# A 4DEnVar scheme for Arome-France : presentation and evaluation

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# outlines

- Introduction to a 4DEnVar DA system

- Proposal for the next AROME-France E-suite.

# Arome-France 3Dvar/3DEnVar

## - 3D-Var / 3DEnVar cost function :

3D-Var : $$J(\delta \mathbf{x}) = \frac{1}{2}(\delta \mathbf{x})^T \mathbf{B}^{-1}(\delta \mathbf{x}) + \frac{1}{2}(\mathbf{d} - \mathbf{H}\delta \mathbf{x})^T \mathbf{R}^{-1}(\mathbf{d} - \mathbf{H}\delta \mathbf{x})$$

$$\epsilon_l^b = \frac{1}{\sqrt{N_e - 1}}(\widetilde{\mathbf{x}}_l^b - \langle \widetilde{\mathbf{x}}^b \rangle)$$

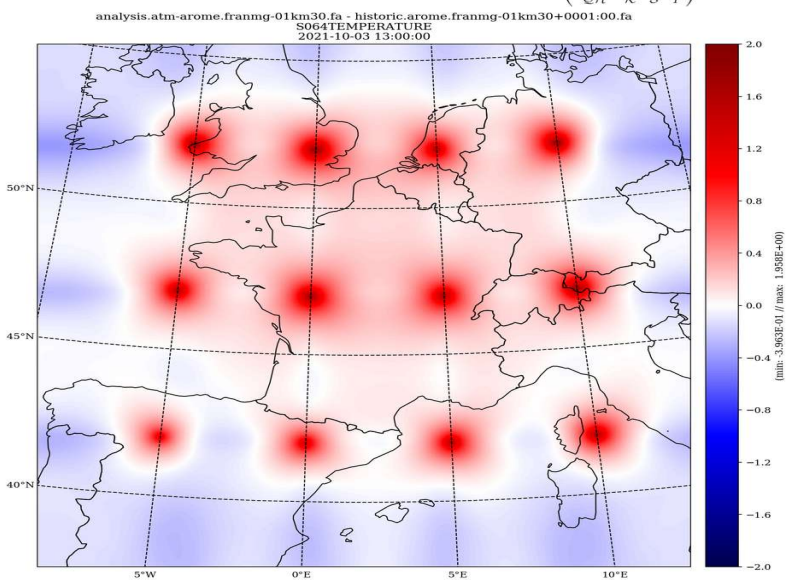
$$\mathbf{X}^b = [\epsilon_1^b, \ldots, \epsilon_{N_e}^b]$$

$$\mathbf{B} = \overline{\mathbf{B}} = \mathbf{K}\mathbf{B}_u\mathbf{K}^T$$

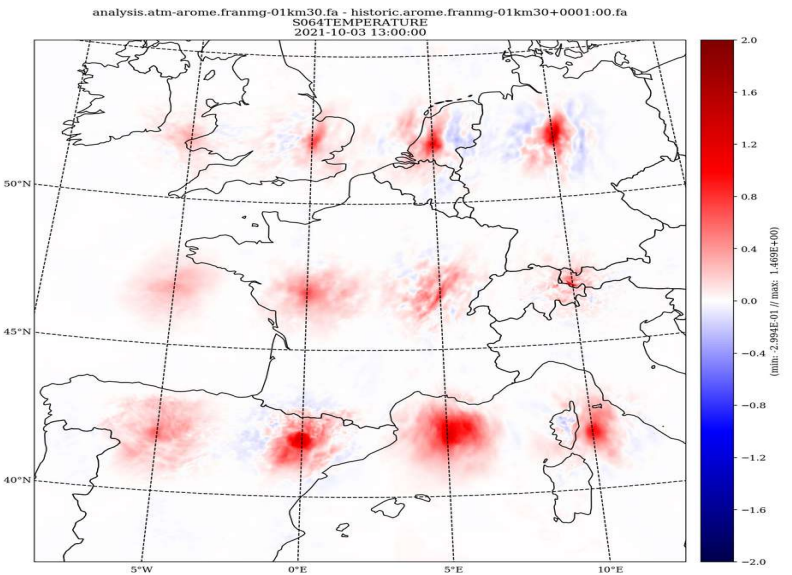
$$\mathbf{B}_u = \begin{pmatrix} \mathbf{C}_\zeta & 0 & 0 & 0 \\ 0 & \mathbf{C}_{\eta_u} & 0 & 0 \\ 0 & 0 & \mathbf{C}_{(T,P_s)_u} & 0 \\ 0 & 0 & 0 & \mathbf{C}_{q_u} \end{pmatrix}$$

$$\mathbf{K} = \begin{pmatrix} I & 0 & 0 & 0 \\ \mathcal{M}\mathcal{H} & I & 0 & 0 \\ \mathcal{N}\mathcal{H} & \mathcal{P} & I & 0 \\ \mathcal{Q}\mathcal{H} & \mathcal{R} & \mathcal{S} & I \end{pmatrix}.$$

$$\mathbf{B} = \widetilde{\mathbf{B}}_e = \mathbf{C} \circ \mathbf{X}^b\mathbf{X}^{bT}$$




3D-Var




3DEnVar

# Towards a 4D scheme

3D-Var :

$$J(\delta\mathbf{x}) = \frac{1}{2}(\delta\mathbf{x})^T\mathbf{B}^{-1}(\delta\mathbf{x}) + \frac{1}{2}(\mathbf{d}-\mathbf{H}\delta\mathbf{x})^T\mathbf{R}^{-1}(\mathbf{d}-\mathbf{H}\delta\mathbf{x})$$

4D-Var :

$$J(\delta\mathbf{x}) = \frac{1}{2}(\delta\mathbf{x})^T\mathbf{B}^{-1}(\delta\mathbf{x}) + \frac{1}{2}\sum_{i=0}^{K}(\mathbf{d}_i-\mathbf{H}_i\mathbf{M}_{0\to i}\delta\mathbf{x})^T\mathbf{R}_i^{-1}(\mathbf{d}_i-\mathbf{H}_i\mathbf{M}_{0\to i}\delta\mathbf{x})$$

→ a LAM 4D-var is available in IFS/ARP/ARO/HAR code but relies on the ALADIN model

- direct model : hydrostatic dynamic, less sophisticated physic (only 4 hydrometeors without graupel), without surfex
- Tangent and adjoint model : hydrostatic, very simple simplified physic

→ In a 4DEnVar scheme :

4DEnVar :

$$J(\underline{\delta\mathbf{x}}) = \frac{1}{2}(\underline{\delta\mathbf{x}})^T\underline{\mathbf{B}}^{-1}(\underline{\delta\mathbf{x}}) + \frac{1}{2}(\underline{\mathbf{d}}-\underline{\mathbf{H}}\underline{\delta\mathbf{x}})^T\underline{\mathbf{R}}^{-1}(\underline{\mathbf{d}}-\underline{\mathbf{H}}\underline{\delta\mathbf{x}})$$

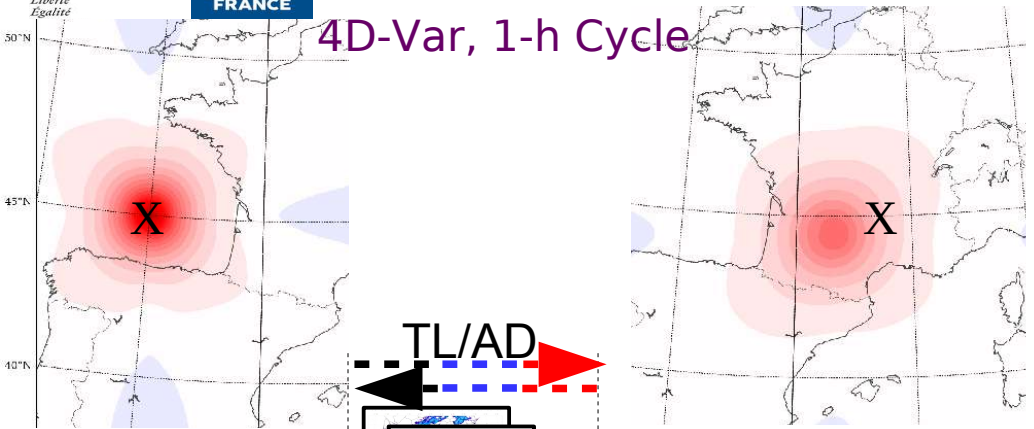
(Desroziers et al. 2014)

