Hybrid Variational/Ensemble Data Assimilation

Dale Barker, Andrew Lorenc, Adam Clayton + many others…

ECMWF Data Assimilation Seminar, 6 September 2011

Outline of Talk

1. 4D-Var and the Ensemble Filter

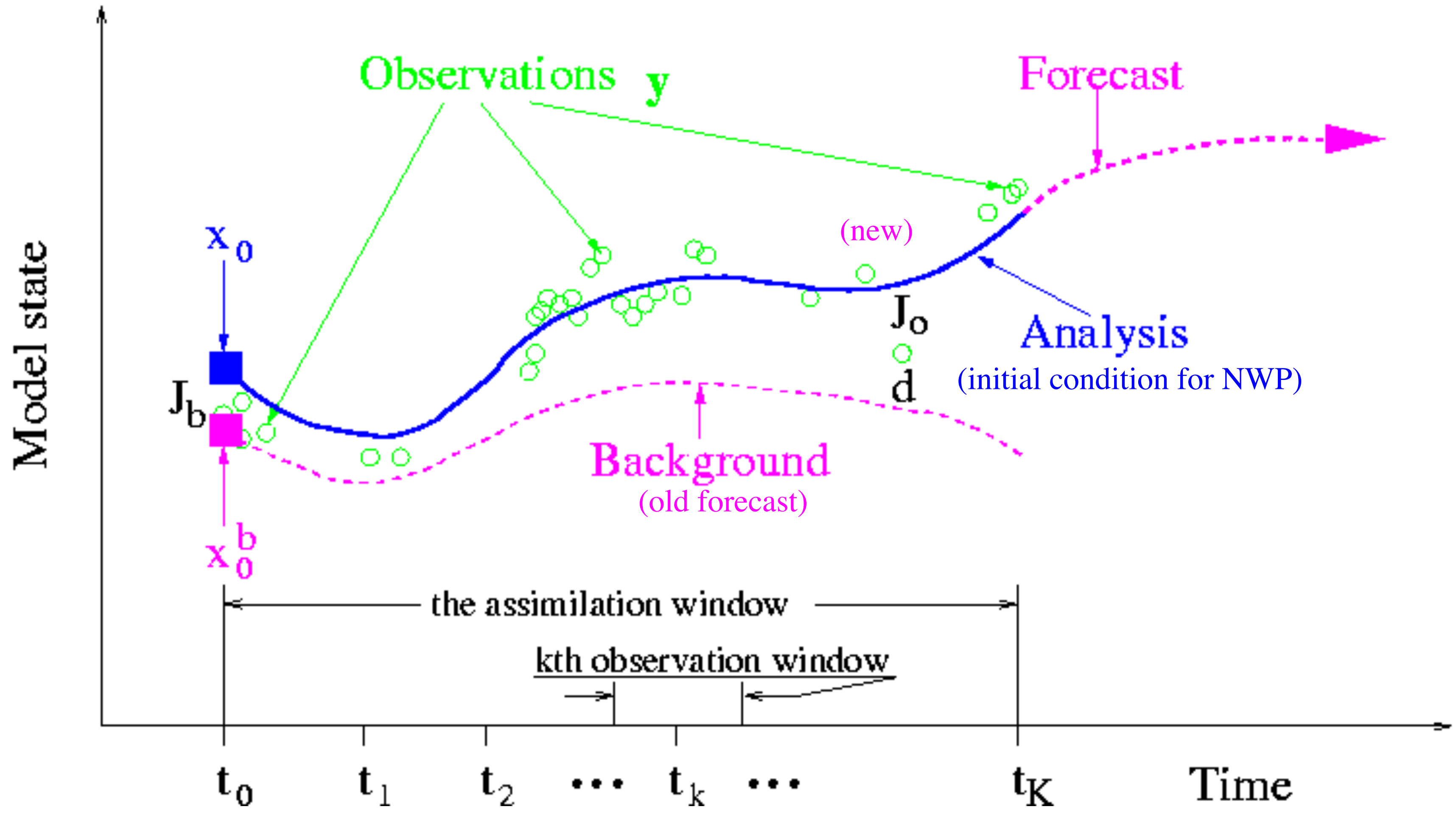
2. Hybrid Variational/Ensemble Data Assimilation

3. The Met Office Hybrid 4D-Var/ETKF Algorithm

4. Met Office Future Plans

1. 4D-Var and the Ensemble Filter

4D Variational Data Assimilation (4D-Var)



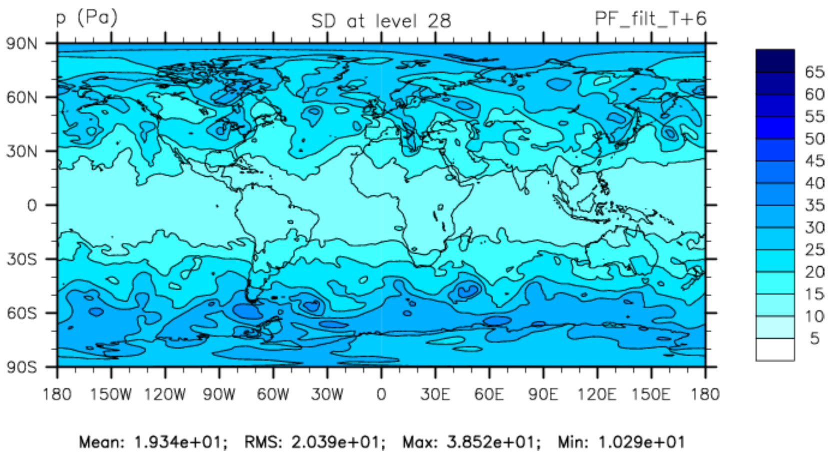
Climatological covariances ($\mathbf{B}_c$)

- Standard 4D-Var is based wholly on climatological covariances (COV):
  - Choose control variable fields that are approximately uncorrelated:

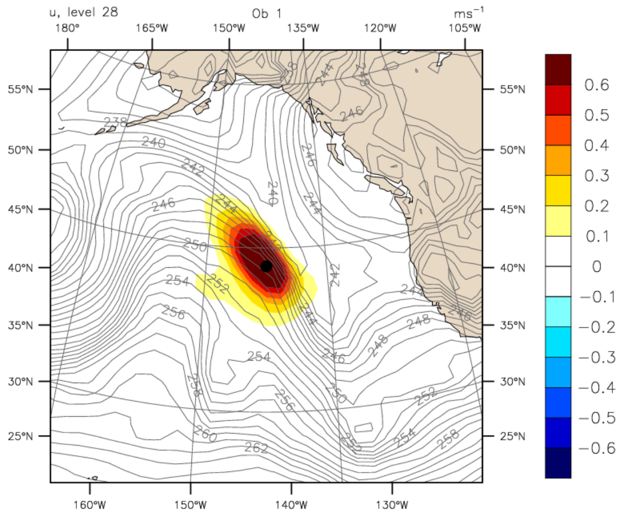
ψ: streamfunction	χ: velocity potential
Ap: Unbalanced pressure	μ: humidity

  - COV covariance model typically imposes constraints e.g. homogeneity, isotropy.
  - Illustrate 4D-Var flow-dependence using 500 samples from climatological B:

SD (pressure)



Pseudo ob test (u)



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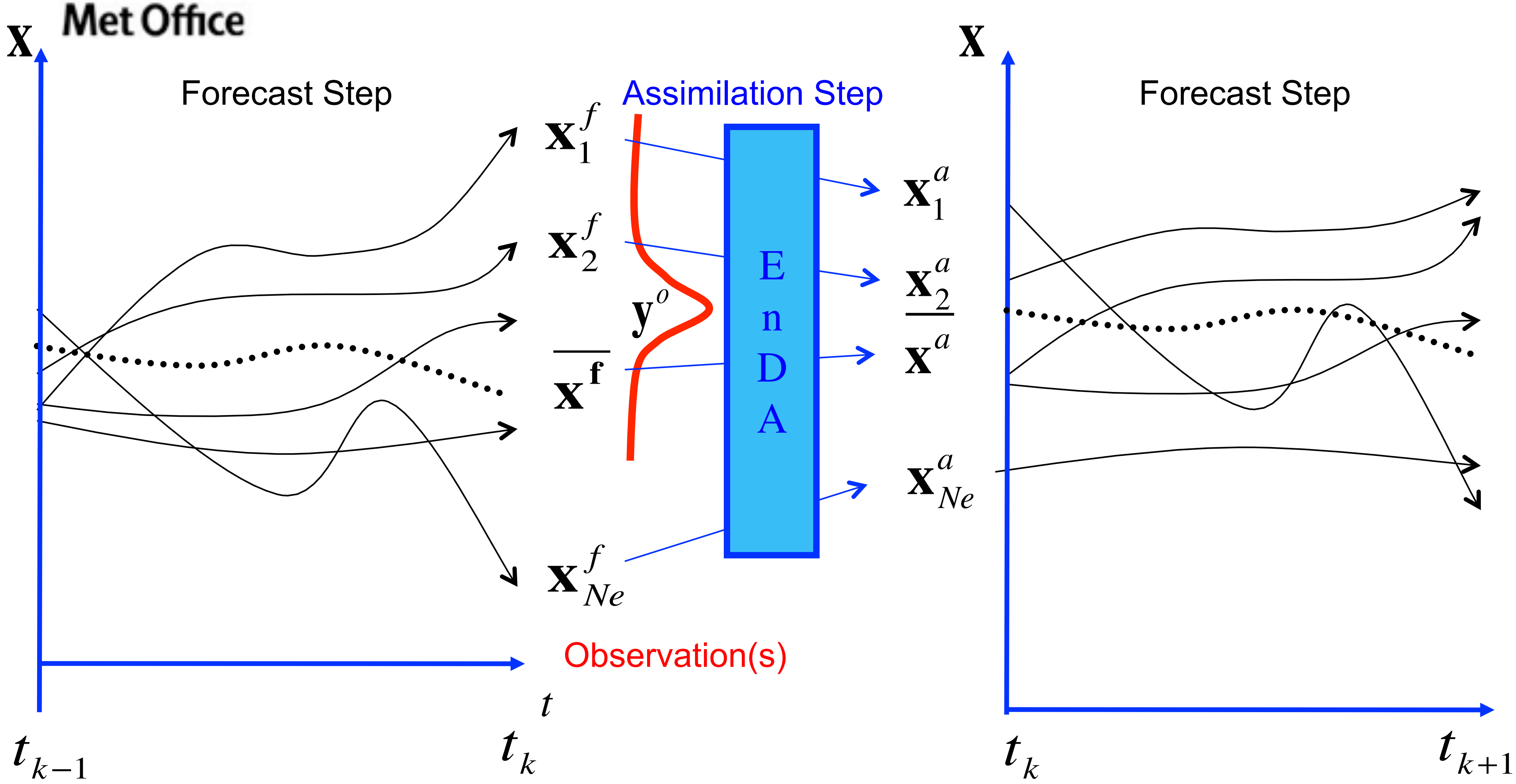
Ensemble Data Assimilation (EnDA)

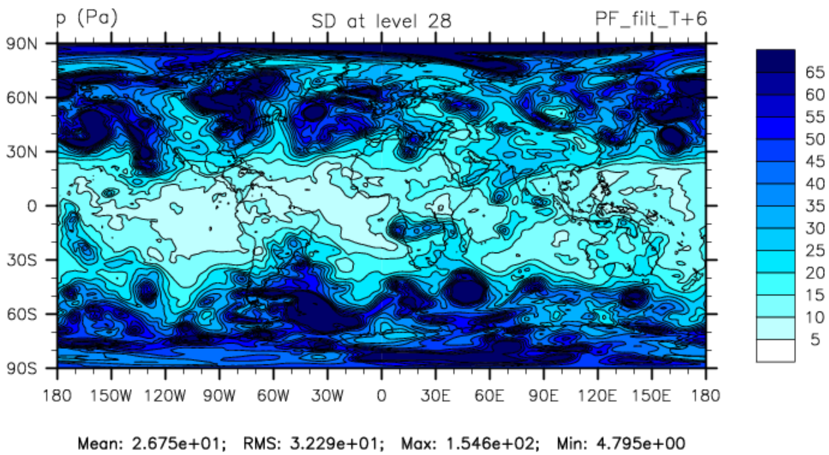


- *Ne* = Ensemble Size (typically 20-200 for real-world NWP).
- Many different flavours of the EnDA algorithm.

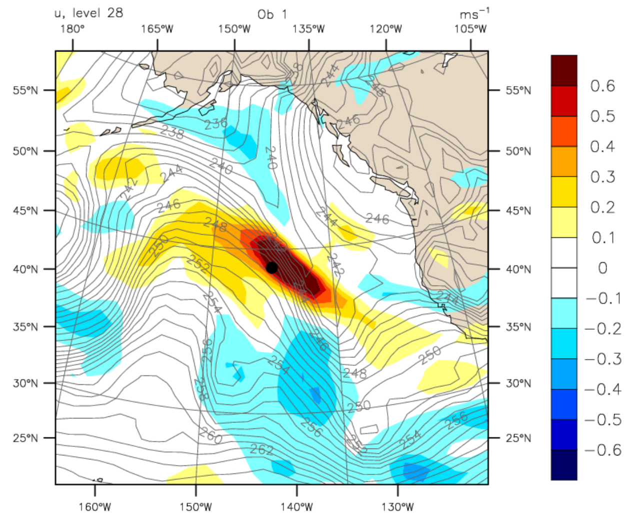
Ensemble covariances ($\mathbf{P}_e$)

- MOGREPS-G:
  - 23 perturbed members (N216L70), aimed at the short-range
  - Ensemble covariance is a simple outer product of the forecast perturbations: $$\boldsymbol{P}_e = \boldsymbol{X}\boldsymbol{X}^T; \quad \boldsymbol{X} = \frac{1}{\sqrt{K-1}}(\boldsymbol{x}_1 - \overline{\boldsymbol{x}}, \boldsymbol{x}_2 - \overline{\boldsymbol{x}}, \ldots, \boldsymbol{x}_K - \overline{\boldsymbol{x}})$$
  - Provides covariances that should reflect the observation distribution, and the effects of recent instabilities; i.e., the "Errors of the Day"

SD (pressure)



Pseudo ob test (u)



