Soft Re-Centred Ensemble of Data Assimilations

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Current EDA and Motivation for Soft Re-Centred EDA

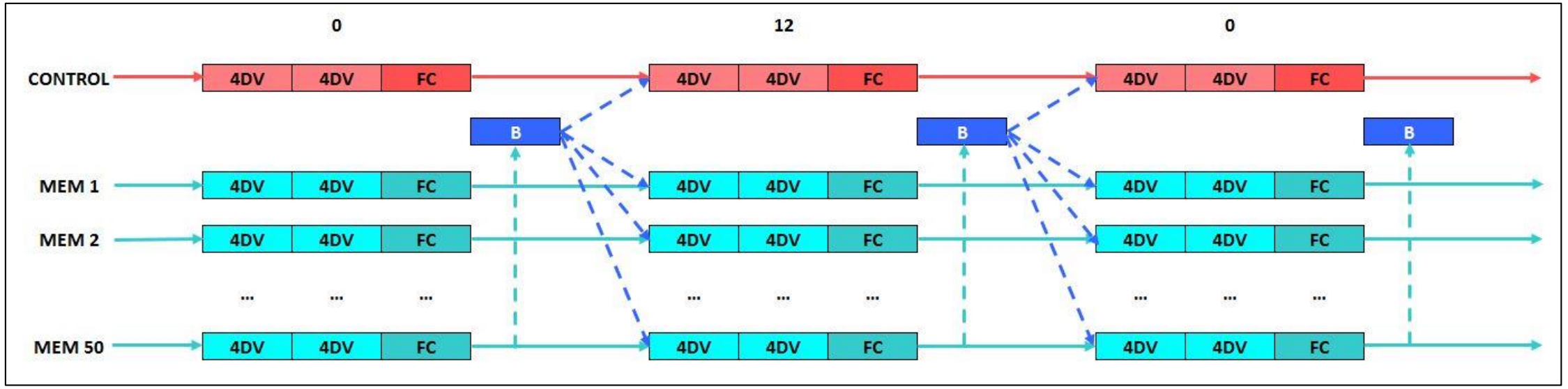
The EDA development is guided by two goals:

- **Provide better B to the 4D-Var analysis, which is a main driver of both deterministic and ensemble forecast skill.** Current EDA has 18km/104km outer/inner loop resolution, which is not enough to support our development of next generation higher resolution 4D-Var.
- **Converge towards a direct initialization of the Ensemble forecasts from reliable EDA members without need of additional inflation.** Current pure EDA forecast skill is insufficient for this because of large performance gap between EDA mean analysis and the higher resolution deterministic 4D-Var (due lower resolution, fewer outer loops and not including most up to date observations at the time of the ensemble forecast).
- We zig-zag towards this ideal, improving in one direction while not degrading progress already achieved in other directions.

Soft Re-Centring is our latest development towards these goals

- **Resolution increase of the EDA to 9km resolution,** equalling the deterministic high resolution analysis and ensemble prediction, would bring us closer towards addressing these issues.
- To achieve this on our current computer it **is necessary to increase the computational efficiency of the EDA**, and this **has led us to the Soft Re-Centred formulation**, which enabled us to move from 18km to 9km EDA at x2.7 in cost, which is within the envelope of cost increases planned on our current computer.
- **The TCo1279/9km soft Re-Centred EDA will become operational in 2024.**

Standard EDA: Pert Members and Control Independent 4D-Var's (common VarBC from Control, **B** from Pert Members)



- Looking at the EDA, reducing 4D-Var minimizations/OL from 2 to 1 is a candidate for efficiency gains.
- But we have 2 OL for a reason, it improves mean ensemble analysis error and gives better chance to extract info from nonlinear observations, improving the error spread estimate.
- Key for performance of the 2OL EDA is improved first guess in the 2nd OL that is closer to observations.
- Can we maintain this quality in 1OL EDA by providing improved first guess to the minimization using background and/or early assimilation outputs from the control member?

Use Control to Speed-Up/Improve Perturbed Members Established Idea!

Previous work	At ECMWF
Desroziers and Berre (2012) suggest use pre-conditioning vectors from the unperturbed control member to speed up convergence of the perturbed members minimizations.	Iterations reduced 25% in EDA 1st minimization. Used in ECMWF operational EDA since 2019, enabled together with other optimizations the move to 50-member EDA at same cost and identical configuration per member as previous 25-member EDA, a 50% saving.
Desroziers and Berre (2012) also suggest use control member to get more accurate starting point for the perturbed minimizations.	Used in current work on soft re-centred EDA.
Lorenc et al. (2016) mean-perturbation method re-formulates members' minimizations as perturbations on top of a mean solution, enabling simplified handling.	Use 'spirit' of this approach without simplifying the EDA formulation: reduce perturbed member's minimizations from 2 to 1, aim for same accuracy and keep cycling full 4D-VAR per member.

Options for Using Control Member Information in Perturbed Members

	Background $x_n'^b$	First-guess $x_n'^{fg}$	Starting control variable $\chi_n^{(0)} = \mathbf{B}^{-1/2}(x_n'^{fg} - x_n'^b)$
(1)	x_n^b	x_n^b	0
(2)	x_n^b	$x_n^b + \delta x_c^{(i)}$	$\chi_c^{(i)}$
(3)	x_n^b	$x_n^b + x_c^b - \bar{x}^b$	$\mathbf{B}^{-1/2}(x_c^b - \bar{x}^b)$, like (7) with less accurate $x_n'^b$
(4)	x_n^b	$x_n^b + x_c^b - \bar{x}^b + \delta x_c^{(i)}$	$\mathbf{B}^{-1/2}(x_c^b - \bar{x}^b + \delta x_c^{(i)})$, like (8) with less accurate $x_n'^b$
(5)	$x_n^b + x_c^b - \bar{x}^b$	x_n^b	$x_n'^{fg}$ less accurate than $x_n'^b$!
(6)	$x_n^b + x_c^b - \bar{x}^b$	$x_n^b + \delta x_c^{(i)}$	$x_n'^{fg}$ less accurate than in (8)
(7)	$x_n^b + x_c^b - \bar{x}^b$	$x_n^b + x_c^b - \bar{x}^b$	0
(8)	$x_n^b + x_c^b - \bar{x}^b$	$x_n^b + x_c^b - \bar{x}^b + \delta x_c^{(i)}$	$\chi_c^{(i)}$

- Perturbed member's background x_n^b and mean of perturbed members' backgrounds $\bar{x}^b$.
- Control member's background x_c^b.
- Control member's i^{th} minimization control variable $\chi_c^{(i)}$ and total increment $\delta x_c^{(i)}$.