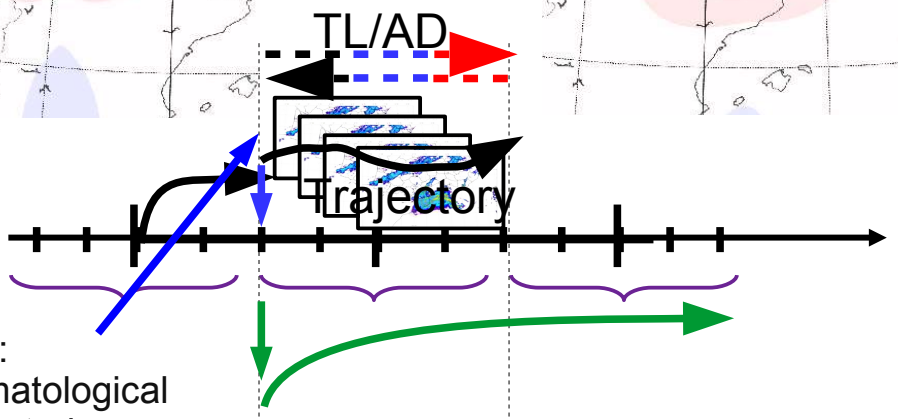
$$\underline{\delta\mathbf{x}} = \begin{pmatrix} \delta\mathbf{x}_0 \\ \delta\mathbf{x}_1 \\ \vdots \\ \delta\mathbf{x}_K \end{pmatrix} \qquad \underline{\mathbf{B}} = \underline{\widetilde{\mathbf{B}}^{\mathrm{e}}} = \begin{pmatrix} \widetilde{\boldsymbol{B}}^{\mathrm{e}}_{0,0} & \widetilde{\boldsymbol{B}}^{\mathrm{e}}_{0,1} & \cdots & \widetilde{\boldsymbol{B}}^{\mathrm{e}}_{0,K} \\ \widetilde{\boldsymbol{B}}^{\mathrm{e}}_{1,0} & \widetilde{\boldsymbol{B}}^{\mathrm{e}}_{1,1} & & \widetilde{\boldsymbol{B}}^{\mathrm{e}}_{1,K} \\ \vdots & & \ddots & \\ \widetilde{\boldsymbol{B}}^{\mathrm{e}}_{K,0} & \cdots & & \widetilde{\boldsymbol{B}}^{\mathrm{e}}_{K,K} \end{pmatrix}$$

Provided by an EDA

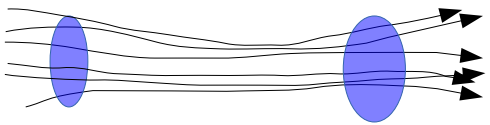
# Towards a 4D scheme

## 4D-Var, 1-h Cycle

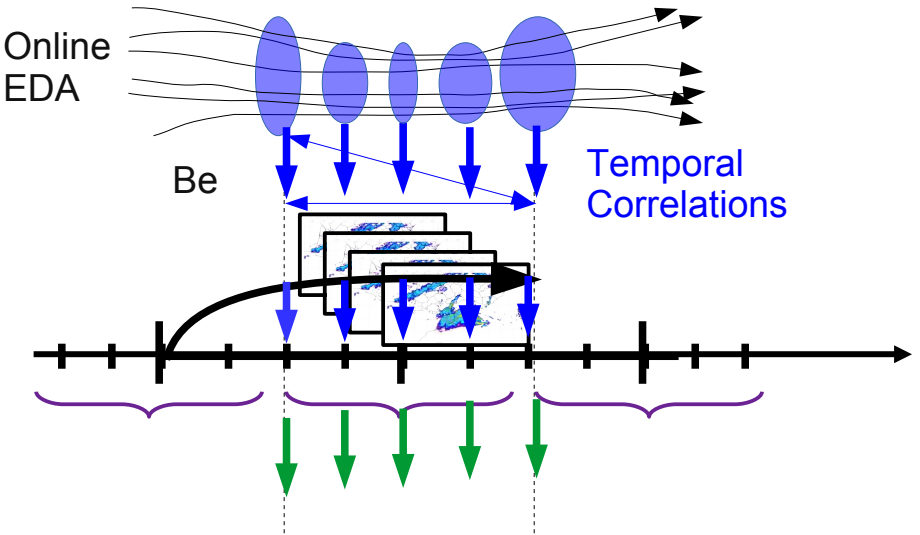


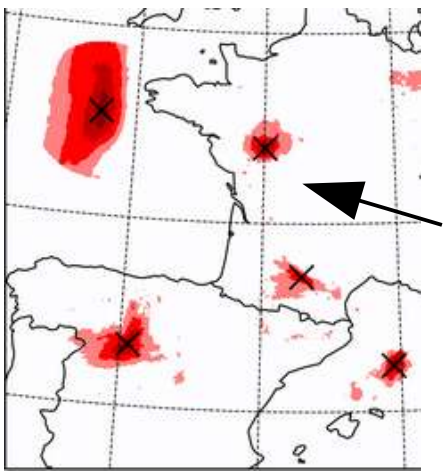




Bm :
-climatological
-spectral
-homogenous
(as in 3dvar)




## 4DEnvar, 1-h Cycle



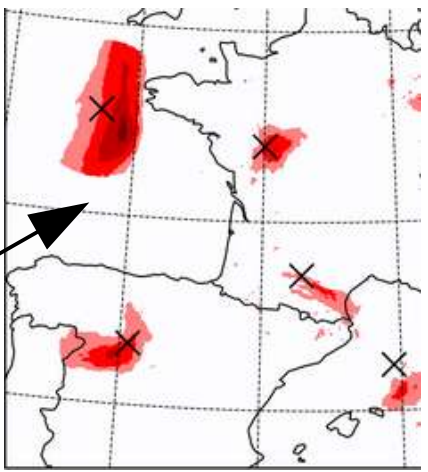



q 850hPa
error
correlation

at h-30m

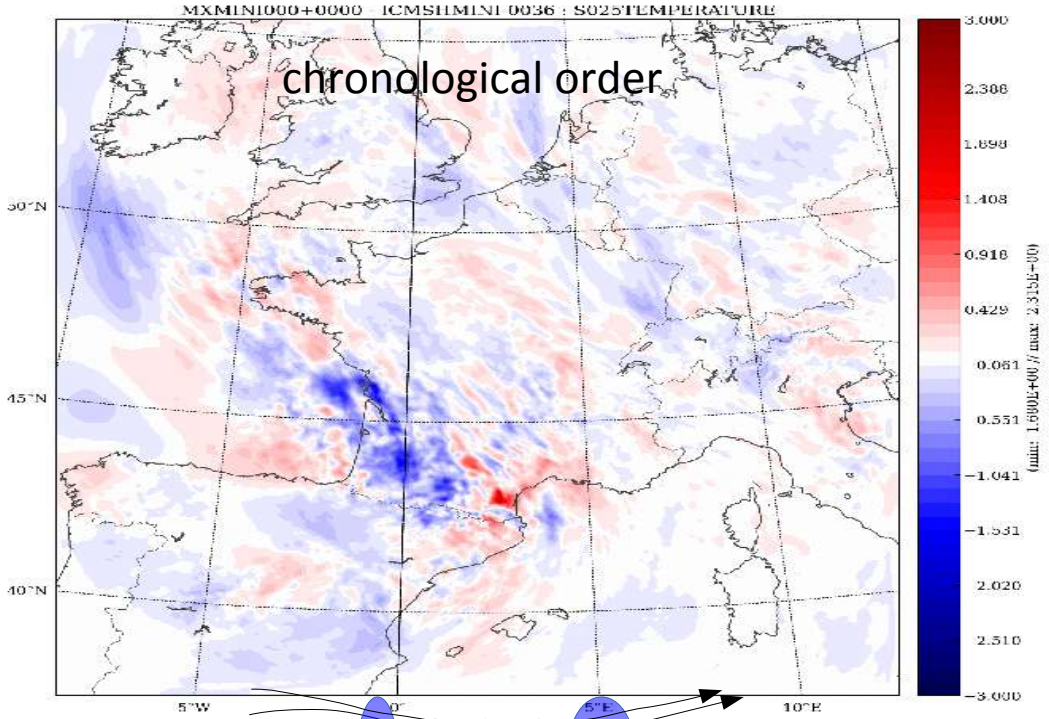
between
h-30m and
h+30m

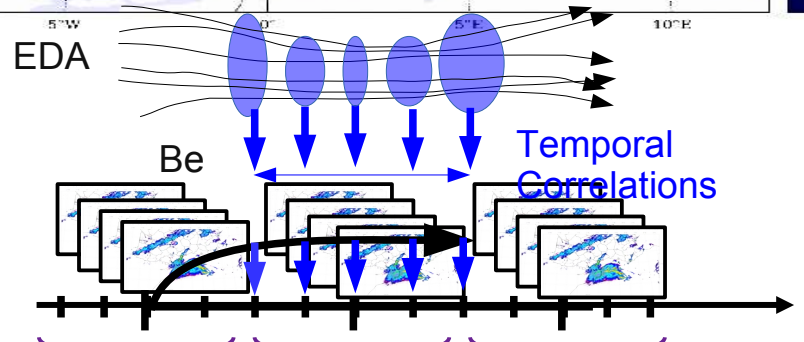
(V. Chabot)