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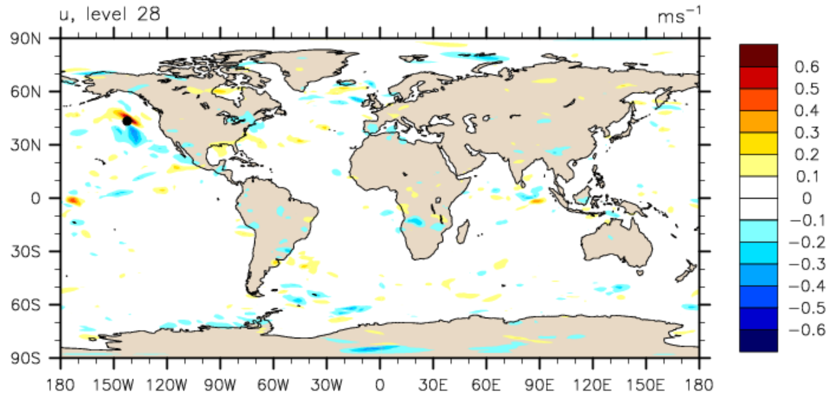
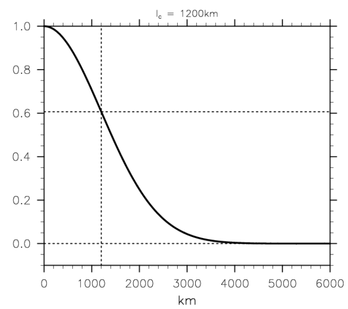
The need to localise $\mathbf{P}_e$

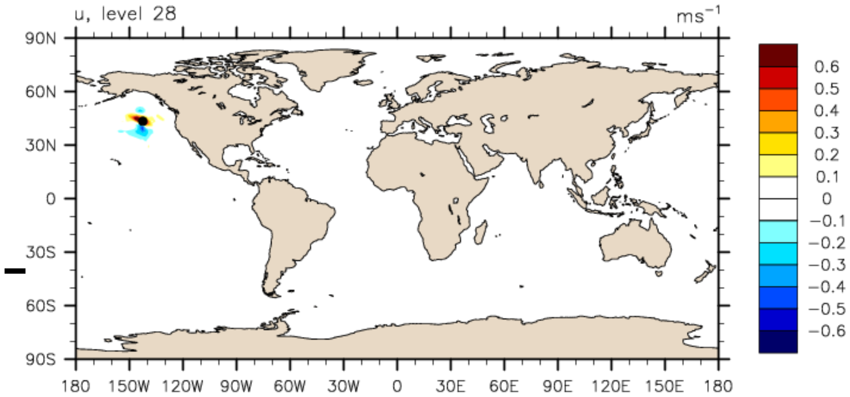
- Due to the finite ensemble size, ensemble covariances are noisy, for example spurious long-range correlations:



- Solution is to localise the covariances by multiplying pointwise with a localising covariance

$\mathbf{P}_e \circ$



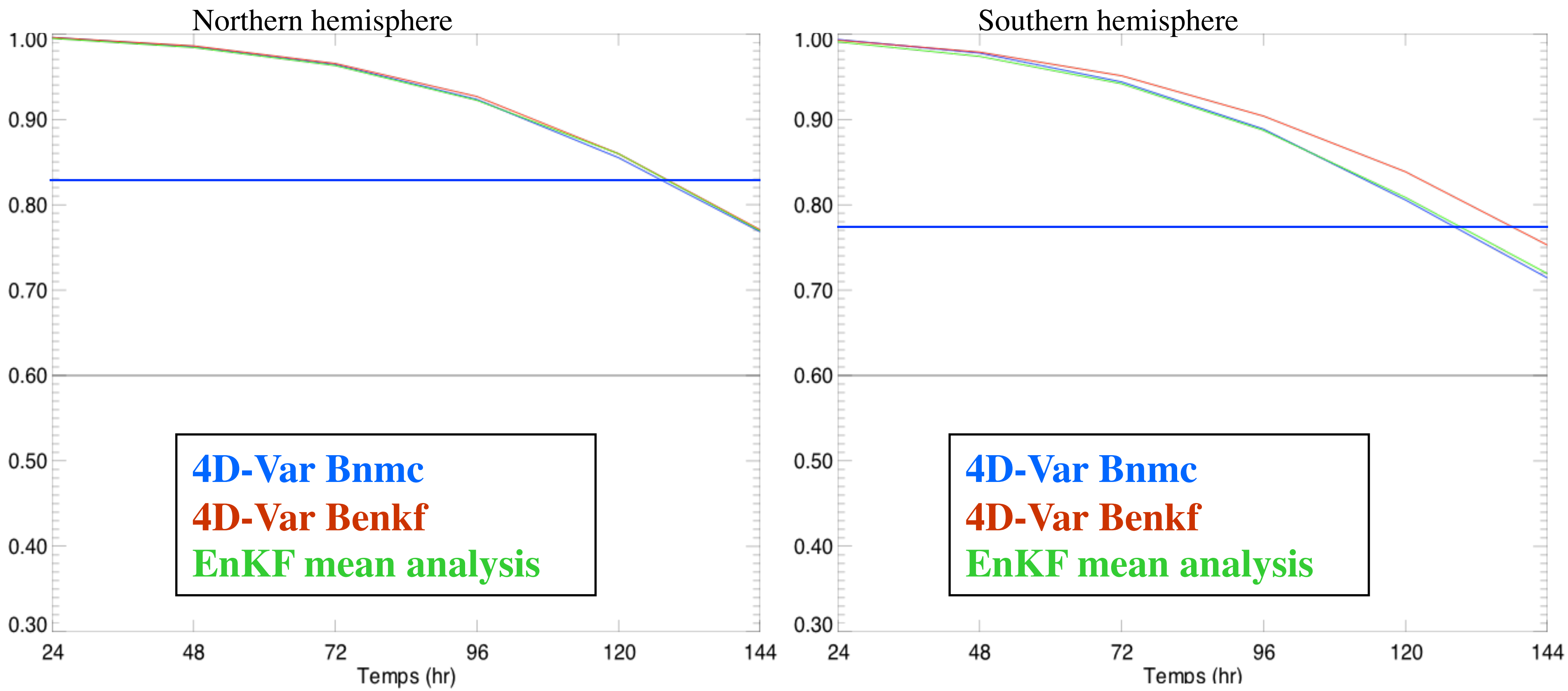


- Crucially, localisation also increases the ‘rank’ of the ensemble covariance; the number of independent structures available to fit the observations.

Comparison of 4D-Var/EnKF

(Buehner et al 2010)

Verifying analyses from 4D-Var with Bnmc



Conclusion: Combined 4D-Var + EnKF covariances->~10hrs SH skill

2. Hybrid Variational/Ensemble Data Assimilation

Hybrid Var/EnDA: Motivation

1) Forecast errors often highly flow-dependent.

2) 4D-Var can introduce flow-dependence, but limited by linearity assumption and static J_b.

3) Ensemble filters provide flow-dependent covariances, but suffer from effects of sampling error.

4) Evidence of optimal mix (hybrid) of static/ensemble background error covariances in OI/3D-Var-based studies, e.g. Hamill and Snyder (2000):

$$\mathbf{B} = b\mathbf{B}_{c\,\mathrm{lim}} + (1-b)\mathbf{B}_{flow-dep}$$

5) Simple model experiments have shown promise, but need to extend to full operational testing.

Example Hybrid Result (Etherton and Bishop 2004)

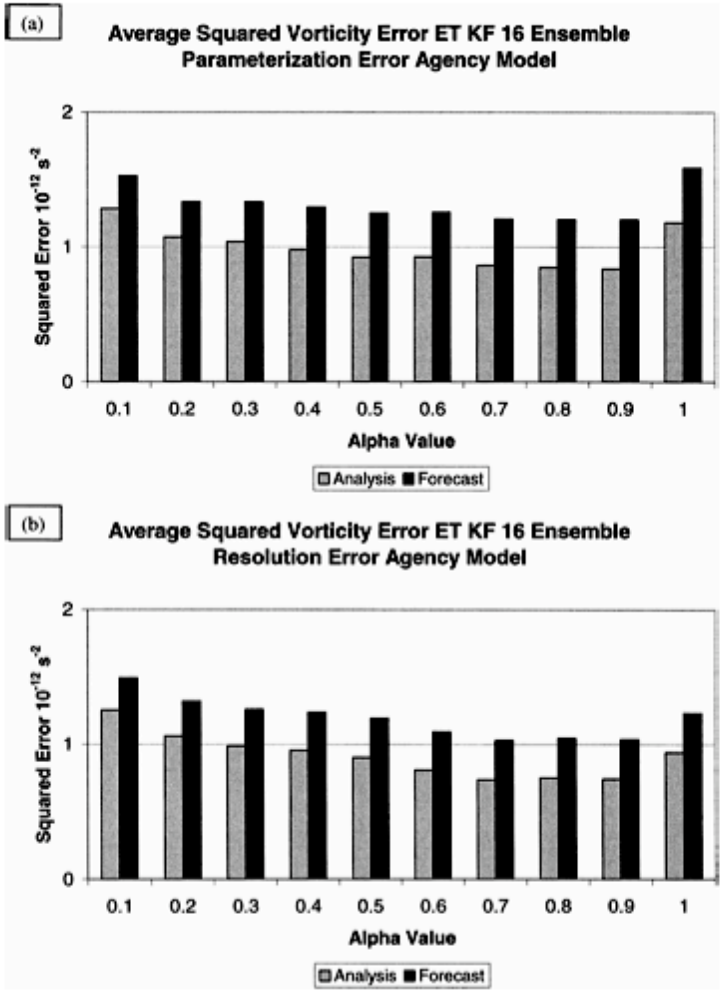


FIG. 5. The daily average squared vorticity error as a function of the parameter alpha (α = 0 being pure ETKF, α = 1 being pure 3DVAR) for when the agency's forecast model had (a) parameterization error or (b) resolution error. A 16-member ETKF-generated ensemble was used for the construction of the flow-dependent error statistics.

- Barotropic vorticity model.
- ETKF not localized.
- 3D-Var framework.
- Optimal mix of Var/Ens covariance ~70/30%.

Hybrid Var/EnDA Via The 'Alpha Control Variable' (Barker 1999, Lorenc 2003)

- Vector of Ensemble Perturbations $\delta\mathbf{X}_f = \left(\delta\mathbf{x}_{f1}, \delta\mathbf{x}_{f2}, \ldots, \delta\mathbf{x}_{fN}\right)$

- Hybrid analysis increment defined as

$$\delta\mathbf{x}_0 = \delta\mathbf{x}_{clim} + \delta\mathbf{x}_{flow-dep} = \mathbf{B}^{1/2}\mathbf{v} + \delta\mathbf{X}_f \circ \mathbf{a}$$

- Ensemble weights **a** constrained by an additional cost-function,

$$J = \frac{W_b}{2}\delta\mathbf{x}_0^T\mathbf{B}^{-1}\delta\mathbf{x}_0 + \boxed{\frac{W_\alpha}{2}\mathbf{a}^T\mathbf{A}^{-1}\mathbf{a}} + \frac{1}{2}\sum_{i=0}^{n}\left[\mathbf{H}_i\delta\mathbf{x}(t_i) - \mathbf{d}_i\right]^T\mathbf{R}_i^{-1}\left[\mathbf{H}_i\delta\mathbf{x}(t_i) - \mathbf{d}_i\right]$$

- Variance conservation implies $\dfrac{1}{W_b} + \dfrac{1}{W_\alpha} = 1$

- W_b=1 is standard 3/4D-Var. W_b=0 fully ensemble covariance (e.g. Liu et al 2008, Buehner et al 2010). **Hybrid is the space in-between!**

Comments on The ACV Method

- 'Incremental, balance-aware' covariance localization is trivial, e.g.

$$\delta\psi_0 = \delta\psi_{c\,\mathrm{lim}} + \delta\psi_f \circ \mathbf{a} \qquad \delta\chi_{u0} = \delta\chi_{uc\,\mathrm{lim}} + \delta\chi_{uf} \circ \mathbf{a}$$

- Covariance **A** equivalent to model-space covariance localization (Lorenc 2003).

- So, like **B** we can define a covariance (localization) model for **A**, e.g.

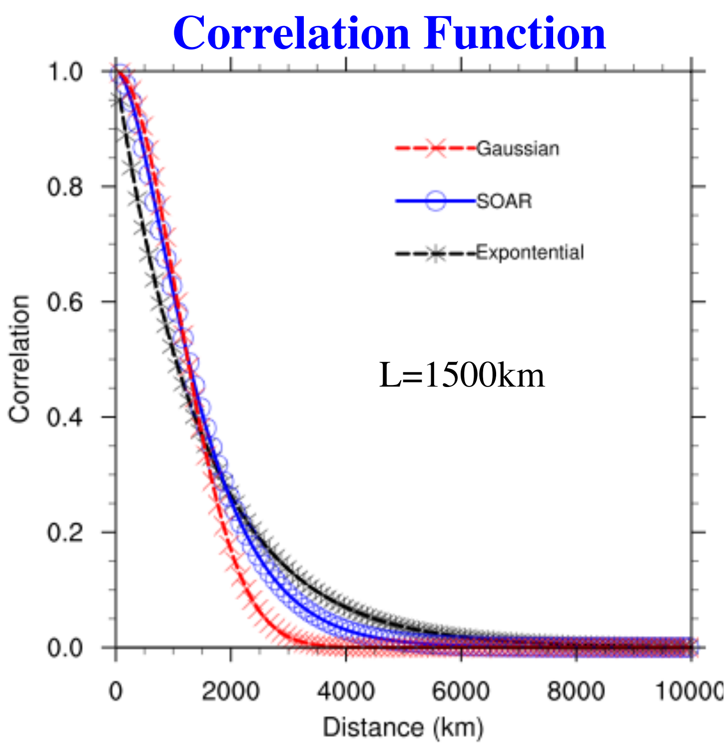
$$\mathbf{a} = \mathbf{A}^{1/2}\alpha \equiv \sigma_\alpha^2 \mathrm{A}_v \mathrm{A}_h \alpha$$

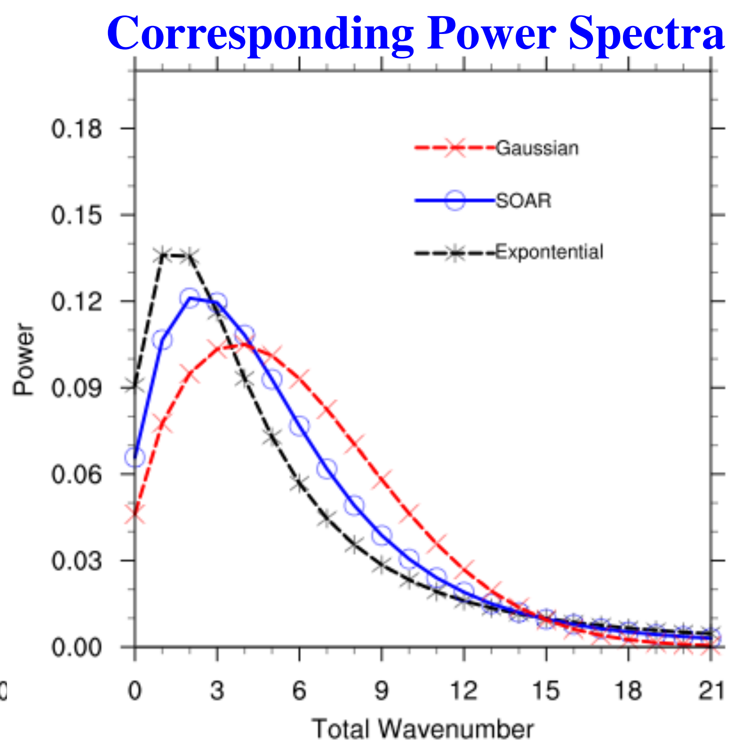
- **A**=**I** implies no localization. Only need one scalar per ensemble member.

