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Scale-dependent localization in ensemble-variational data assimilation: Application in global and convective-scale systems

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Outline

1. An approach to improve spatial covariance localization in EnVar : scale-dependent localization (SDL)

2. Application in two EnVar-based DA systems
   a) A simplified version of ECCC's global operational system
   b) Meteo-France AROME convective-scale system (R&D version)

Localisation

- Spatial covariance localization is essential to obtain useful analyses with “small” ensembles (a 256-member ensemble is still "small"!).

- Currently, ECCC's EnVar uses simple localization of ensemble covariances, similar to EnKF: single length scale in both horizontal and vertical localizations based on Gaspari and Cohn (1999) 5th order piecewise rational function.

- Comparing various NWP studies, seems that the best amount of horizontal localization depends on application/resolution:
  - convective-scale assimilation: ~10km
  - mesoscale assimilation: ~100km
  - global-scale assimilation: ~1000km – 3000km (2800km at ECCC)

A one-size-fits-all approach for localization does not seem appropriated for analysing a wide range of scales.

Scale-dependent localisation (SDL)

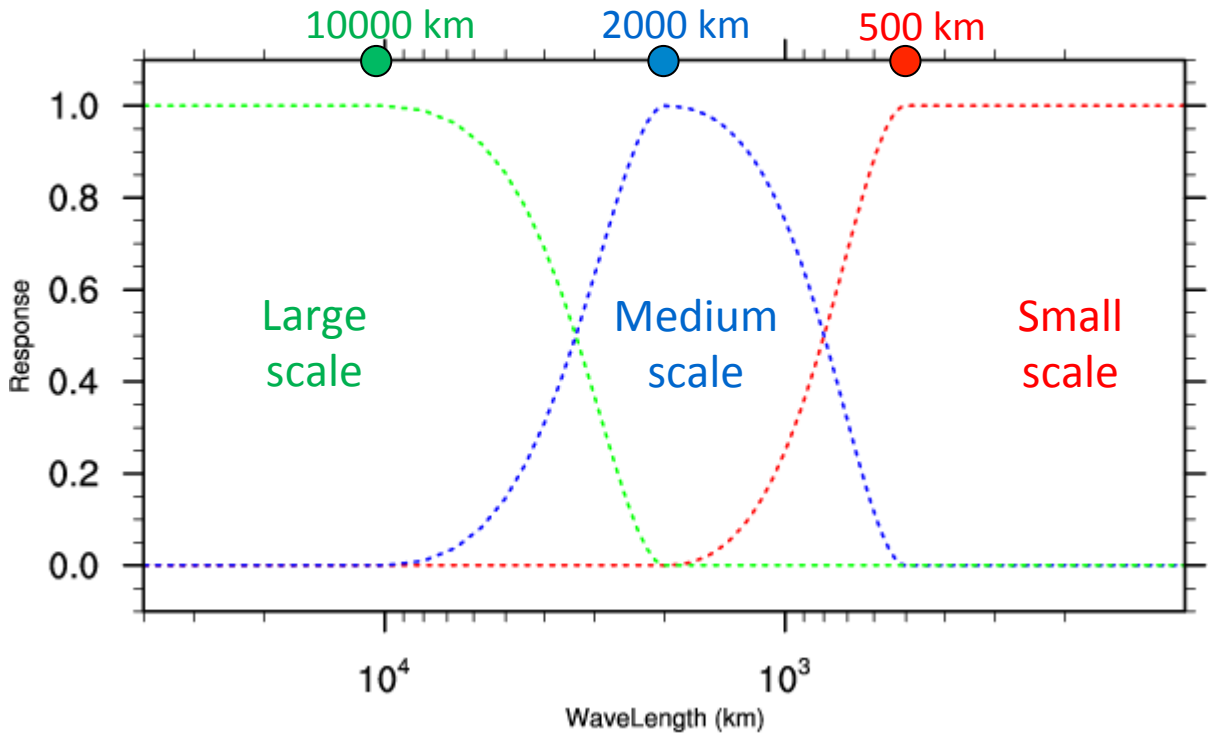
Definition: Simultaneously apply appropriate (i.e. different) localization to different range of scales.

- The approach can be applied to both horizontal and vertical localization but this presentation will only focus on horizontal-scale-dependent horizontal localization.

- Pros:
  - Seems appropriated for multi-scale analysis.
  - In limited-area: Could avoid the need of multi-step or large-scale blending approaches.
- Cons:
  - Adds more parameters to tuned.
  - Increases the cost of the analysis step (at least in our formulation).

Horizontal Scale Decomposition

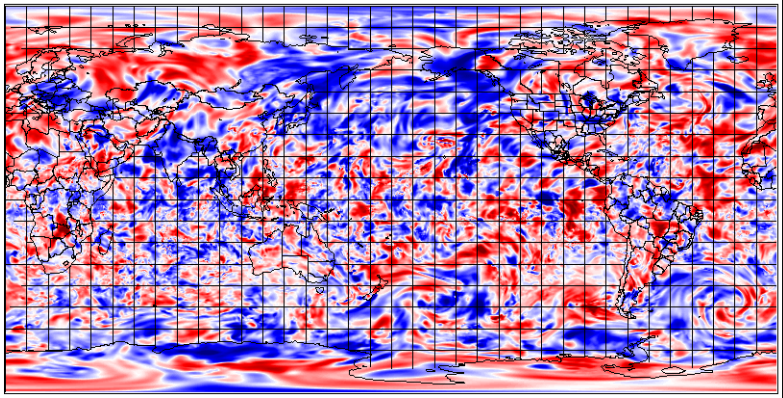
Filter response functions for decomposing with respect to 3 horizontal scale ranges



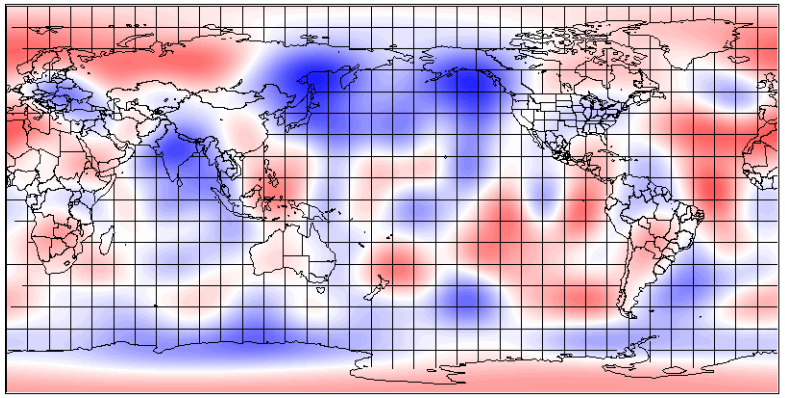
Horizontal Scale Decomposition

Perturbations for ensemble member #001 – Temperature at ~700hPa

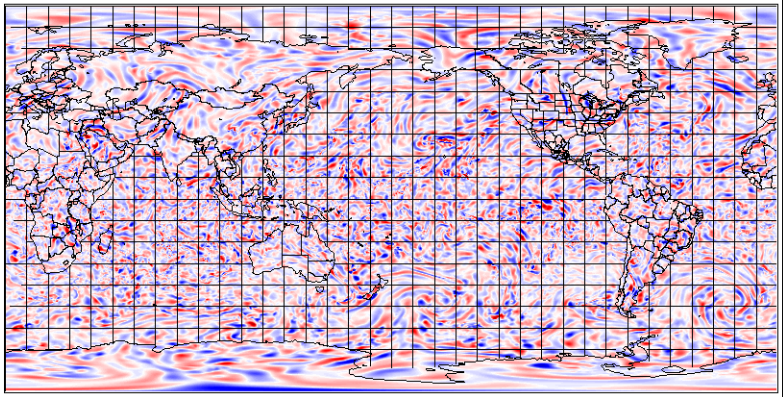
Full



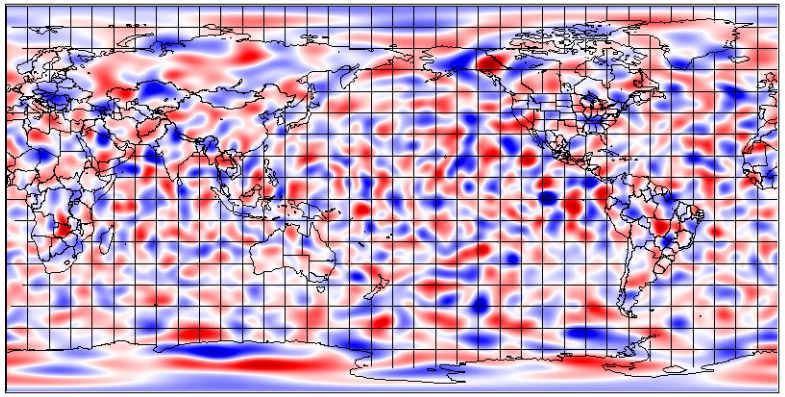
Large scale



Small scale



Medium scale



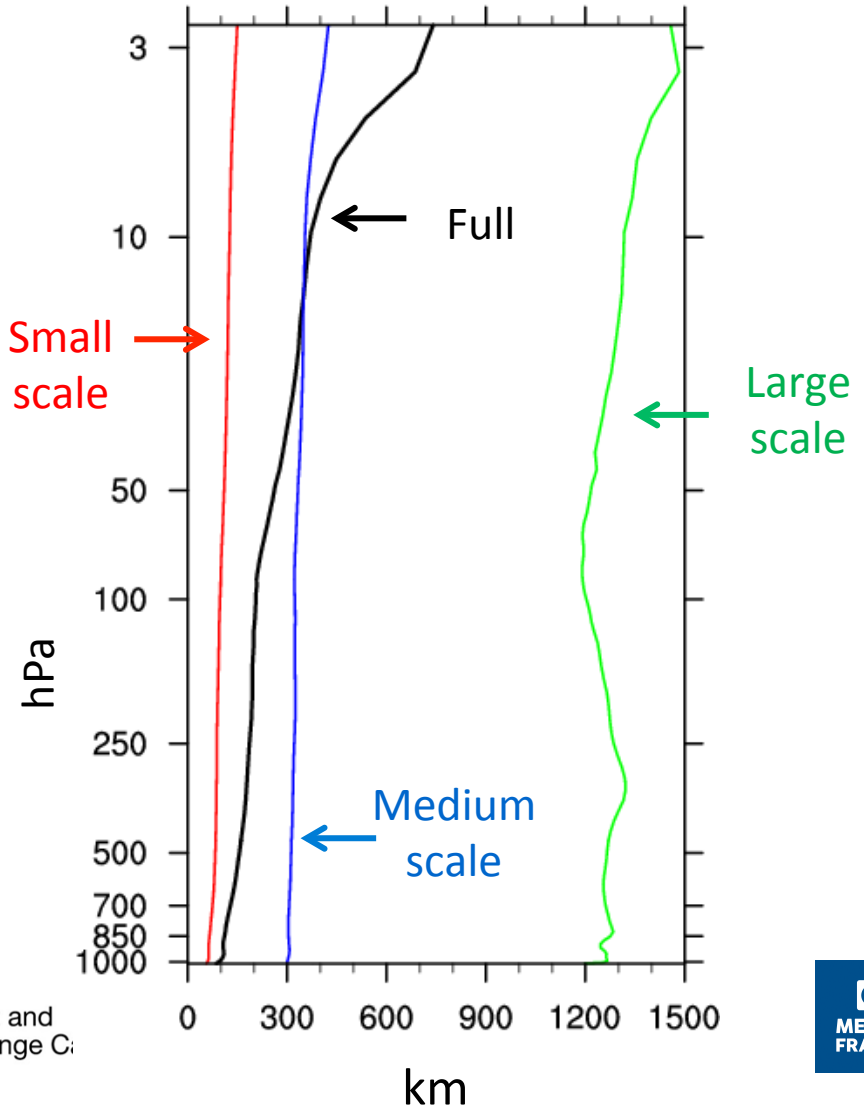
Horizontal Scale Decomposition

Homogeneous horizontal correlation length scales

6-h temperature perturbation from 256-member EnKF

Horizontal scale-dependent localization leads to (implicit)…

vertical-level-dependent horizontal localization



Horizontal Scale Decomposition

Waveband integrated variances

Large scale

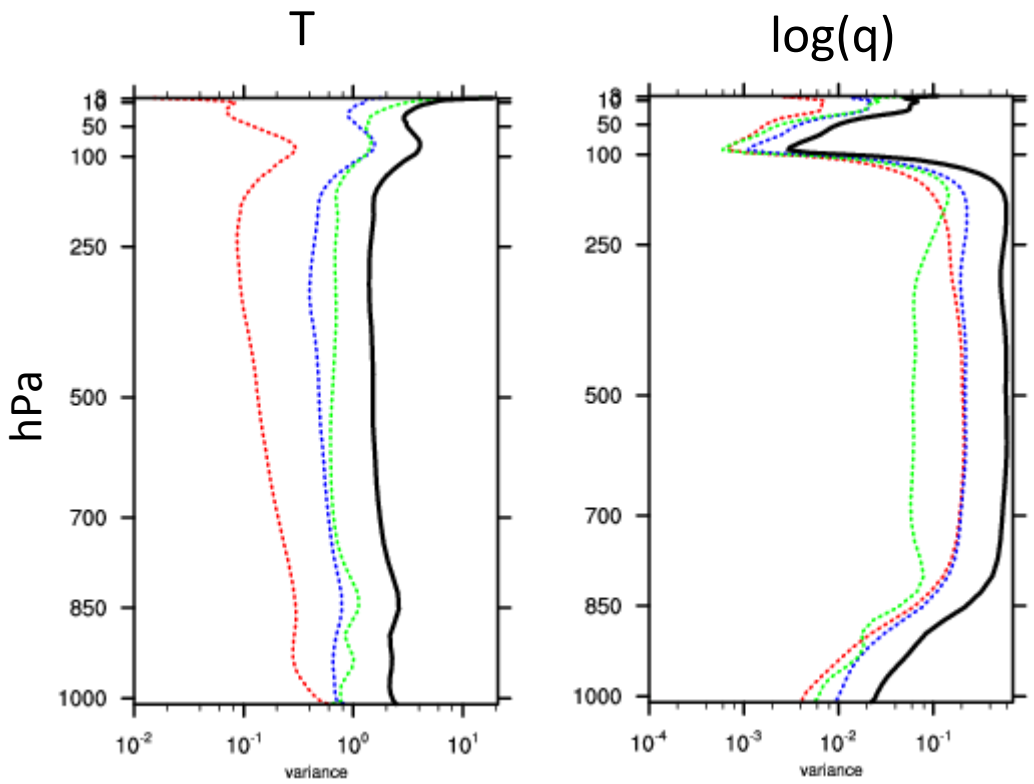
Medium scale

Small scale

All the scales

Horizontal scale-dependent localization leads to (implicit)…

variable-dependent horizontal localization



6-h perturbation from 256-member EnKF

Scale-dependent localisation (SDL)

The basic idea (from Buehner and Shlyaeva, 2015, *Tellus*)

- The original ensemble covariances with localization

$$\mathbf{B}_L = \sum_k \mathbf{e}_k \mathbf{e}_k^T \circ \mathbf{L}$$

k: member index

- With a scale-decompose ensemble

$$\mathbf{e}_{k,j} = \mathbf{F}_j \mathbf{e}_k \qquad \mathbf{e}_k = \sum_j \mathbf{e}_{k,j}$$

F: filtering step
j: scale index

$$\mathbf{B}_L = \sum_{j1} \sum_{j2} \sum_k \mathbf{e}_{k,j1} \mathbf{e}_{k,j2}^T \circ \mathbf{L}$$

- With scale-dependent localization

$$\mathbf{B}_{SDL} = \sum_{j1} \sum_{j2} \sum_k \mathbf{e}_{k,j1} \mathbf{e}_{k,j2}^T \circ \mathbf{L}_{j1,j2}$$

EnVar with $B^{1/2}$ preconditioning (ECCC)

Current (one-size-fits-all) Approach

- Analysis increment computed from control vector ($\mathbf{B}^{1/2}$ preconditioning) using:

$$\Delta \mathbf{x} = \sum_k \mathbf{e}_k \circ \left(\mathbf{L}^{1/2} \boldsymbol{\xi}_k \right)$$

k: member index

Scale-dependent Approach (as in Buehner and Shlyaeva, 2015, *Tellus*)

