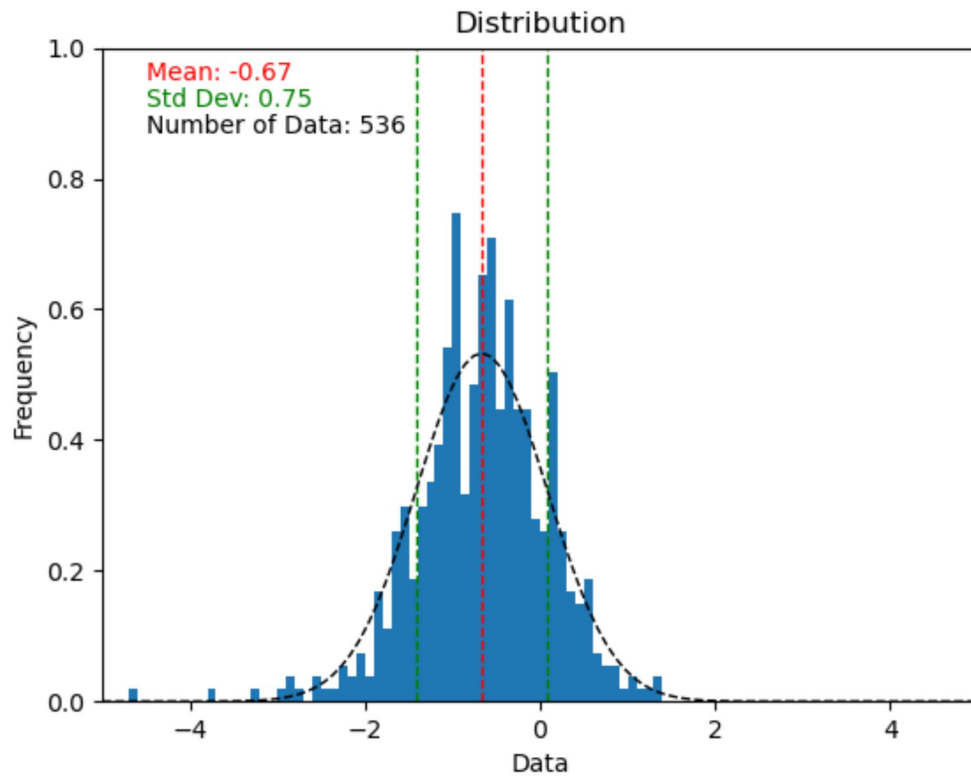


In conclusion of a preliminary study on SGN data, we retained 2 values for dx : 7 km and 12 km

# Observation quality control



# Observation quality control



Example of the distribution of the (obs-guess) for the NS gradient of the station AUBT during the summer experiment with dx=7km (left) and dx=12km (right)

# Observation quality control

Creation of a whitelist in several steps :