- Convenient to use standard control variable transforms for localization operators A_v, A_h, but not essential.

A_h: Horizontal Covariance Localization

- Example: Truncated power spectrum from empirical correlation with scale *L:*

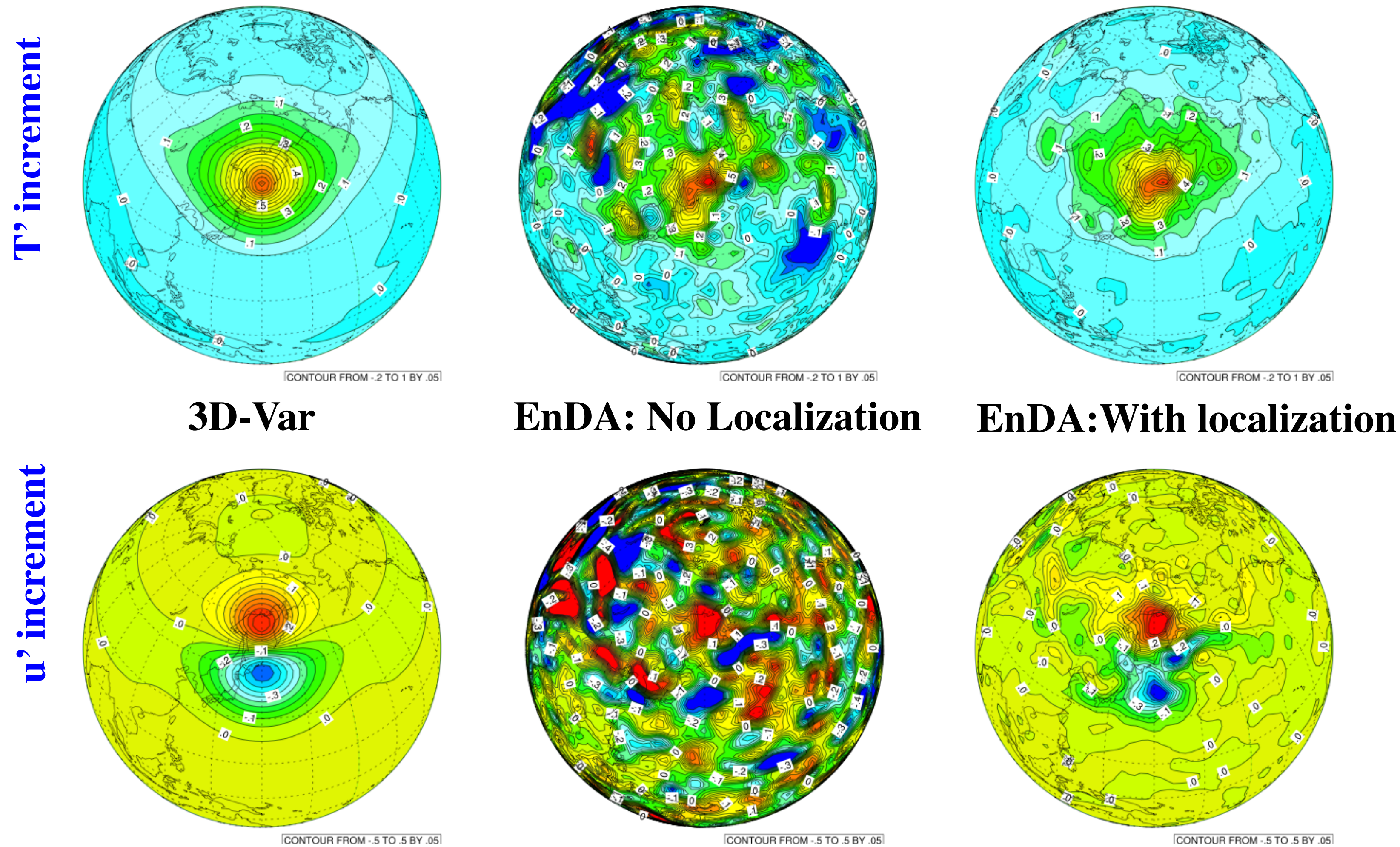




- Spectral localization permits significant reduction in size of alpha control variable.

Alpha Covariance Localization (Extreme example: 1 ob + 2 members!)

- Single T observation (O-B, s_o=1K) at 50N, 150E, 500hPa.



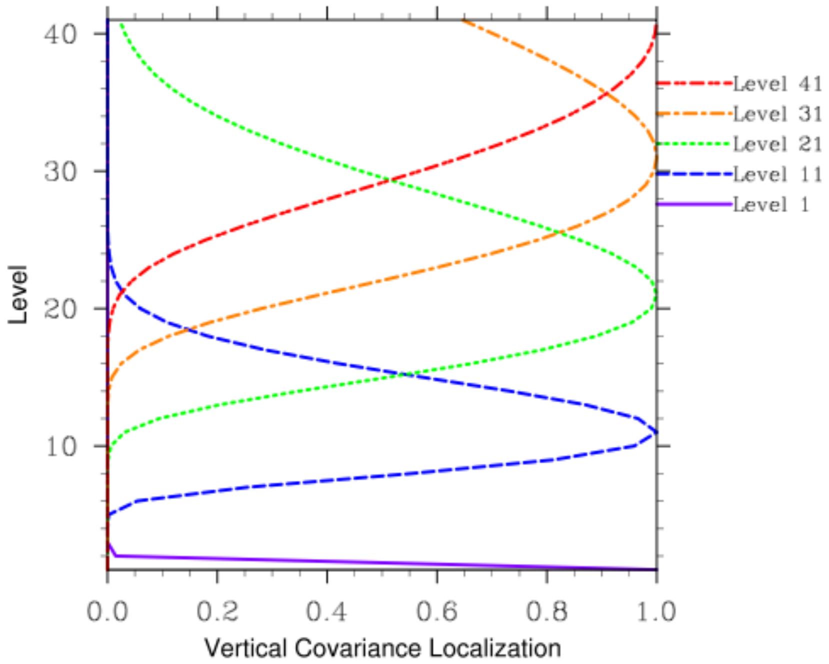
A_v: Vertical Covariance Localization

WRF Example: Gaussian with level-dependent localization scale:

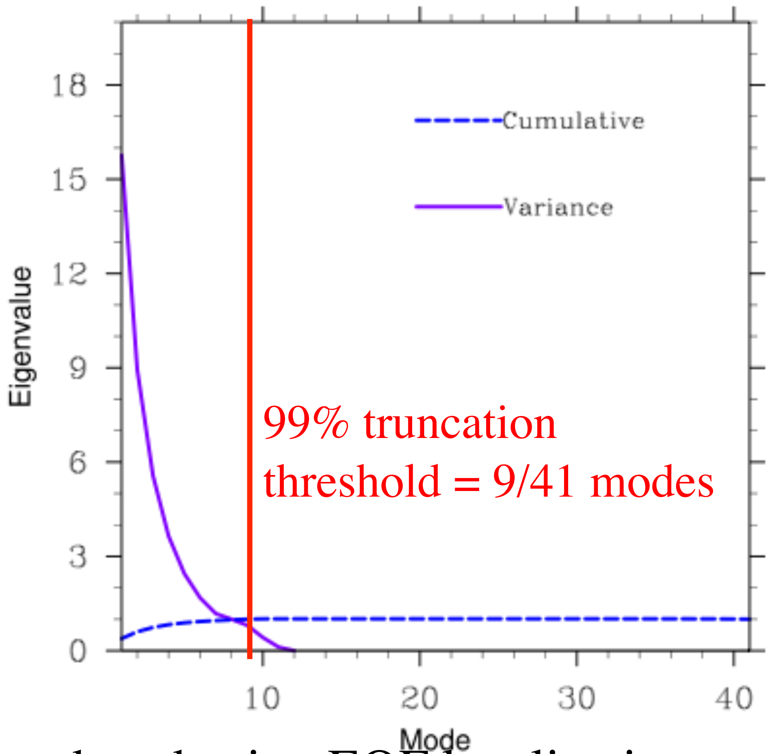
$$\rho(k-k_c) = \exp\left[-\left(k-k_c\right)^2 / L_c^2\right]$$

$$L_c = 20k_c / 41$$

Correlation Function

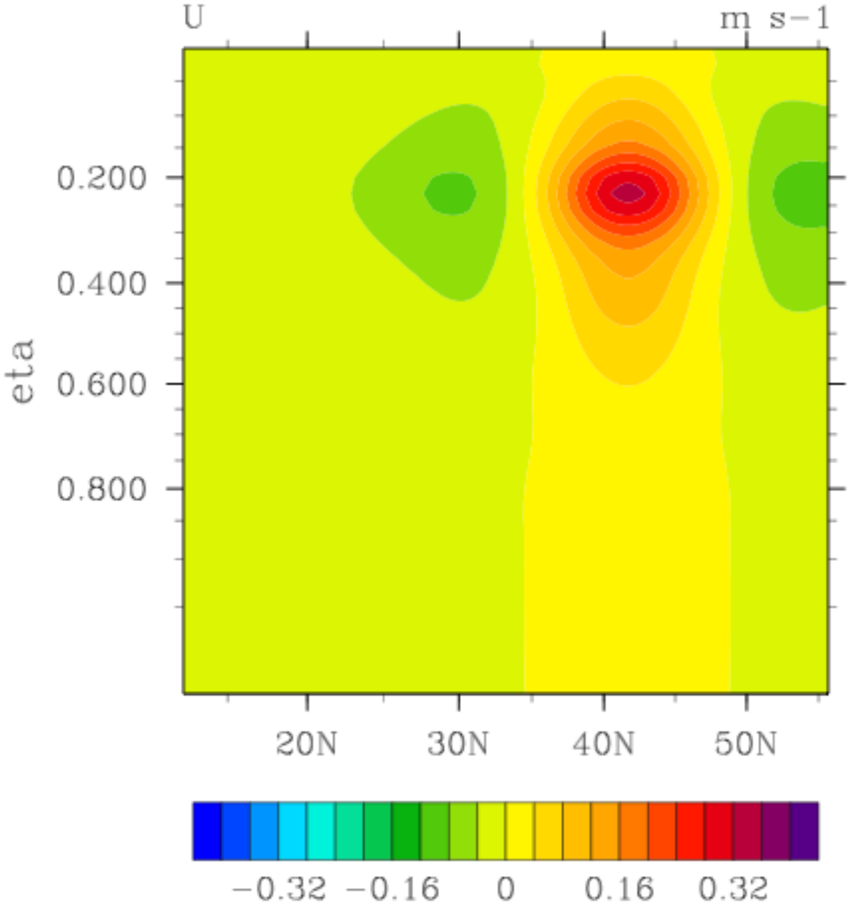


Eigenvalues

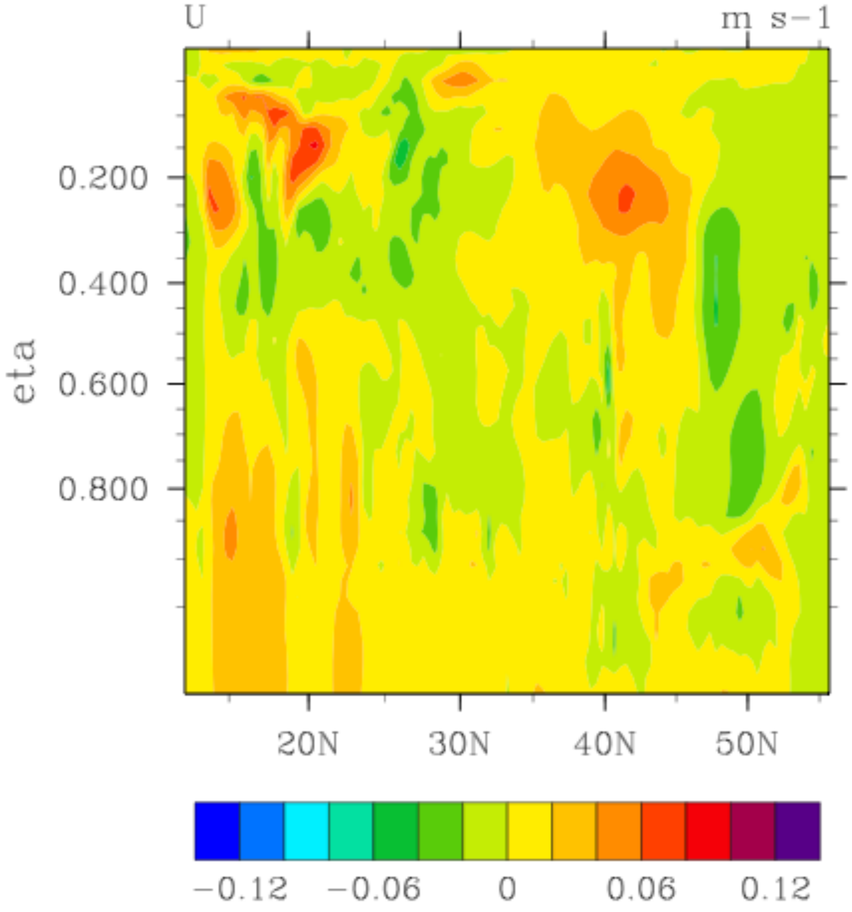


Again, number of additional control variables reduced using EOF localization.