- Varying amounts of smoothing applied to same set of amplitudes for a given member

$$\Delta \mathbf{x} = \sum_k \sum_j \mathbf{e}_{k,j} \circ \left(\mathbf{L}_j^{1/2} \boldsymbol{\xi}_k \right)$$

k: member index
j: scale index

where $e_{k,j}$ is scale *j* of normalized member *k* perturbation

EnVar with B preconditioning (Meteo-France)

Current (one-size-fits-all) Approach

- Analysis increment computed from control vector (**B** preconditioning) using:

$$\Delta \mathbf{x}_o = \sum_k \mathbf{e}_k \circ \left(\mathbf{L} (\mathbf{e}_k \circ \Delta \mathbf{x}_i) \right)$$

k: member index

Scale-dependent Approach

- Direct application to the above formulation

$$\Delta \mathbf{x}_o = \sum_{j1} \sum_{j2} \sum_k \mathbf{e}_{k,j1} \circ \left(\mathbf{L}_{j1,j2} (\mathbf{e}_{k,j2} \circ \Delta \mathbf{x}_i) \right)$$

j: scale index

- Reformulation using $\mathbf{B}^{1/2}$ $\mathbf{B}^{T/2}$

$$\Delta \mathbf{x}_o = \sum_k \sum_j \mathbf{e}_{k,j} \circ \left(\mathbf{L}_j^{1/2} \xi_k \right) \qquad \xi_k = \sum_j \mathbf{L}_j^{T/2} (\mathbf{e}_{k,j} \circ \Delta \mathbf{x}_i)$$

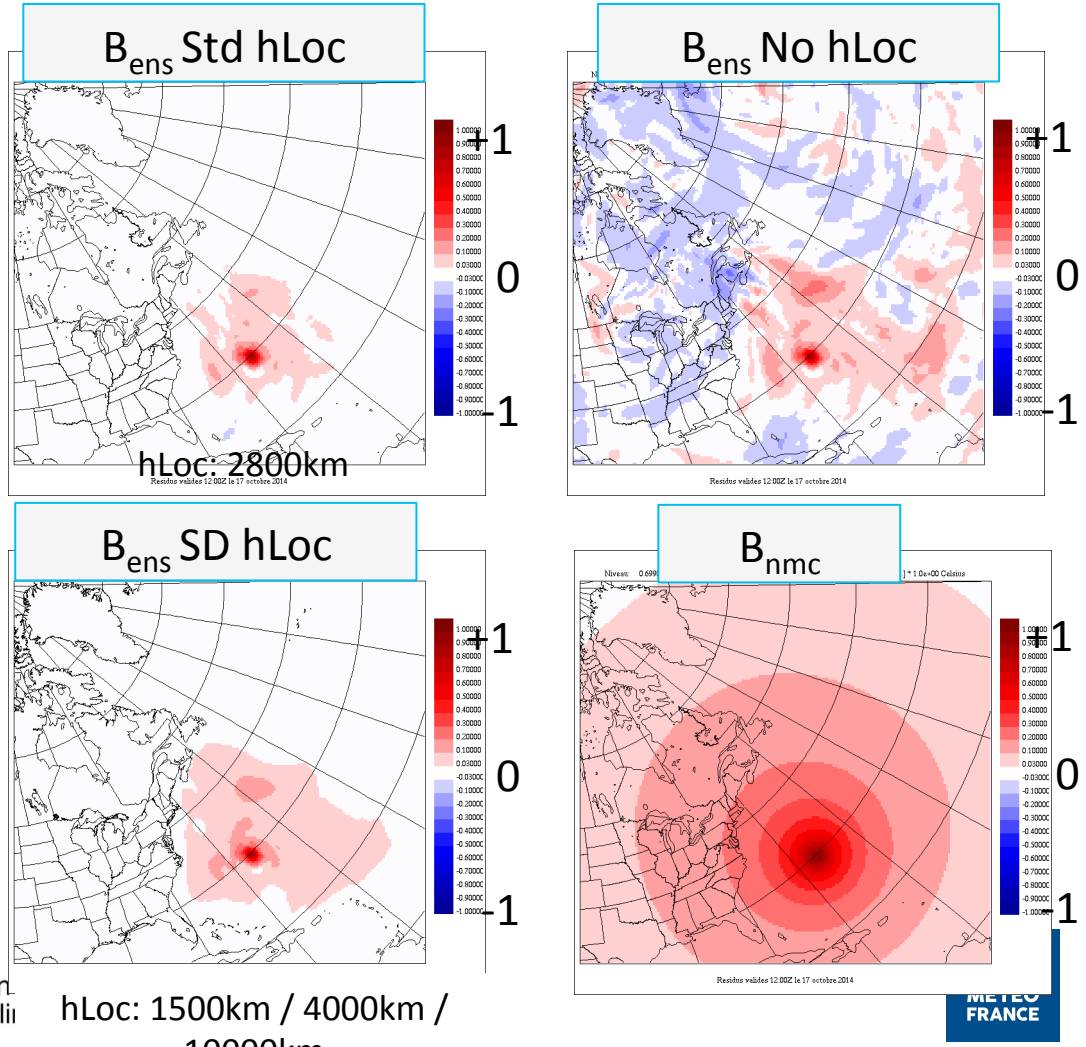
Application in a global EnVar system:
ECCC's Global Determinisitic Prediction System

- 256 ensemble member @ 50km
- Localization in spectral space
- Determinitic forecast @ 25 km

Scale-dependent covariance localization

Impact in single observation DA experiments

700 hPa T observation at the center of **Hurricane Gonzalo** (October 2014)

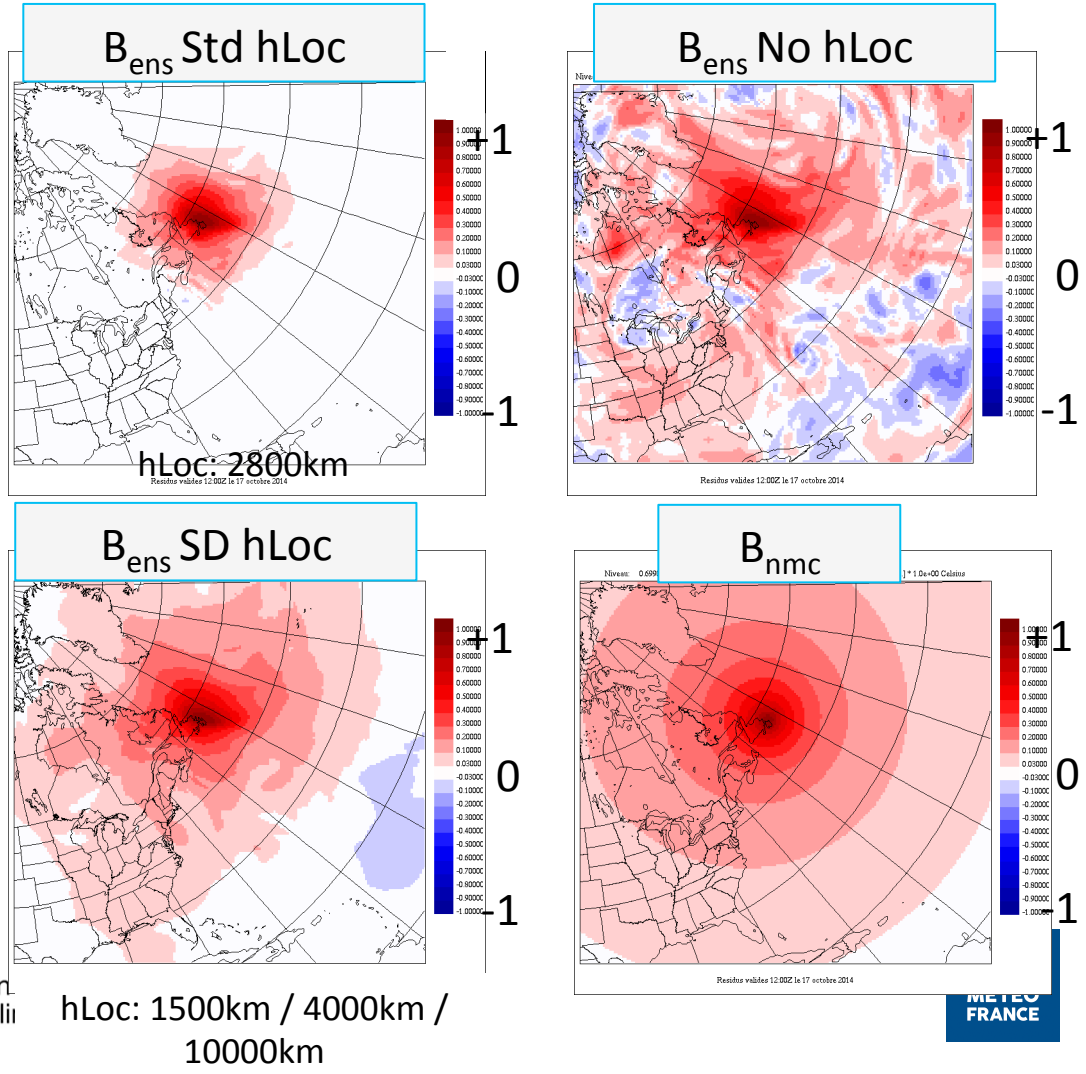


Normalized temperature increments (correlation-like) at 700 hPa resulting from various B matrices.

Scale-dependent covariance localization

Impact in single observation DA experiments

700 hPa T observation at the center of a **High Pressure**



Normalized temperature increments (correlation-like) at 700 hPa resulting from various B matrices.

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Scale-dependent covariance localization

Forecast impact

- 2.5-month trialling (June-August 2014) in our global NWP system.

- 3DEnVar with 100% B_{ens} used in both experiments

  1) Control experiment with hLoc = 2800 km, vLoc = 2 units of ln(p)

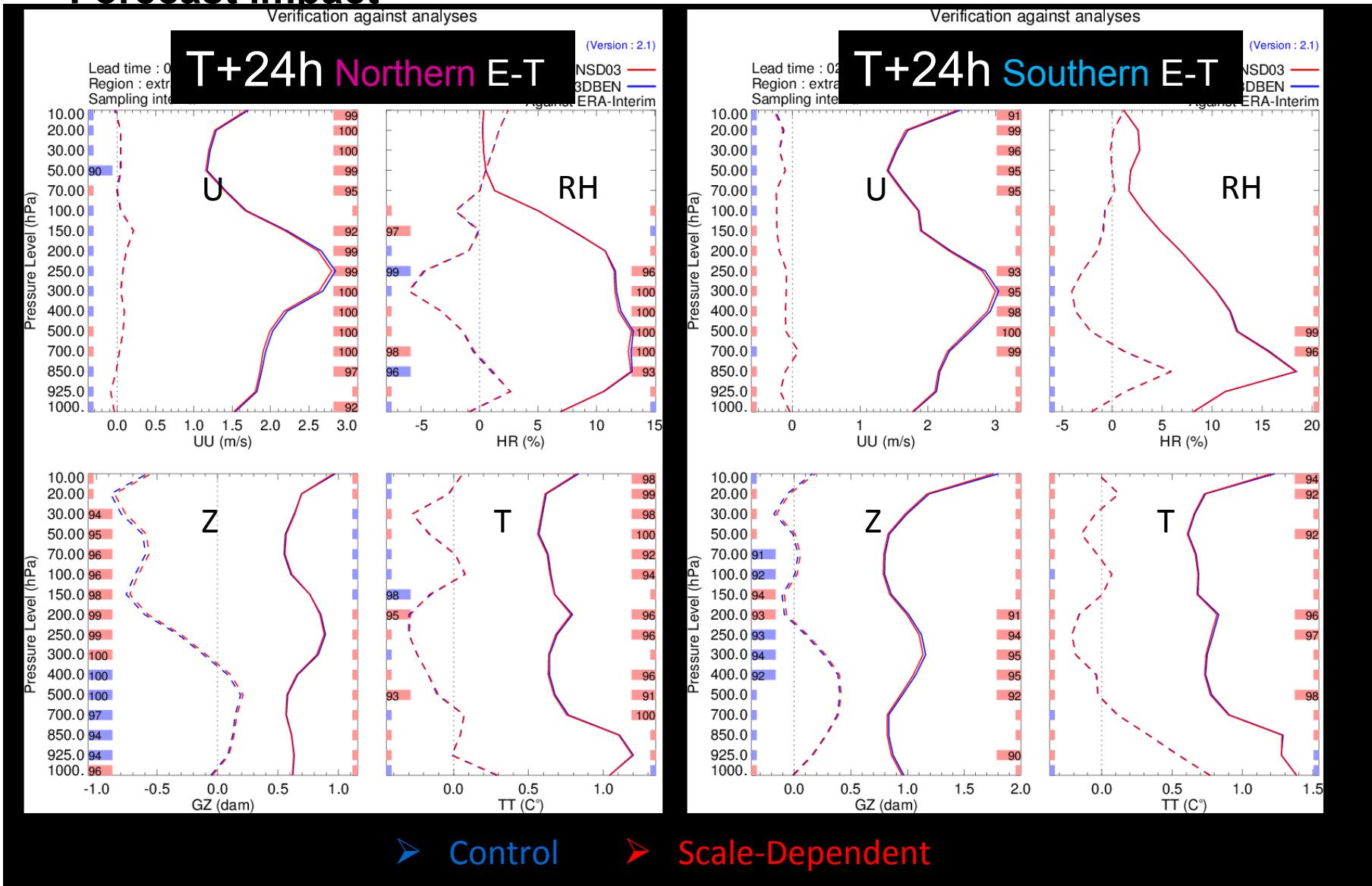
  2) Scale-Dependent experiment with a 3 horizontal-scale decomposition
     I. Small scale uses hLoc = 1500 km
     II. Medium scale uses hLoc = 2400 km
     III. Large scale with uses = 3300 km

     } Ad hoc values!