Less accurate, not tested

Tested

Best in Test = Soft Re-Centring

Soft Re-Centred EDA: Equations and Interactions

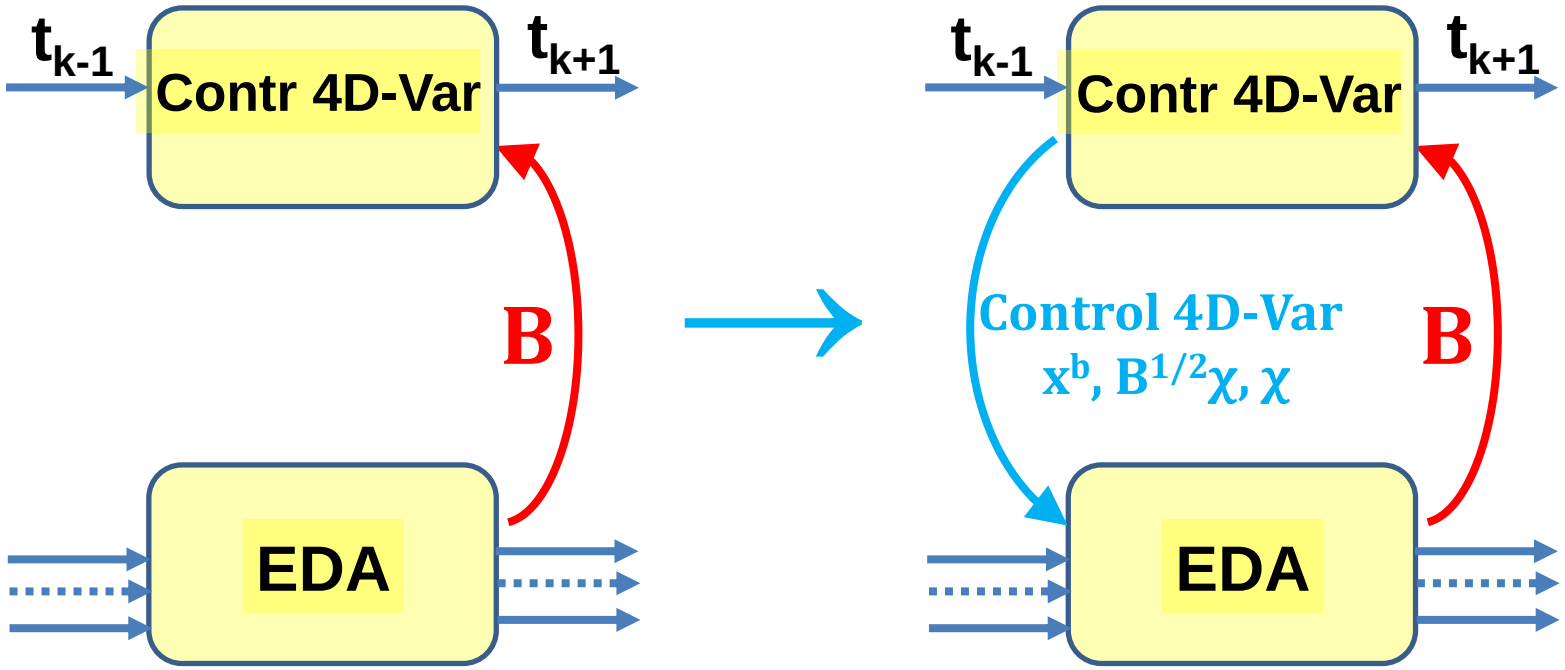
Best test results when perturbed members background was re-centred on control's background and their minimizations started from controls first guess (from first minimization, *i=1*), which in practice is implemented through two additional increments and corresponding control variable:

$$x_n'^b = x_n^b + (x_c^b - \bar{x}^b)$$

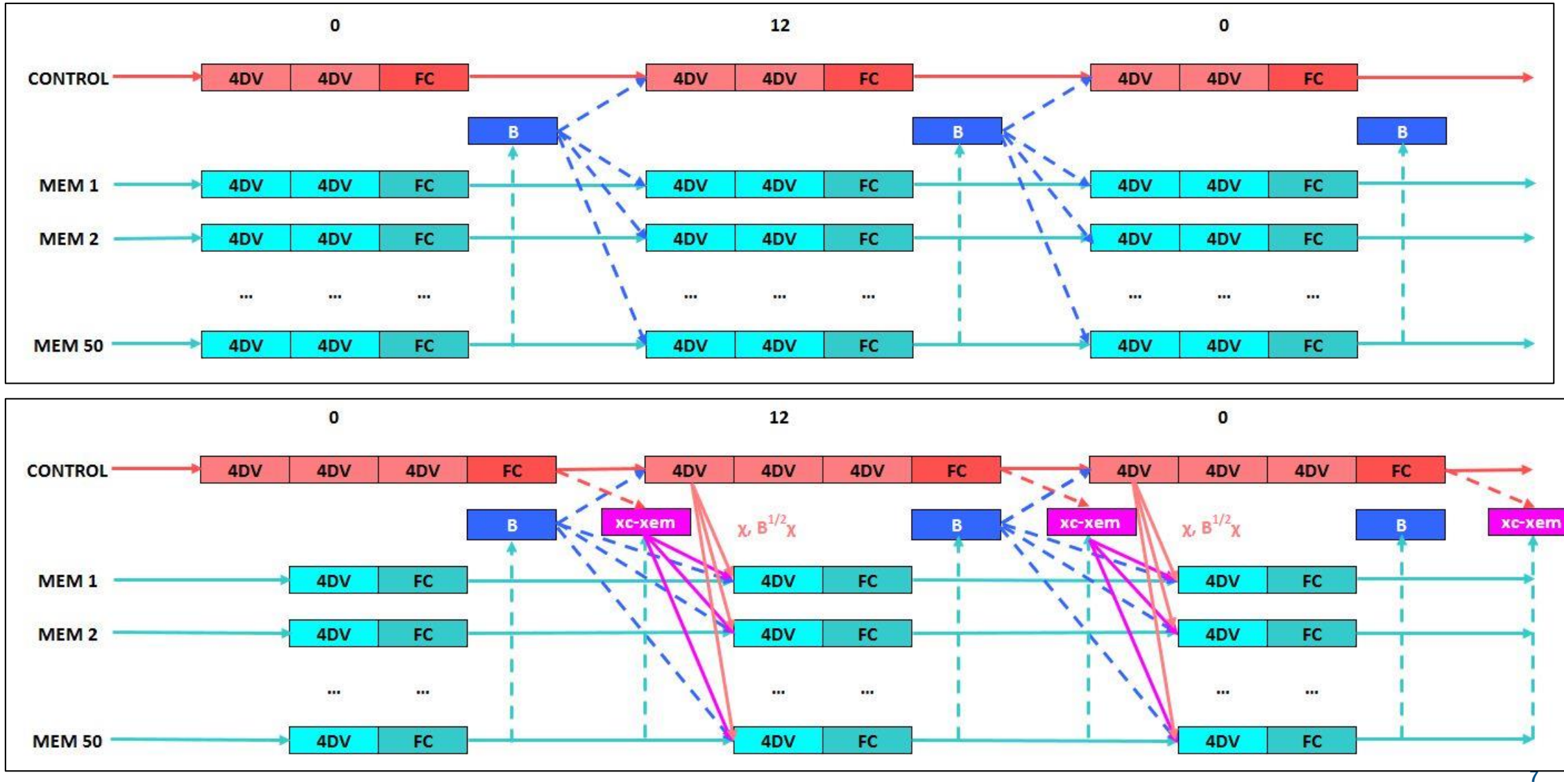
$$x_n'^{fg} = x_n'^b + B^{1/2}\chi_c^{(1)}$$

$$\chi_n^{(0)} = \chi_c^{(1)}$$

Note: We add a constant increment to all perturbed members rather than add 50 perturbations to control. Tested different resolutions of background re-centring increments, 50km as good as full resolution.