# 4D Temperature increment at 850 hPa

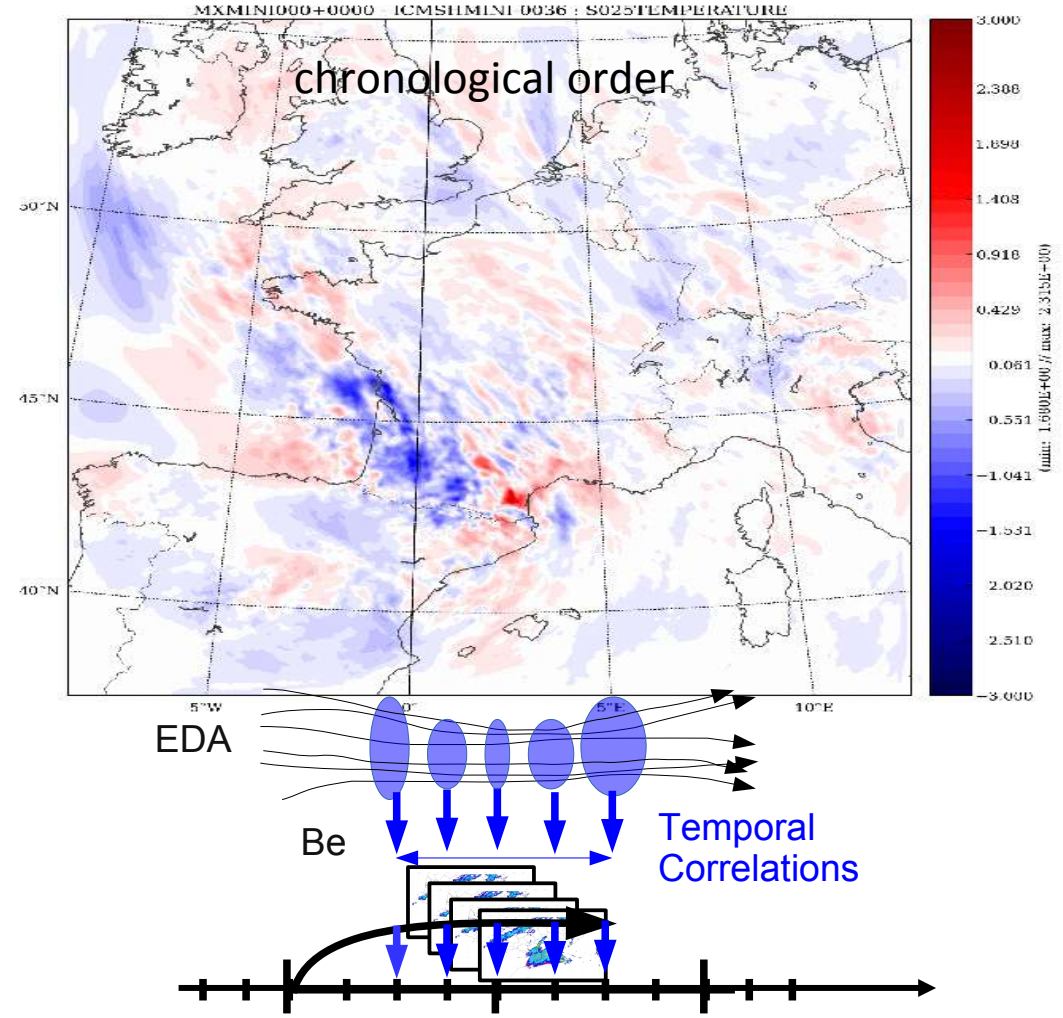
- 4D increment provided by a 1hr 4denvar minimisation using five 15 min timeslots