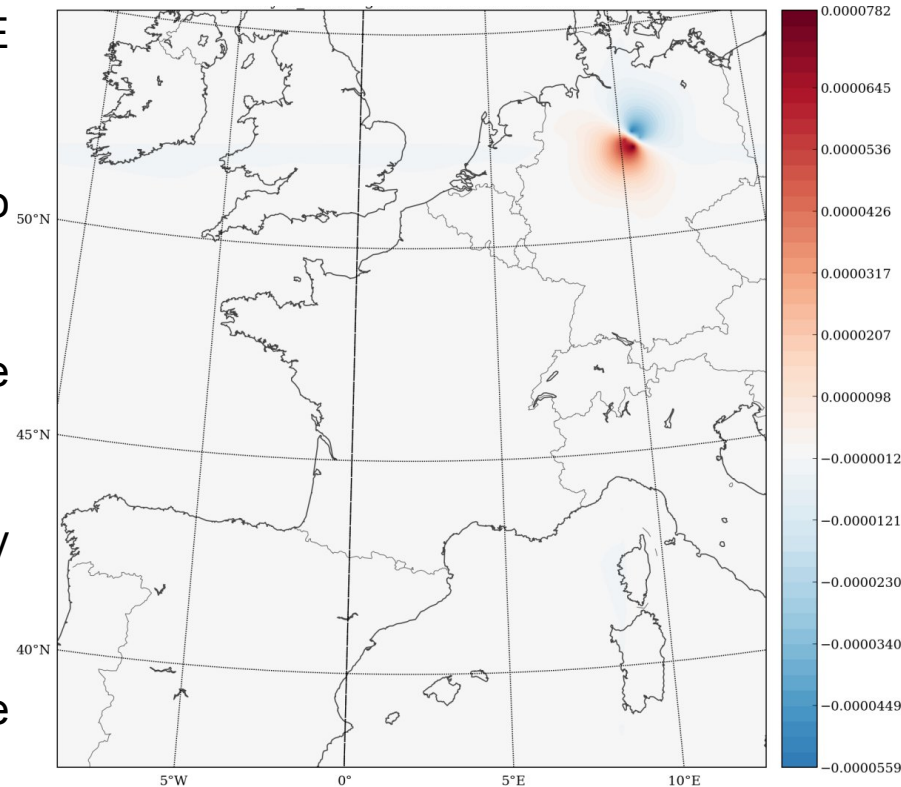
- 1) Rejection values for ZTD and the gradients (bias and stdev)
- 2) Station in whitelist only if ZTD and the 2 gradients are OK
- 3) Geographical thinning : 10 km inter-distance

```
WL_rejection_values : 14.0000000 16.0000000 1.00000000 3.00000000 1.00000000 3.00000000
10.0000000
nombre initial de stations valides : 411
nombre de stations conservees : 257
nombre de mauvais ZTD : 40 47 87 84
nombre de mauvais GNS : 62 68 130 68
nombre de mauvais GEW : 56 64 120 64
```

```
stations trop proches : GRAC GRAS 0.00000000
stations trop proches : IGNF MLVL 6.95629930
stations trop proches : IGNF OP71 3.81012225
stations trop proches : IGNF OPMT 3.11095166
stations trop proches : IGNF VITY 4.91884661
stations trop proches : IXSG SBGS 4.91884661
stations trop proches : IXSG SBL2 4.91884661
stations trop proches : MIM2 MZAN 0.00000000
stations trop proches : MSRT UZER 8.79910088
stations trop proches : MTDM STS2 7.62024450
stations trop proches : NAYC NVPT 6.22190332
stations trop proches : NOYL RENN 6.95629930
stations trop proches : STNZ TRIG 3.11095166
stations trop proches : TLIA TLSE 0.00000000
stations trop proches : TLIA TLSG 0.00000000
nombre de stations conservees après thinning : 211
```

# Single observation experiment

- ❑ GPS IGS station located at  $52.29619^{\circ}\text{N}$ ,  $10.45975^{\circ}\text{E}$  with only horizontal gradients assimilated (no ZTD)
- ❑ Results analyzed at model level 60 corresponding to  $\sim 820$  hPa in the lower troposphere
- ❑ Analysis increments show a localized impact around the observation with a radius of influence of about 240 km
- ❑ A dipole structure is observed in specific humidity increments with zero increment at the observation point
- ❑ Positive increments appear to the west and negative increments to the east



The system is able to extract asymmetric information from tropospheric delay gradients and propagate it consistently in the analysis

# Experiment configuration

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For the experiments in this study, two one-month periods of data over France were provided by the German analysis centre GFZ. These datasets contain both ZTD and the two tropospheric gradients North-South and East-West. From these data, BUFR files were created to be assimilated in the AROME-France model in the usual way.

- Winter period: from January 2 to 28, 2022 – 319 stations available
- Summer period: from August 10 to September 8, 2022 – 314 stations available

Two experiments were conducted for each period, with different settings for the parameter dx: 7 km and 12 km. For these experiments, the only GNSS data used came from the GFZ observation set, with the usual data from EGVAP being removed.

