

Trials of the Met Office 4DEnVar system

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4th International Symposium on Data Assimilation, Kobe, February 24th 2015

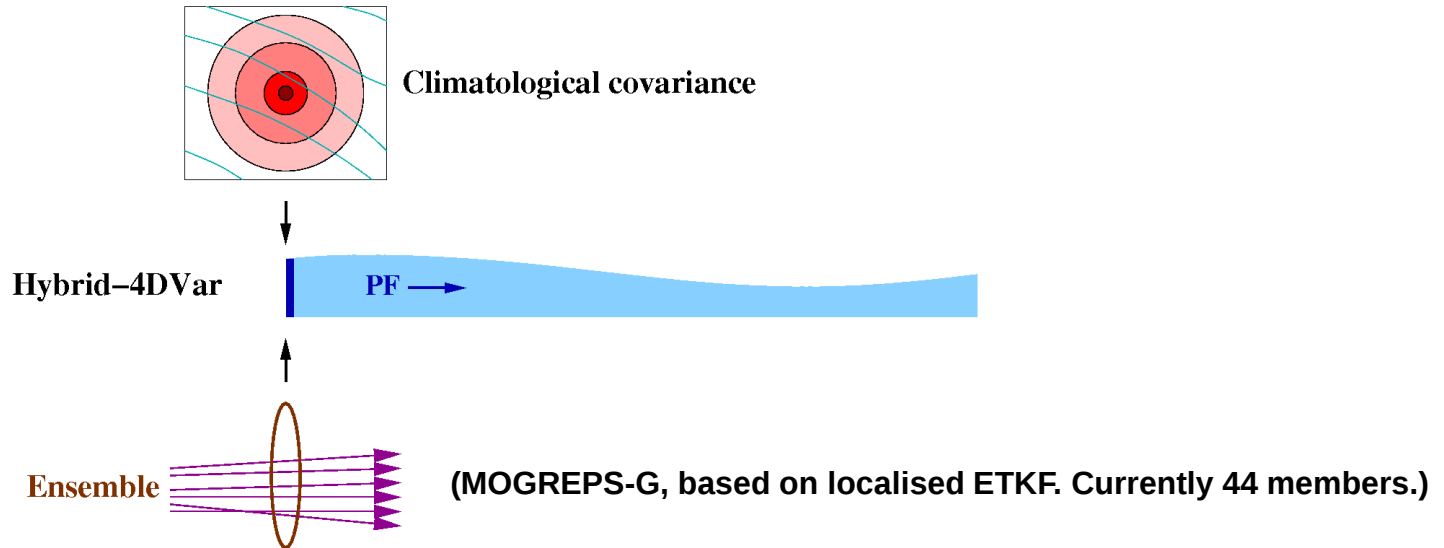


Outline of talk

- Hybrid-4DVar → Hybrid-4DEnVar
- Hybrid-4DEnVar trials at KMA
 1. Increased ensemble weight and size
 2. Correction to columnar mass-divergence
 3. Horizontal waveband localisation
- "Optimal" vertical localisation
- Future work

Hybrid-4DVar

(Operational at the Met Office since July 2011)



- Background error covariance at beginning of window:

$$\mathbf{B} = \beta_c^2 \mathbf{B}_c + \beta_e^2 \mathbf{B}_e$$

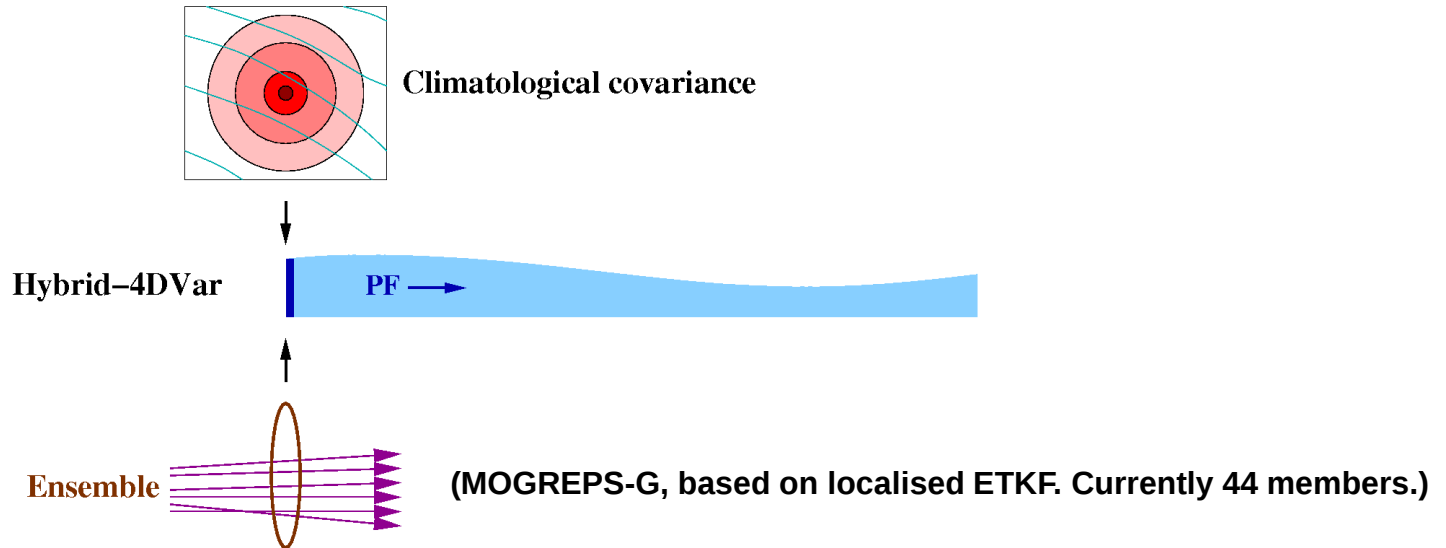
Climatological covariance Ensemble covariance

$$\mathbf{B}_e = \mathbf{C} \circ \mathbf{P}_e^f$$

Spatial localisation covariance Raw ensemble covariance

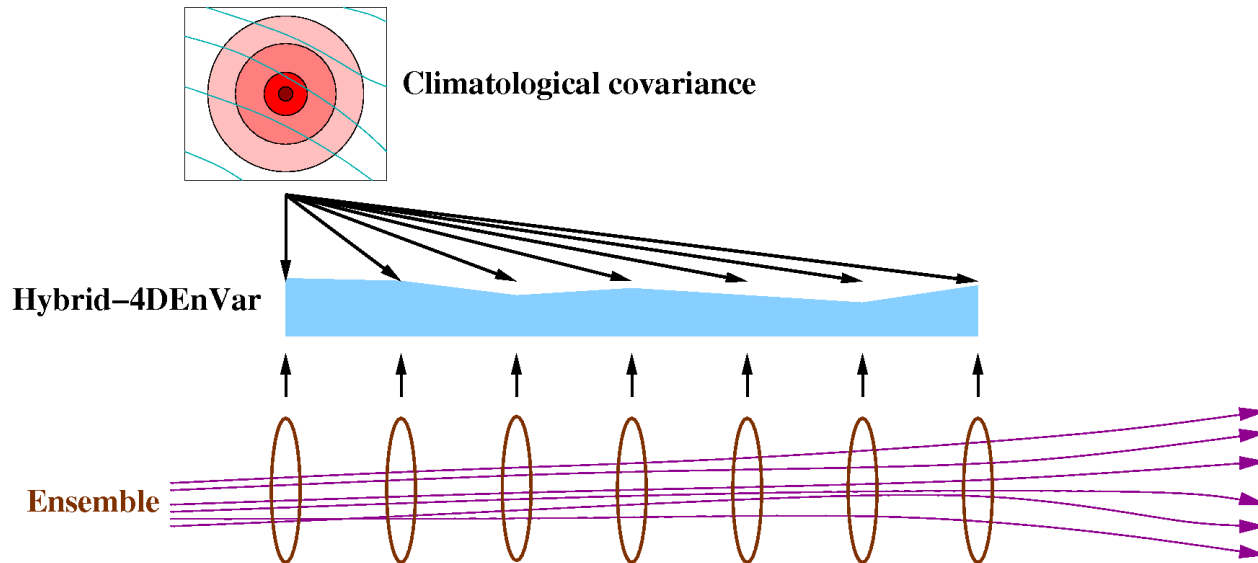
Hybrid-4DVar

(Operational at the Met Office since July 2011)