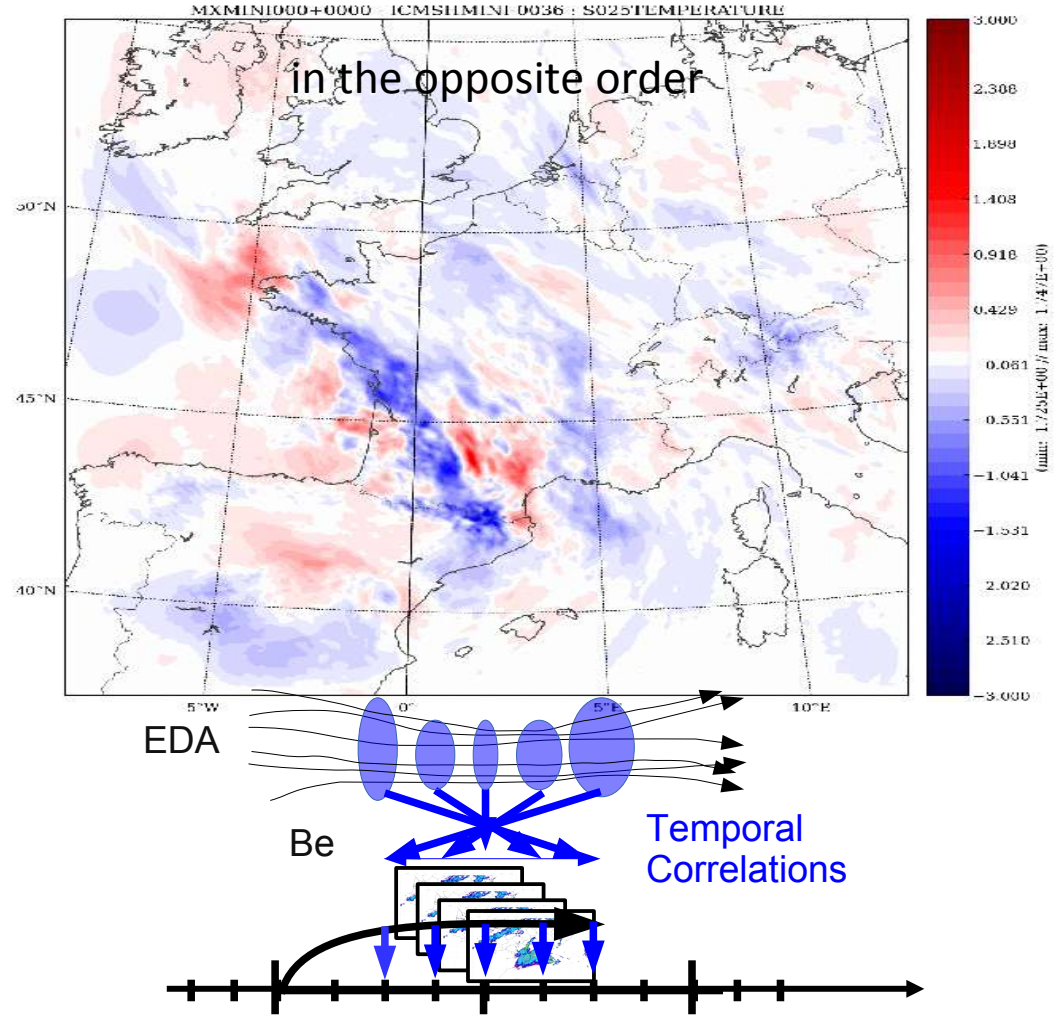


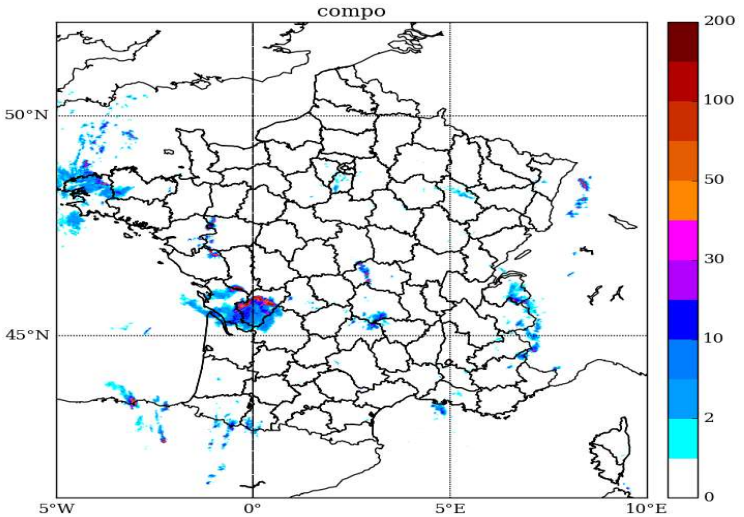
# 4D Temperature increment at 850 hPa

- temporal consistency : same background, same observations but different order

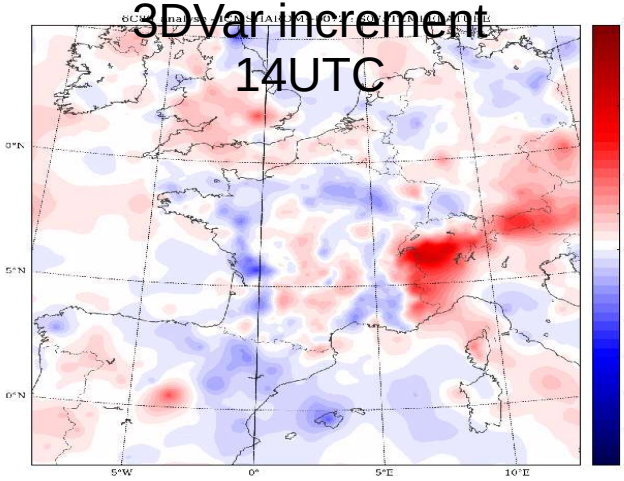


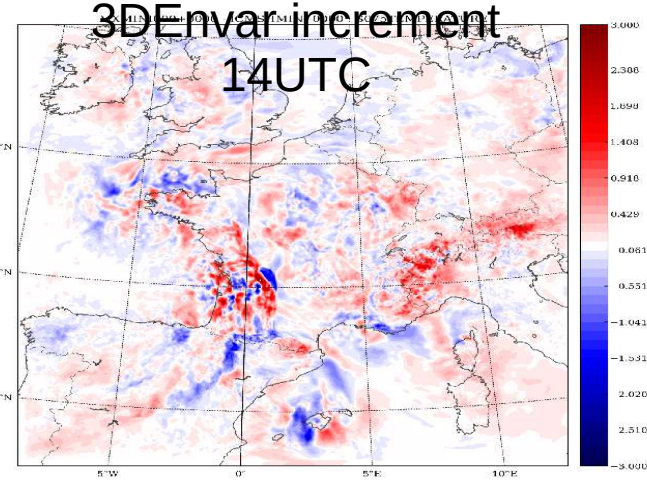
# 4D Temperature increment at 850 hPa



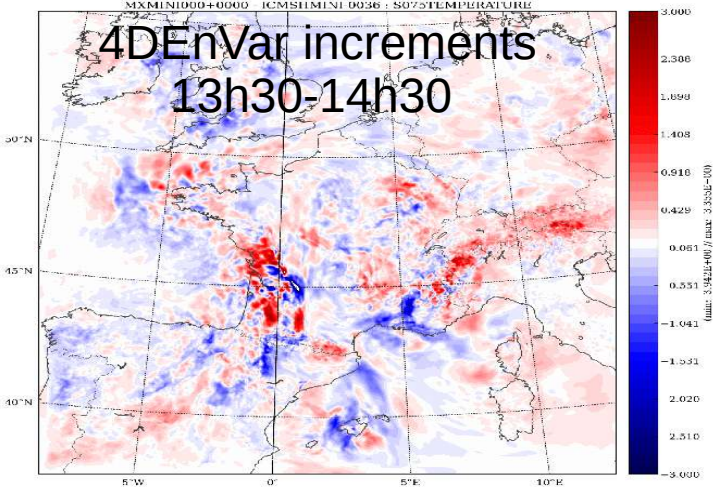

3DVar increment
14UTC



3DEnvar increment
14UTC



4DEnVar increments
13h30-14h30

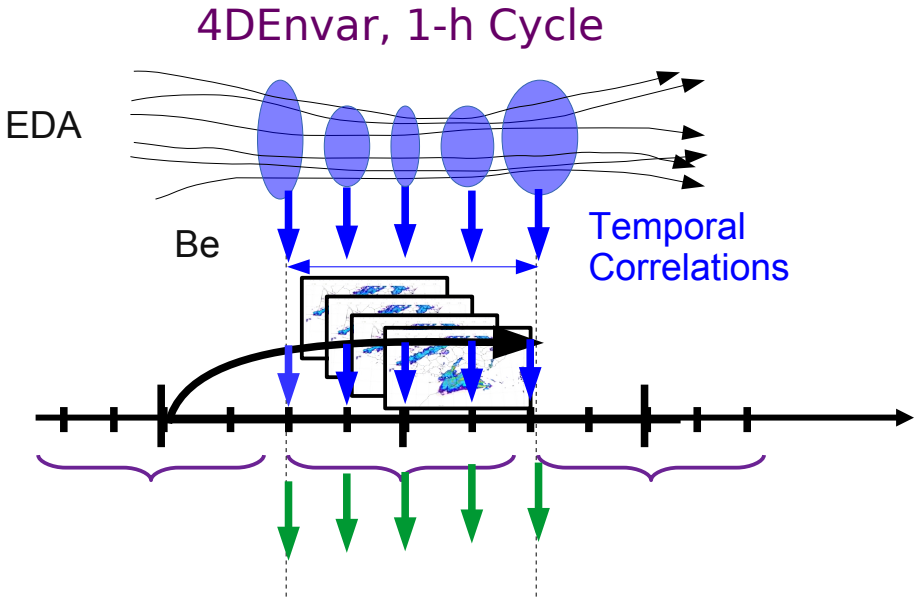


# outlines

- Introduction to a 4DEnVar DA system

- Proposal for the next AROME-France E-suite.

# Configuration




AROME-France :
- operations (cy46) : 3D-Var 1h cycle
- current E-suite (cy48) : 3DEnVar 1h cycle

=> next E-suite (cy49) : 4DEnVar  1h cycle

- 1h Cycle with 5 timeslots : 3*15min + 2*7min

- assimilating all operational observations with 15 min radar, Ground-based GNSS, SEVIRI radiances (geostationary platforms) and surface stations

- localization : same as in 3DEnvar : 25-150 km

- Perturbations every 15 minutes from the same perturbed forecasts from Arome-France EDA  (4h30-5h30-00h15, 5h30-6h30 and 6h30-7h30 depending on the assimilation time) 3,2km Hydrostatic

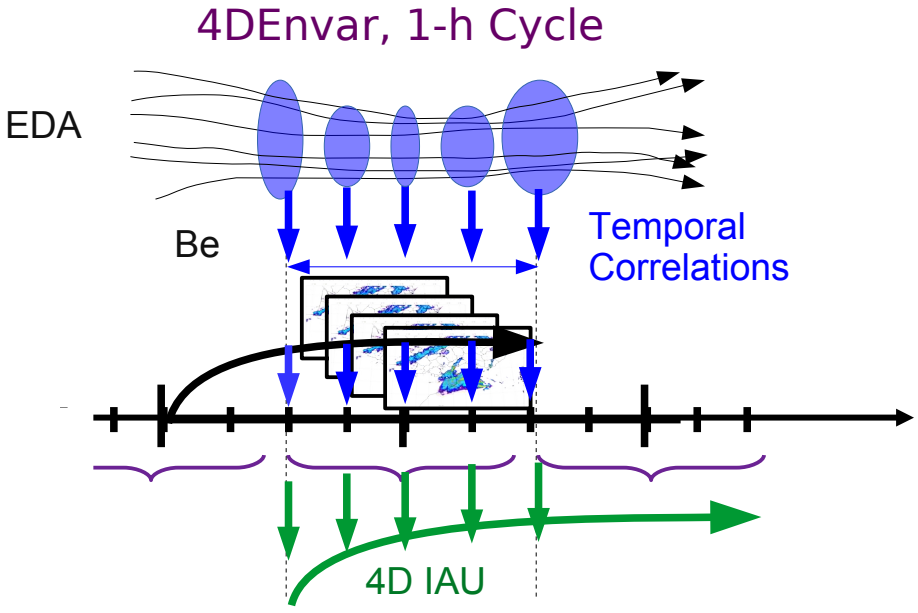
# Configuration

OOPS scripting  as in 3DEnVar:

- screening + minim in a single task
- script and json adapted to the 4D states

Ex :  ICMSHOOPSINIT  =>  ICMSHO000INIT,  ICMSHO015INIT,  ICMSHO030INIT,
ICMSHO045INIT,  ICMSHO001INIT

**No need for a forecast in the 4D screening (contrary to masterodb) :**
**oops is able to read each 3D background state file that corresponds exactly to each observation time-slot of the 4D assimilation window**



# Configuration

4DEnvar, 1-h Cycle

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"cost_type": "3D-Var",
"Jb": {
    "Background": {
        "state": [
            {
                "date": "{{now.iso8601()}}",
                "term": "PT0H",
                "ifile": "0",
                "variables": [],
                "expver": "OOPS"
            }
        ],
    },