The operational variational debiasing of the ZTD was disabled and replaced by static debiasing based on the monitoring results, as for the gradients. Since the AROME-France 3DVar has a 1-hour assimilation window, one observation per hour can be assimilated for each station (if it is on the whitelist and has successfully passed the screening quality control).

# Experiment configuration

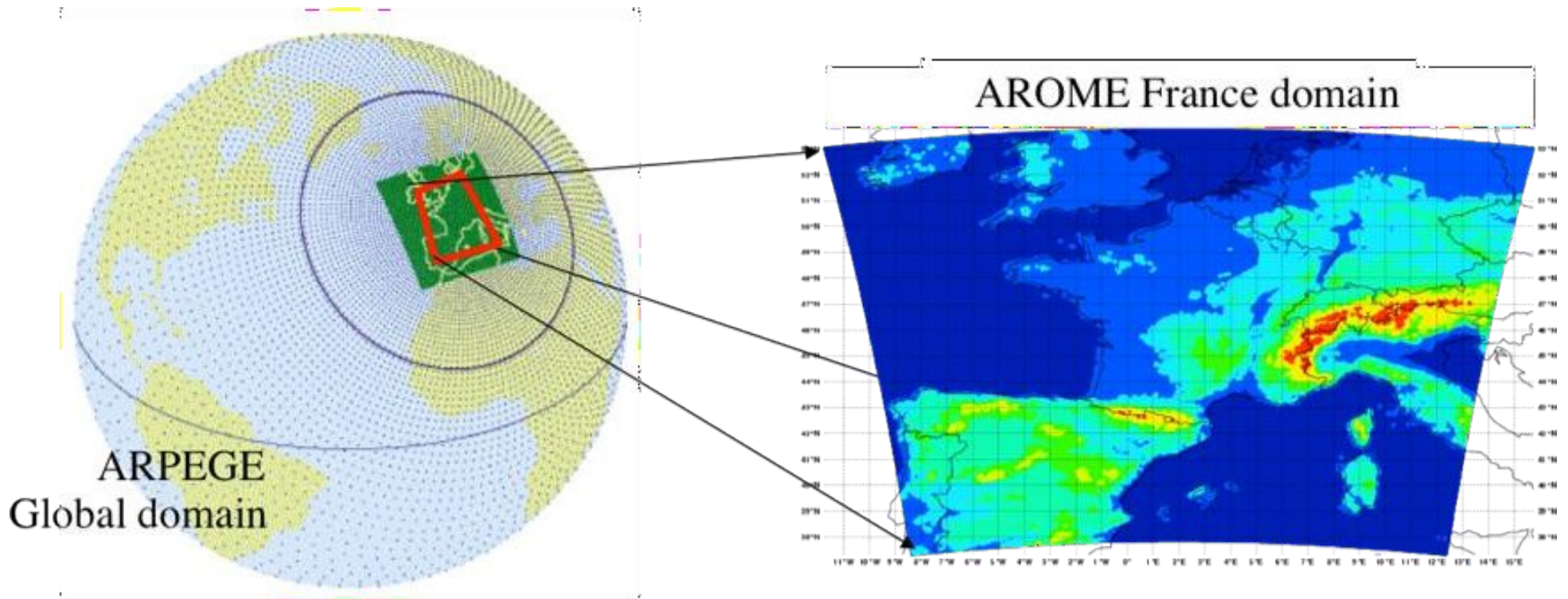
Due to time constraints, **observation errors** were estimated in a basic manner from the (obs-guess) errors produced by the monitoring: the observation error variance is set, for each observation, to half the (obs-guess) error variance. This calculation assigned standard deviation values between 0.4 mm and 1 mm, with an average of around 0.6 mm, for the gradients placed on the whitelist. This is consistent with the value of 0.5 mm suggested by Dousa et al. (2016).