Single ob test
(250hPa u, O-B=1m/s, sigma_o=3.3m/s)



3D-Var

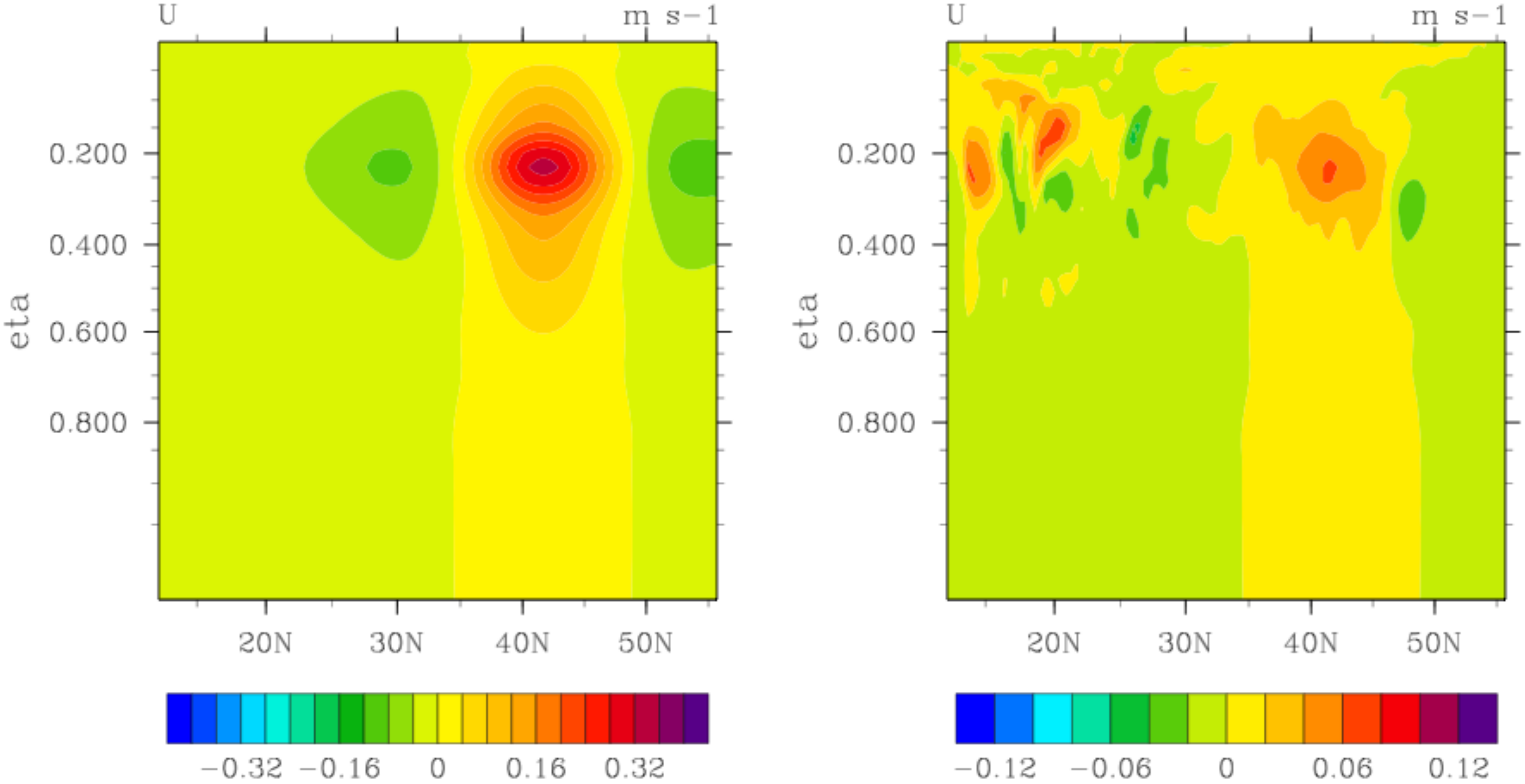


$W_b=0$, $\mathbf{A}=\mathbf{I}$

Single ob test

(250hPa u, O-B=1m/s, sigma_o=3.3m/s)

Impact of Vertical Localization

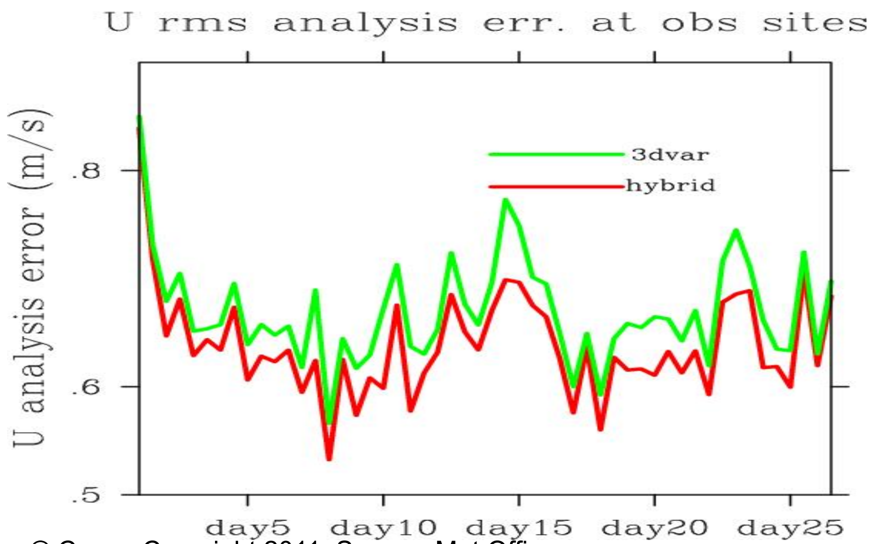


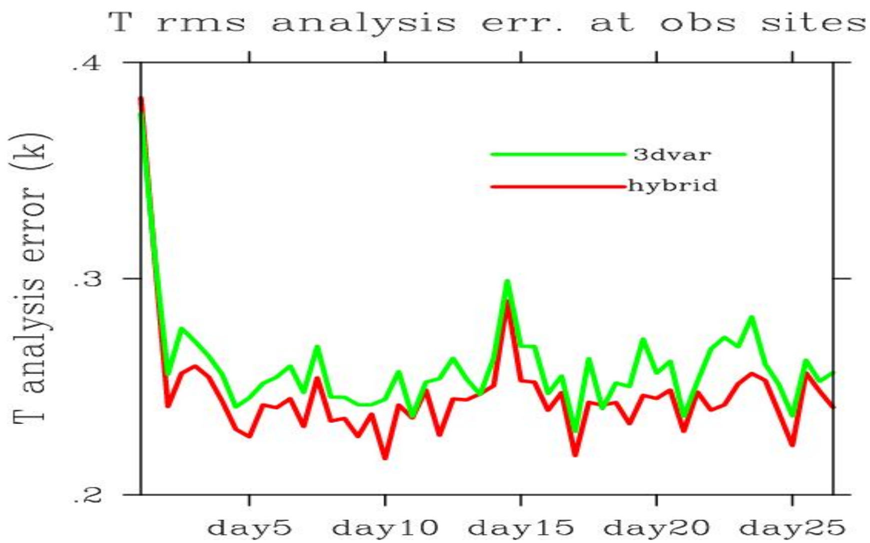
3D-Var

$W_b=0$, $\mathbf{A}=A_v$

Hybrid 1-Month OSSE Trial: Analysis Error (Wang, Barker, Hamill and Snyder 2008a)

- WRF 3D-Var-based study in US domain.
- Low (200km) resolution.
- Sondes only. No cycling.
- Equal weight (0.5) on static/ETKF error covariances
- Hybrid significantly better than the pure 3D-Var:





3. The Met Office Hybrid 4D-Var/ETKF

Operational NWP Models: 19th July 2011

Global

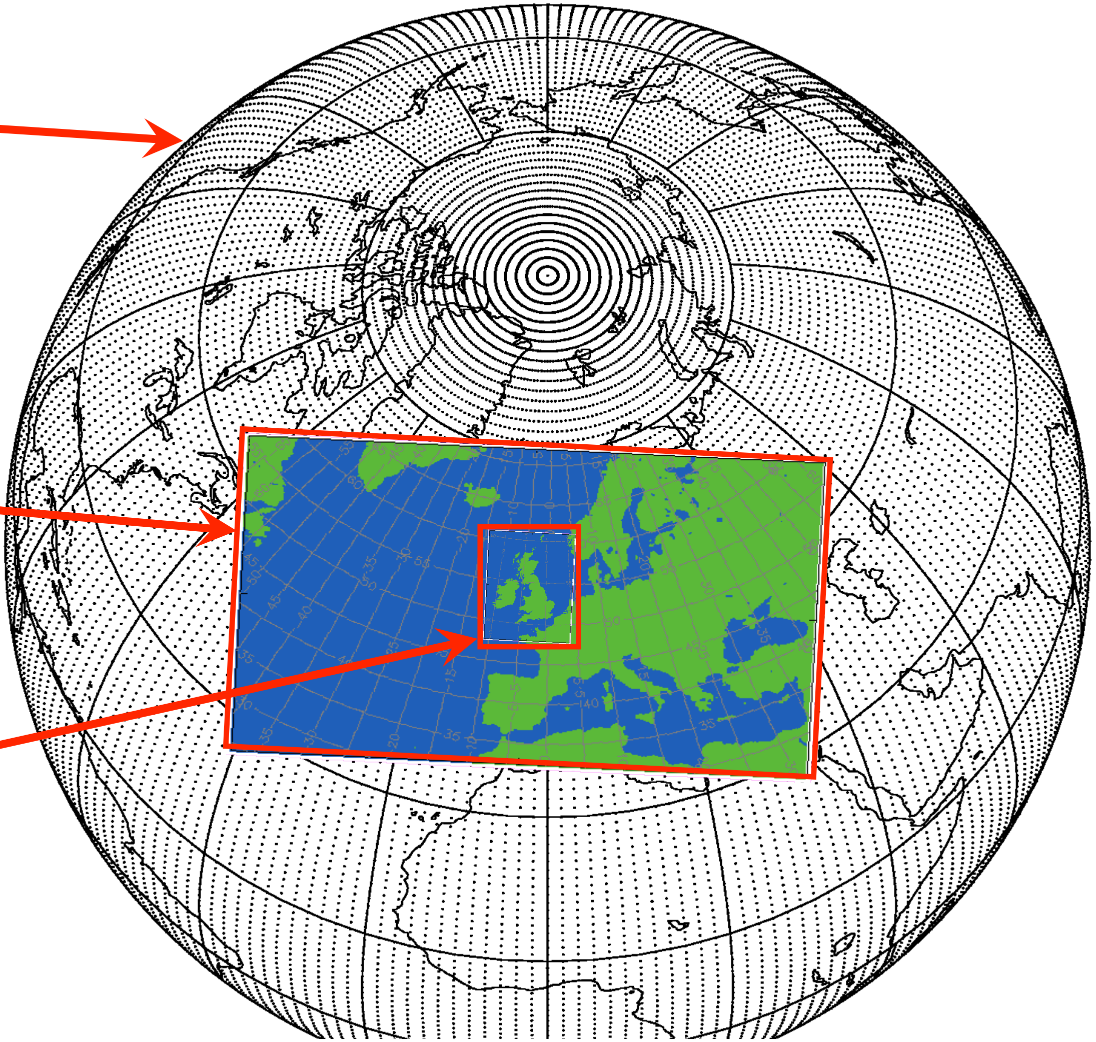
- 25km 70L
- 4DVAR – 60km inner loop
- 60h forecast twice/day
- 144h forecast twice/day
- *+24member EPS at 60km 2x/day*

NAE

- 12km 70L
- 4DVAR – 24km
- 60h forecast
- 4 times per day
- *+24member EPS at 18km 2x/day*

UK-V *(& UK-4)*

- 1.5km 70L
- 3DVAR (3 hourly)
- 36h forecast
- 4 times per day



Met Office Global Regional Ensemble Prediction System = MOGREPS

Operational NWP Models: 20th July 2011

Met Office

Global

- 25km 70L
- Hybrid 4DVAR – 60km inner loop
- 60h forecast twice/day
- 144h forecast twice/day
- *+24member EPS at 60km 2x/day*

NAE

- 12km 70L
- 4DVAR – 24km
- 60h forecast
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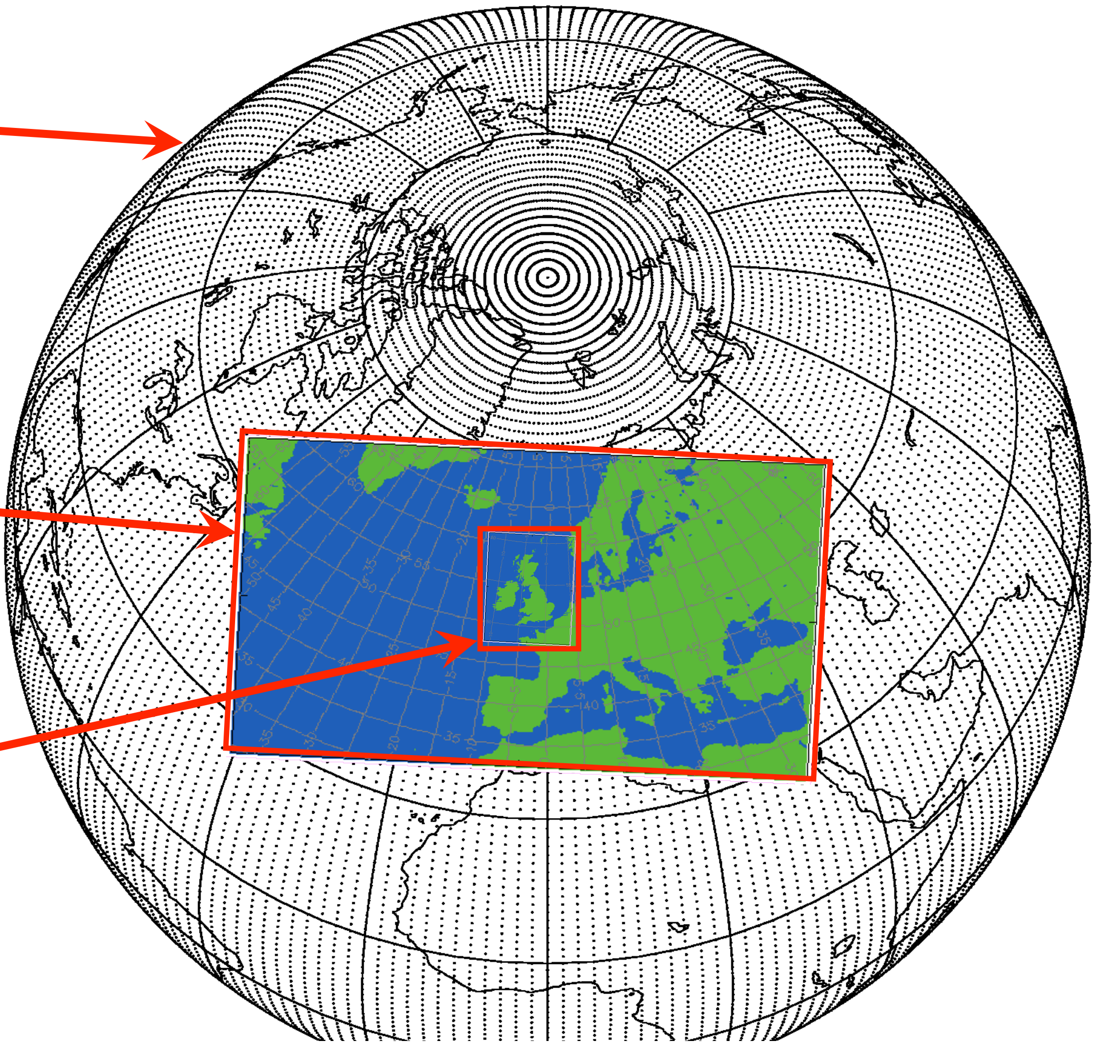
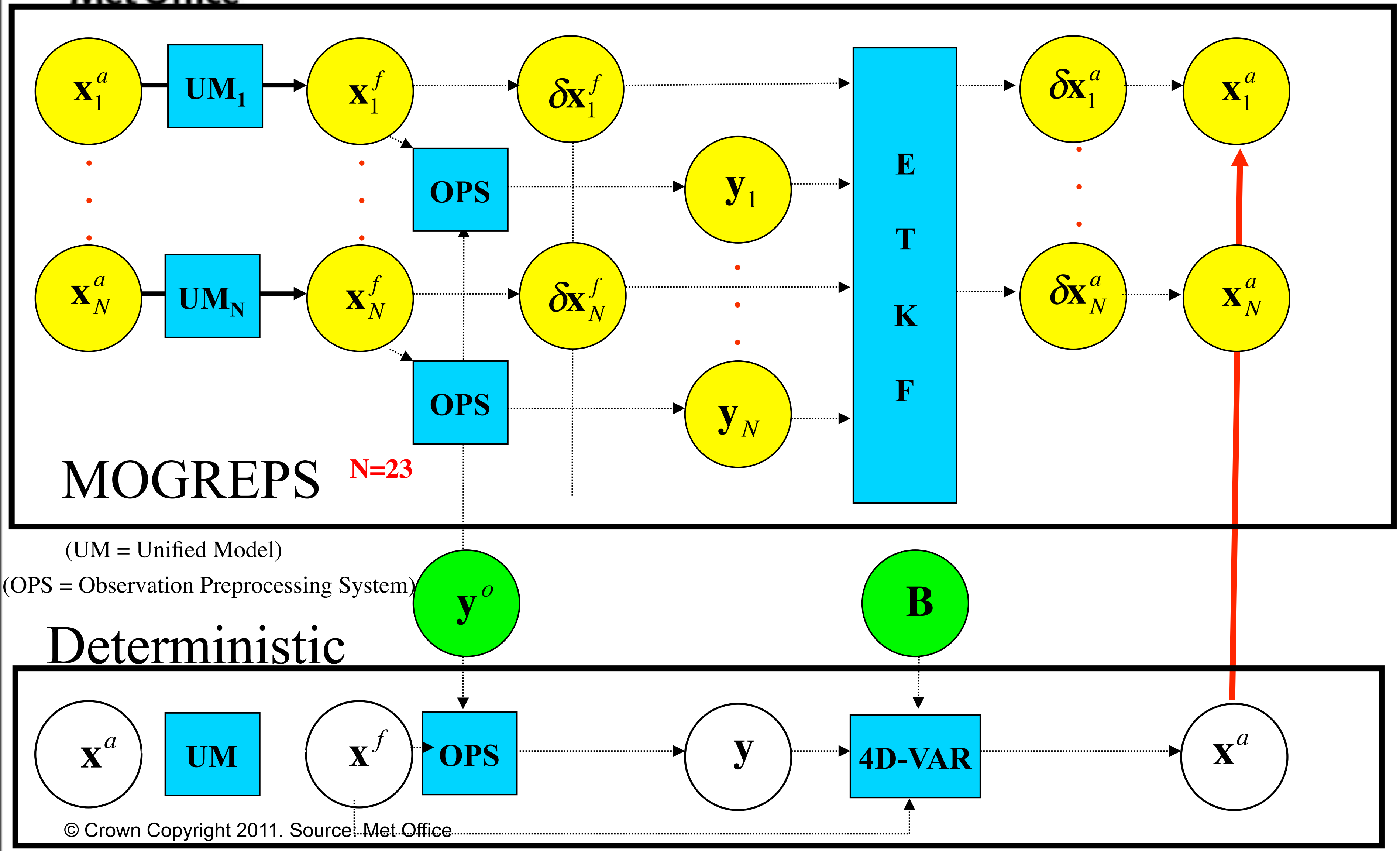