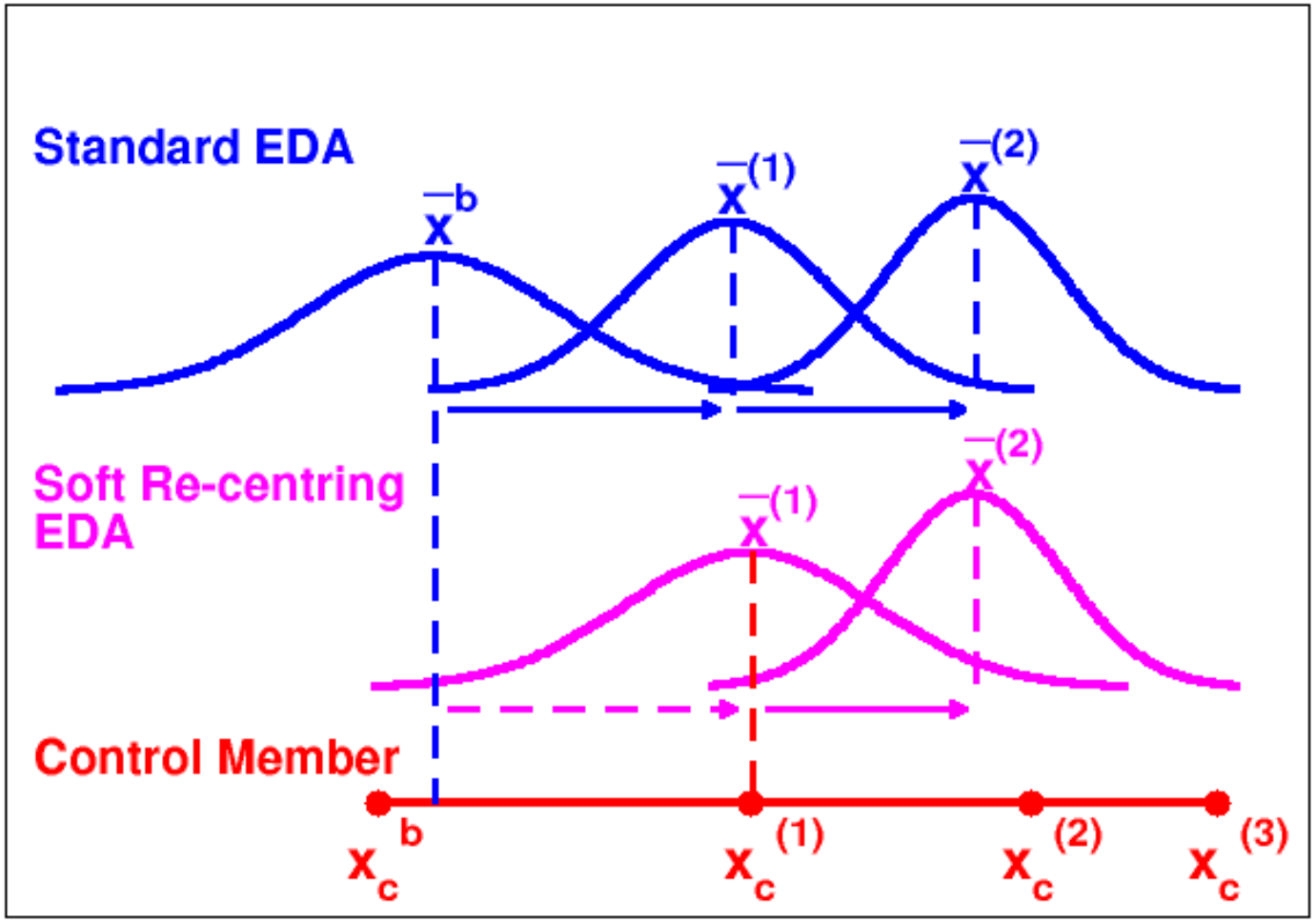
Soft Re-Centred EDA: Pert Members' x^b and x^{fg} Shift by Control => 1OL≈2OL (common VarBC from Control, **B** from Pert Members)



Soft Re-Centred EDA => One Outer Loop Equals Two!

Re-centring perturbed members bckground on control's background and start their minimizations from controls first guess is:

- Technically AND quality wise practically equivalent to doing two outer loops.
- Saves one EDA minimization, 30%, for same quality, enabling higher resolution EDA.
- Control runs more/higher resolution minimization for higher quality.
- The soft re-centred EDA is three times more computationally efficient than our pre-2019 EDA.

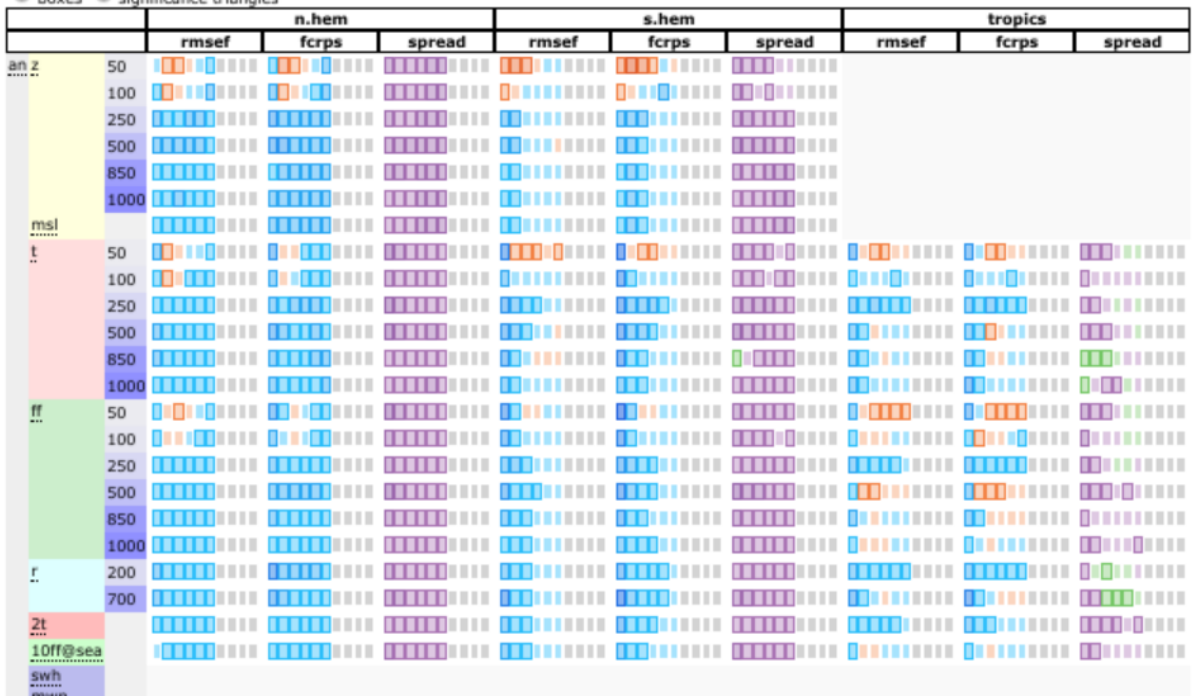


Soft Re-Centred EDA TCo639/18km: Impact on EDA skill - ENS started directly from FG+BG REC 1OL vs 2OL EDAs

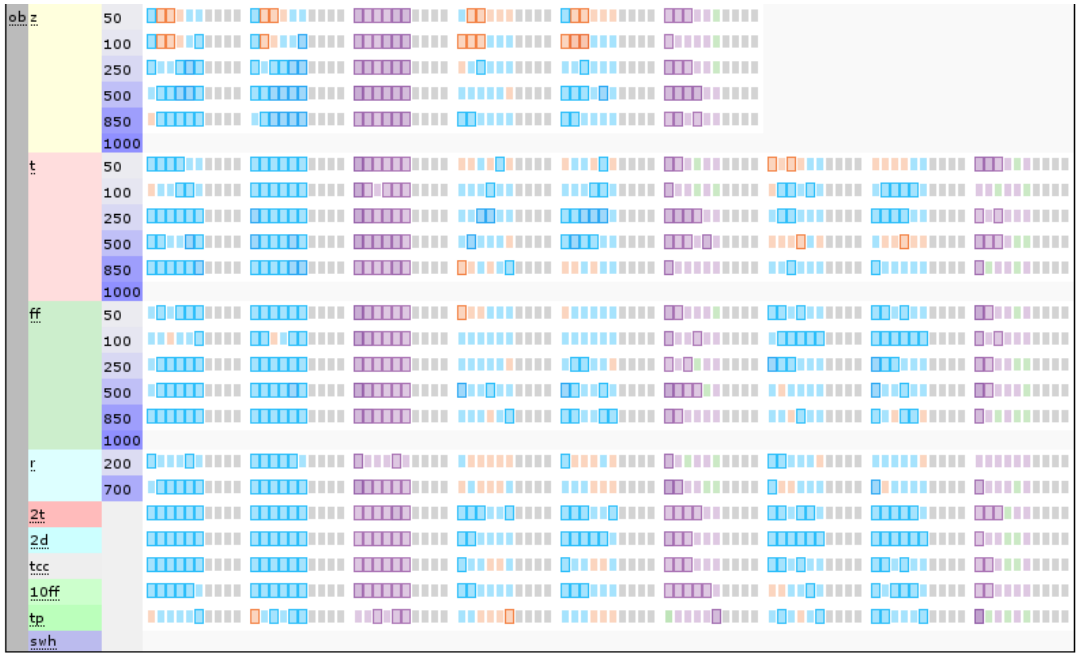
hfra vs hfry scorecard

dates=[2019010500,2019010512,2019010600,...,2019032000,2019032012]
steps=[24, 48, 72, 96, 120, 144, 168, 192, 216, 240]
reftypes=['an', 'ob']
streams=enfo
expvers=(cntrl:hfry, exper:hfra)
vstreams=['qrdxsim_an', 'qrdxsim_ob']
classs=rd
confidence=95.0

rmsef fcrps spread
n.hem s.hem tropics europe n.atl n.amer n.pac e.asia arctic antarctic (all)
boxes significance triangles