AGDE	43.17	3.28	6.01	13.82	0.01	0.68	-0.47	0.71
AILT	47.52	3.21	2.79	9.77	0.99	0.54	1.48	0.49
AJAC	41.55	8.45	15.73	11.45	0.13	0.71	0.41	0.66
ALBM	43.56	2.09	11.59	13.41	-1.11	0.55	-1.00	0.73
ALGY	47.27	5.36	4.21	11.58	-0.29	0.62	-0.25	0.66
ALU2	47.02	3.37	4.16	11.68	1.68	0.31	1.52	0.39
AMIY	47.58	2.43	9.24	11.07	-0.77	0.54	0.79	0.59
AMNS	49.51	2.14	7.62	10.70	1.55	0.40	-0.23	0.65
ANAY	45.14	4.41	8.36	13.34	-1.06	0.90	0.85	0.45
ANDE	48.47	4.57	10.57	10.70	-0.13	0.67	-0.66	0.70
ANGE	47.28	-0.33	9.37	9.86	0.99	0.54	0.18	0.58
ANGL	46.24	-1.24	9.71	10.11	0.36	0.58	0.51	0.60

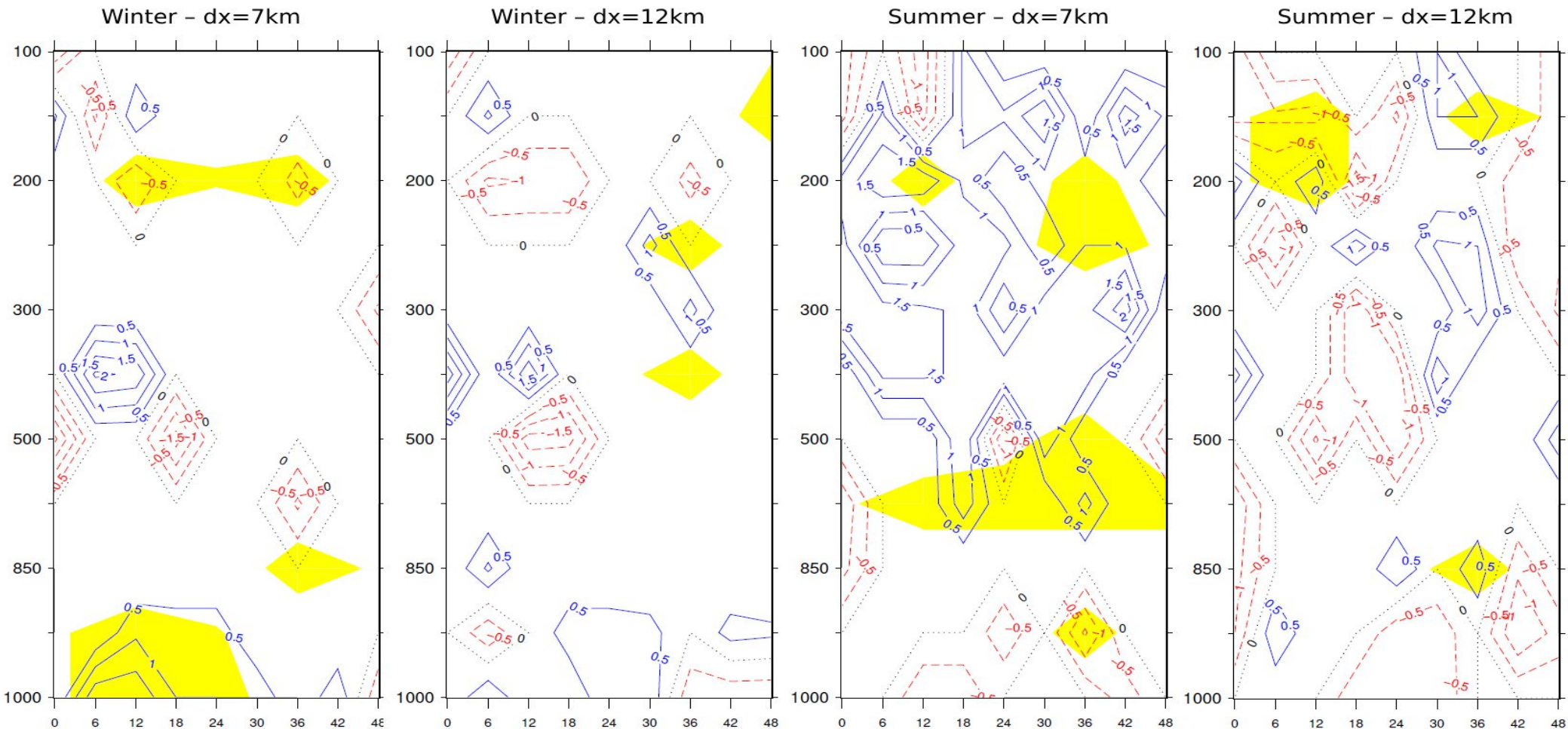
Extract of a whitelist

# Experiment configuration

The regional AROME-France 3DVar model has a resolution of 1.3 km and 90 vertical levels. Its boundary conditions are provided by the global ARPEGE model. It is initialized using a 3D assimilation system with hourly cycling, combining observations over a one-hour window and a short-term forecast.