Met Office Global Regional Ensemble Prediction System = MOGREPS

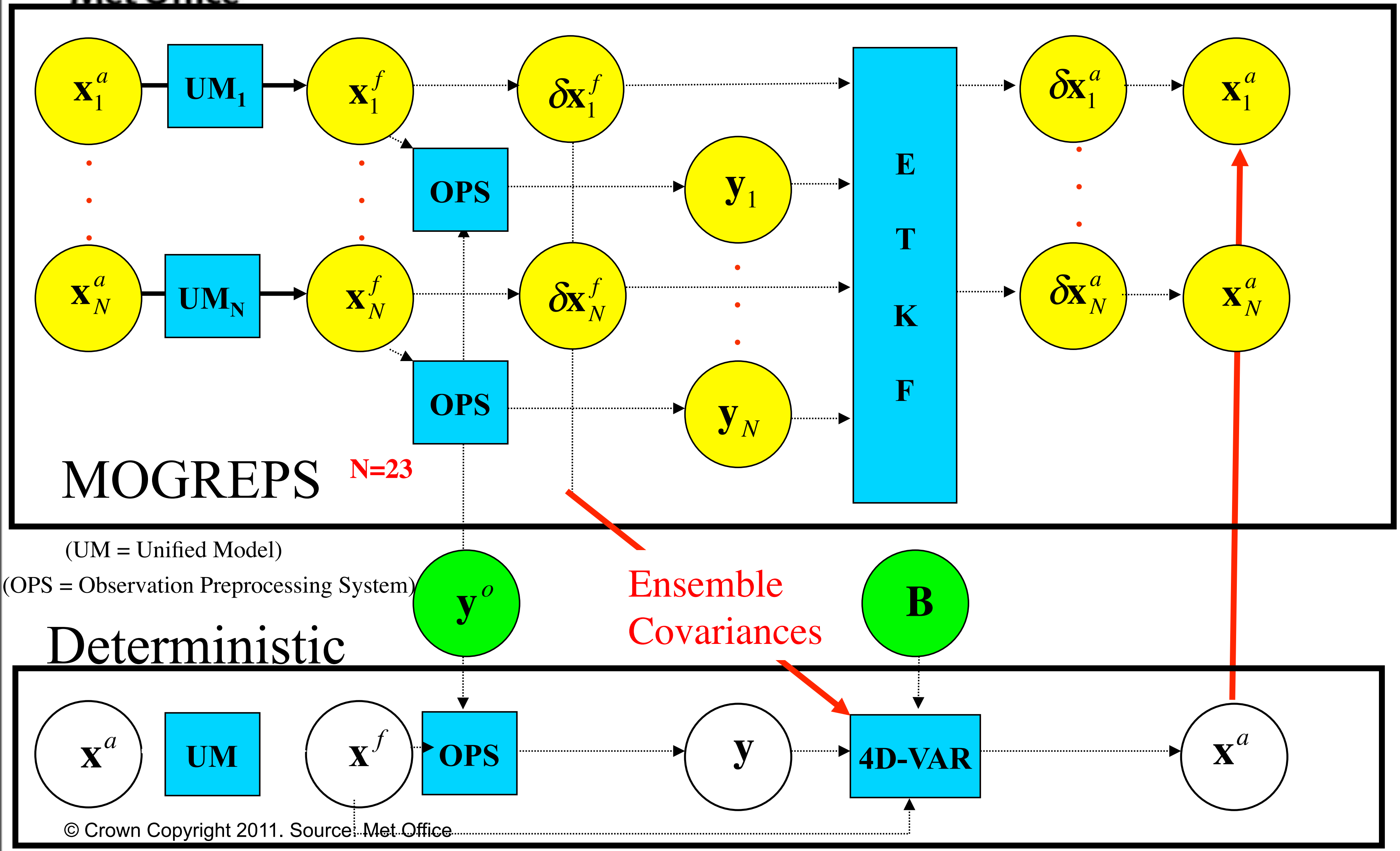
1-Way Coupled 4D-Var/ETKF

$$\mathbf{y}_n = H(\mathbf{x}_n^f), \sigma_o, \ldots \qquad \mathbf{x}_n^a = \mathbf{x}^a + \delta\mathbf{x}_n^a$$



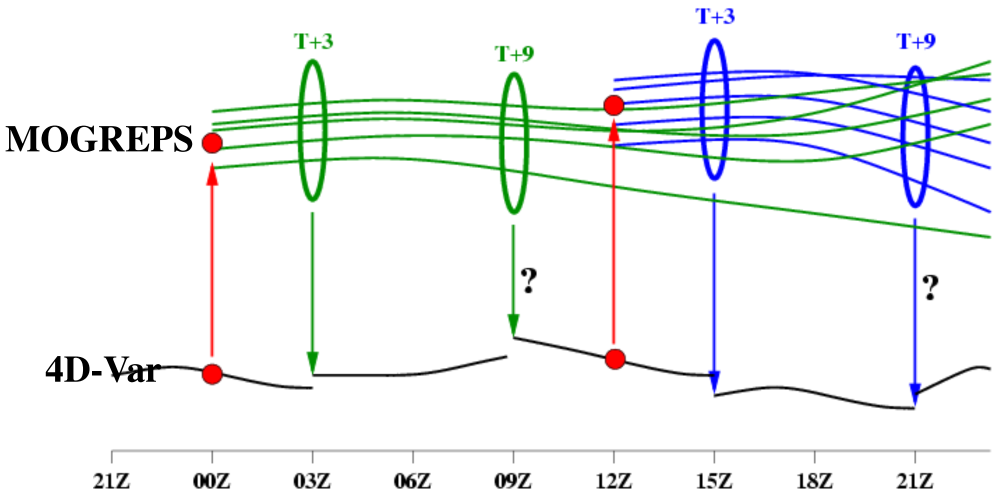
2-Way Coupled 4D-Var/ETKF

$$\mathbf{y}_n = H(\mathbf{x}_n^f), \sigma_o, \ldots \qquad \mathbf{x}_n^a = \mathbf{x}^a + \delta\mathbf{x}_n^a$$



Hybrid V0.0: Trial Configurations

- **Global** **~90km L38** model
  - – Incremental 3/4D-Var (~120km)
  - – 24m ETKF ensemble (~90km)

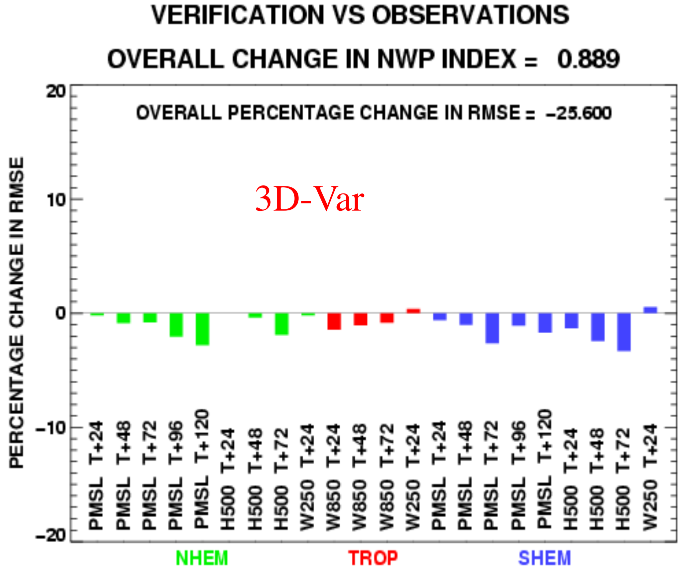


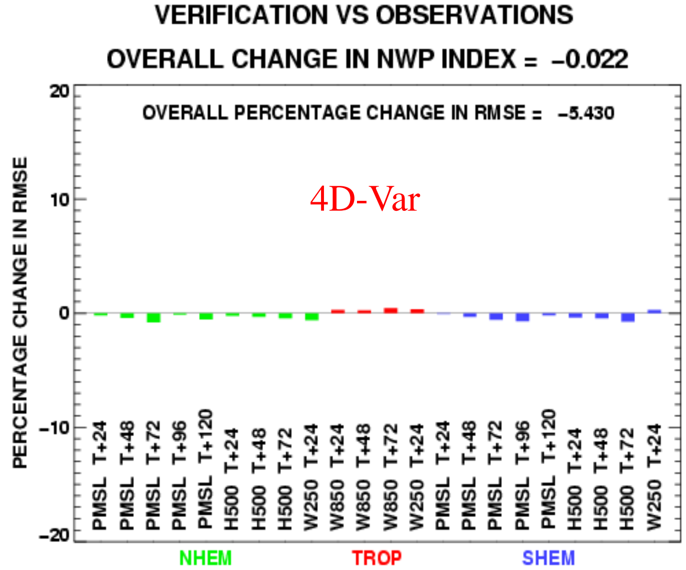
- **Trial period**: 5 – 31st May 2008

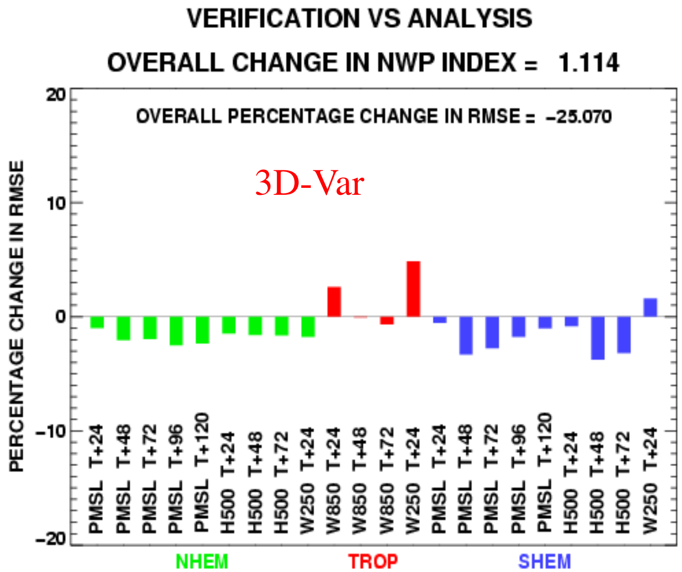
- **Observations:** Surface, Scatwind, Satwind, Aircraft, Sonde, ATOVS, SSMI, AIRS, GPSRO, SSMIS, IASI

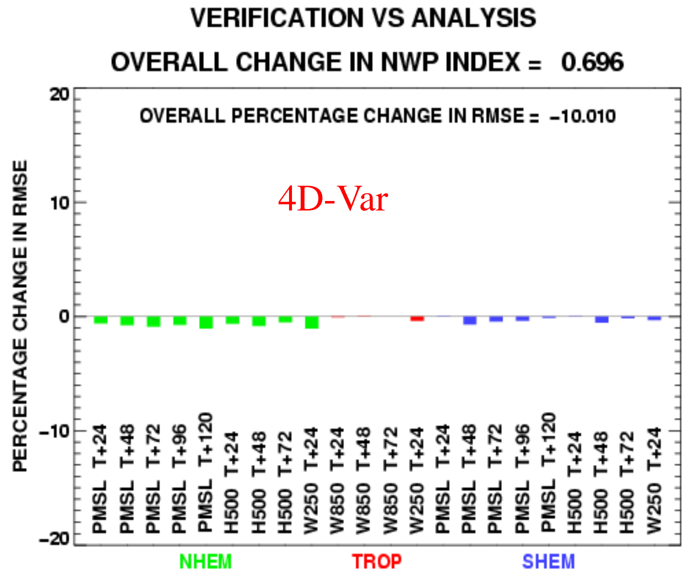
- **Hybrid configuration:**
  - – Localization: 1500km (T10) Gaussian. Horizontal only. 'Balance-aware'.
  - – Climatological/Ensemble Covariances Given Equal Weight (W_b=2).
  - – No tuning.