ENS from 1OL FG+BG Rec EDA: hfra
ENS from standard 2OL EDA: hfry
Blue: Improvement
Purple: Increased Spread



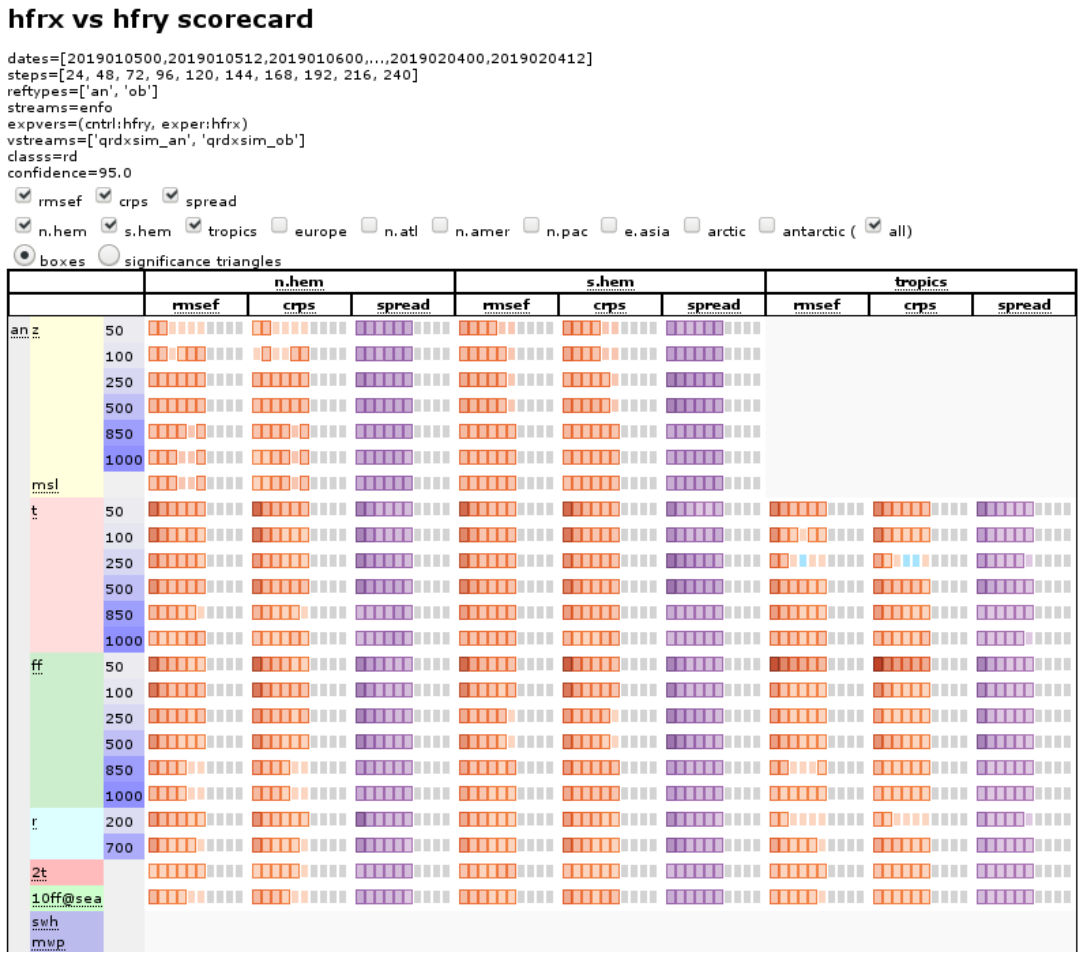
Vs. own analysis

Vs. observations

Soft Re-centred EDA TCo639: Impact on EDA skill - ENS started directly from 1OL vs 2OL EDAs

If we do 1OL without re-centring, perturbed members degraded!

ENS from 1OL EDA: hfrx
ENS from standard 2OL EDA: hfry
Orange: Degradation
Purple: Increased Spread