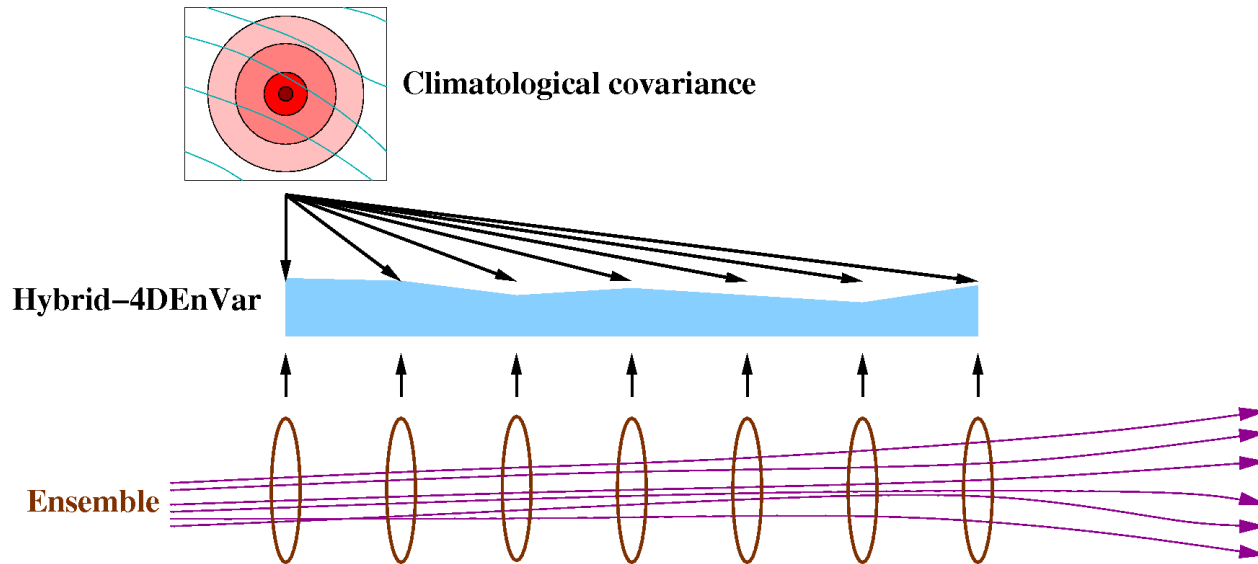
- **B** implicitly propagated by a linear “Perturbation Forecast” (PF) model:
 - ~100 PF + adjoint forecasts run serially.
 - But PF model doesn’t scale well.
 - And difficult to keep PF model in line with forecast model.
- We need an alternative scheme for future supercomputers that excludes the PF model...

Hybrid-4DEnVar



- No PF model, but much more IO required to read ensemble data:
 - 11 times faster with 22 N216 members and 384 PEs. (IO around 30% of cost)
- Analysis consists of two parts:
 - A 3DVar-like analysis based on the climatological covariance $\mathbf{B}_c$
 - A 4D analysis consisting of a linear combination of the ensemble perturbations.
- Localisation is currently in space only: same linear combination of ensemble perturbations at all times.

Hybrid-4DEnVar



- Generalises to a unified deterministic/ensemble analysis system: **En-4DEnVar**.
- (Met Office En-4DEnVar system completed, and currently being tuned.)