     Same vLoc (2 units of ln(p)) for every horizontal-scale

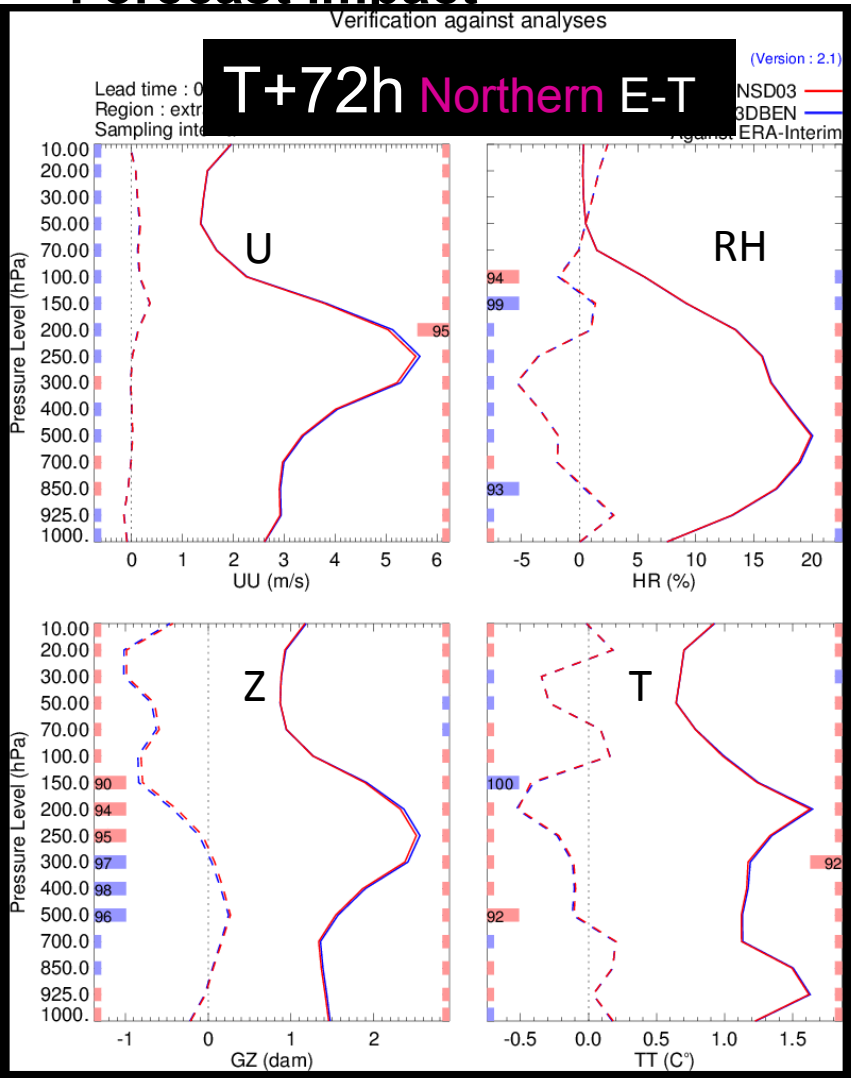
Scale-dependent covariance localization

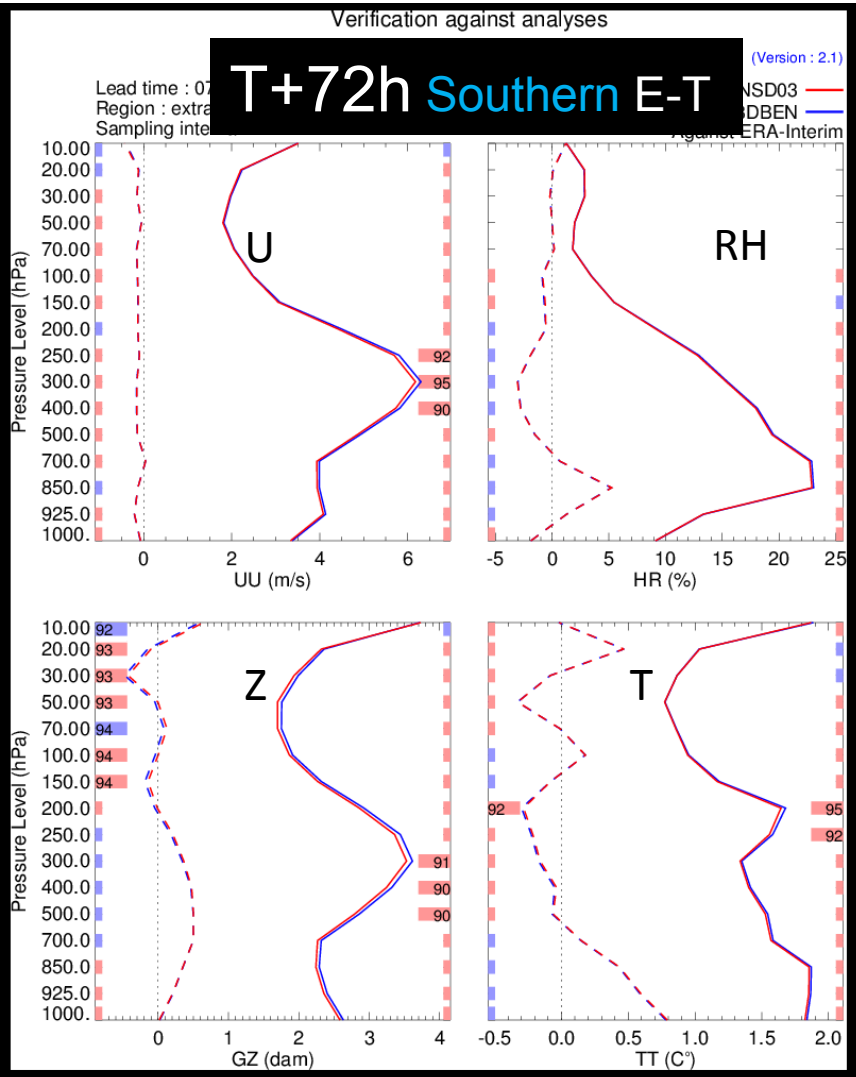
Forecast impact



Scale-dependent covariance localization

Forecast impact

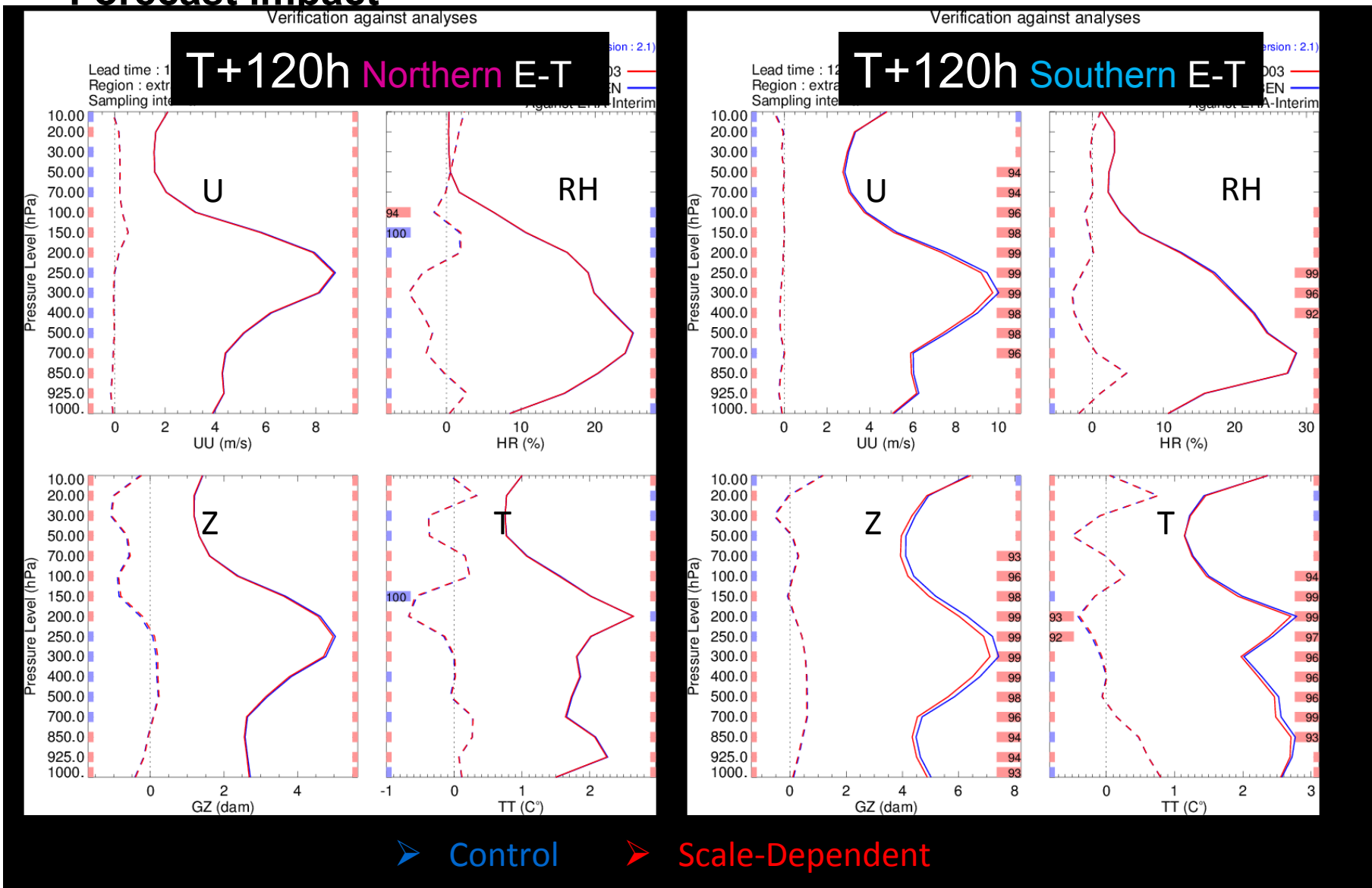




➢ Control ➢ Scale-Dependent

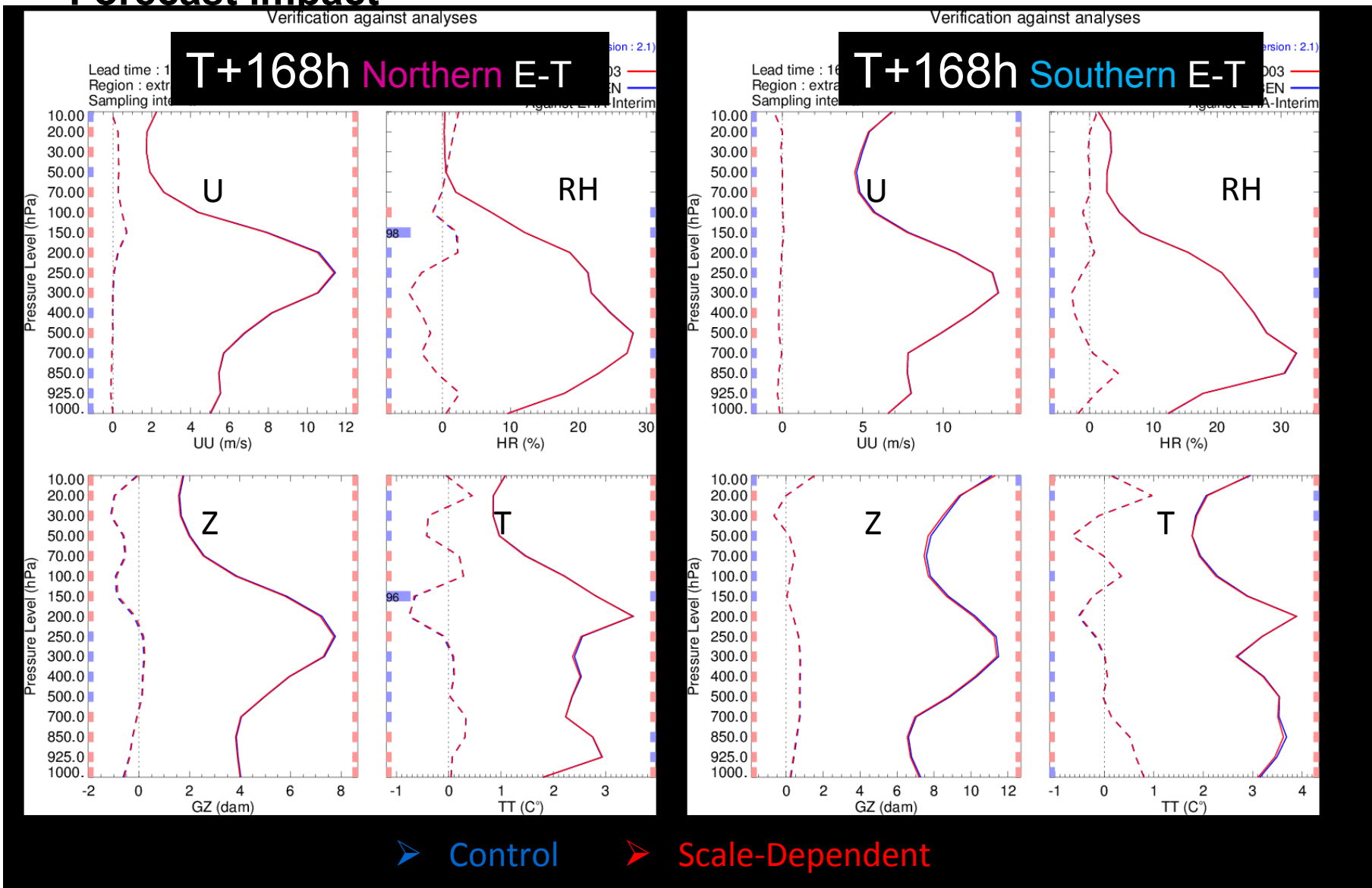
Scale-dependent covariance localization

Forecast impact



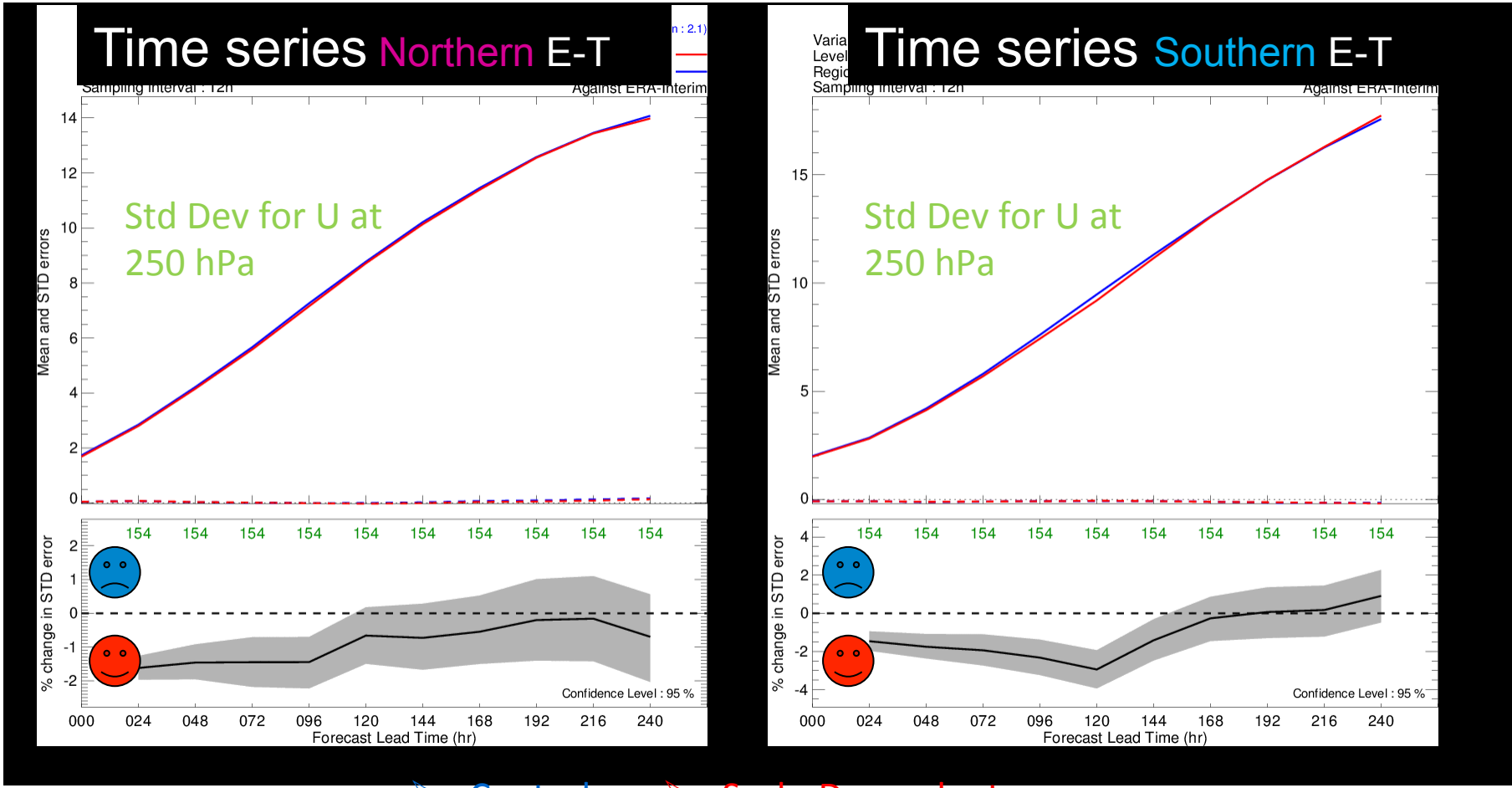
Scale-dependent covariance localization

Forecast impact



Scale-dependent covariance localization

Forecast impact



Control Scale-Dependent

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Scale-dependent covariance localization

Forecast impact

Is it possible to do as good as SDL with a single localization approach?

After all, perhaps our one-size-fits-all horizontal localization radius of 2800 km is not optimal...