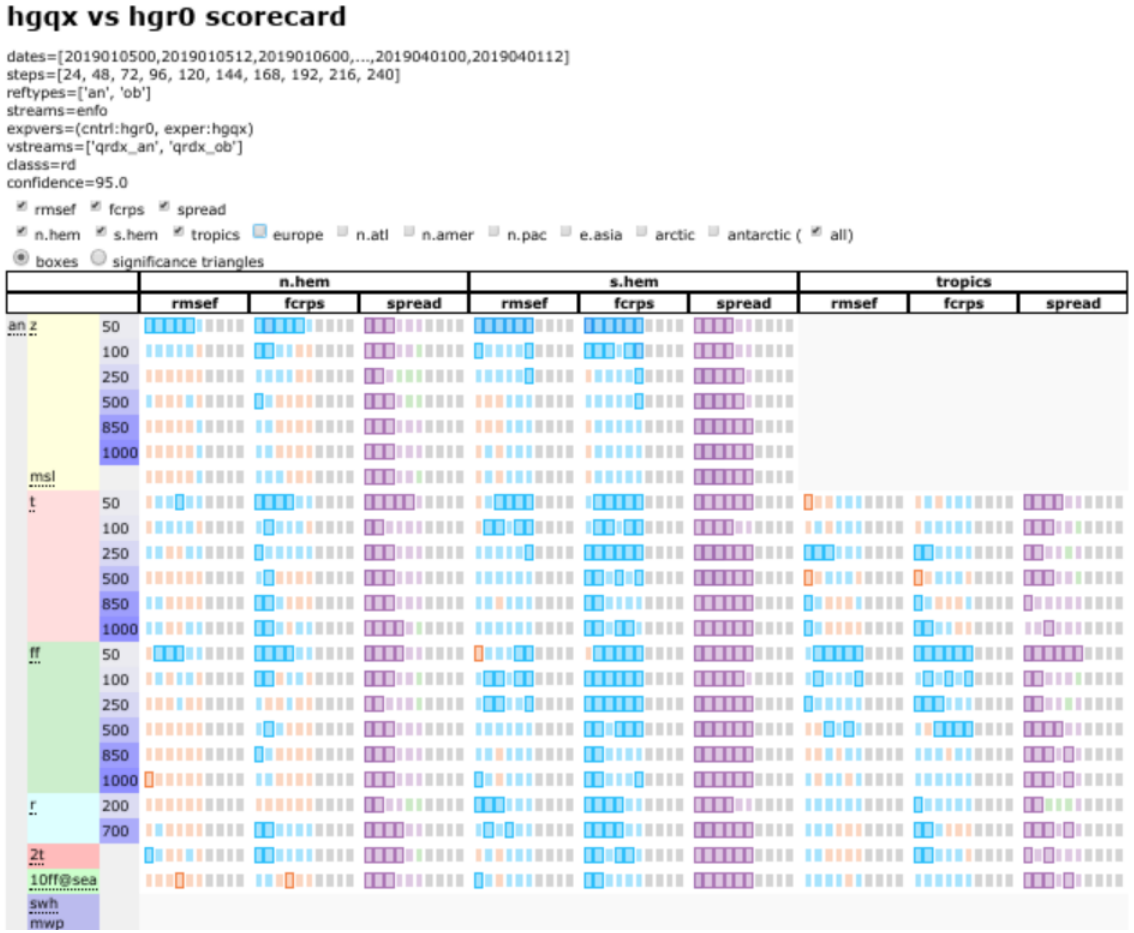


Vs. own analysis

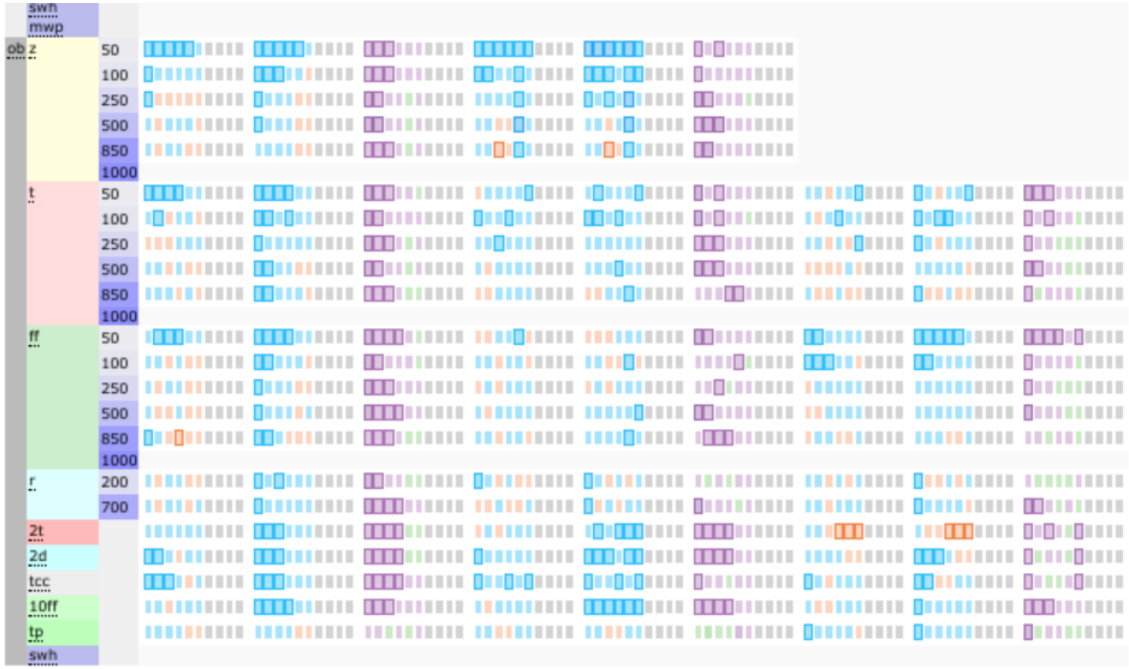
Vs. observations

Soft Re-Centred EDA TCo639: Impact on ENS skill for ENS started from operational-like setup FG+BG REC 1OL vs 2OL EDAs

Operational-like = perturbed members FC re-centred on control AN + SV.



ENS from 1OL SoftREC EDA: hgqx
ENS from standard 2OL EDA: hgr0
Blue: Improvement
Purple: Increased Spread

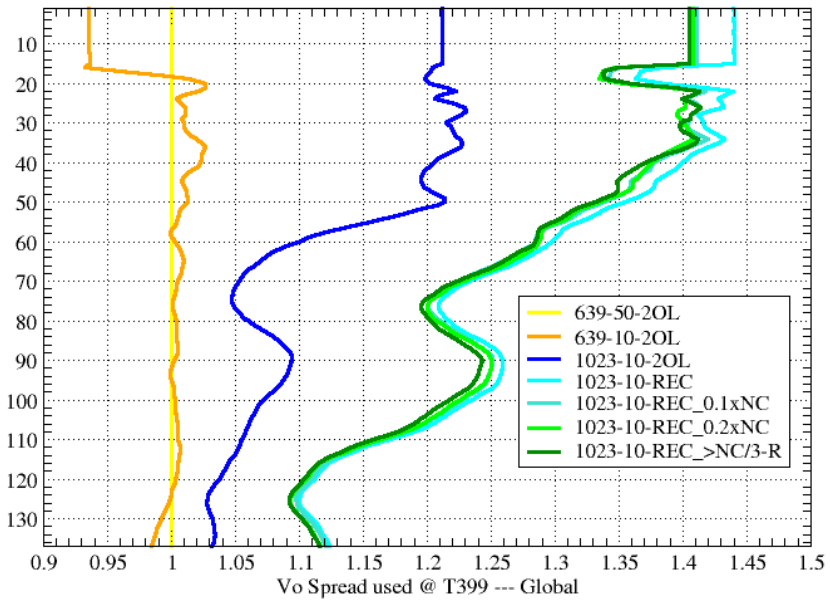


Vs. 0001 analysis

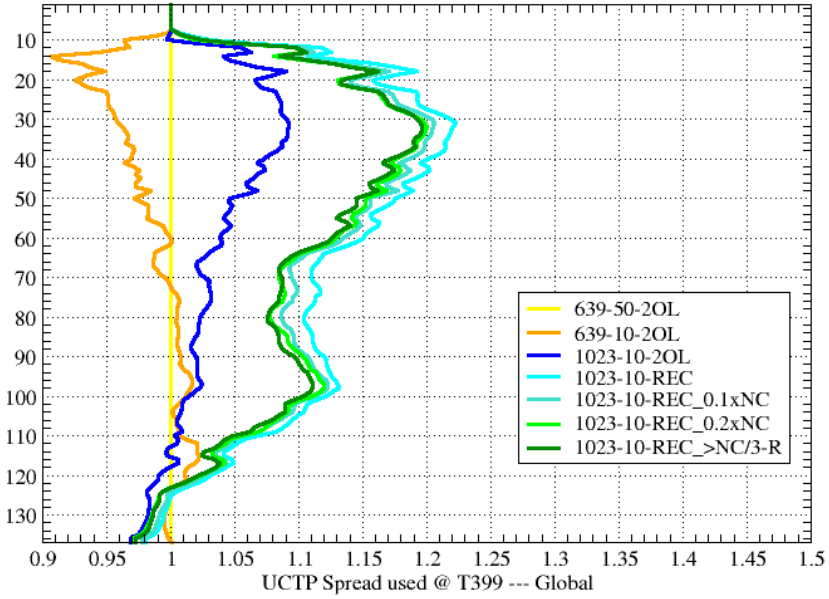
Vs. observations

EDA Resolution Increase+Soft Re-centring => Spread Increase

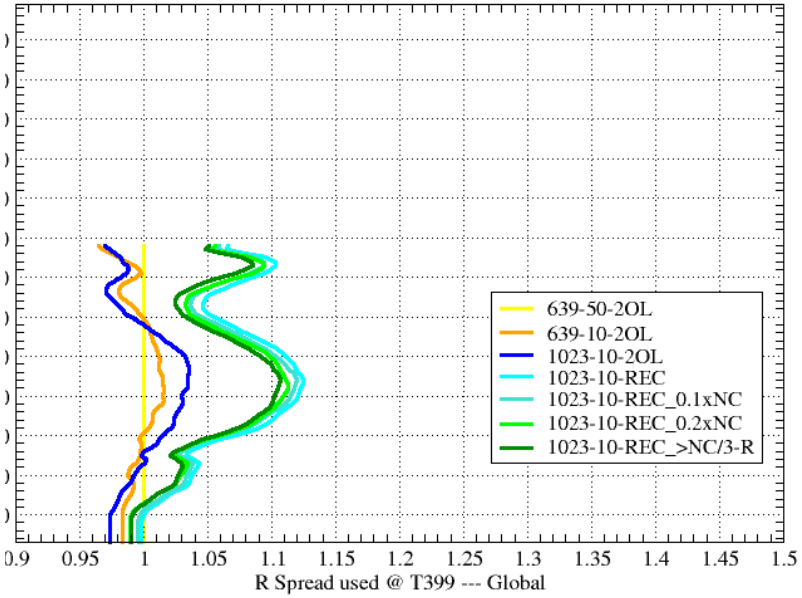
- Spread used in the 4DVar analysis (truncation T399) increases significantly, especially for vorticity.
- Resolution adds significantly, TCo639 (orange) to TCo1023 (blue) 2OL with TL191 inner loops.
- Soft re-centring adds further spread at TCo1023 (three greenish new climate, cyan old climate).
- Note reduction in BL for T/RH, due to deficiency in near-surface spread.