V0.0 3/4D-Var Hybrid Trial Results









Hybrid V0.0: Trial Results (2010)

- First tests of impact of hybrid in a full observation 4D-Var.
- Initial month-long trials performed (May 2008 period). Verification:

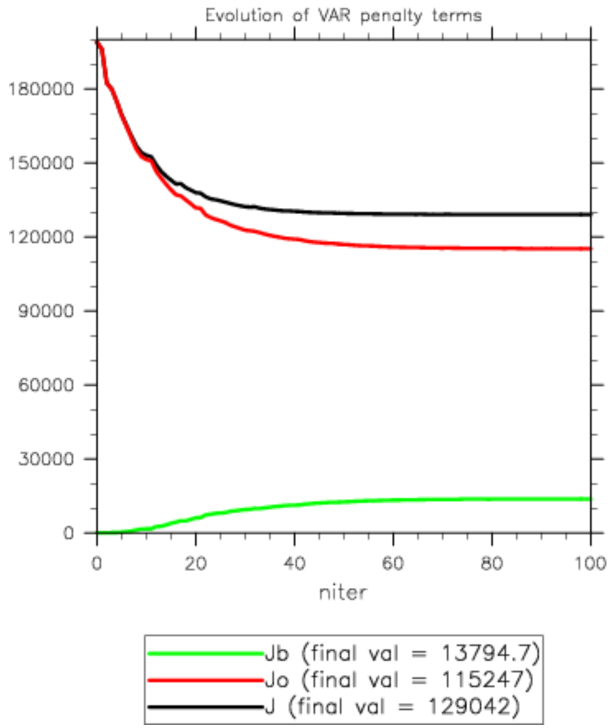
Impact on NWP Index	3D-Var Hybrid vs. 3D-Var	4D-Var Hybrid vs. 4D-Var	4D-Var vs. 3D-Var
Verification vs. Obs	+0.78%	-0.39%	+2.7%
Verification vs. Analysis	+0.94%	+1.33%	+1.3%

- Positive benefit vs. 3D-Var mode, neutral in 4D-Var.
- Reasonably pleasing result given system has not yet been tuned at all.
- Still work to do to justify operational implementation…..

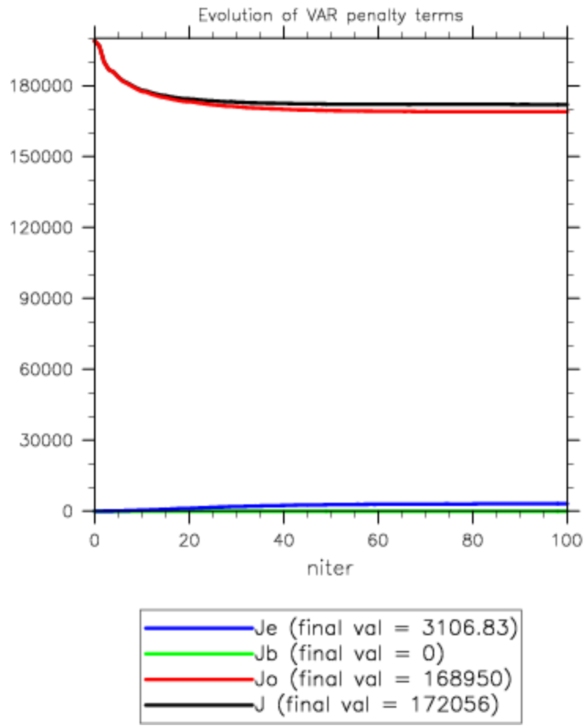
Met Office

3D-Var Hybrid Cost Function Evolution

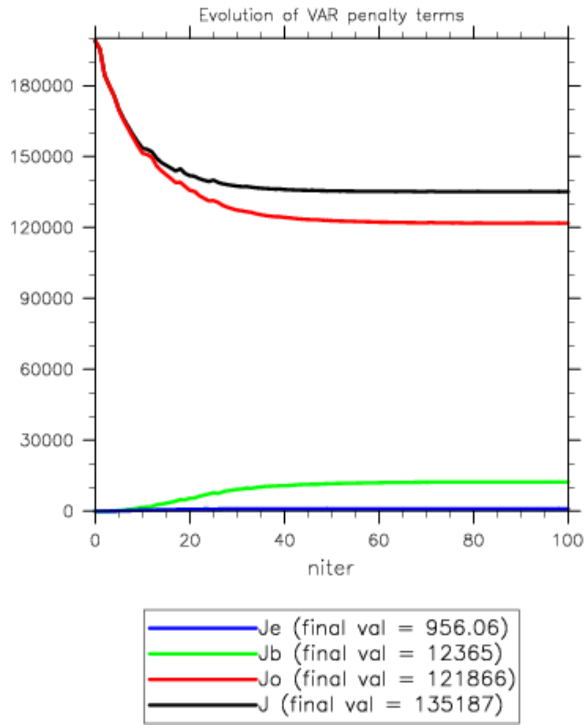
Pure 3D-Var



Pure Ensemble Covariance, Horizontal Localization



Hybrid Covariance, Horizontal Localization

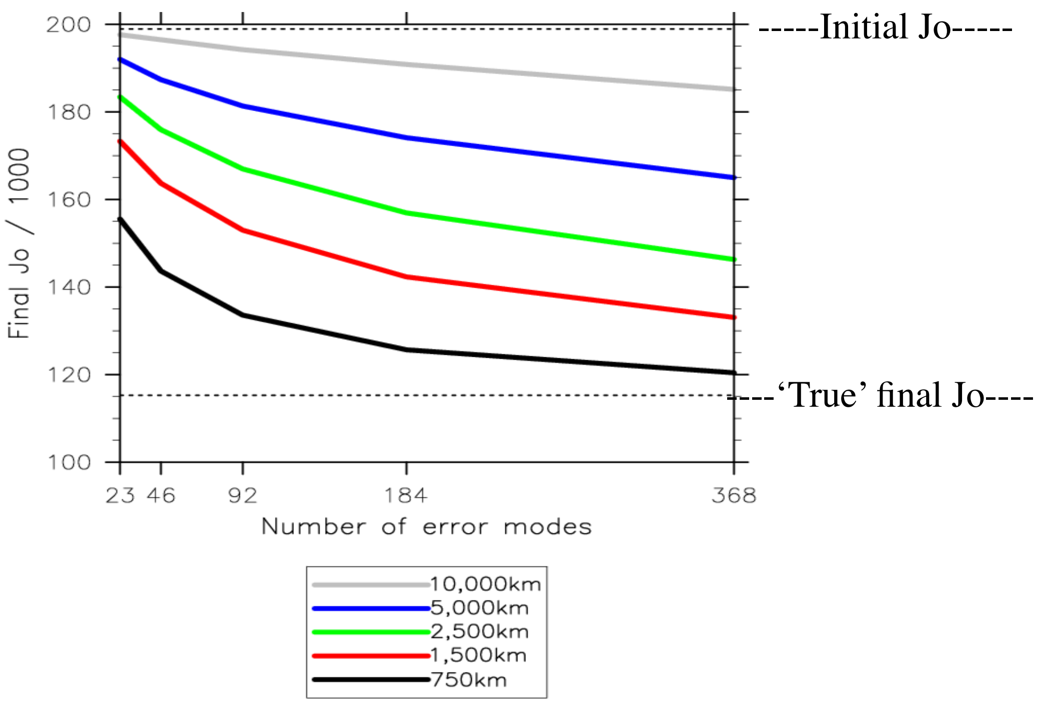


- Ensemble covariances from 24 member ETKF are significantly rank-deficient.
- Observations massively underused.
- Hybrid helps, but still underfitting observations relative to pure 3D-Var.

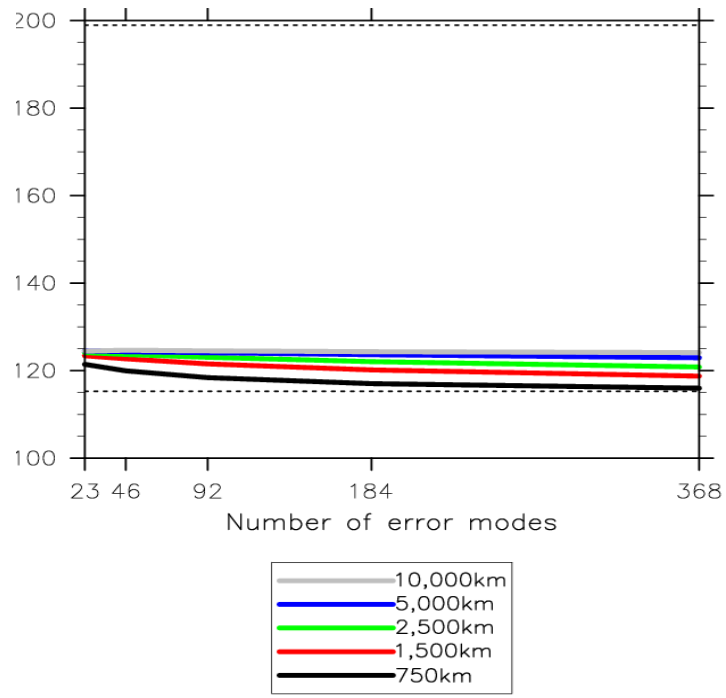
Estimation of Ensemble Sampling Error

Method: Simulate ensemble by sampling climatological **B**. Study effect of ensemble size, localization, hybrid on minimization.

Pure Ensemble Covariance



Hybrid Covariance

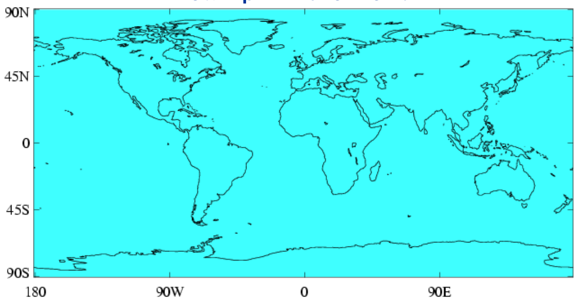


- Pure ensemble covariance still significantly underfitting observations, even with O(400) ensemble members, and reduced localization scales.
- **Solution: Additional covariance inflation to maintain Var fit to observations.**

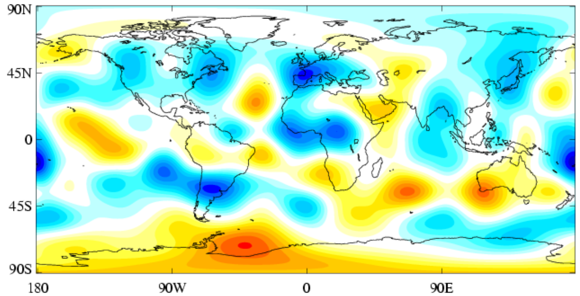
Impact Of Imbalance

- Despite 'balance-aware' localization, hybrid introduces significant imbalance to analysis.
- Cause is large-ensemble pressure perturbations, which get projected onto the localisation scale:

Mean p1 increment

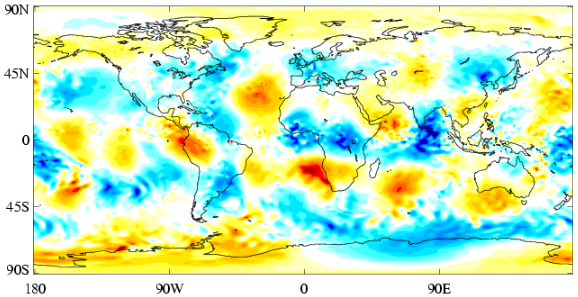


Effect of localisation

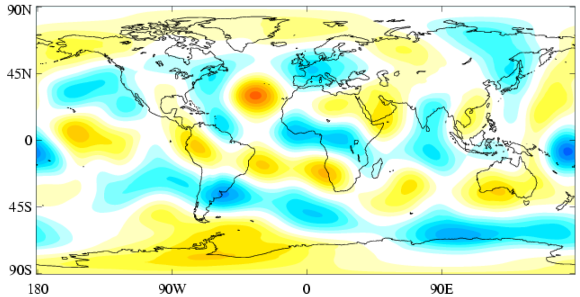


- Mean p (level 1) increment alone explains significant proportion of imbalance:

Full imbalance



Imbalance from global mean pressure increment

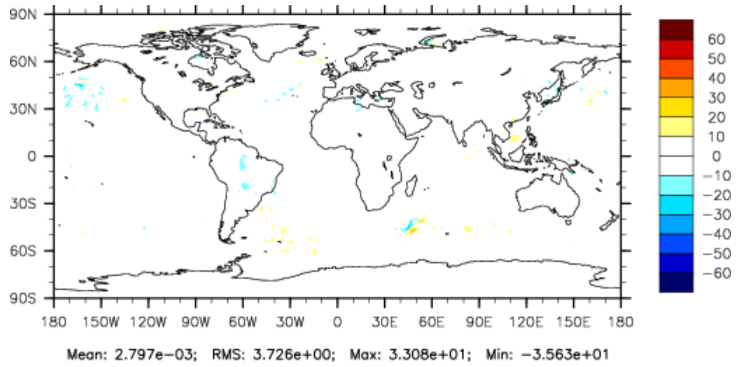


Met Office

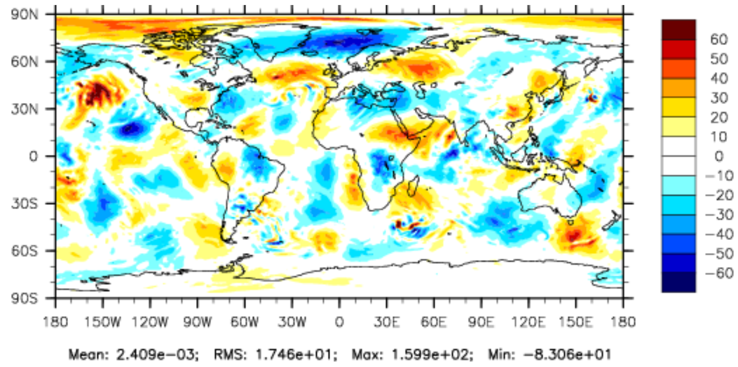
High-pass “anti-aliasing” filter

- **Solution: Scales >> localisation scale filtered from input ensemble perturbations**