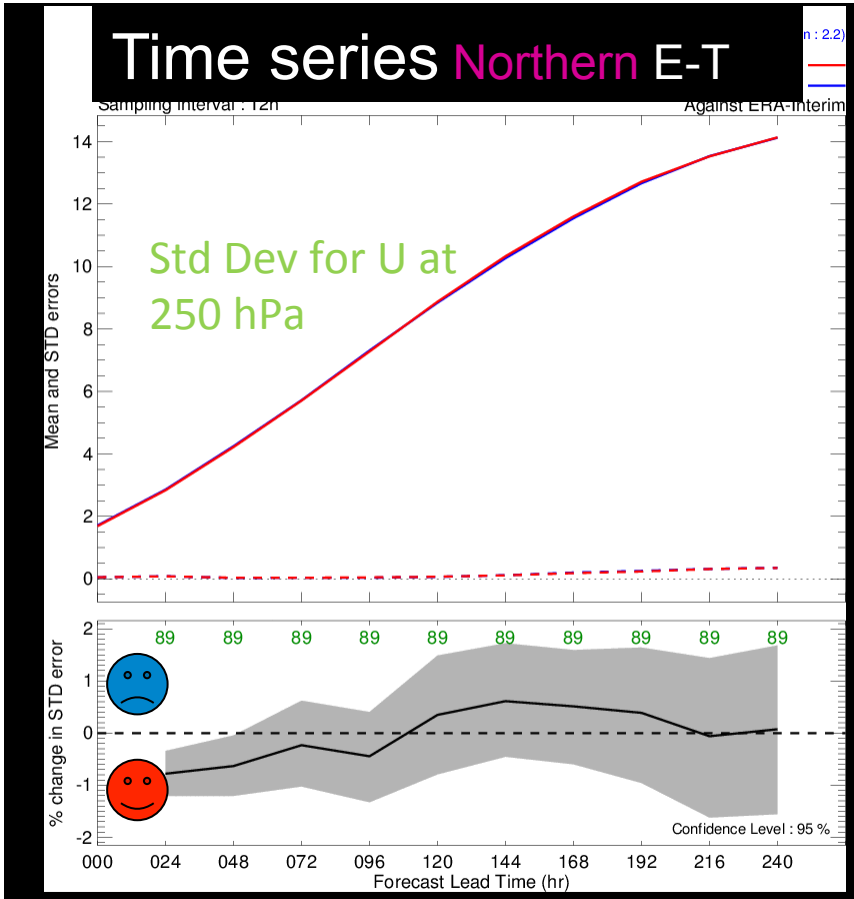
- 2 new 1.5-month trialling (June-July 2014) with a single localization approach (still using 3DEnVar with 100% B_{ens})

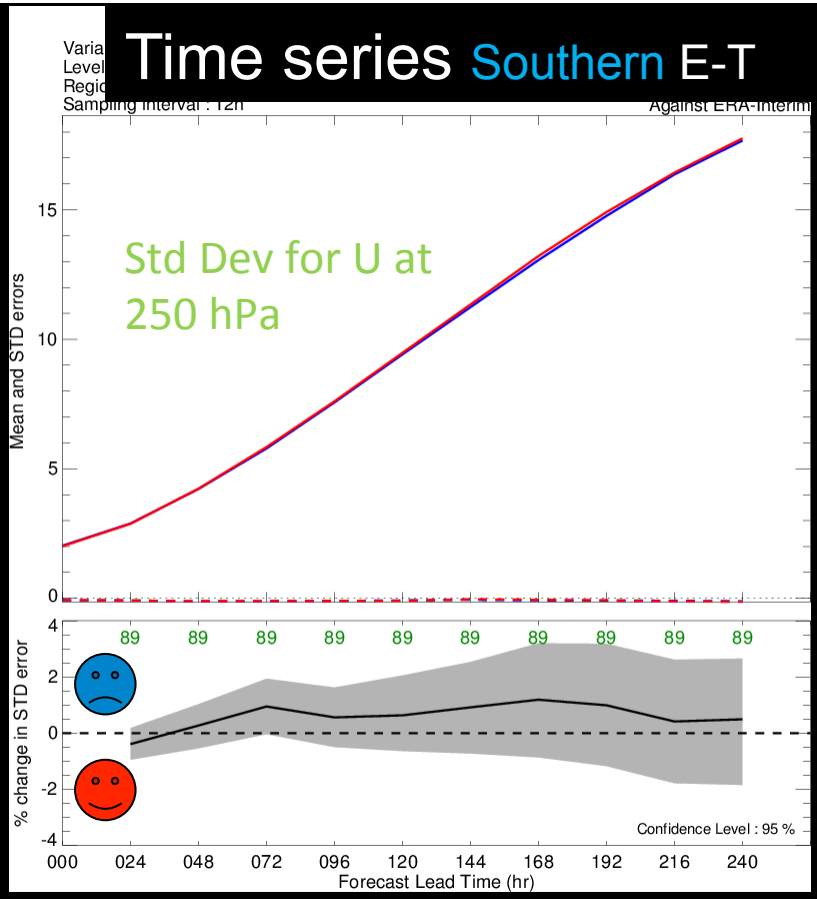
  1) hLoc = 2400 km (the value used for medium scale in SD hLoc)

  2) hLoc = 3300 km (the value used for large scale in SD hLoc)

Scale-dependent covariance localization

Forecast impact





- Control (hLoc = 2800 km)
- hLoc = 2400 km

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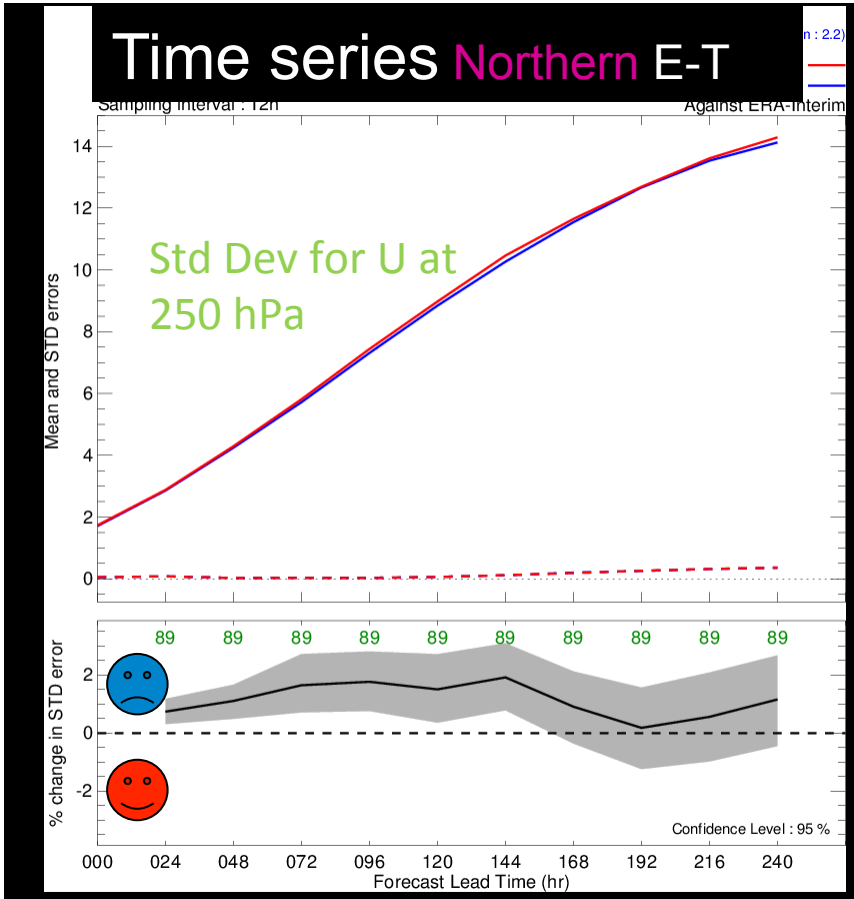
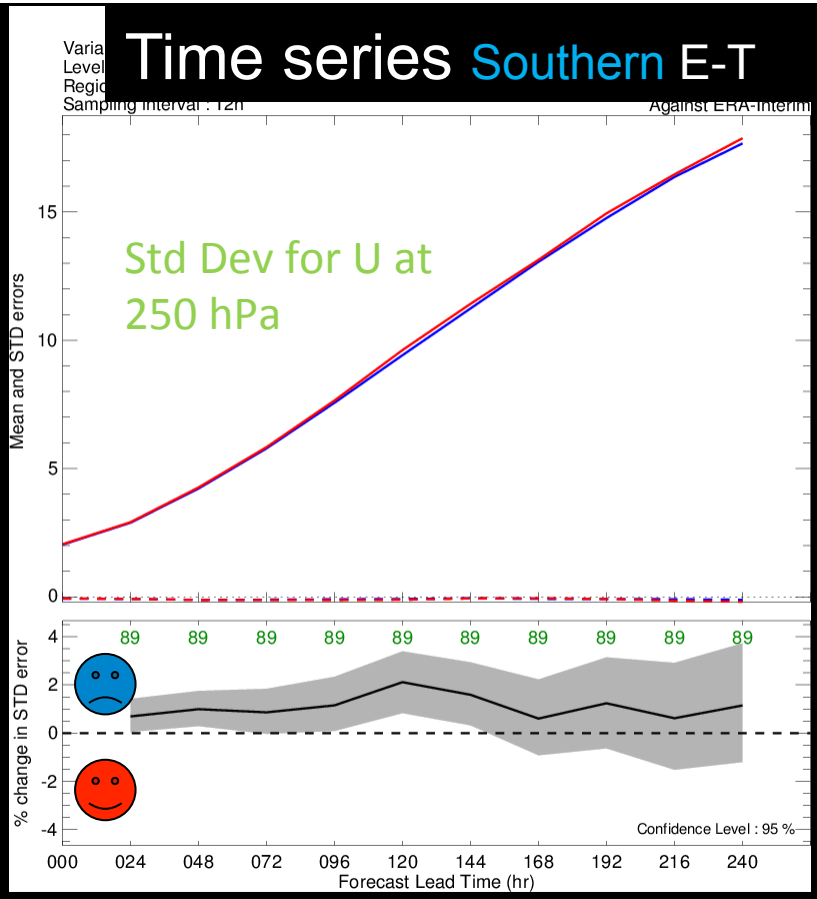
Scale-dependent covariance localization

Forecast impact





- Control (hLoc = 2800 km)
- hLoc = 3300 km

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Scale-dependent covariance localization

Impact on dynamical balance – Rotational Part

It is well know that localization can disrupt the dynamical balance of the analysis increments.

Does the SDL increase or decrease this problem?

Balance diagnostics as in Caron and Fillion (2010; MWR)

- Rotational part: Charney's (1955) nonlinear balance equation

$$\nabla^2\Phi' = f\zeta' + 2\left[\left(\frac{\partial\bar{u}_r}{\partial x}\frac{\partial v'_r}{\partial y} - \frac{\partial\bar{u}_r}{\partial y}\frac{\partial v'_r}{\partial x}\right) + \left(\frac{\partial u'_r}{\partial x}\frac{\partial\bar{v}_r}{\partial y} - \frac{\partial u'_r}{\partial y}\frac{\partial\bar{v}_r}{\partial x}\right) + \left(\frac{\partial u'_r}{\partial x}\frac{\partial v'_r}{\partial y} - \frac{\partial u'_r}{\partial y}\frac{\partial v'_r}{\partial x}\right)\right] - \frac{\partial f}{\partial y}u'_r$$

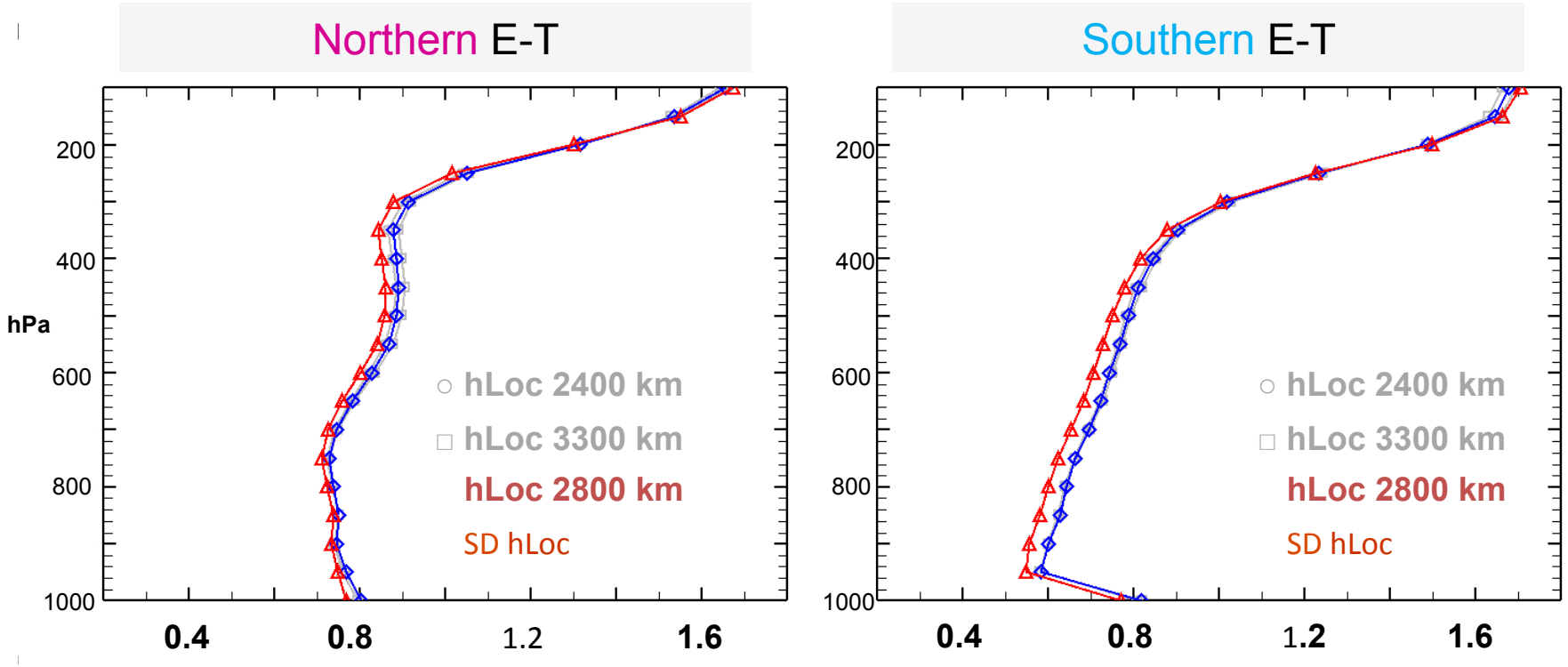
Mass Wind

One conclusion from Caron and Fillion: Both horizontal and vertical localization have significant deleterious effect on the rotational balance with the largest detrimental impact coming from the vertical localization.