Vorticity



Unbalance Temperature

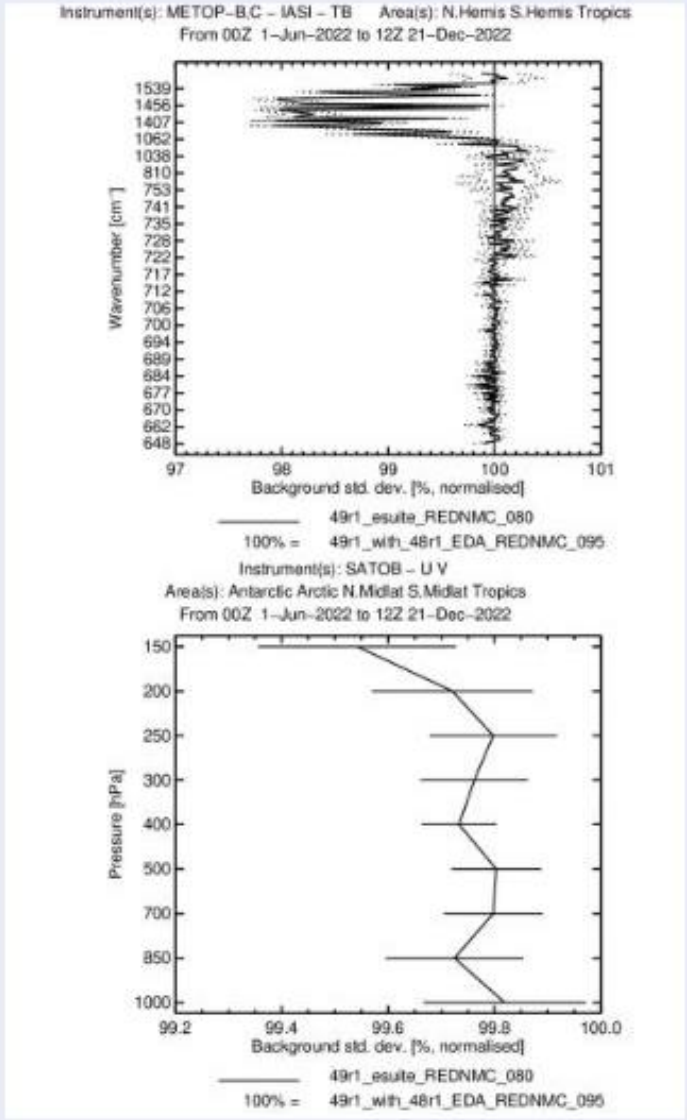


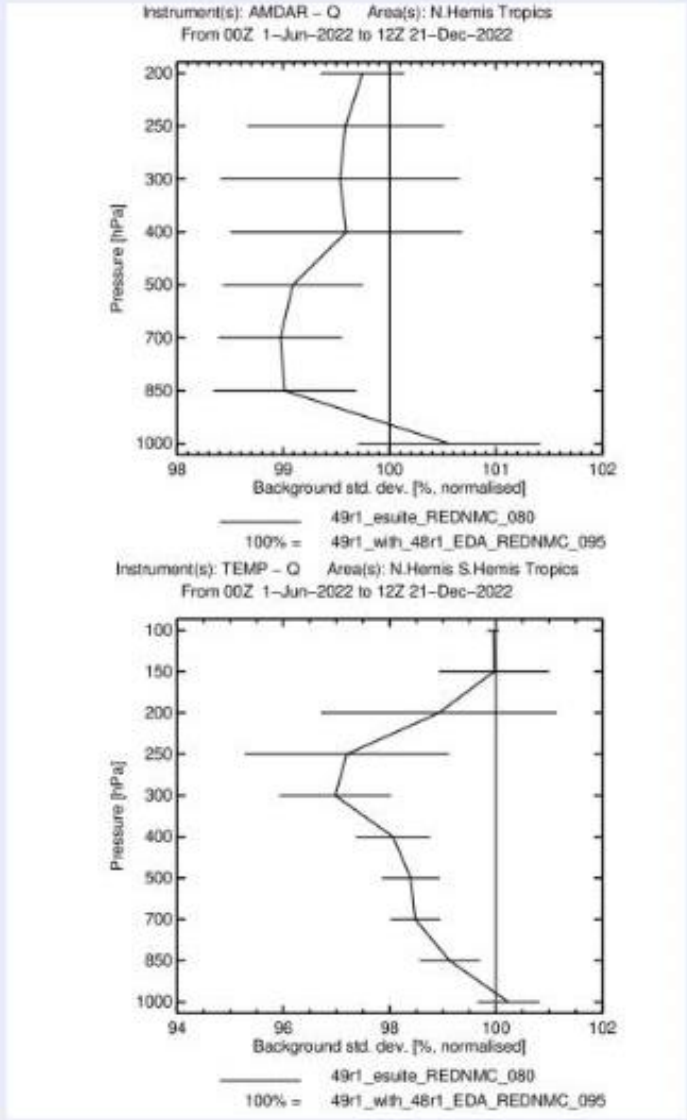
Relative Humidity

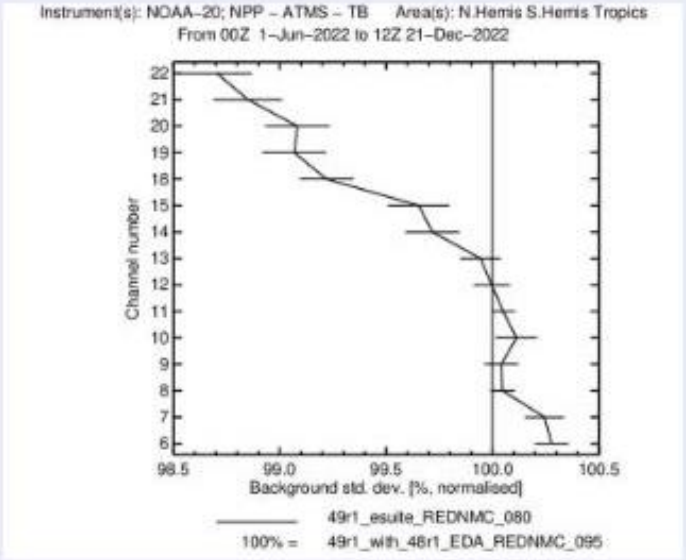
Soft Re-Centred EDA Implementation for 2024

Current 18km EDA	Soft Re-Centred 9km EDA
2 minimizations control, 104km inner loops	**3 minimizations control, 50/50/40km**, accurate state for re-centring
2 minimizations members, 104km	**1 minimization members, 50km**, soft re-centred on first minimization of control, **results equivalent to two minimizations 50km/50km.**
Model uncertainty parameter scheme SPPT, lacks physical consistency.	**New Stochastically Perturbed Parametrisation scheme (SPP),** maintains physical consistency in the perturbations.
Compensations in the Kalman Gain addressing lack of spread particularly in Extra-Tropics, including **34% inflation of B/R** and spread-skill adjusted climatology mixed with errors of day in **B. No spread inflation.**	**B/R inflation reduced to 13%, all other compensations removed**. Removing compensations from **B** allows more direct impact of ensemble changes on spread and Kalman Gain. **Still no spread inflation.**
Observation errors have been tuned against stable “compensated” **B** and SPPT levels over last years.	**Some observation error re-tuning needed** after **B** compensations have been removed and new SPP. Done in next cycle as follow-up.