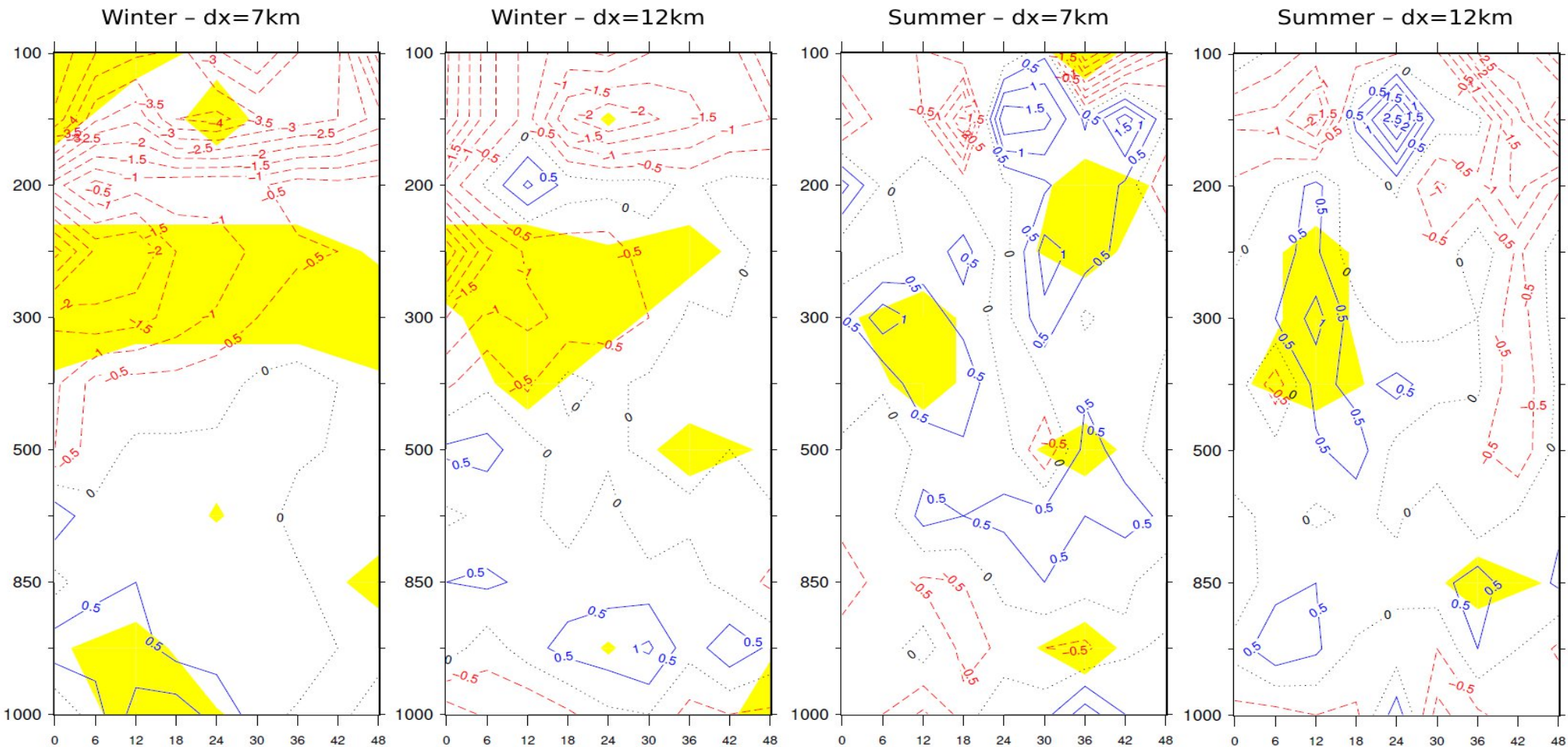


# Scores against the ECMWF analyses



*Verification against the ECMWF IFS analysis for **temperature**. From left to right, the scores for the winter experiments with  $dx=7\text{km}$  and  $dx=12\text{km}$ , then the scores for the summer experiments with  $dx=7\text{km}$  and  $dx=12\text{km}$ . Positive scores are in blue, negative scores are in red, and areas of 95% significance are in yellow*

# Scores against the ECMWF analyses



*Verification against the ECMWF IFS analysis for **relative humidity**. From left to right, the scores for the winter experiments with  $dx=7\text{km}$  and  $dx=12\text{km}$ , then the scores for the summer experiments with  $dx=7\text{km}$  and  $dx=12\text{km}$ . Positive scores are in blue, negative scores are in red, and areas of 95% significance are in yellow*

# Verification against precipitation

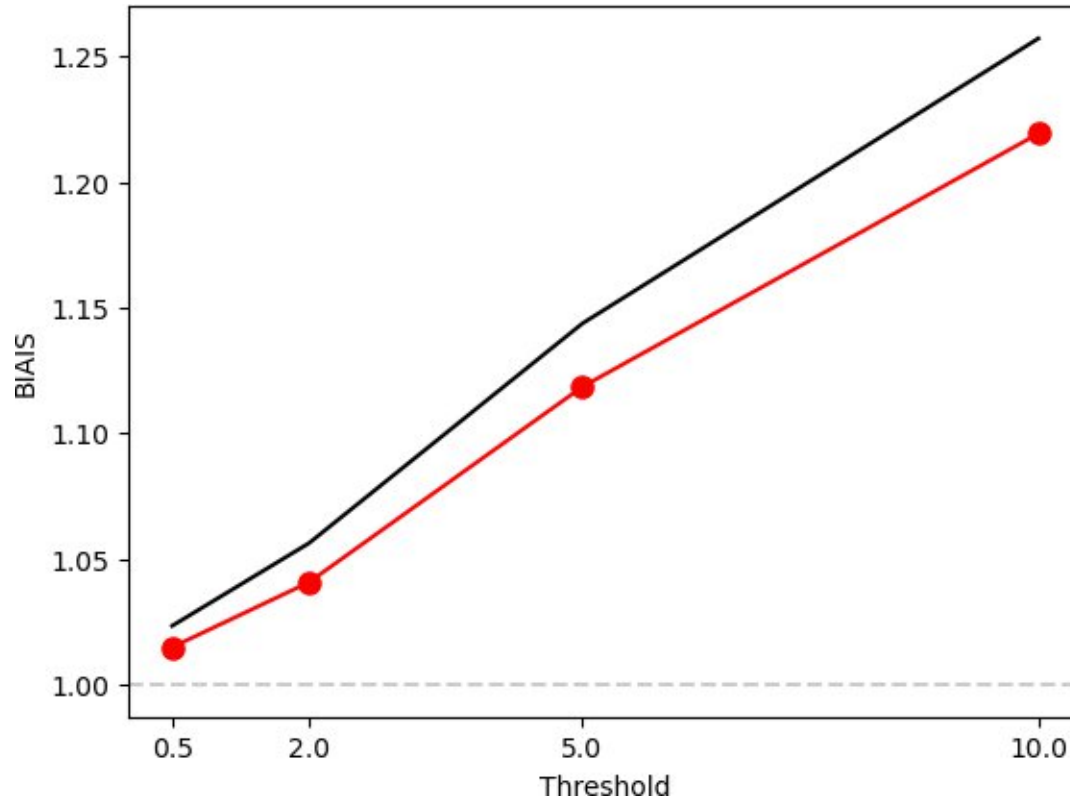
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Beyond the scores, we have evaluated the impact of gradients on weather forecasts, particularly precipitation. For the 4 experiments, we plotted precipitation accumulation maps over 6-hour and 12-hour periods and performed statistical contingency calculations.