Scale-dependent covariance localization

Impact on dynamical balance – Rotational Part

Vertical profile of average normalized departure from (n-l) balance



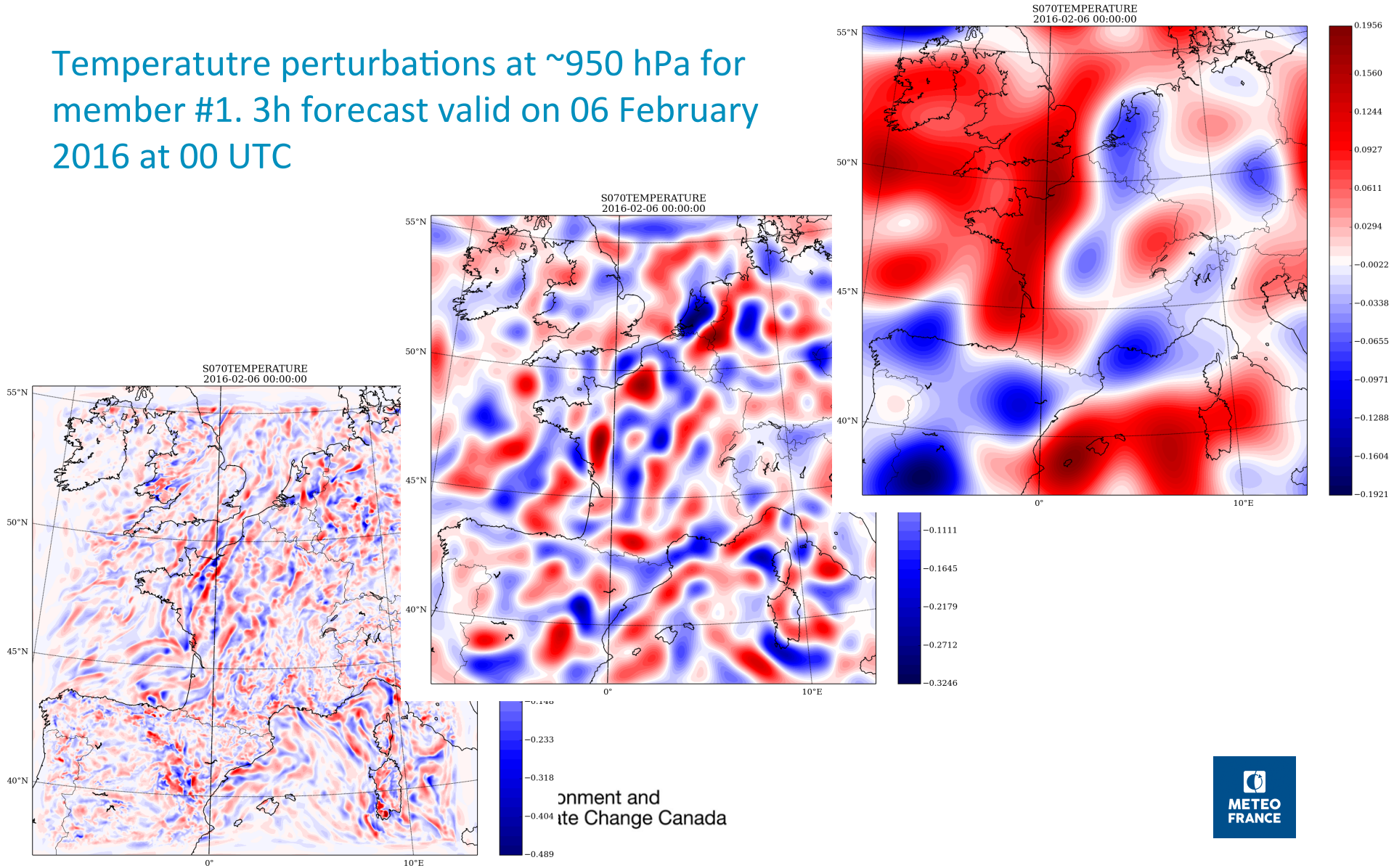
Application in a convective-scale EnVar system:

Meteo-France's AROME R&D version

- 25 ensemble member @ 3.8km
- Localization in spectral or gridpoint space
- Determinitic forecast @ 3.8 km

(Adhoc) scale-decomposition for AROME

Temperatutre perturbations at ~950 hPa for member #1. 3h forecast valid on 06 February 2016 at 00 UTC



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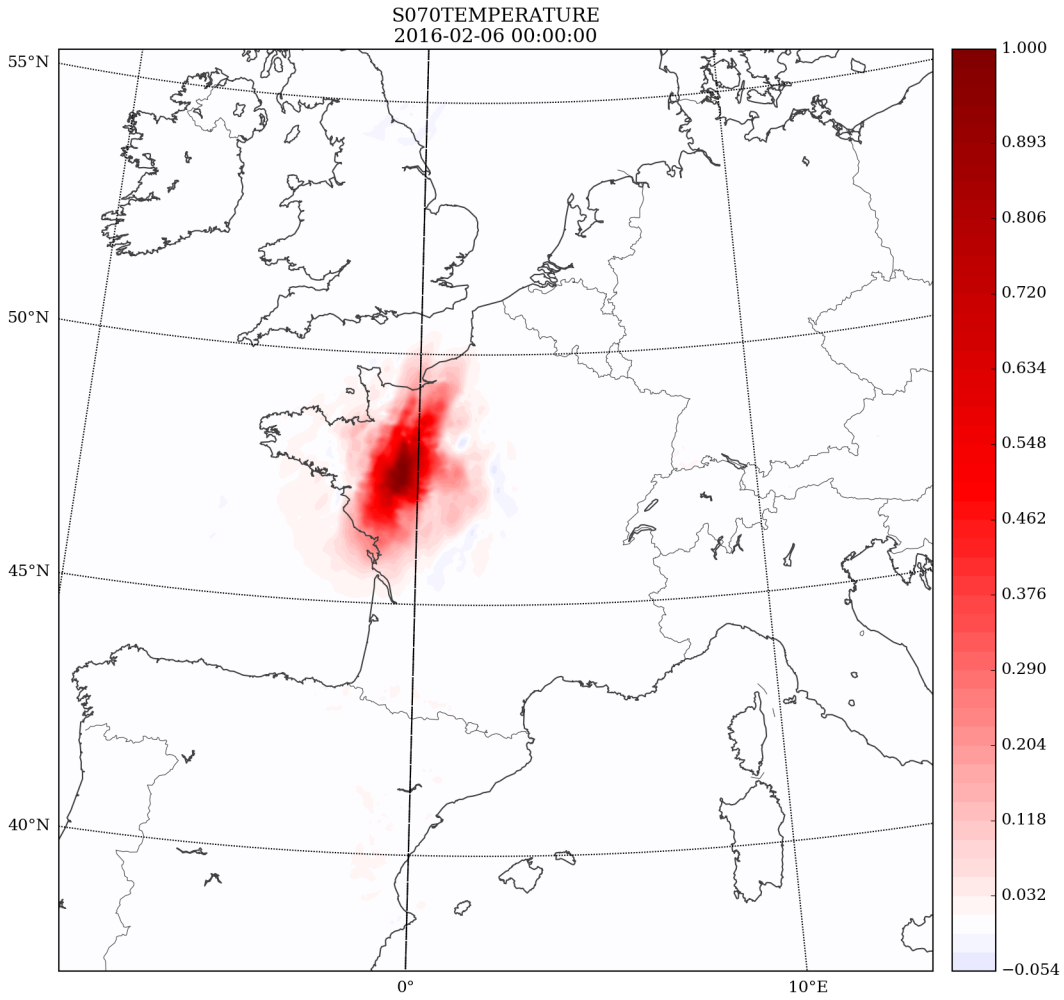
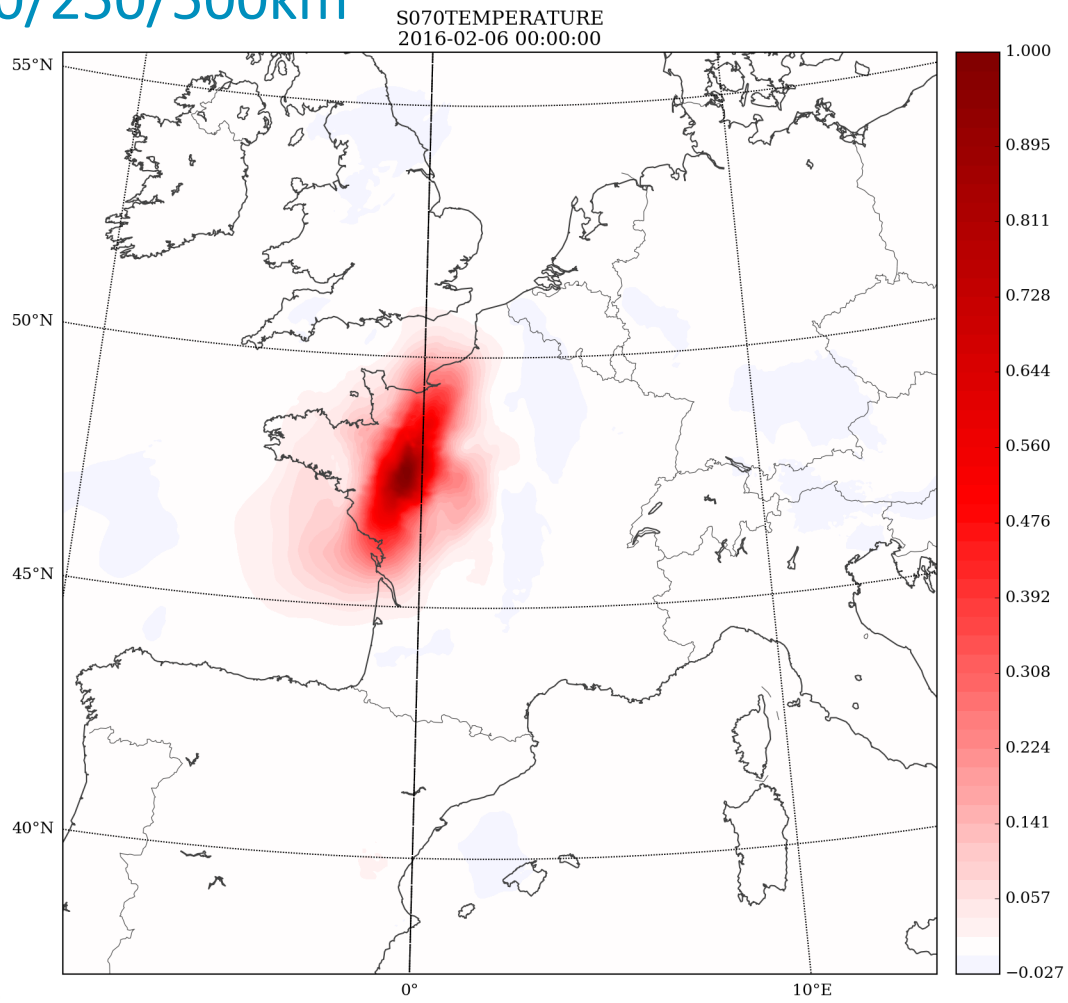
Pseudo-single obs - Frontal case

SP 250km



Pseudo-single obs - Frontal case

SP-SDL 080/250/500km



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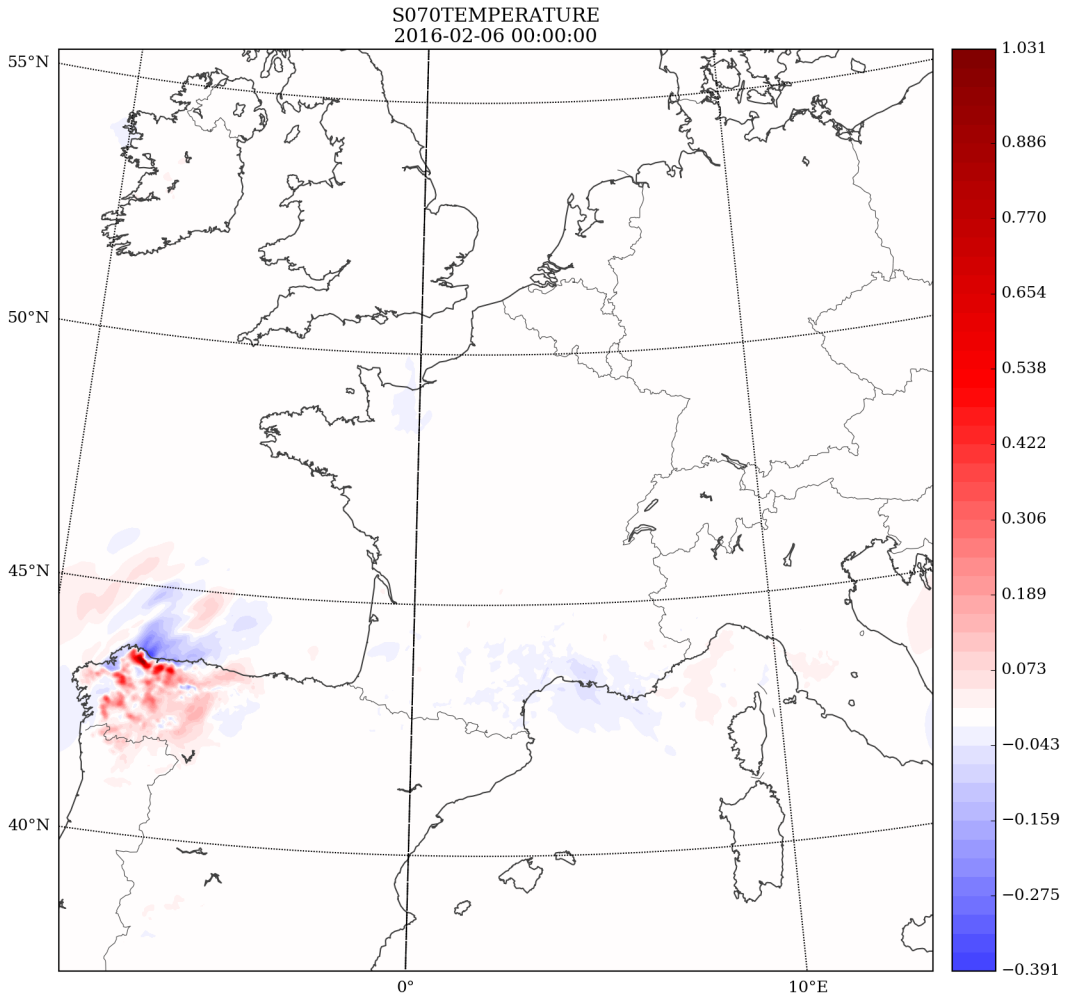
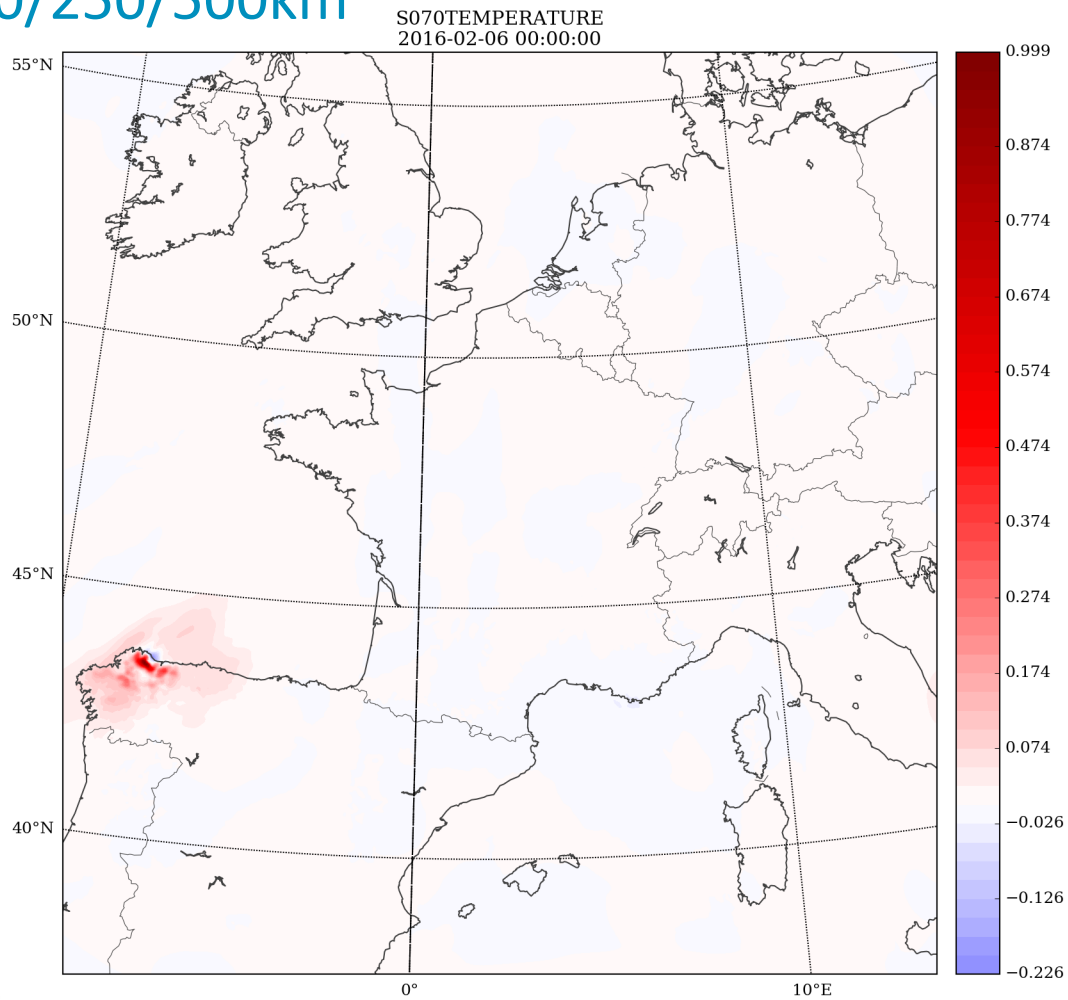
Pseudo-single obs - Convective case