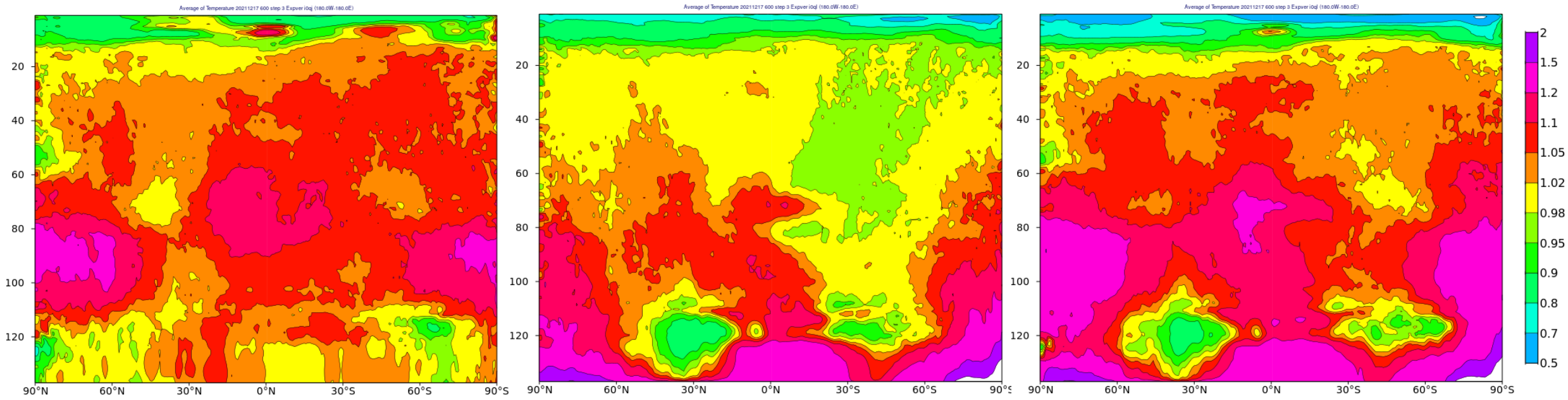
Humidity Improvements from EDA Resolution Increase, O-B







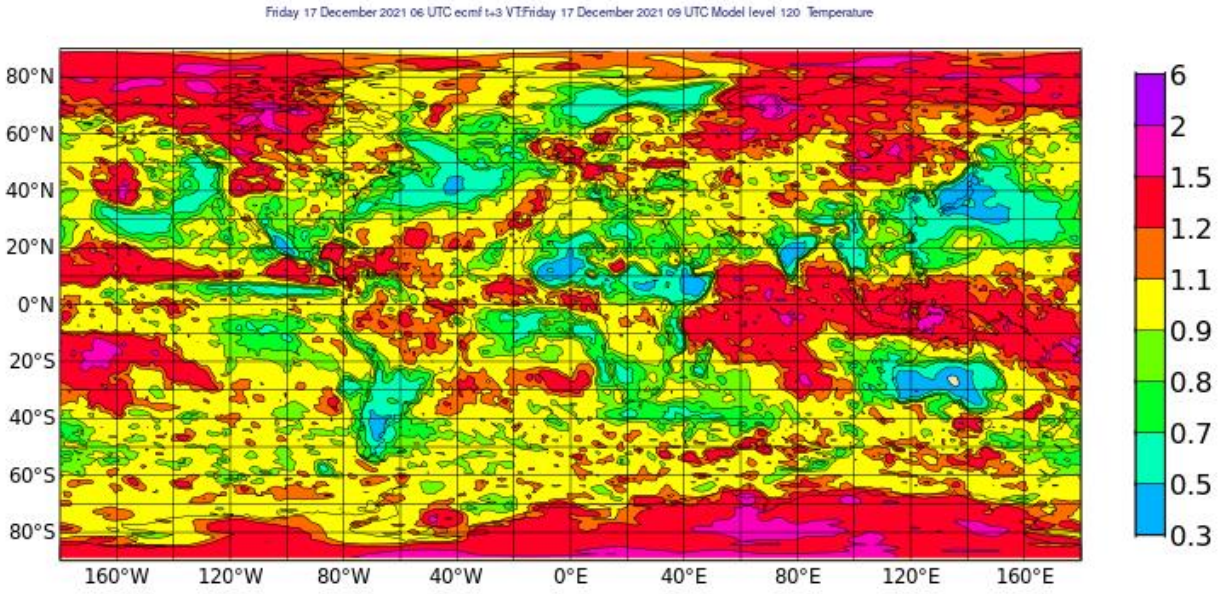
Spread Ratio Soft Re-centred TCo1279 EDA w/wo SPP vs TCo639 Std EDA: T



+TCo1279/9km SRec +SPP +TCo1279 SRec +SPP

- Significant spread increase from both EDA resolution increase to TCo1279 (mainly above BL) and the SPP (mainly in BL). Much larger than in a normal cycle, for T over 20% increase max values.
- Desirable increase, but observation errors and SPP (main sources of spread) were developed and tuned in a TCo639 EDA environment → Need obserror+SPP refining as follow up.

Spread Ratio SPP on top of TCo1279 SRec EDA: T



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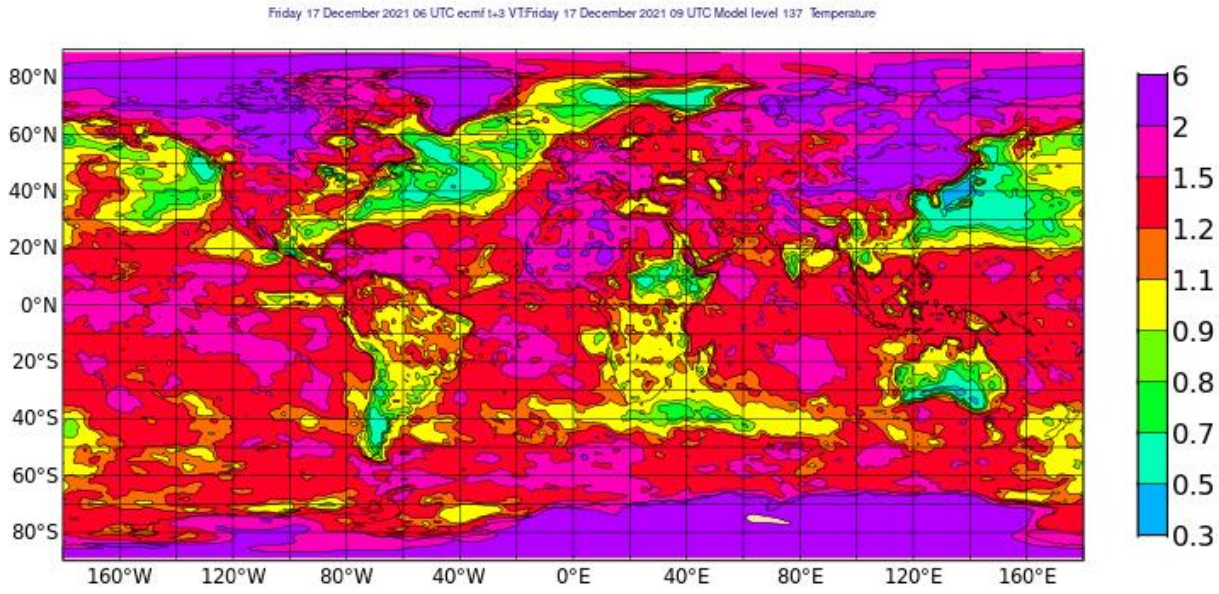
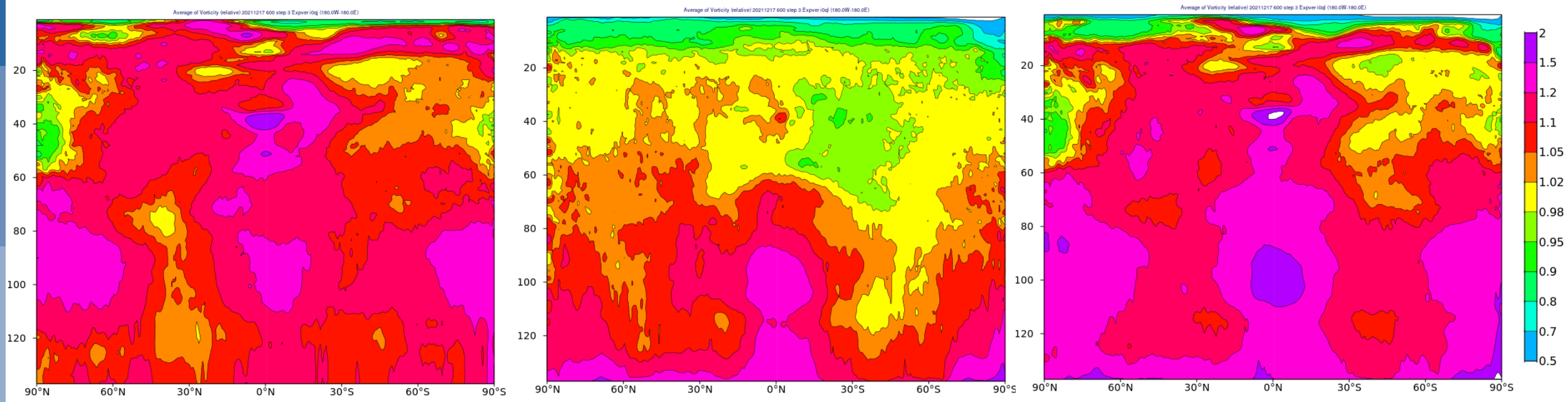