    "Covariance": {









       "covariance": "ens_interpol",
        "date": "{{now.iso8601()}}",
        "ensemble_resol": {
            "namelist": "naml_standard_geometry_t319",
            "is_alternative": {},
            "orogfile": "unused"
        },
        "interpol": {
            "id_interpol": "201",
            "variables": ["u", "v", "t", "q", "sp"],
            "param": {
                "all": {}
            },
            "grid_2d": {}
        },
```

```
"cost_type": "4DEnVar",
"Jb": {
    "Background": {
        "state": {
            "__bronx_tpl_engine__": "loop",
            "__loopiterator__": "timeslot_centers",
            "__loopvariables__": "timeslot_center",
            "__body__": {
                "date": "{{(now - window_lmargin).iso8601()}}",
                "term": "{{timeslot_center.iso8601()}}",
                "ifile": "0",
                "variables": [ ],
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            }
        },
    },
    "Covariance": {
         "envar_times" : {
            "__bronx_tpl_engine__" : "loop",
            "__loopiterator__" : "timeslot_centers",
            "__loopvariables__" : "timeslot_center",
            "__body__" : {
             "reference_time" : "{{(now - window_lmargin + timeslot_center).iso8601()}}"
    }
  },
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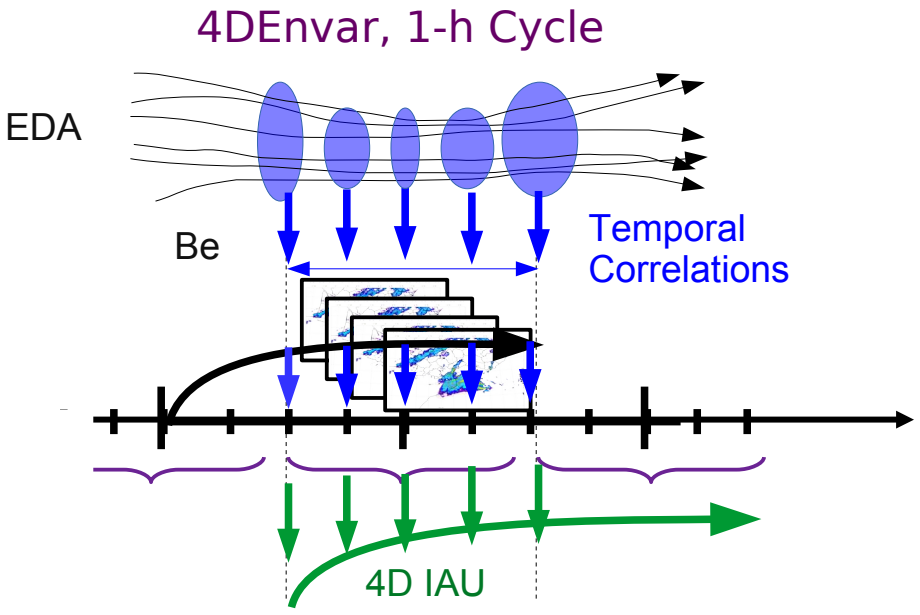
           "orogfile": "unused"
       },
       "interpol": {
           "id_interpol": "201",
           "variables": ["u", "v", "t", "q", "sp"],
           "param": {
               "all": {}
           },
           "grid_2d": {}
       },
```