SP 250km



Pseudo-single obs - Convective case

SP-SDL 080/250/500km



Performed DA and forecast cycles

- 2 weeks trialling (February 2016) were used testing many horizontal localization lengtscale for both SDL and ‘one-size-fits-all’ approaches.
- Extension to 1 month for both the control experiment and the best performing SDL configurations
- Spectral and gridpoint (recursive fitler) localization were used/compared.
- The same horizontal-scale decomposition (3 wave band) was used in all the SDL experiments.
- 3-hourly DA cycle
- 30-hour forecasts issued from 00, 06, 12 and18 UTC

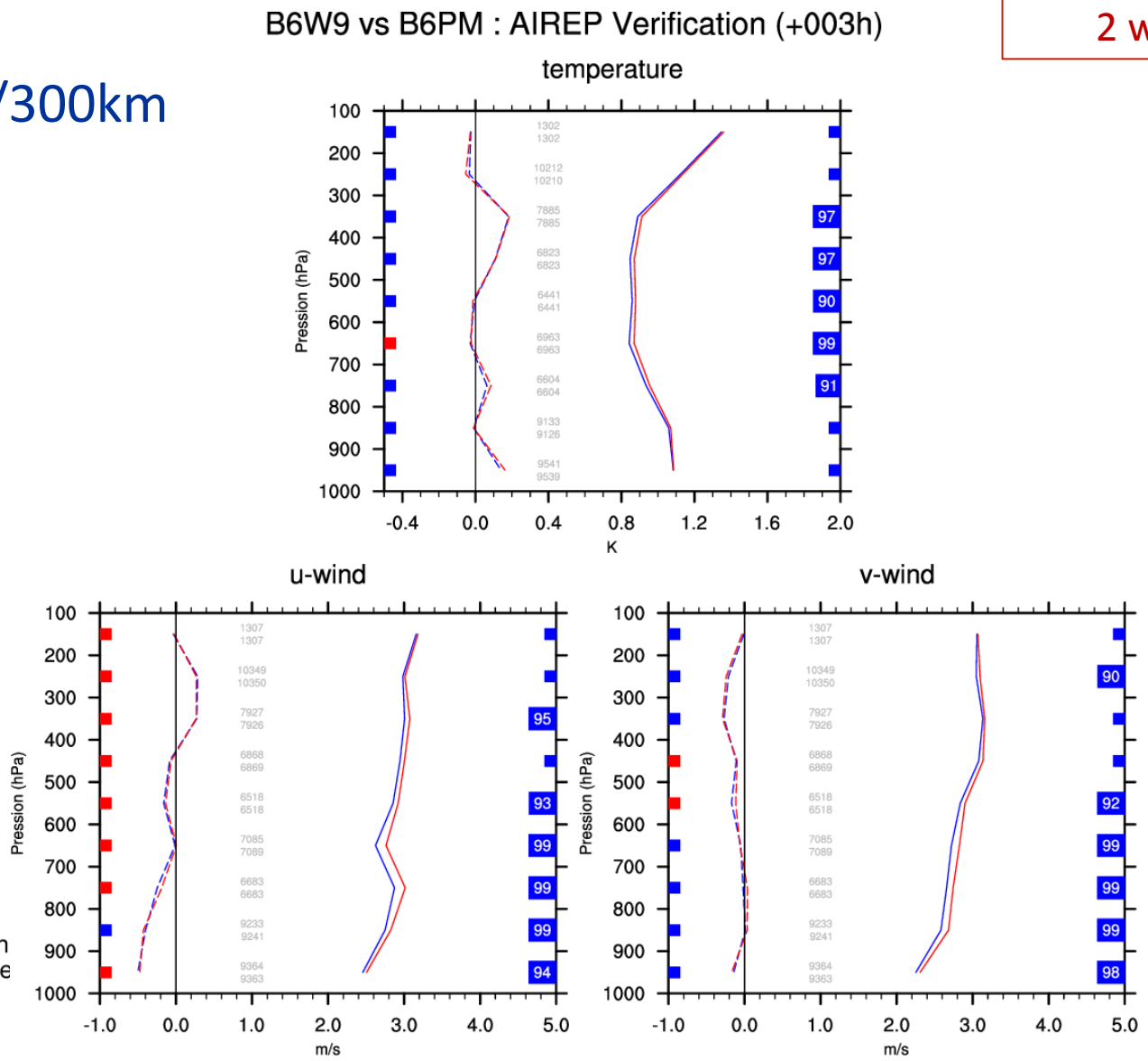
Verification against aircraft

2 weeks

SP 075/150/300km

vs

SP 250km



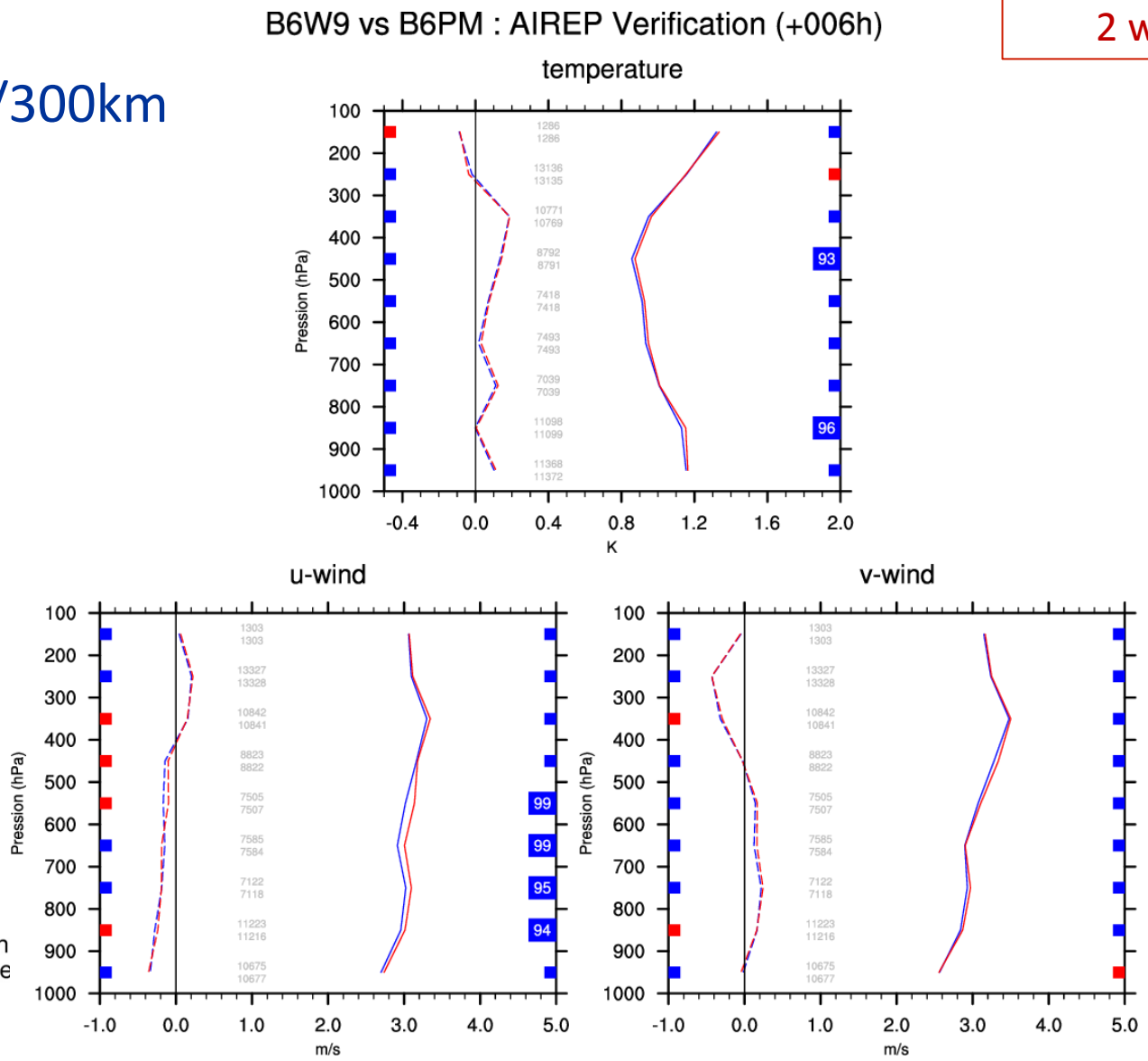
Verification against aircraft

2 weeks

SP 075/150/300km

vs

SP 250km



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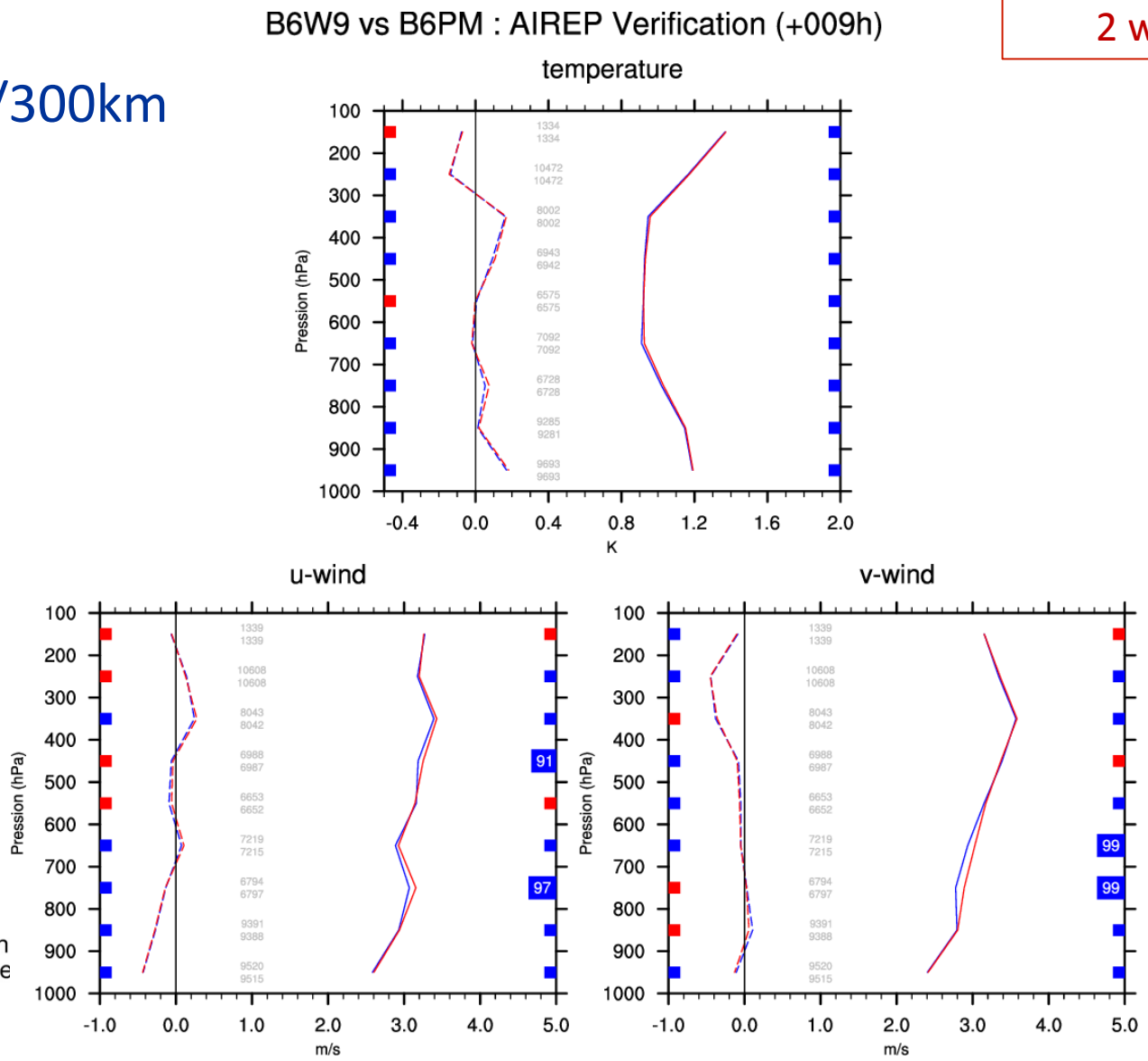
Verification against aircraft

2 weeks

SP 075/150/300km

vs

SP 250km



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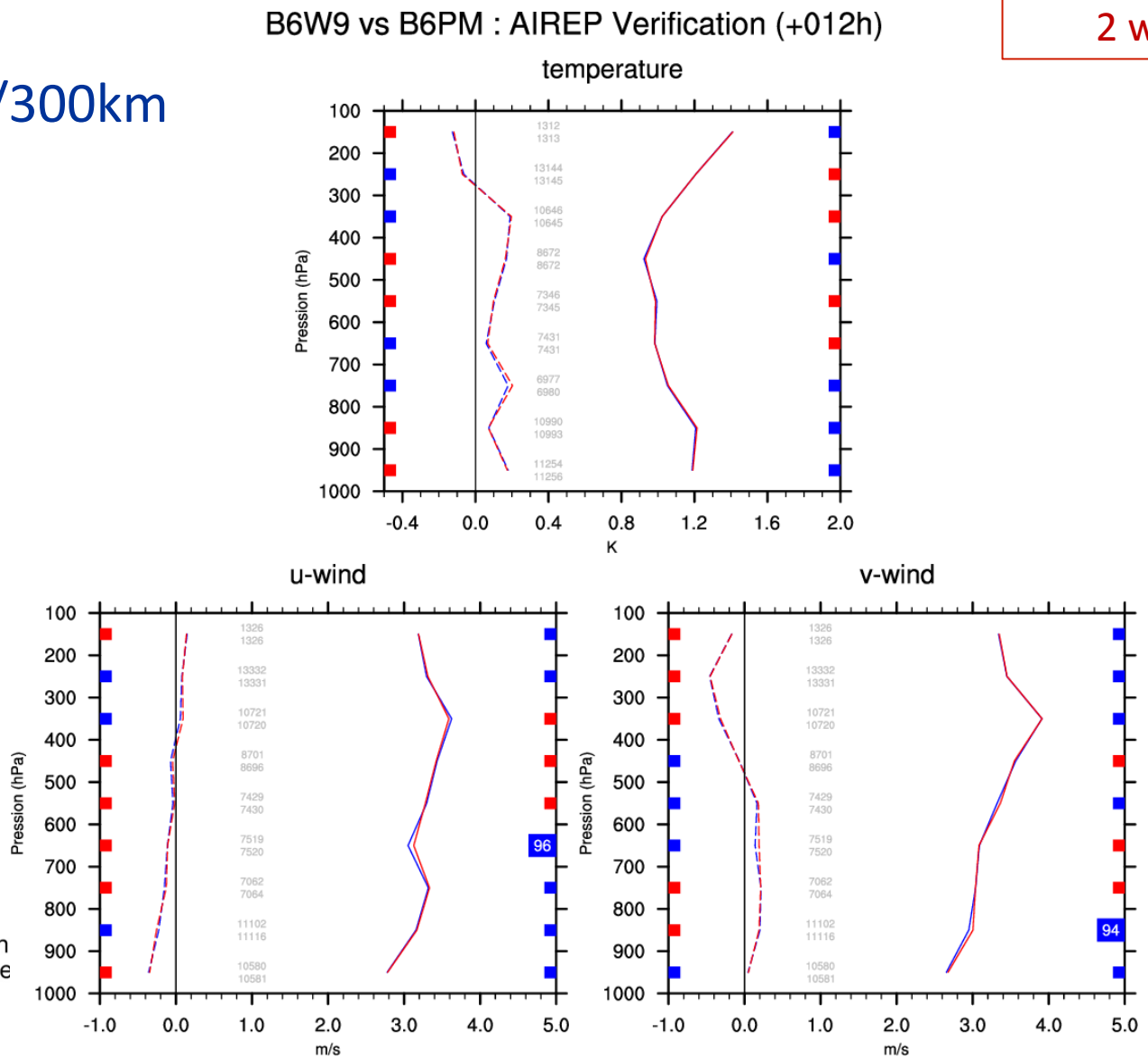
Verification against aircraft