L137

- Interesting feature of SPP is general increase in the BL spread, but with decrease in certain areas, especially over ocean just east of the continents in NH. This is spotlight December, so may change over seasons. But may reflect the more physical behaviour of SPP.

Spread Ratio Soft Re-centred TCo1279 EDA w/wo SPP vs TCo639 Std EDA: VO



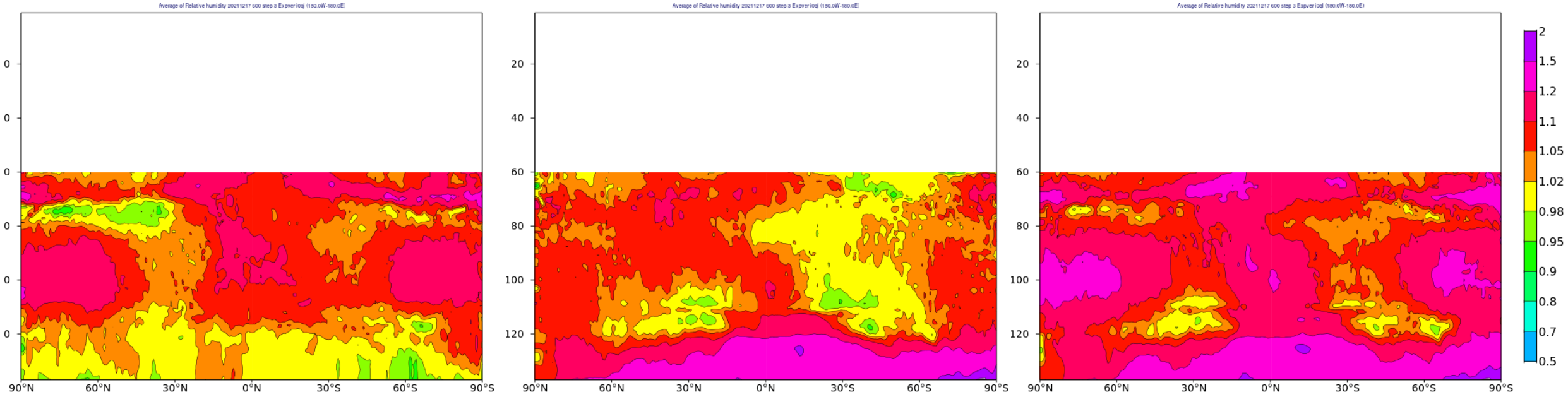
+TCo1279/9km SRec

+SPP

+TCo1279 SRec +SPP

- In vorticity, the maximum spread increase is in the Tropics, where both resolution and SPP contribute.
- We also see that here like in temperature the spread increase varies by level and altitude.
- Further refinement will then come from re-evaluation of observation errors in this environment in next cycle and further refinement of SPP—too complex to do in same cycle as resolution increase+SPP.

Spread Ratio Soft Re-centred TCo1279 EDA w/wo SPP vs TCo639 Std EDA: R



+TCo1279/9km SRec

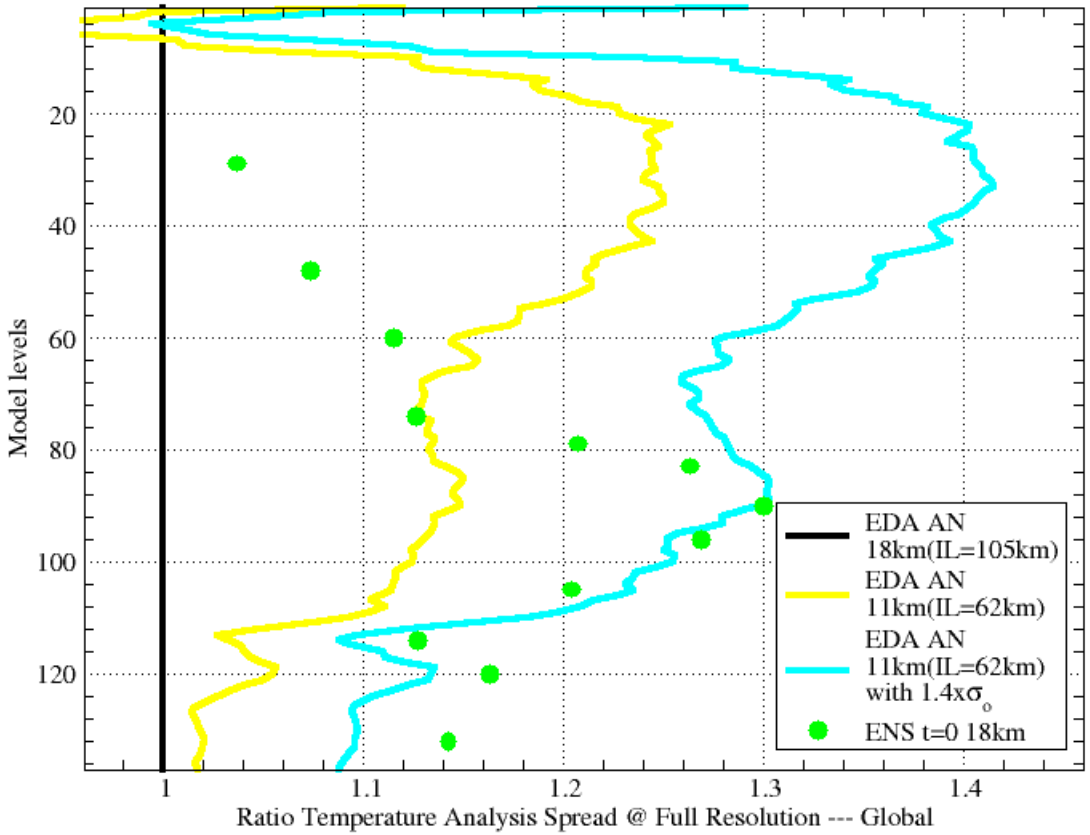
+SPP

+TCo1279 Srec +SPP

EDA Resolution Increase: Direct Initialisation of ENS from EDA?

Not there yet! nvestigating direct initialisation of the ENS from the EDA over next couple of years:

1. Resolution upgrade of EDA to TCo1279/9km closes 40% of the reliability gap in analysis error, will be implemented 2024.
2. Remaining 60% of the gap from improvements in model uncertainty and observation errors. On right we increased obs errors/perturbations by 40% => initial spread increases to match ENS with SV, but decays in time => **horizontal obs correlations** may help.
3. Cost-effective early-delivery EDA for the ensemble to have the latest available observations. Design without significant cost increase, combining continuous DA and other ideas.



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