# 4D IAU




* OOPS scripting as in 3DEnVar:

- screening + minim in a single task
- script and json adapted to the 4D states

Ex : ICMSHOOPSINIT => ICMSHO000INIT, ICMSHO015INIT, ICMSHO030INIT, ICMSHO045INIT, ICMSHO001INIT

**No need for a forecast in the 4D screening (contrary to masterodb) : oops is able to read each 3D background state file that corresponds exactly to each observation time-slot of the 4D assimilation window**

* Challenge : how to use the 4D increment ? In theory, all 3D states are statistically equivalent, and the new forecast can be initiated from any of them :
  - the first one (as in 4D-Var) ?
  - the central one (as in 3D-Var or 3DEnvar) ?
  - actually, better results are obtained by using 20% of all of them by 4D IAU

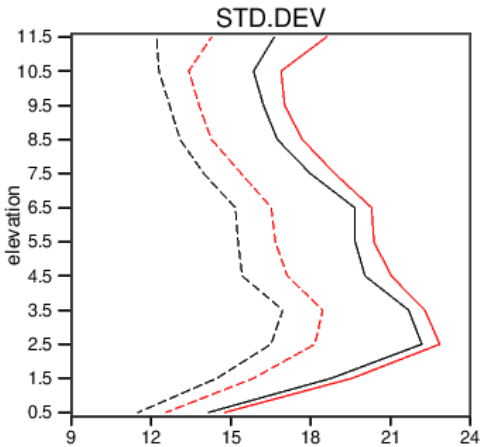
4D IAU (20 % of the 5 Inc.)

3D IAU of the Central Inc. (as in 3DEnVar)

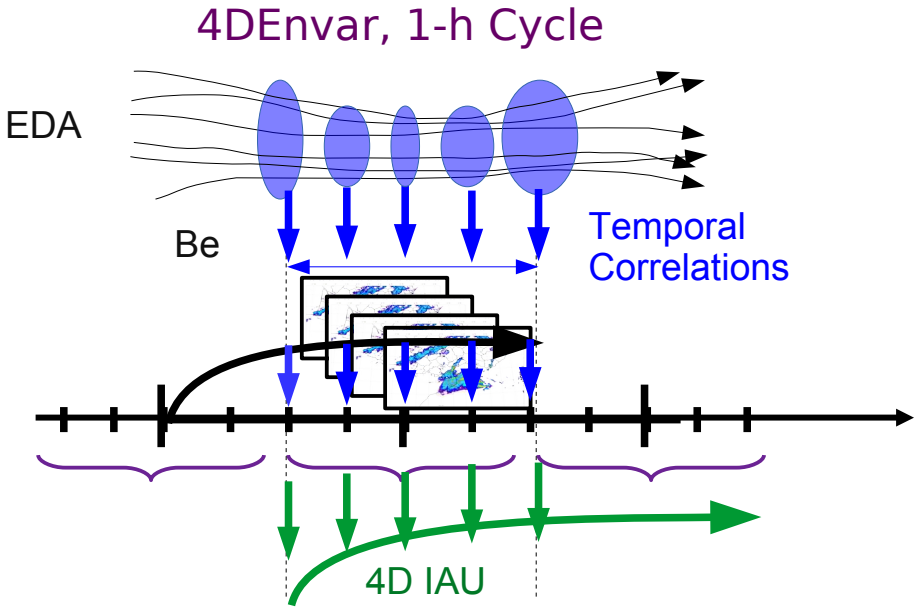
Obs-Guess

Obs-Analysis

RADAR Globe
Used RH



# Numerical cost




* Numerical cost Vs 3DEnVar :

- screening+minim : time x 2, memory x 5 :

=> need for 24 belenos nodes to run screening+minim in 12 min (12 nodes for 3DEnvar in 10 min or 34 nodes to run a 24h arome forecat in 30 min).

- due to the use of 4D IAU : time x 2 due to the forecast to produce the next background : need for a 2 hr forecast range instead of 1 hr

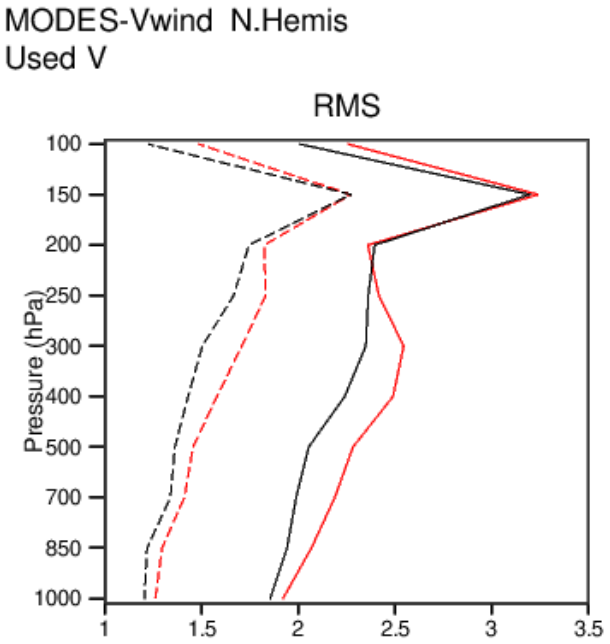
=> +5min on the current 12 nodes used for the DA background

**All these additional numerical costs are affordable on the current MF's HPC**

# Assimilation cycle statistics : (obs-guess) and (obs-analysis) 20231016-20231216

MODES wind :
- more consistent obs-guess comparison
- ~ obs number (+ 4 %)