2 weeks

SP 075/150/300km

vs

SP 250km



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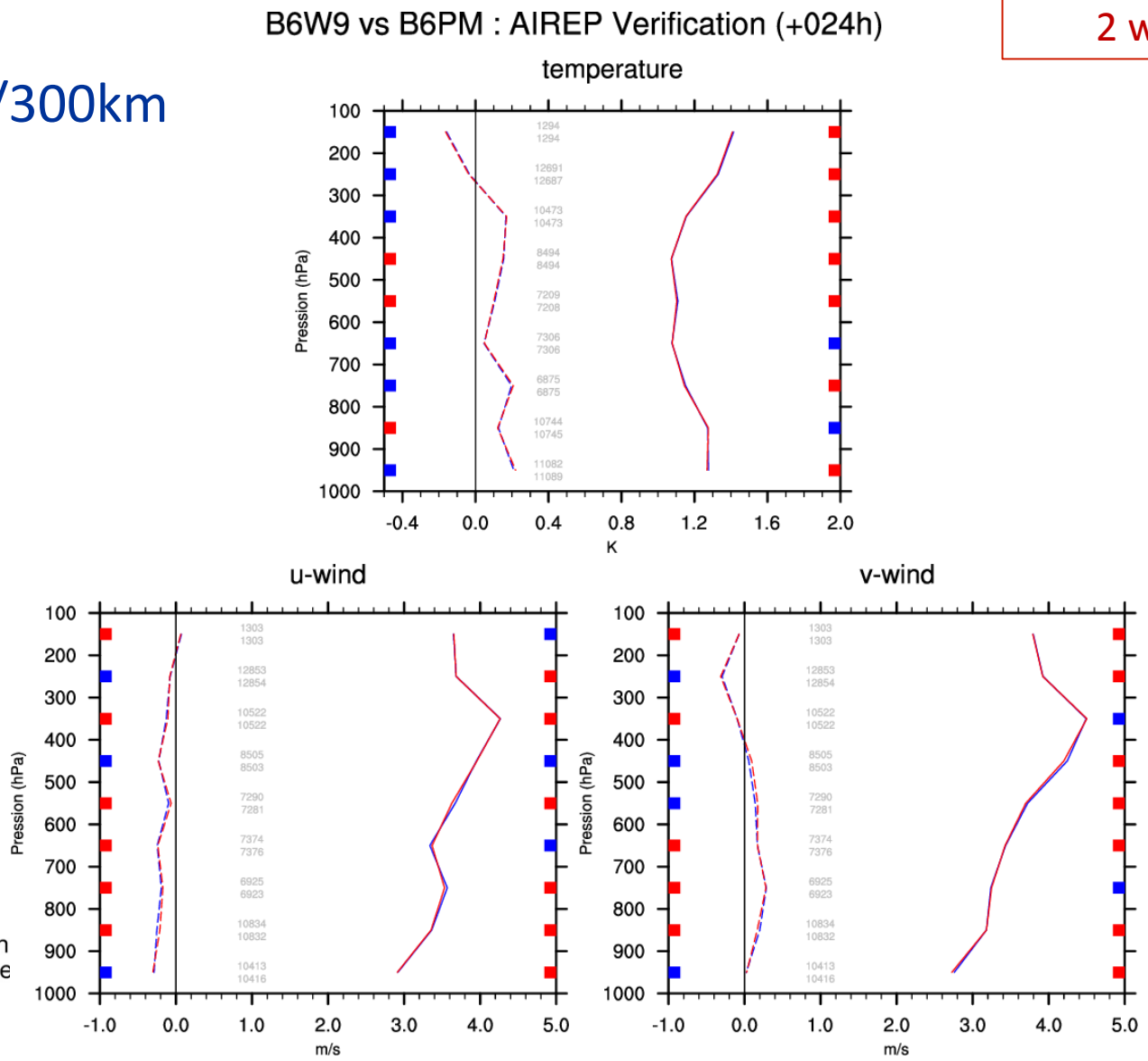
Verification against aircraft

2 weeks

SP 075/150/300km

vs

SP 250km



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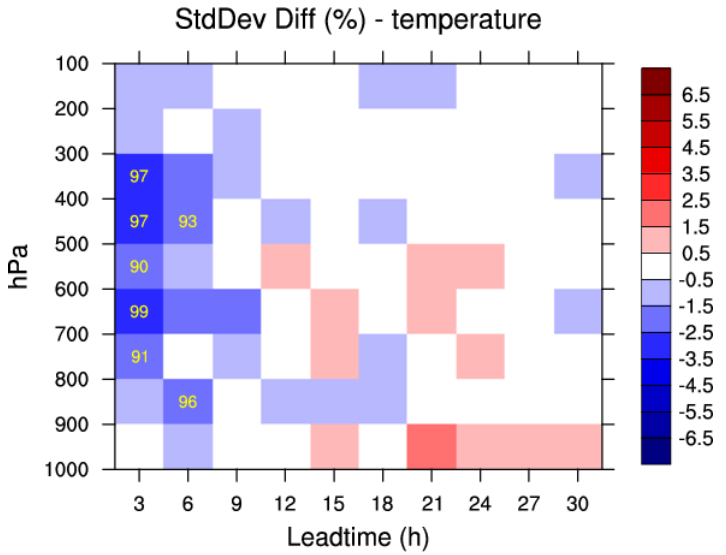
Verification against aircraft(+3 to +30h, 3h)

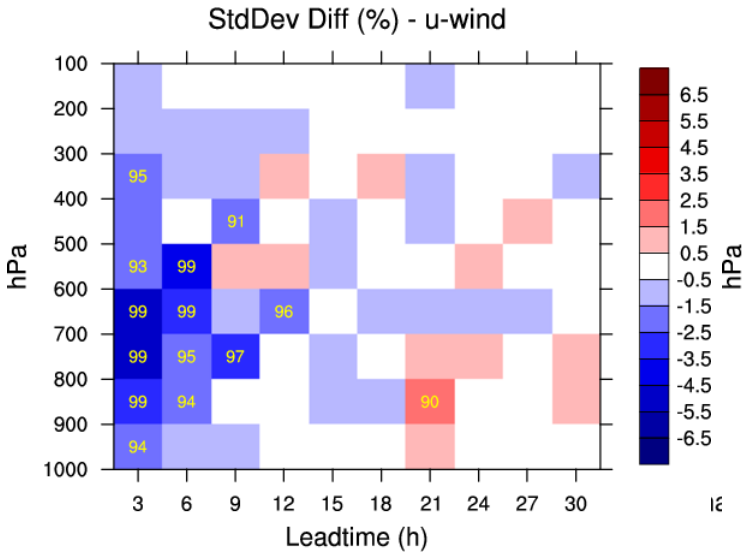
SP 075/150/300km

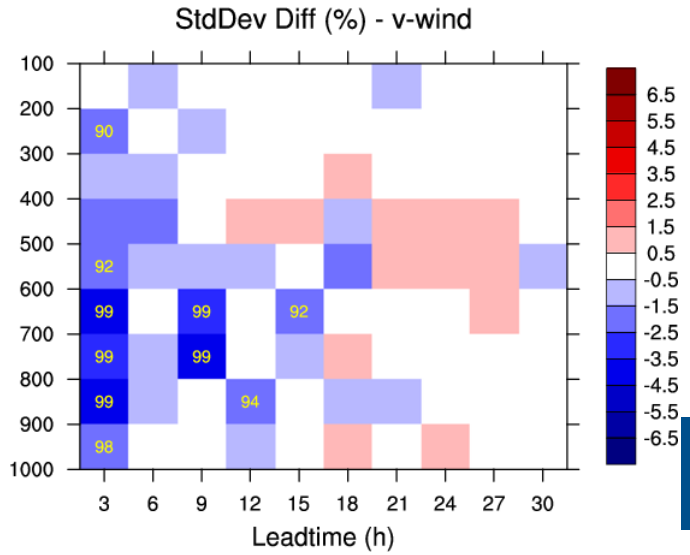
vs

SP 250km

2 weeks







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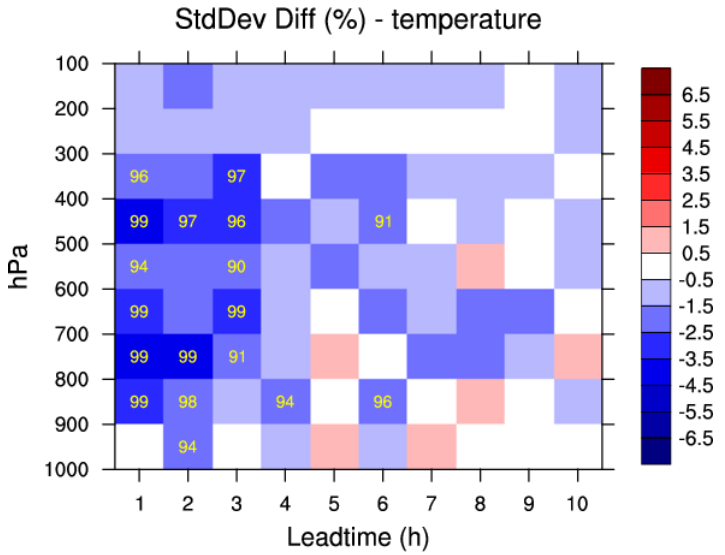
Verification against aircraft (+1 to +10h, 1h)

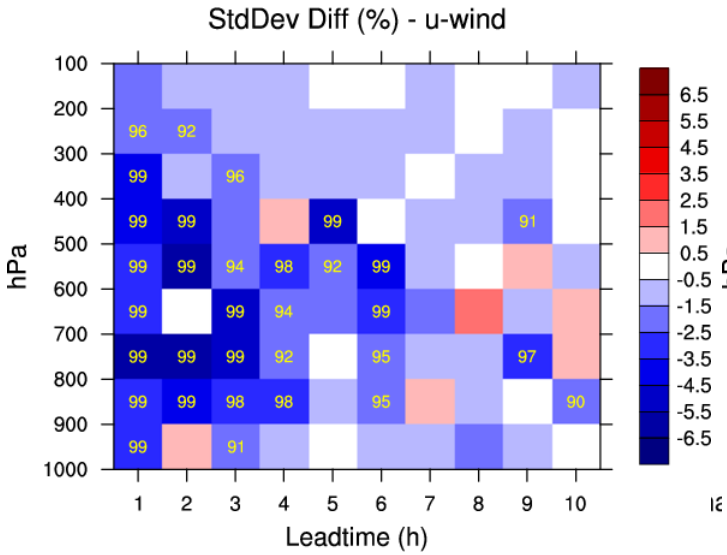
2 weeks

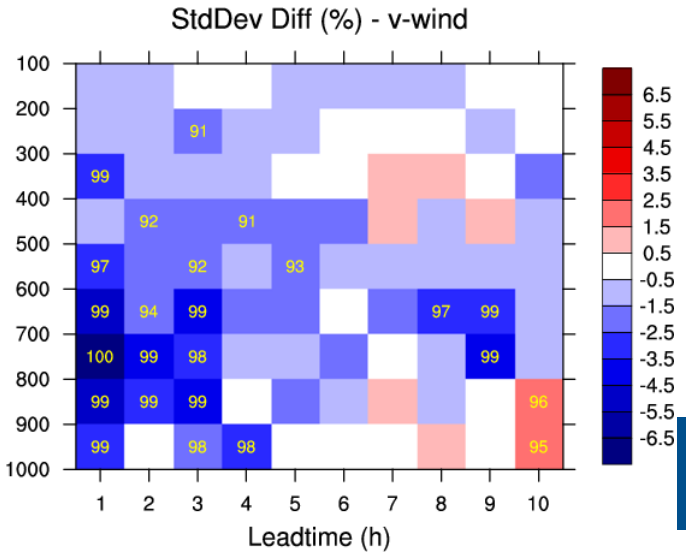
SP 075/150/300km

vs

SP 250km







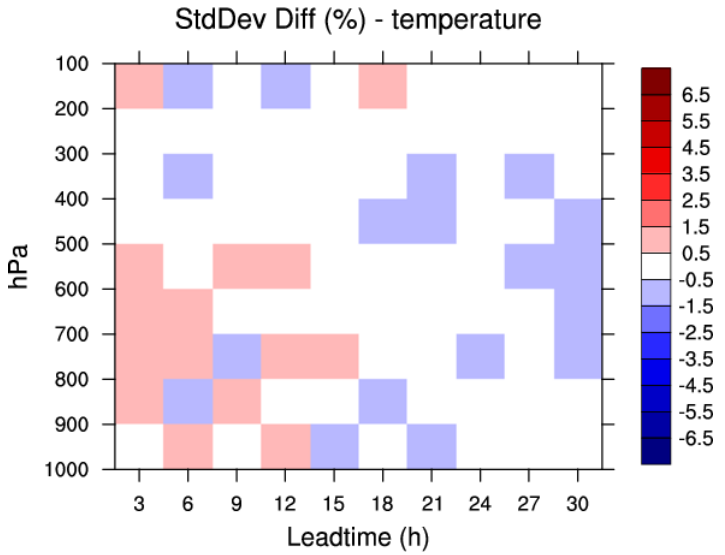
Verification against aircraft (+3 to +30h, 3h)

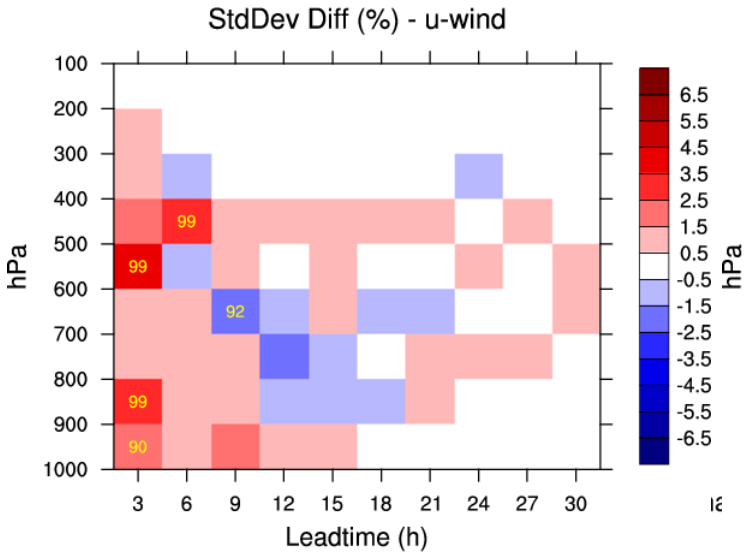
2 weeks

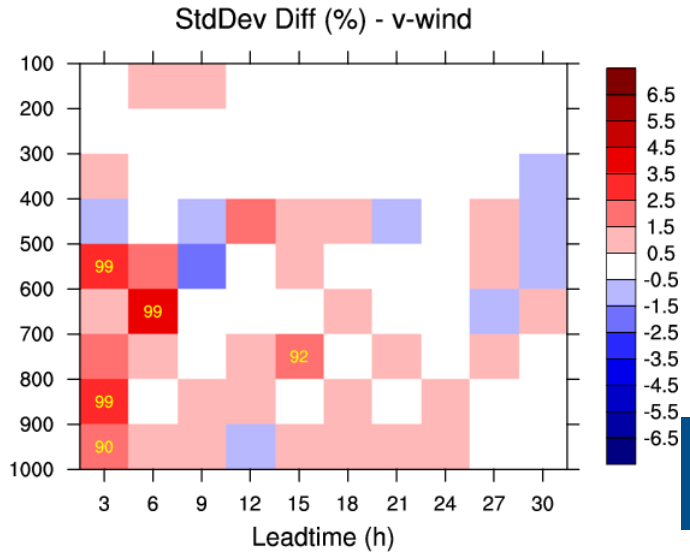
SP 300km

vs

SP 250km







METEO FRANCE

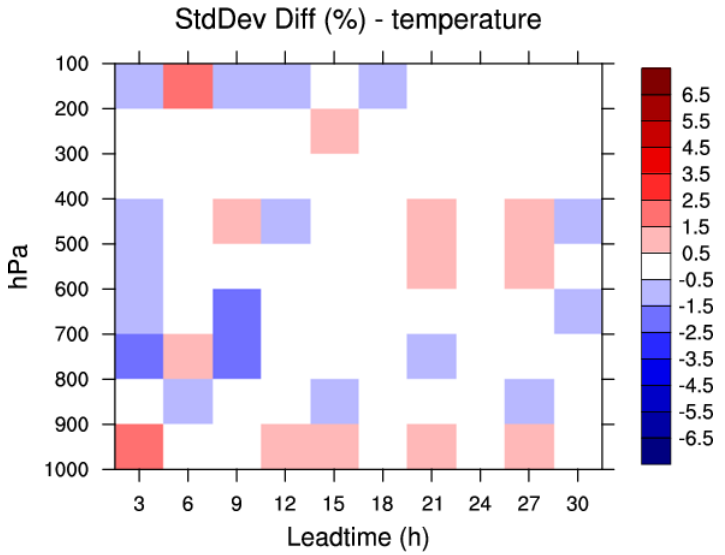
Verification against aircraft (+3 to +30h, 3h)