The winter experiments show the least impact from gradients, likely due to the fewer observations in the whitelist, but also because summer convective situations are more favourable for observing significant impact of this type of observations.

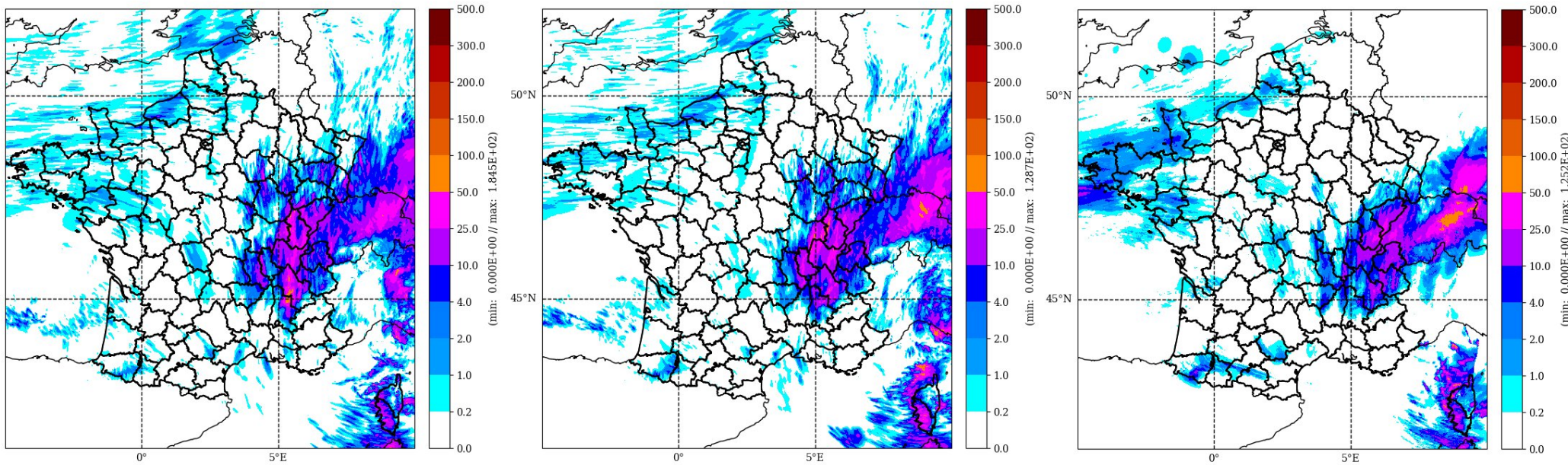
In the summer experiments, the impact on accumulated precipitation is not always noticeable, but when it is, it is very often positive. This is particularly the case for the experiment with  $dx=12$  km, which shows a significant reduction of the mean frequency biases for all thresholds.