- and reduced obs-guess and obs-analysis

Radar HU :
- obs number x 4
- reduced obs-guess and obs-ana

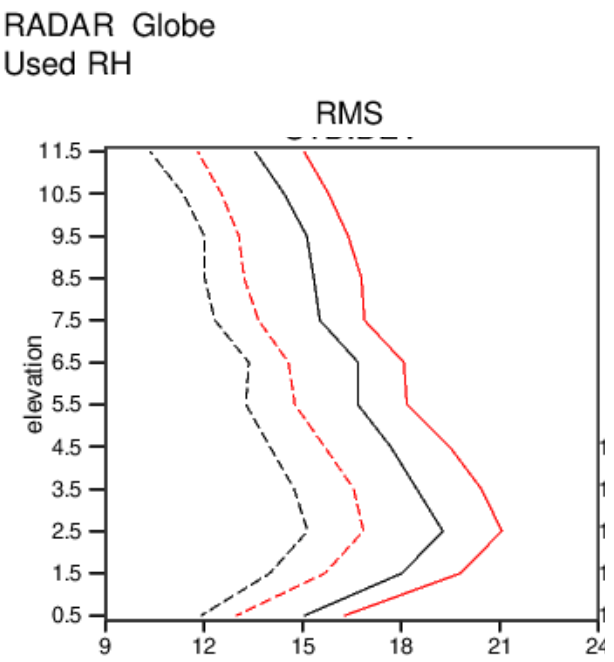



4DEnVar

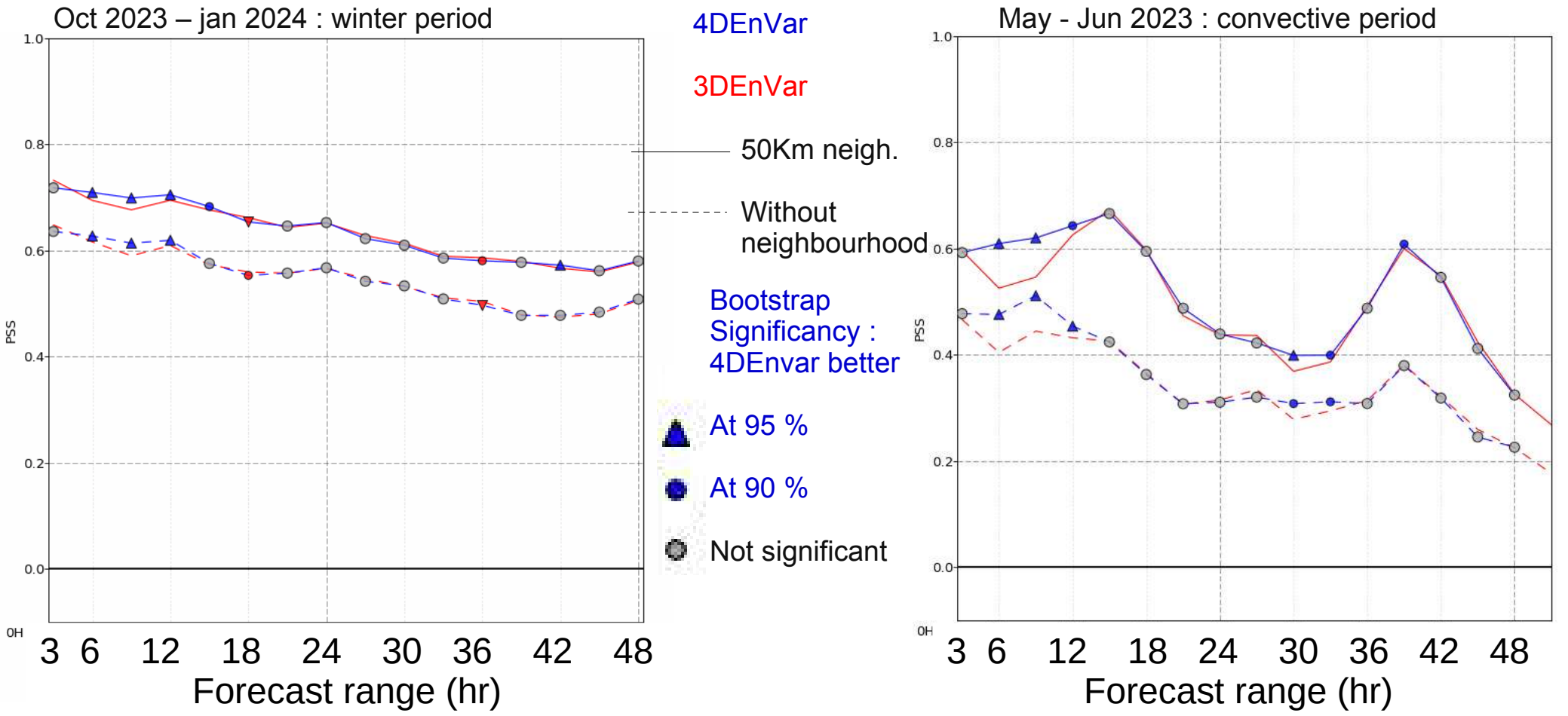
3DEnVar

Obs-Guess

Obs-Analysis

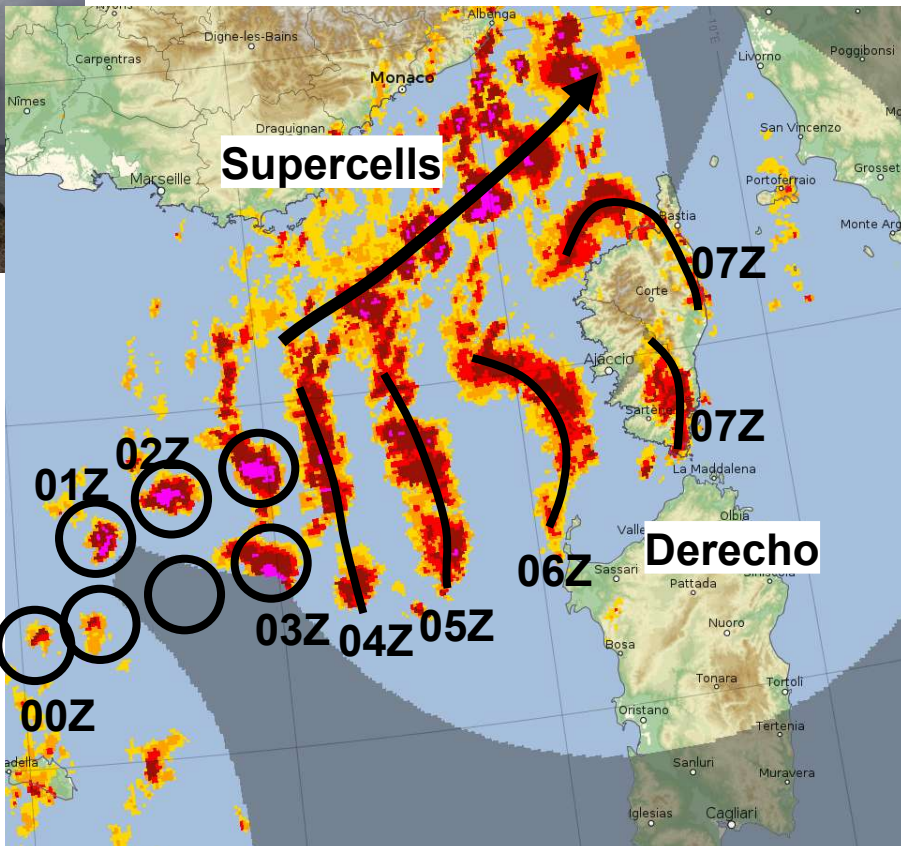


# Long range forecast performances (00 UTC) : PSS for RR3h against raingauges : 2mm/3h threshold (but representative of other thresholds)



# Case study : derecho over Corsica 18 Aug. 2022

- 100-120 km/h generalized wind gusts
- 200-225km/h maximal wind gusts
- 5 casualties
- only an late orange warning !!



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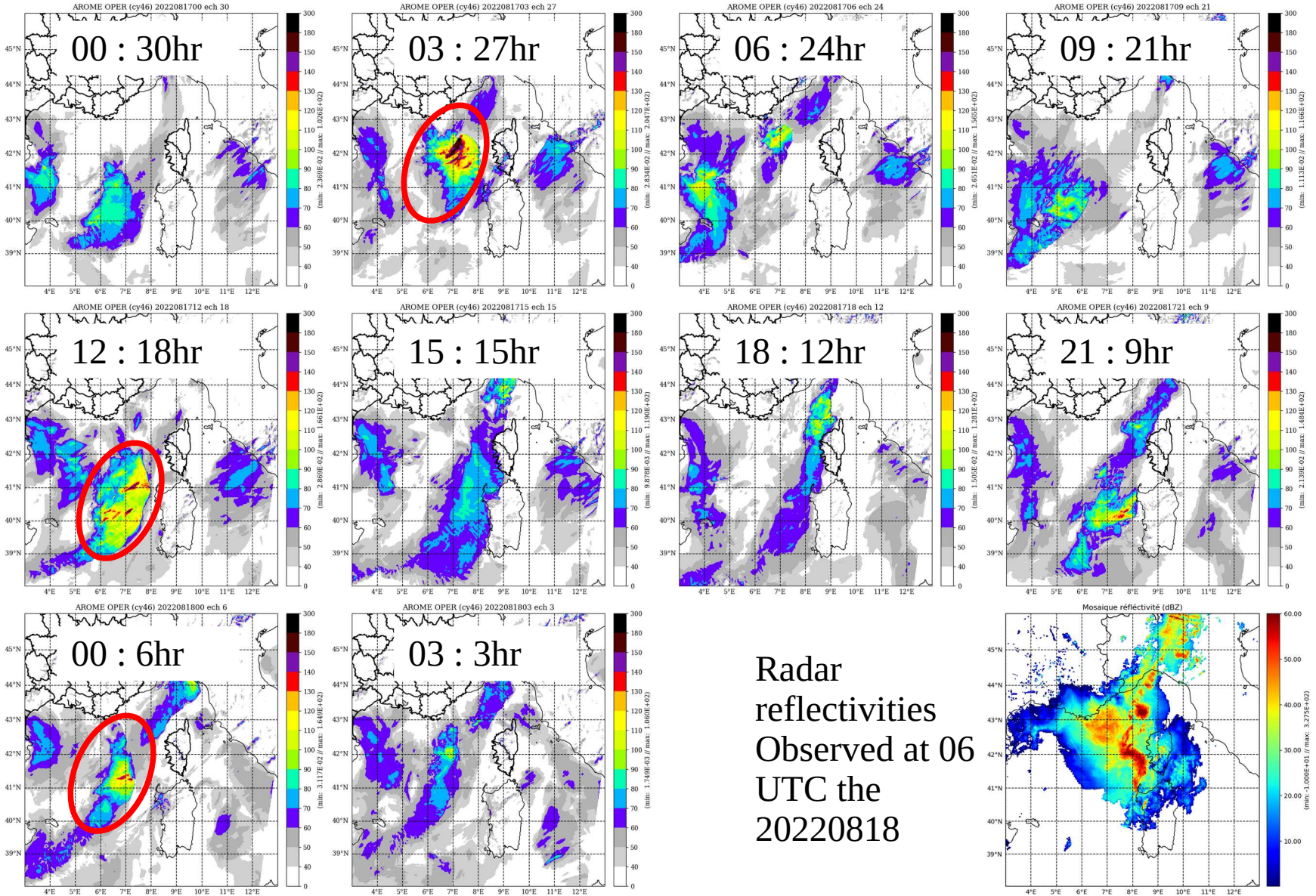
METEO FRANCE

# 3D-Var

20220817

Wind gusts simulated by the different Arome-france forecasts valid at 06 UTC the 20220818 using 3D-Var : 3 forecasts simulate an interesting signal (Yellow > 110 Km/h)

20220818




Radar reflectivities Observed at 06 UTC the 20220818

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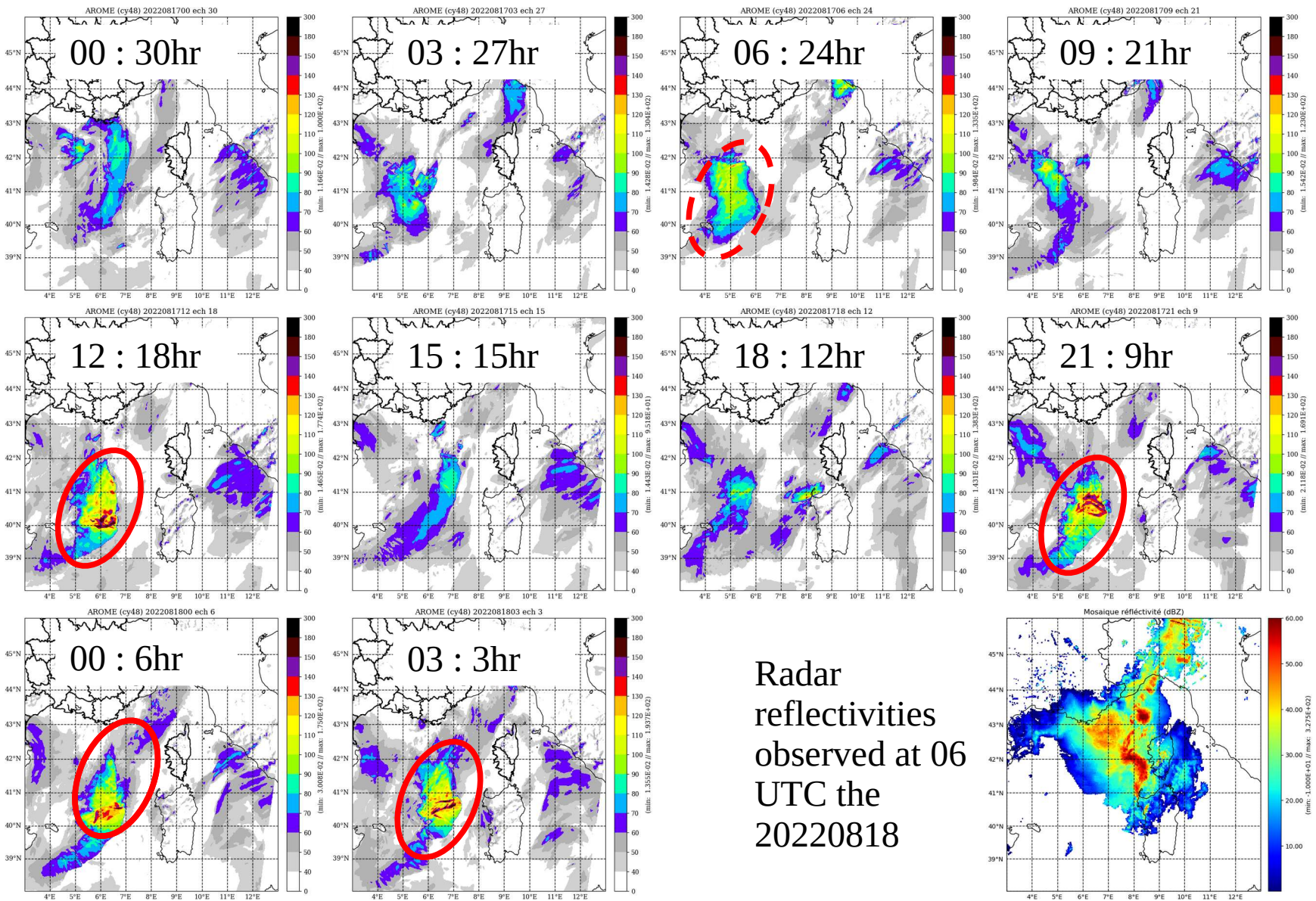
METEO FRANCE

# 3DEnVar

20220817

Wind gusts simulated by the different Arome-france forecasts valid at 06 UTC the 20220818 using 3DEnVar : 5 forecasts simulate an interesting signal, especially the last 3 ones (Yellow > 110 Km/h)

20220818




Radar reflectivities observed at 06 UTC the 20220818

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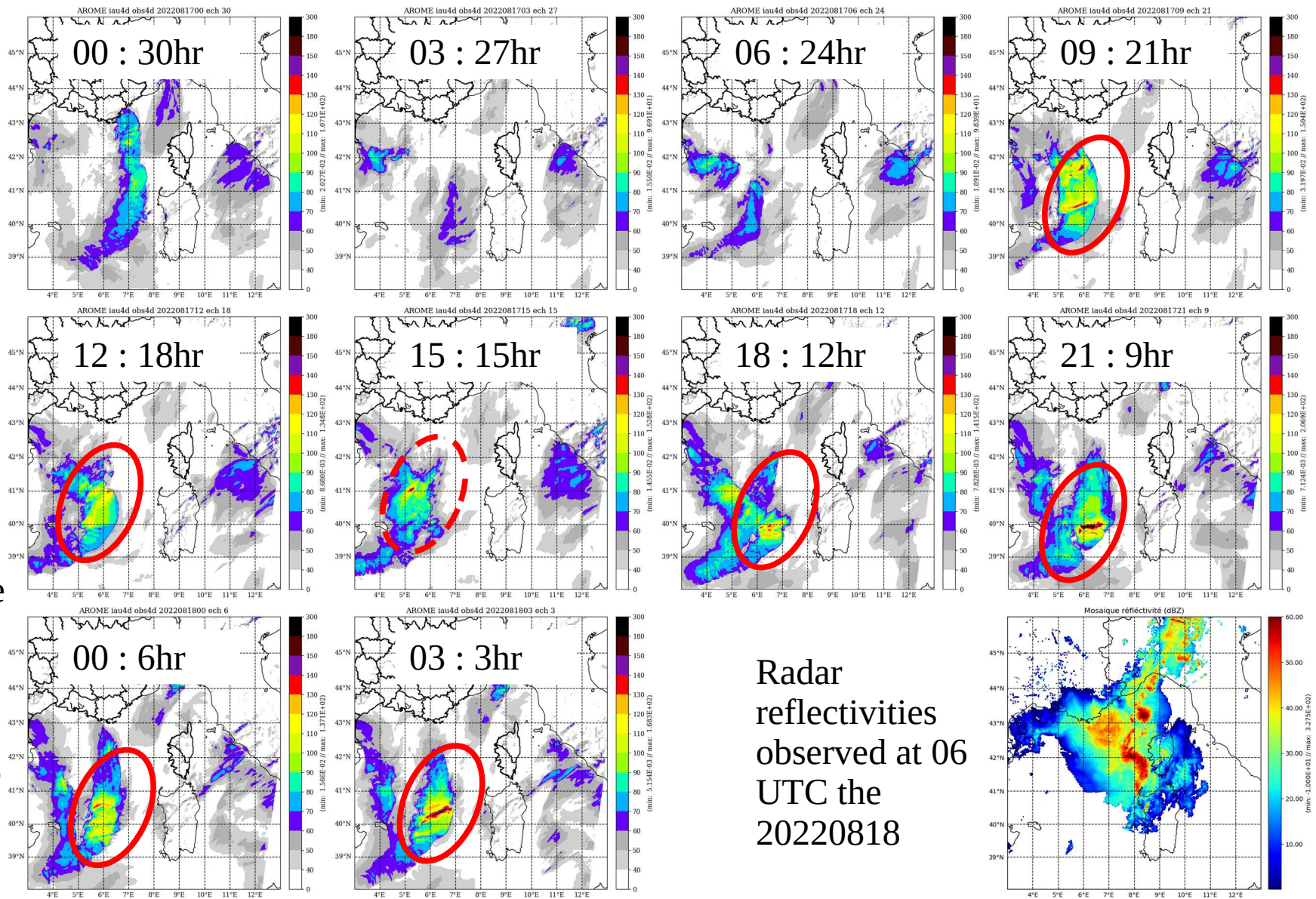
METEO FRANCE

# 4DEnVar

20220817

Wind gusts simulated by the different Arome-france forecasts valid at 06 UTC the 20220818 using 4DEnVar : the last 7 forecasts simulate an interesting signal (Yellow > 110 Km/h)

20220818