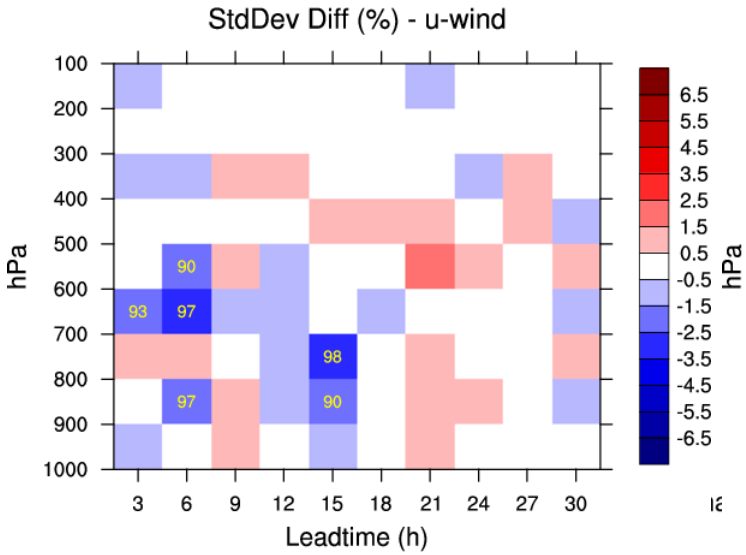
SP 200km

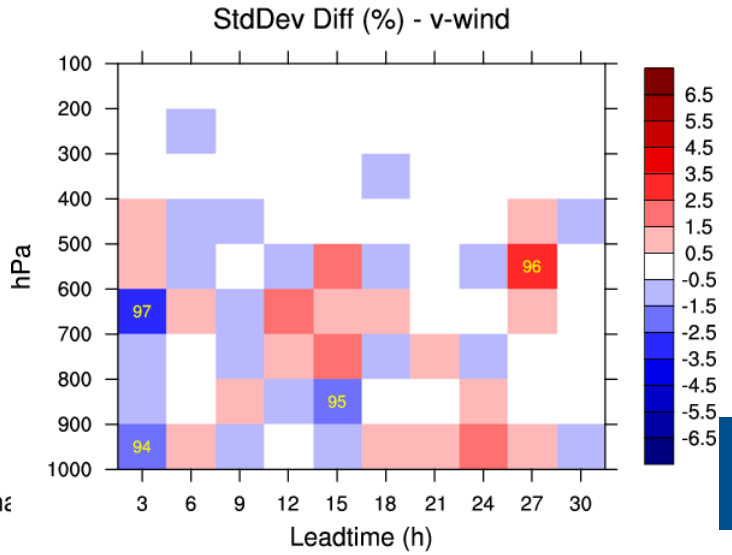
vs

SP 250km

2 weeks







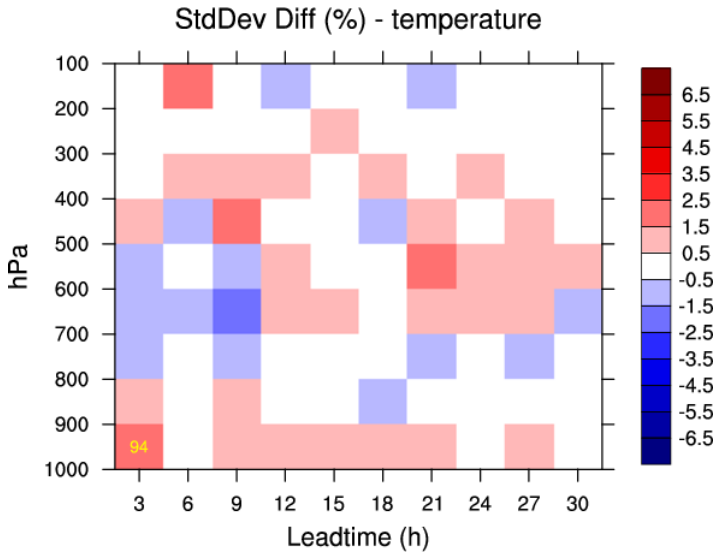
Verification against aircraft (+3 to +30h, 3h)

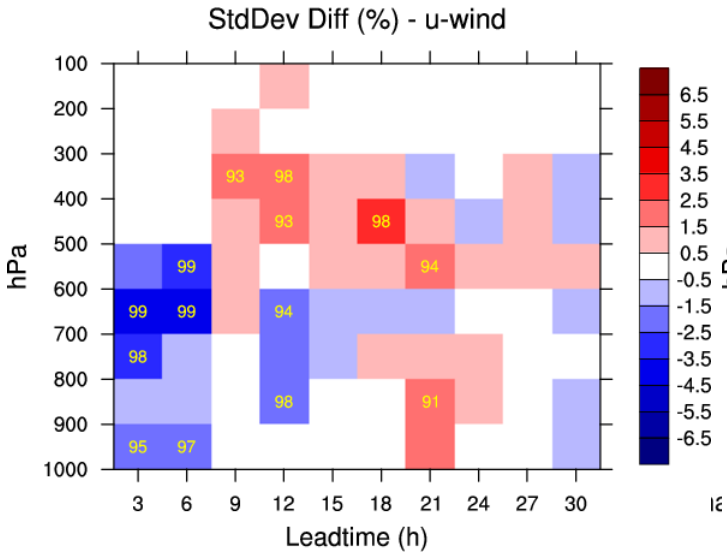
2 weeks

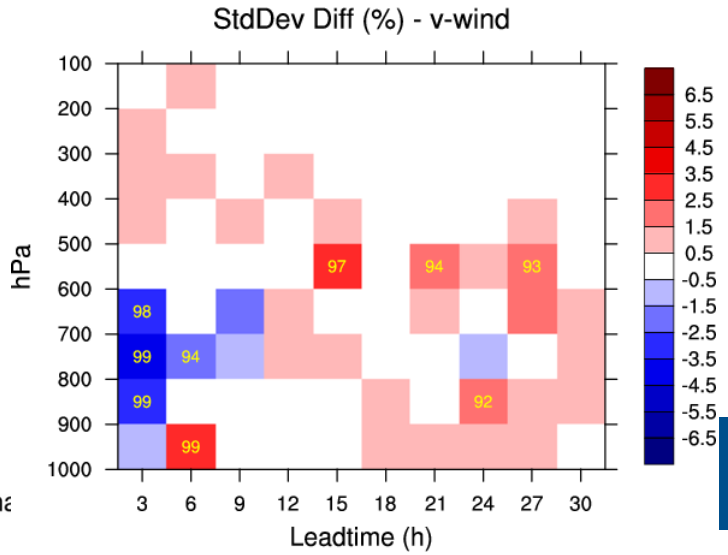
SP 150km

vs

SP 250km







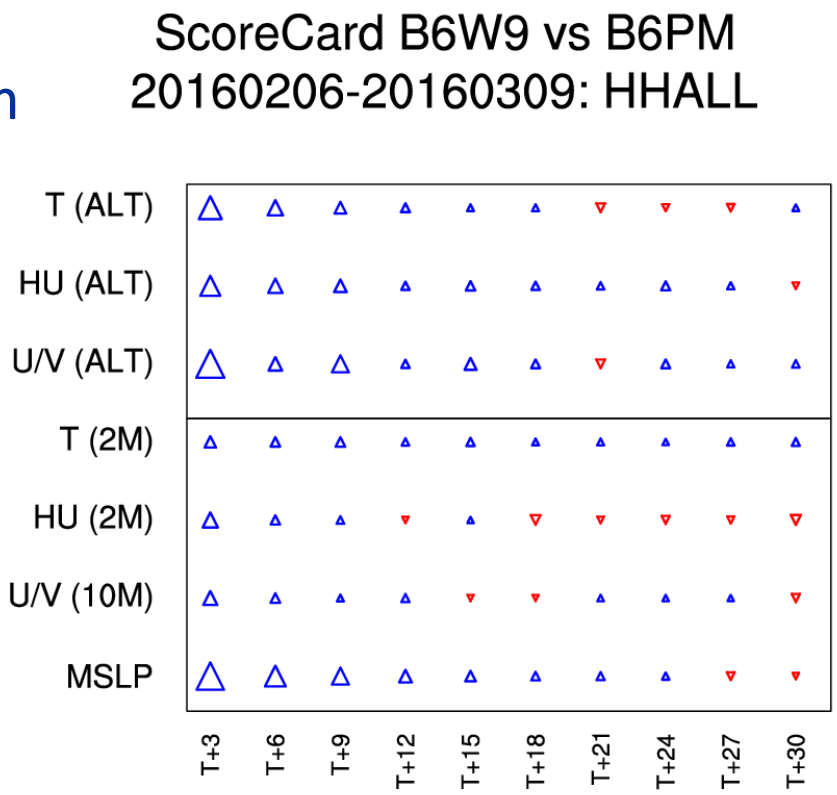
Full verification (+3 to +30h, 3h)

1 month

SP 075/150/300km

vs

SP 250km



Environn
Changen

METEO FRANCE

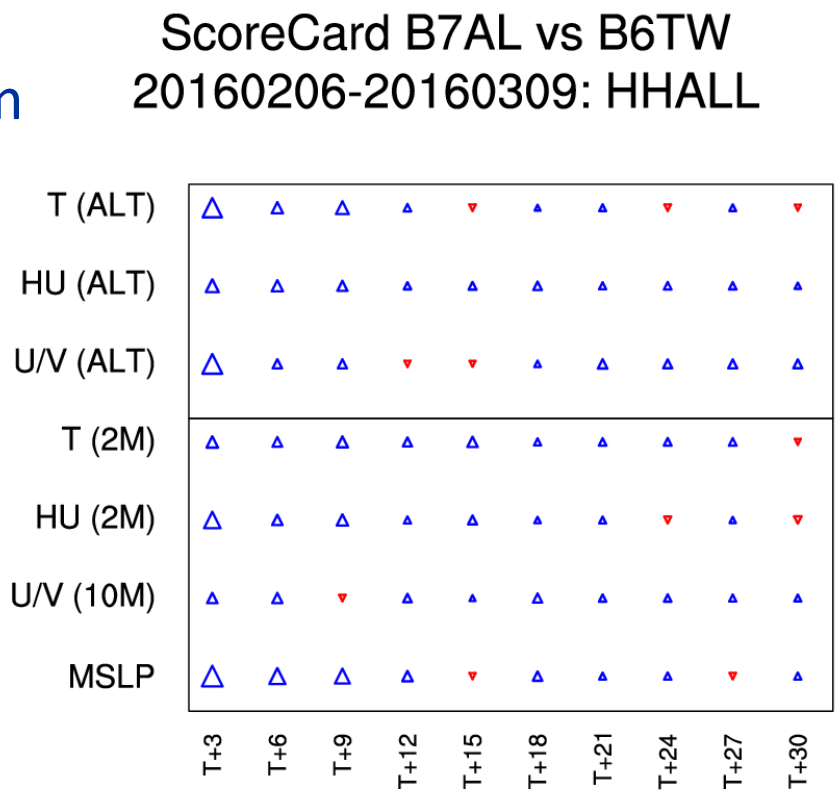
Full verification (+3 to +30h, 3h)

1 month

RF 075/150/300km

vs

RF 250km



Environn
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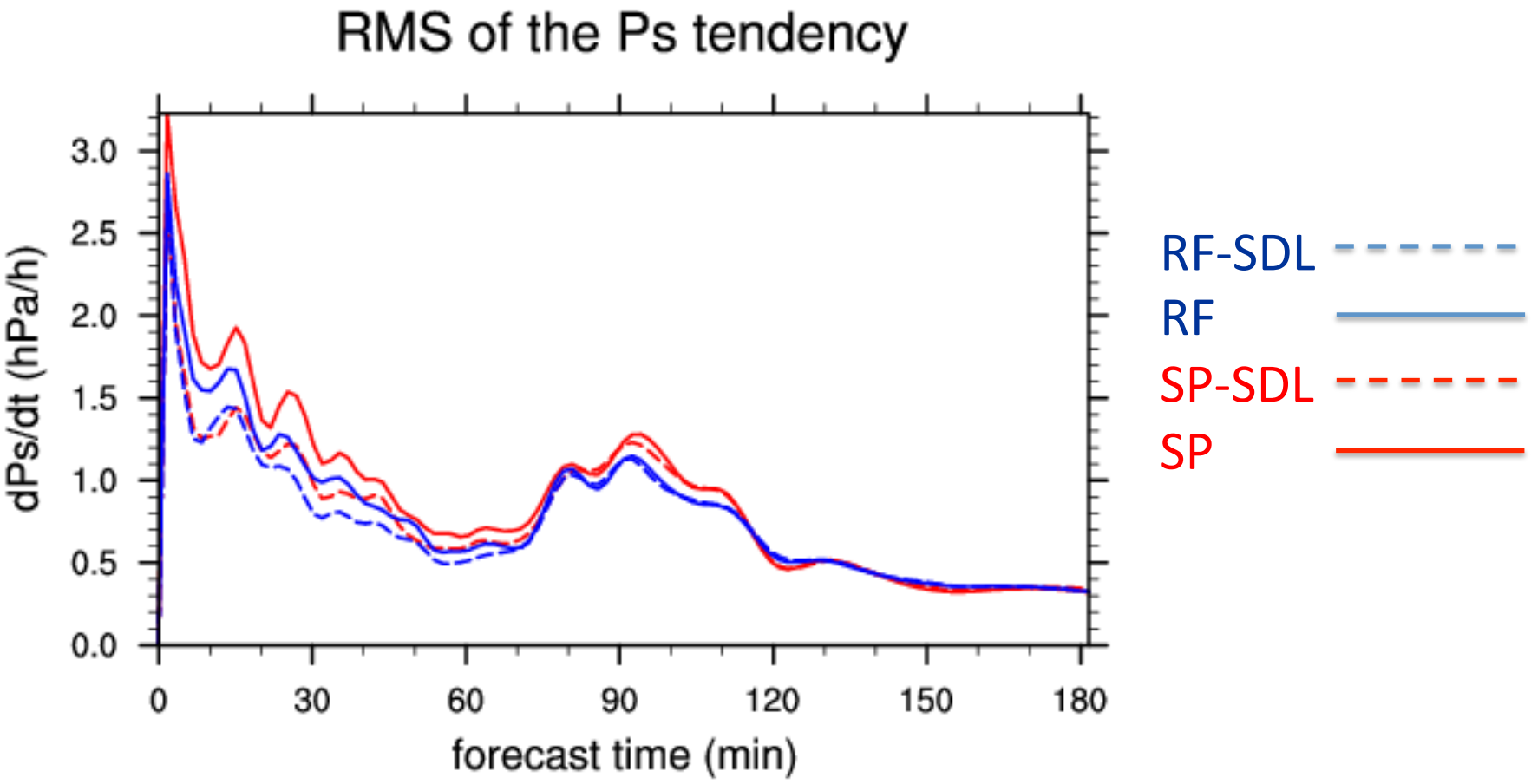
METEO FRANCE

Impact on balance



Summary and conclusion

- SDL is feasible and straightforward to implement in EnVar, but more expensive than using single-scale localization.
  - In the SDL experiments reported here: 3x to 3.5x more expensive

- Results using a horizontal-scale-dependent horizontal localization indicate small forecast improvements in both systems examined. However, the time-scales over which the SDL method impacted the forecasts are completely different:
  - Improvements up to day 5 were noticed in the global system,
  - In the convective-scale system, they were limited mostly in the first 9 hours of the forecasts

- In terms of dynamical balance, SDL seems to alleviate somewhat the imbalance generated by the localization.

- Finding the optimal SDL setup is not straightforward.
  - No objective approach has been found useful so far.