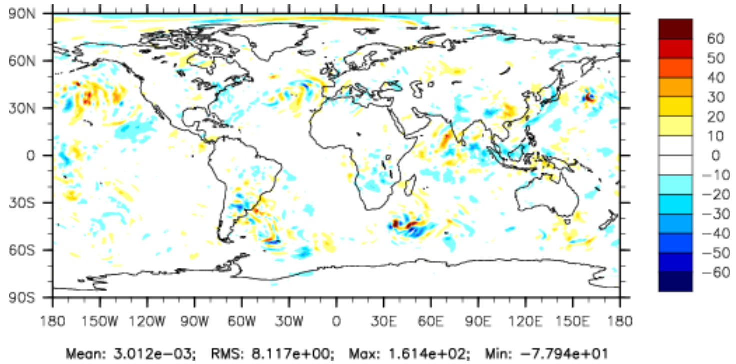
p1 time-filter increment (Pa): without localisation



with localisation



with localisation and high-pass filtering

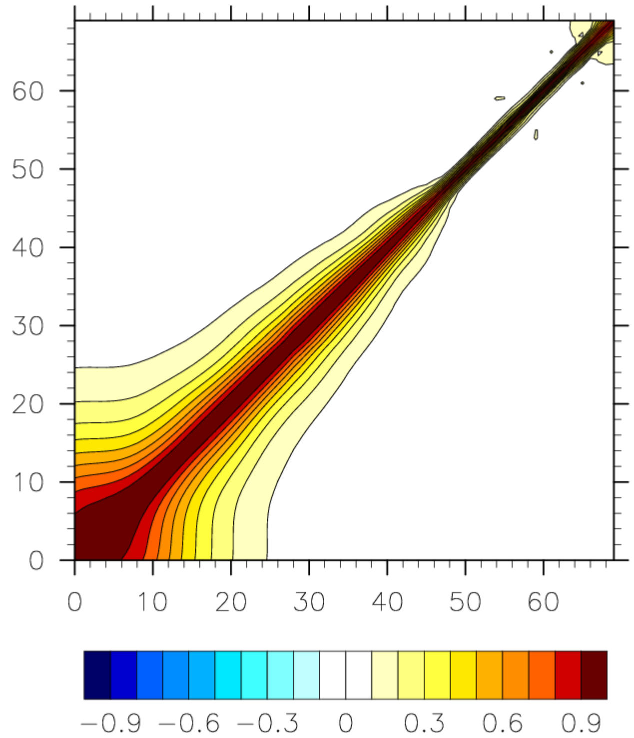


V1.0 4D-Var Hybrid Trials (2011)

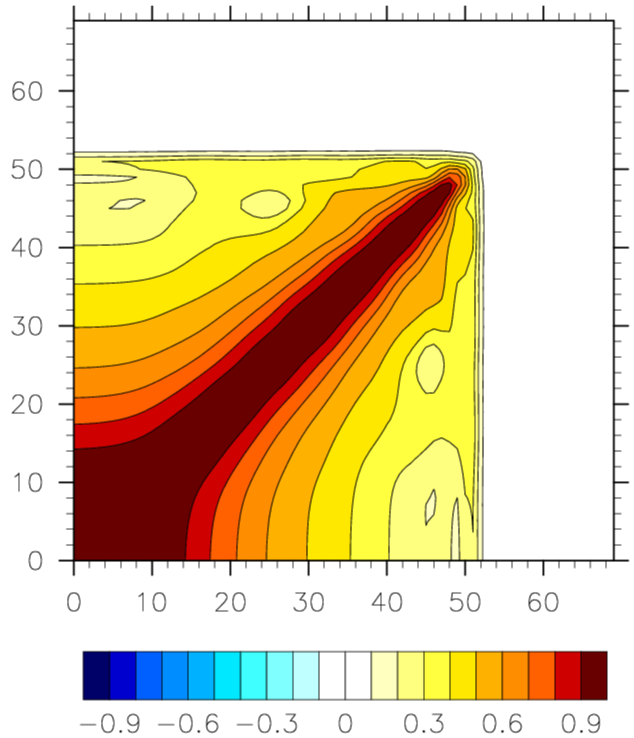
- Two periods: Dec09/Jan10 (29 days, uncoupled); Jun10 (28 days, coupled + uncoupled).
- **Model configuration:**
  - **Global forecast model**: N320L70: ~40km, 70 levels (80km model top).
  - **MOGREPS-G**: N216L70: ~60km. 23 perturbed members.
  - **4D-VAR**: N108L70/N216L70: ~120km→~60km.
- Horizontal localisation scale reduced to L_c = 1200km.
- Vertical localization: EOFS defined by climatological streamfunction covariances
- Relaxation to standard climatological covariances between 16 and 21km.

Met Office Vertical Localisation

- Vertical localisation obtained by modifying the streamfunction correlations from $\mathbf{B}_c$:



Absolute climatological ψ correlations



Localising covariance

- Problem: Significant spurious correlations within stratosphere/mesosphere.
- **Solution: Ensemble covariance removed above 21 km (~ level 54), for safety!**

V1.0 4D-Var Hybrid Trial Results

Verification vs. observations

Better/neutral/worse

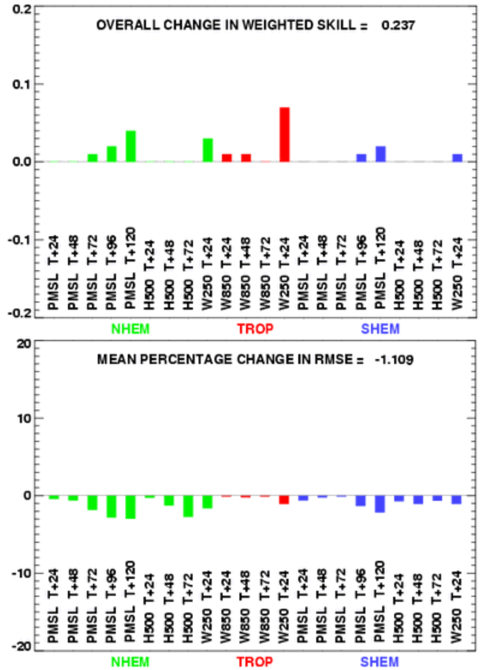
	NH	TR	SH
Dec uncoupled (29 days)	29/94/0	6/117/0	12/109/2
Jun coupled (28 days)	34/89/0	9/114/0	46/74/3

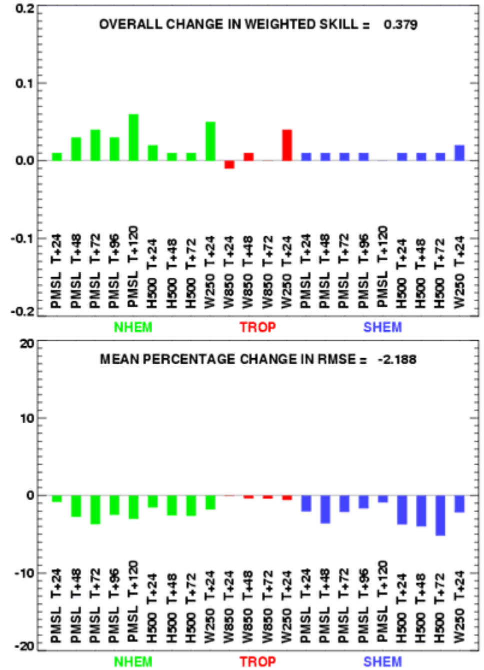
Dec uncoupled: +1.2

Jun coupled: +1.6

Skill:

RMSE:





V1.0 4D-Var Hybrid Trial Results

Verification vs. Met Office analyses

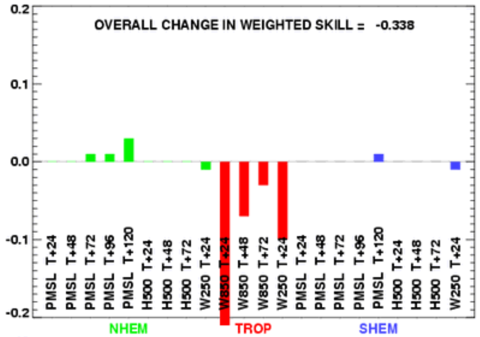
Better/neutral/worse

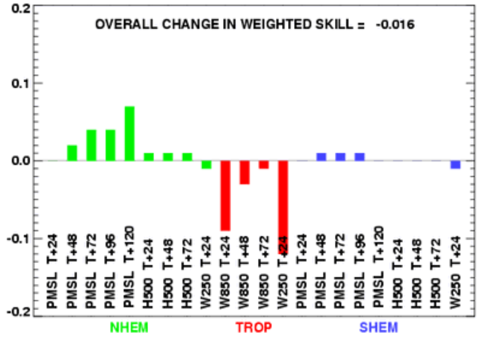
	NH	TR	SH
Dec uncoupled (29 days)	16/91/16	7/69/47	3/106/14
Jun coupled (28 days)	49/63/11	9/86/28	18/82/23

Dec uncoupled: -4.0

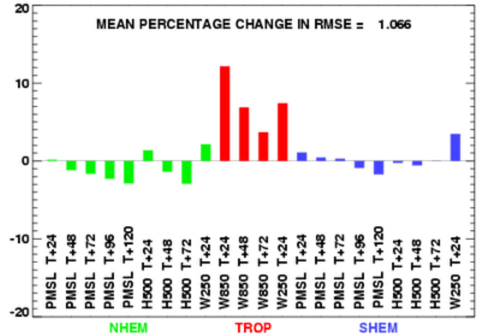
Jun coupled: -0.2

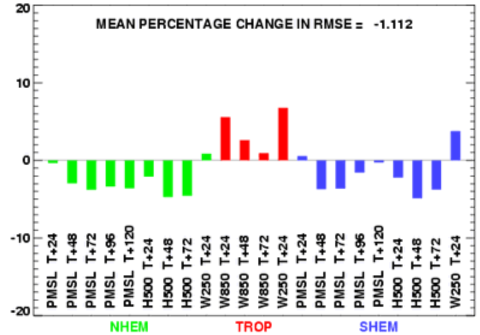
Skill:





RMSE:





V1.0 4D-Var Hybrid Trial Results

Verification vs. ECMWF analyses

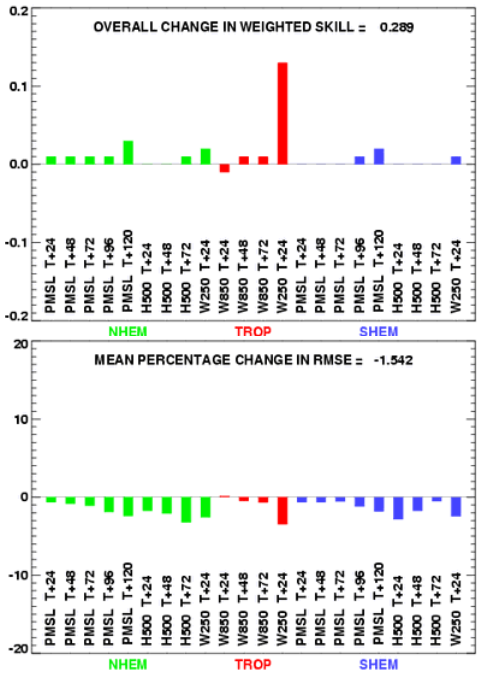
Better/neutral/worse

	NH	TR	SH
Dec uncoupled (29 days)	35/79/0	39/75/0	14/100/0
Jun coupled (23/28 days)	51/63/0	27/87/0	46/66/2

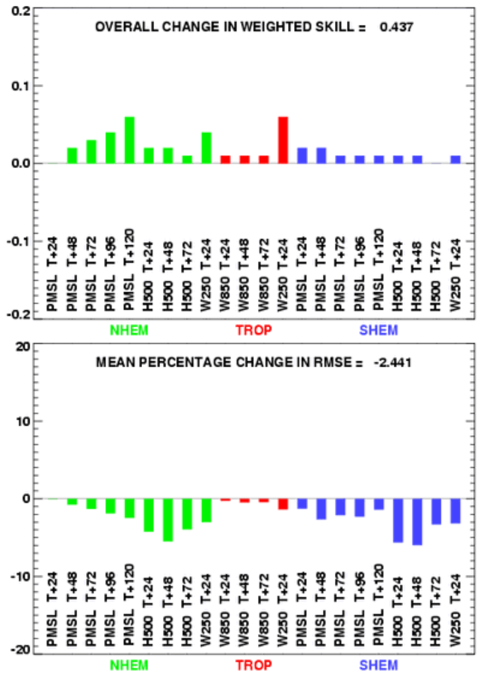
Skill:

RMSE:

Dec uncoupled: 1.721 (1.338%)



Jun coupled: 1.337 (1.298%)



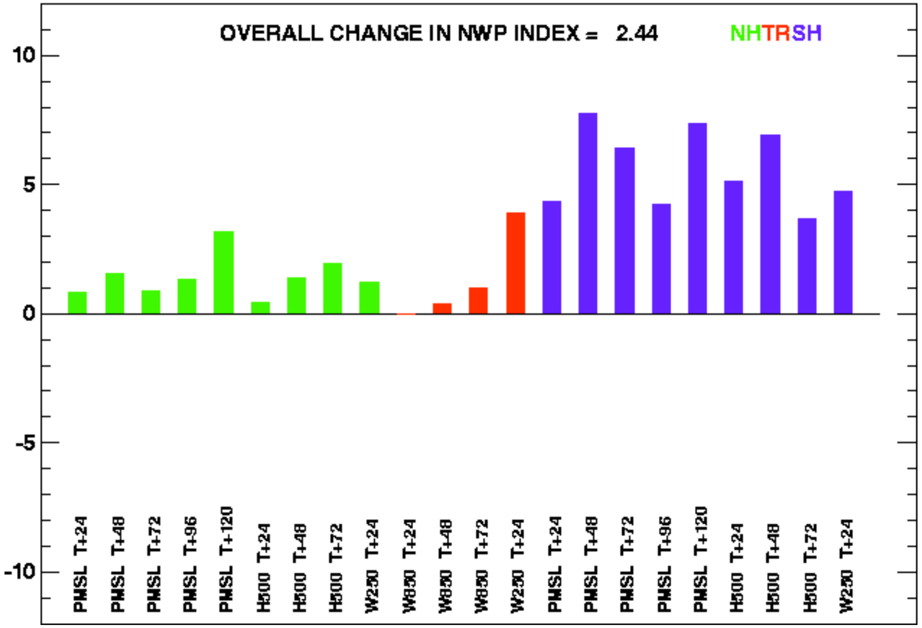
July 2011 Global Data Assimilation Upgrade **Package**

- Assimilation method
  - Hybrid 4D-Var algorithm.
  - Moisture control variable: Replacing RH with scaled humidity variable
- Observation changes
  - Introduce METARS
  - GOES/Msat-7 clear-sky radiances, extra IASI (land)
  - Revisions to MSG clear-sky processing and GPSRO
  - Reduced spatial thinning (ATOVS/SSMIS/IASI/AIRS/ aircraft)

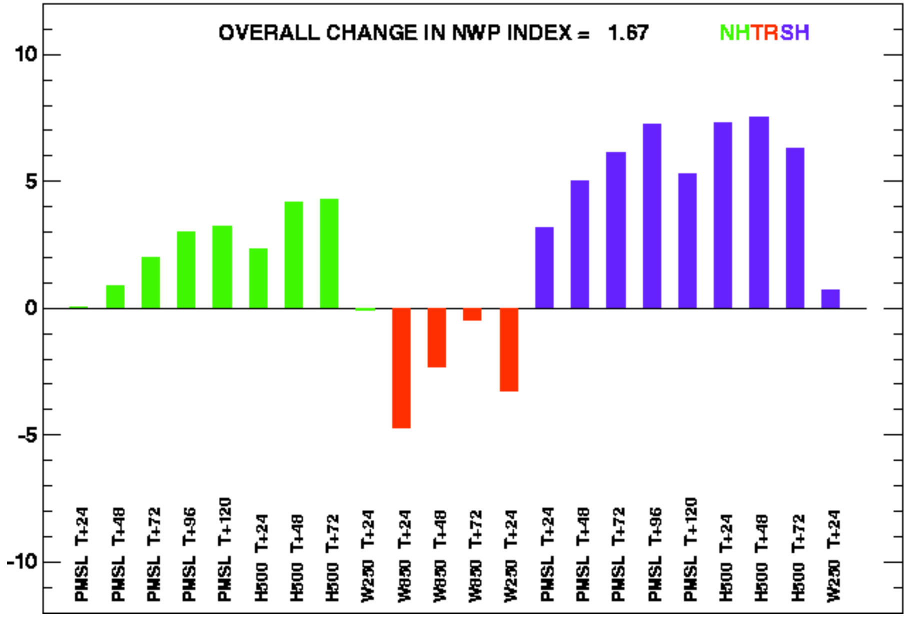
DA/SA Upgrade Pre-Operational Testing: June 20 – July 27 2011

%Reduction in RMSE For Critical Met Office Forecast Parameters:

Vs. Observations



Vs. Met Office analyses



- Biggest reduction in overall global forecast error for many years.
- First time in memory that all parameters have reduced error vs obs. (usually a mix).