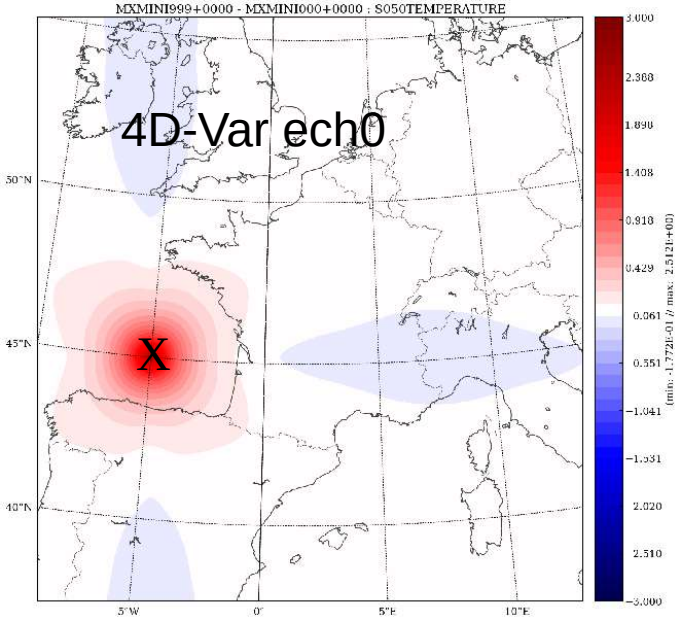

Radar reflectivities observed at 06 UTC the 20220818

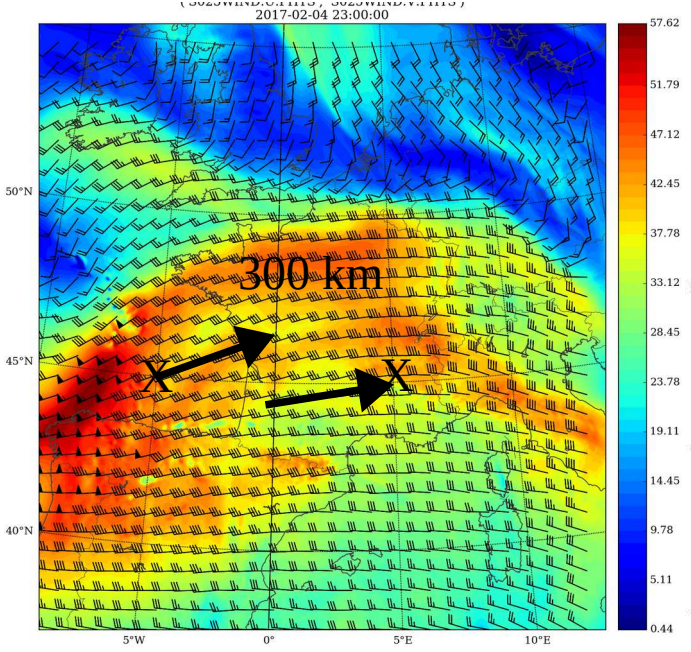
# Conclusion

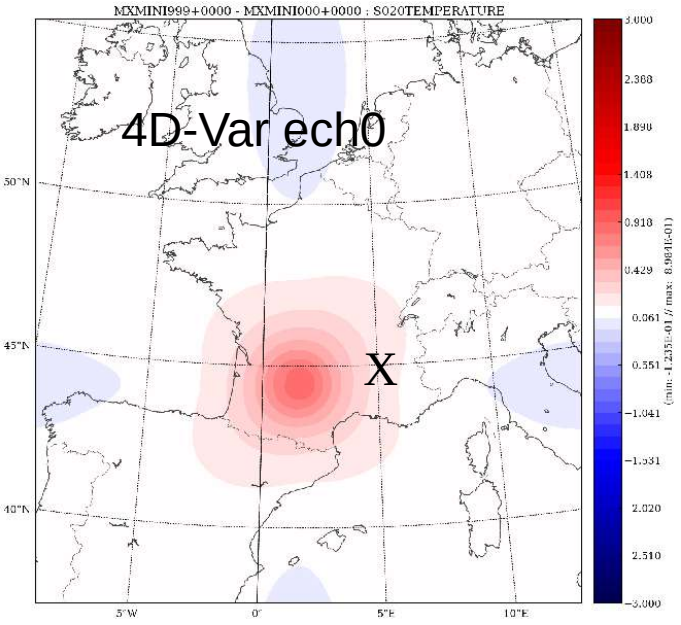
A 4DEnVar scheme, utilising OOPS, has reached a sufficient level of maturity and has been well evaluated within the Arome-France framework :

- The temporal dimension is managed by the temporal background error cross-correlations, which are directly estimated from the AROME-France EDA (perturbed non-linear model forecasts)
- This allows for the assimilation of 15-min frequency observations in the 1 hr cycle
- Screening + minim run in 12 min on 24 MF's HPC nodes which is affordable operationally
- General performances (classical scores) are comparable to those of 3DEnVar, but precipitation scores (especially during convective periods) and the simulation of severe events have been improved.
- This 4DEnVar configuration is proposed for incorporation in the next MF E-suite, in addition to Scale Dependent Localisation (V. Vogt) and direct assimilation of radar reflectivities (M. Martet).

Thank you for your attention …


MXMINI999+0000 - MXMINI000+0000 : S050TEMPERATURE
4D-Var ech0
X
50°N
45°N
40°N
5°W
0°
5°E
10°E
3.000
2.368
1.890
1.408
0.910
0.429
0.061
0.551
−1.041
−1.531
2.020
2.510
−3.000
(min.-1.7721E-01 // max. 2.5121E+00)


2017-02-04 23:00:00
300 km
X
X
50°N
45°N
40°N
5°W
0°
5°E
10°E
57.62
51.79
47.12
42.45
37.78
33.12
28.45
23.78
19.11
14.45
9.78
5.11
0.44


MXMINI999+0000 - MXMINI000+0000 : S020TEMPERATURE
4D-Var ech0
X
50°N
45°N
40°N
5°W
0°
5°E
10°E
3.000
2.368
1.890
1.408
0.910
0.429
0.061
0.551
−1.041
−1.531
2.020
2.510
−3.000
(min.-1.2135E-01 // max. 0.9041E-01)