# Verification against precipitation



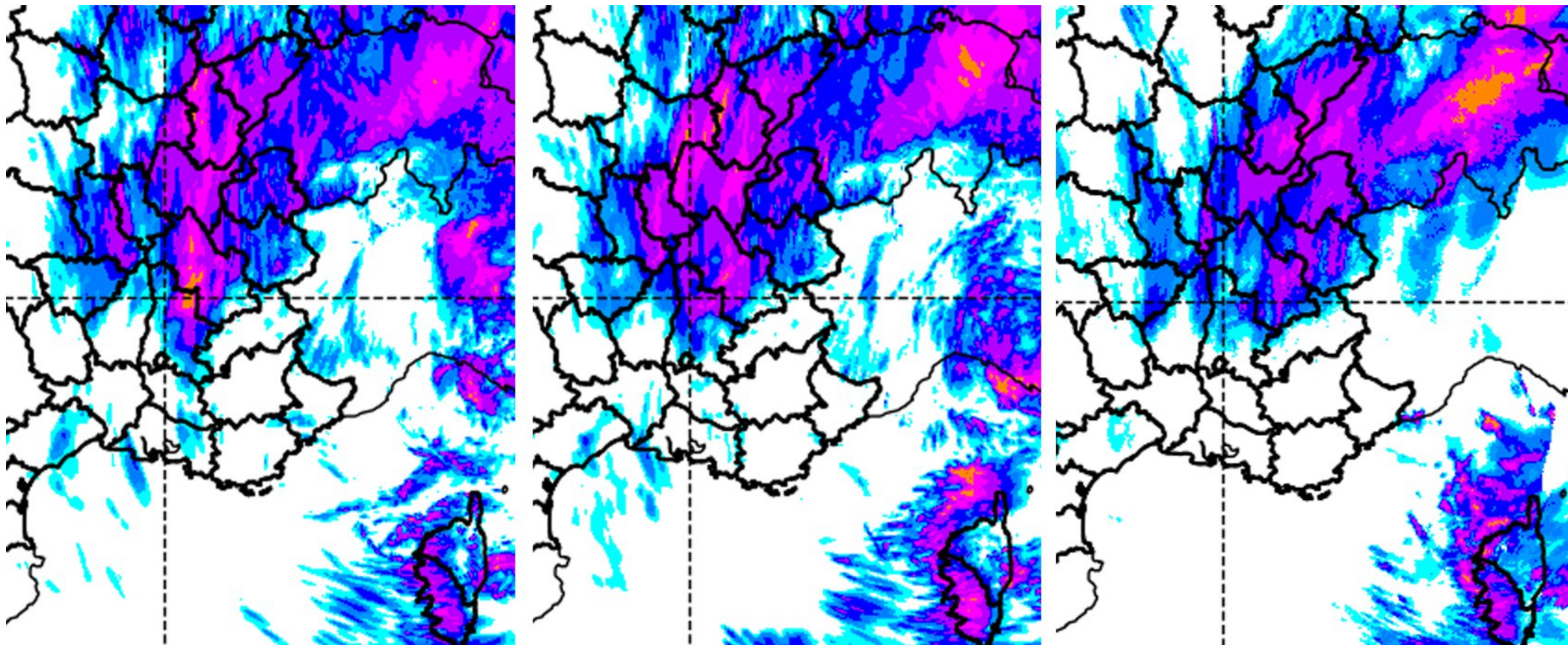
Mean frequency bias of the contingency table for exceedance of different thresholds. Summer experiment with  $dx=12$  km. Reference is in black, experiment in red. Values higher (respectively lower) than 1 stand for events simulated more (respectively less) often by the model than observed by the radar and rain gauges fusion product ANTILOPE. Large dots indicate significant values.

# Verification against precipitation



Cumulative precipitation on August 19, 2022, from 00:00 to 12:00. The reference is on the left, the experiment with dx=12 km in the centre, the observation by the Antelope fusion product on the right.

# Verification against precipitation



Cumulative precipitation on August 19, 2022, from 00:00 to 12:00. The reference is on the left, the experiment with  $dx=12$  km in the centre, the observation by the Antilope fusion product on the right.

# Conclusion and further works on gradients

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- The results for gradients are encouraging and demonstrate that the approach is working well at a preliminary stage
- However, the study does not yet allow us to select a definitive value for  $dx$
- Further experiments with a larger number of observations, improved error statistics, and well-defined rejection thresholds are required
- The added value of 3DEnVar compared to 3DVar should be assessed
- The comparison between gradients and slant delays remains to be done

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**Thank you for your attention**