4. Future Work

Operational NWP Configs: Spring 2013 (Tentative)

Met Office

Global

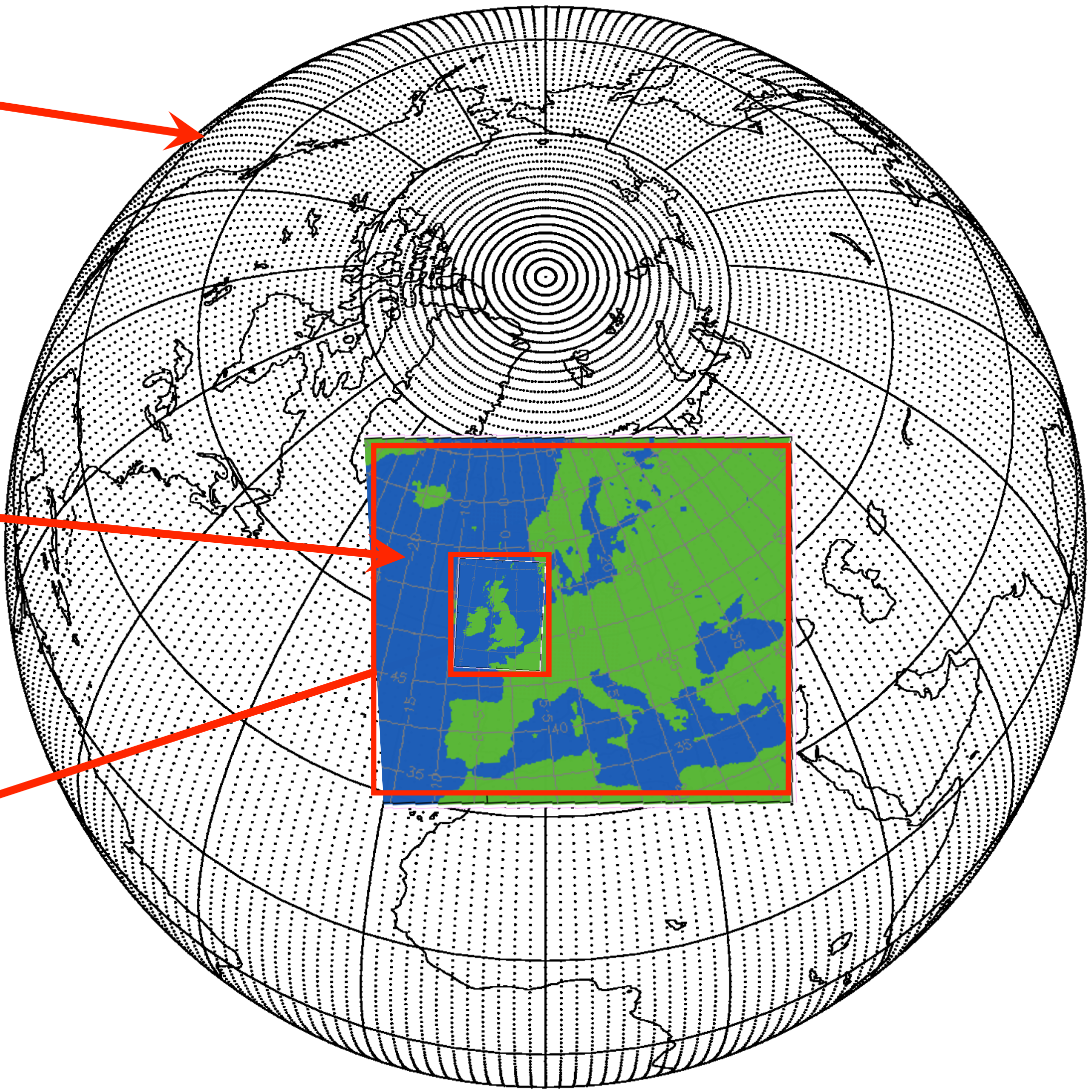
- 16-20km 85L (85km top)
- Hybrid 4DVAR (50km inner-loop)
- 60 hour forecast twice/day
- 144 hour forecast twice/day
- 48/12member 40km MOGREPS-G 4*

MOGREPS-EU

- Common NWP/reanalysis domain.
- 12Km 70L (40km top)
- 3D-Var (or NoDA)
- 48 hour forecast
- 12 members ; 4 times per day

UKV

- 1.5km 70L (40km top)
- 3DVAR (hourly)
- 36 hour forecast, 4 times per day
- 12 member 2.2km MOGREPS-UK



Met Office

Operational NWP Configs: Dec 2015(Very Tentative!)

Global

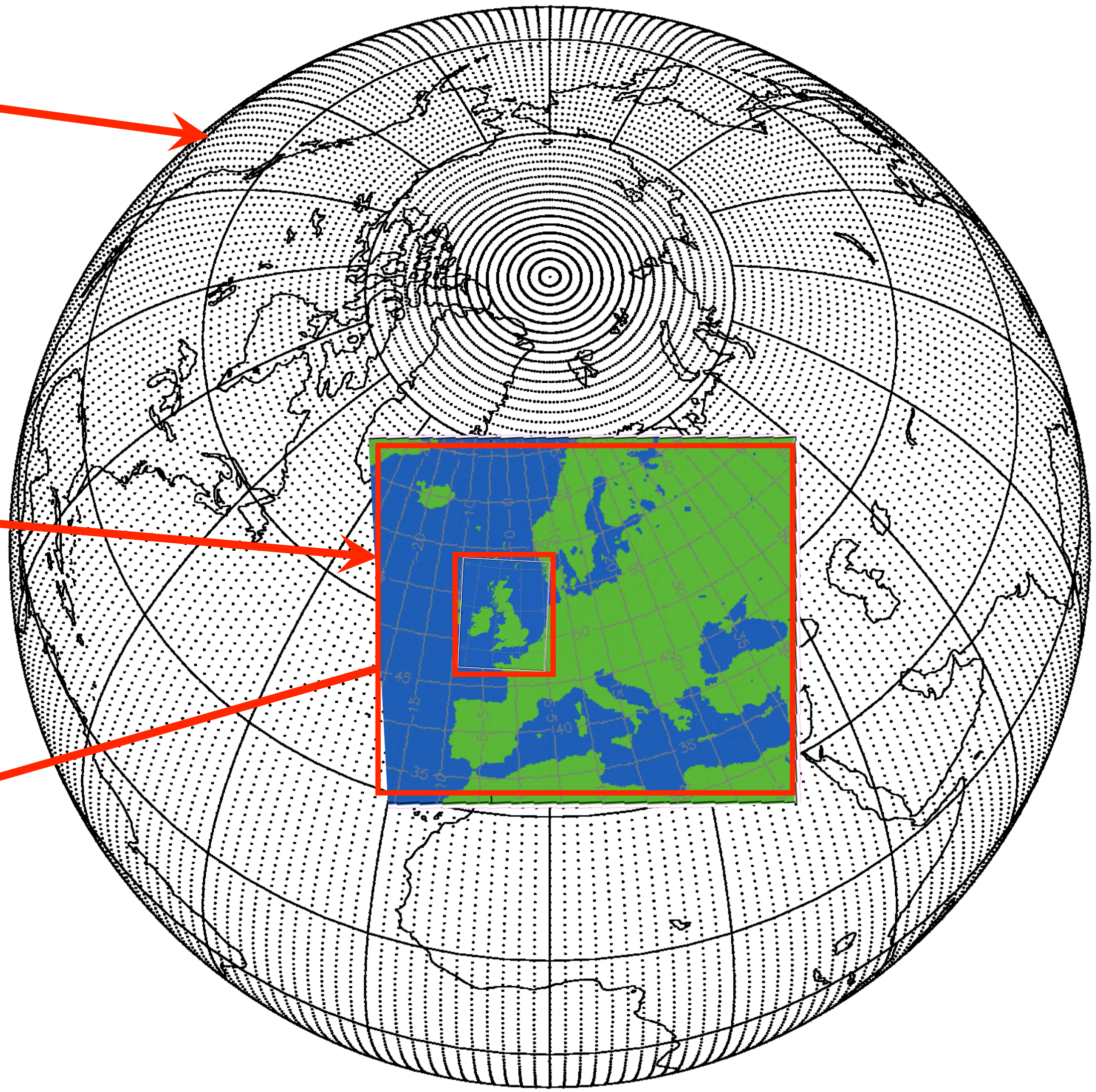
- 12-14km 110L (85km top)
- EnDA (in variational framework)
- 60 hour forecast twice/day
- 144 hour forecast twice/day
- 192/24member 30km MOGREPS-G

MOGREPS-EU

- Common NWP/reanalysis domain.
- 12Km 70 L (40km top)
- NoDA (or possibly still 3D-Var?)
- 48 hour forecast
- 4 times per day

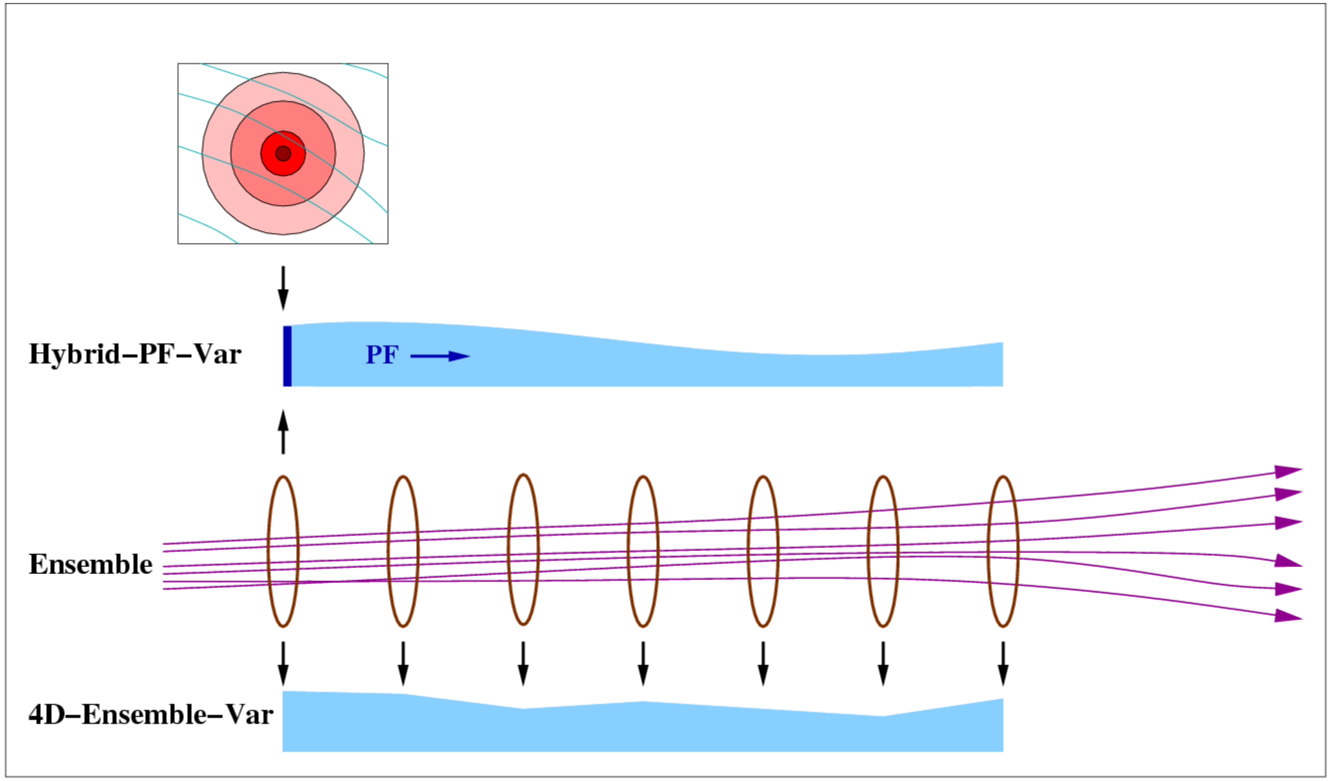
UKV

- 1.5km 70L (40km top)
- Hybrid 4DVAR (or EnDA?)
- 36 hour forecast
- 4 times per day
- 40 member 2.2km MOGREPS-UK



Beyond hybrid: 4D-Ensemble-Var

- Current hybrid just the first step in tighter coupling of DA and ensemble forecasting…



Strategy Going Forward

- Continue to optimize 4D-Var: SE + algorithmic changes.

- Continue to develop hybrid for short/medium-term (1997-2015):
  - Increase ensemble size, more sophisticated localization, etc.
  - Consider replacing ETKF as ensemble perturbation generator.
  - Develop convective-scale hybrid 3/4D-Var (2012-2015).

- Develop 4D-Ensemble-Var:
  - Code and test within current VAR framework (2011-2013).
  - Extend to an ‘Ensemble of 4D-Ensemble-Vars’ (2013-2015).
  - Retire PF model if/when 4D-Ensemble-Var beats 4D-PF-Var.

Thank you!