Results from early low-resolution trials

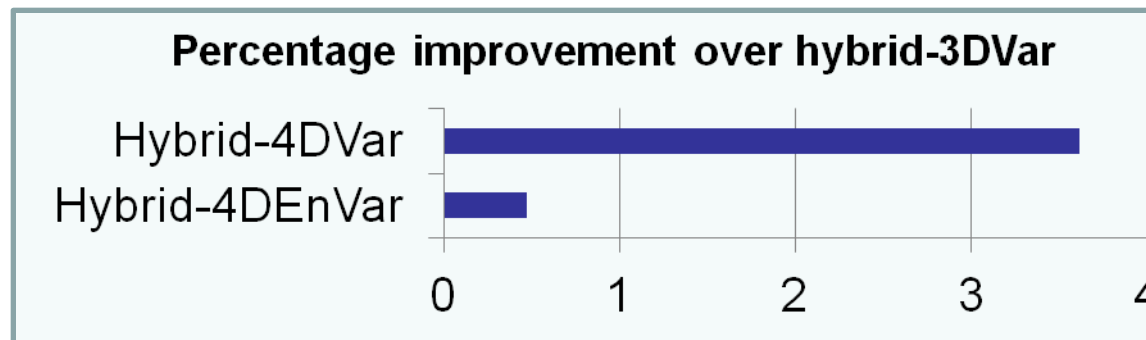
Forecast: ~42 km

Period:

July 2013

Ensemble: ~62 km, 44 members

Hybrid weighting: 80% $\mathbf{B}_c$ / 50% $\mathbf{B}_e$



- Results reported in Lorenc et al (2015), Mon. Wea. Rev..
- Poor 4DEnVar performance vs. 4DVar mainly due to 3DVar-like $\mathbf{B}_c$.
- So success of hybrid-4DEnVar depends on reducing the dependency on $\mathbf{B}_c$:
 - Better processing of the ensemble
 - Better and larger ensembles



Hybrid-4DEnVar trials at KMA

Forecast: ~25 km

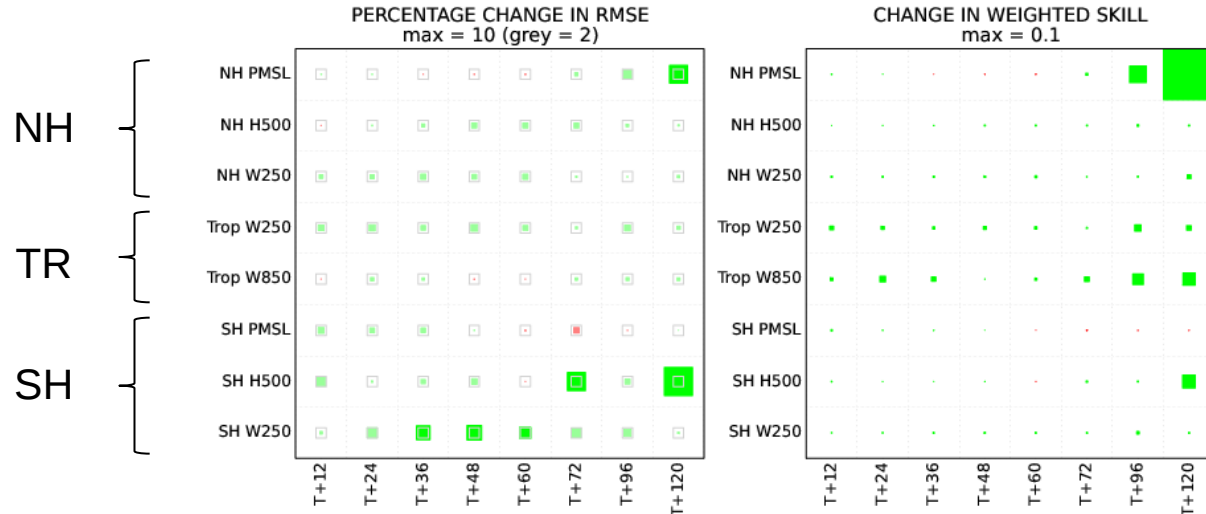
Period: 8-13 August 2013 (23 days)

Ensemble: ~33 km

Analysis: ~33 km 4DEnVar or ~48 km 4DVar

- **Verification**

- Met Office “NWP index” fields against observations.
- Example:

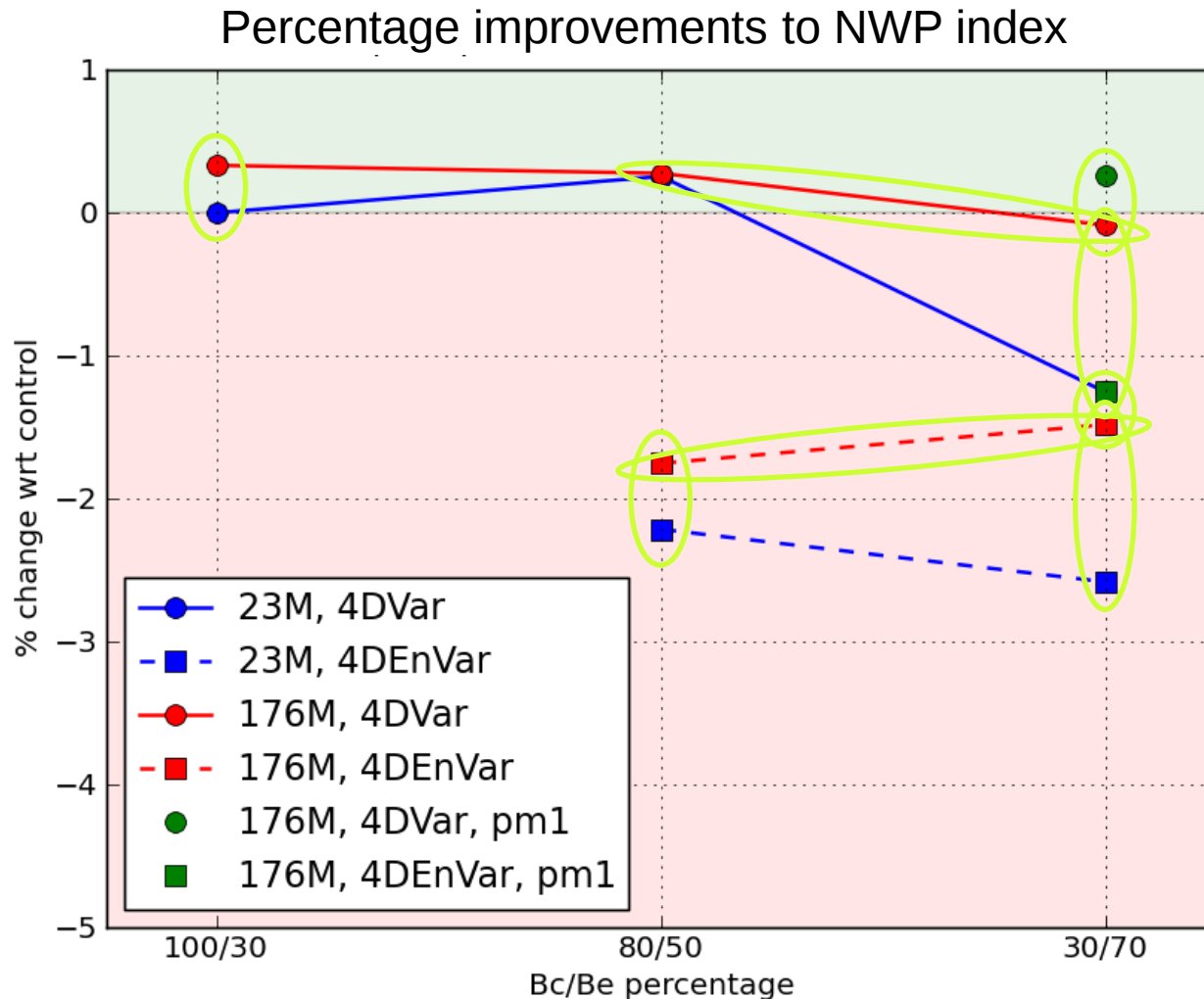


Change to index:
+0.973 %

- Overall NWP index is the sum of the weighted skill scores.
- **Typical yearly improvement:** 1~2%, from model and DA changes.

Hybrid-4DEnVar trials at KMA

Increased ensemble size and weight



Modest improvement when increasing the ensemble size

But much larger improvement when the ensemble weight is high

4DVar performs worse with high ensemble weight, 4DEnVar performs better

Using ensemble modes from the wrong time ("pm1": +/- 1hr) brings a small benefit

Hybrid-4DEnVar trials at KMA

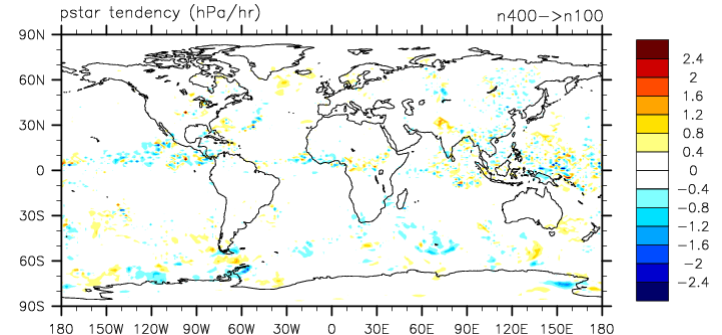
Correction to columnar mass-divergence

- Surface pressure tendency given by vertically-integrated mass convergence:

$$\frac{\partial p_0}{\partial t} = - \sum_{k=1}^N \nabla \cdot (\Delta p_k \mathbf{v}_k)$$

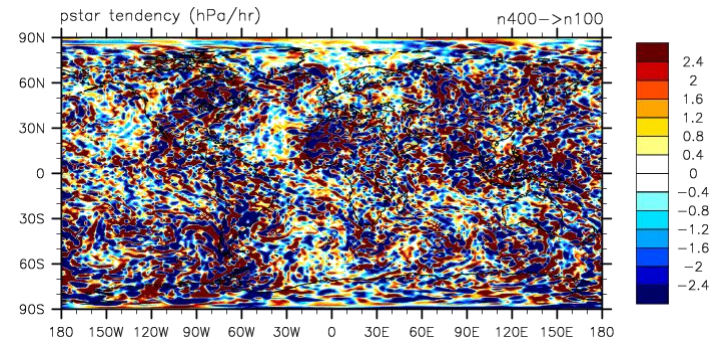
- Dines compensation:**

Mass convergence into a column is approximately balanced by mass-divergence, so surface pressure tendency is relatively small:



Random $\mathbf{B}_e$ sample (no localisation)

- However, vertical localisation destroys this balance:



Random $\mathbf{B}_e$ sample (vert. localisation)

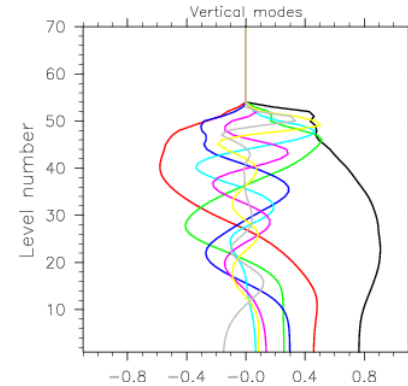


Met Office

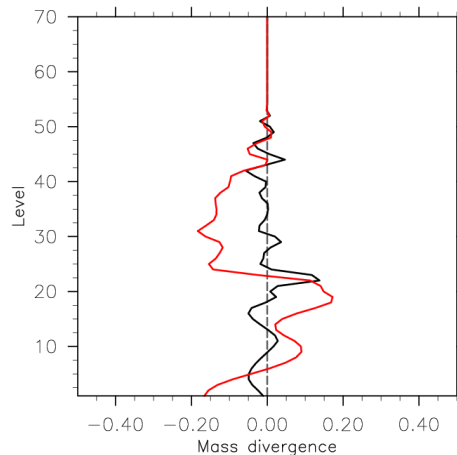
Hybrid-4DEnVar trials at KMA

Correction to columnar mass-divergence

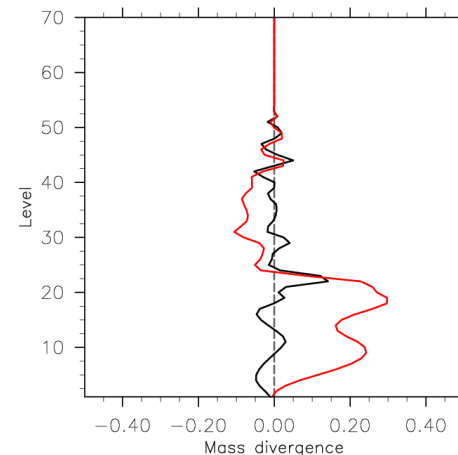
- Imbalance is caused by projection onto the eigenvectors of the vertical localisation matrix:



- To restore balance, we add a correction to the velocity potential increments. (Same correction field at all levels, but multiplied by β_e .)



Without correction



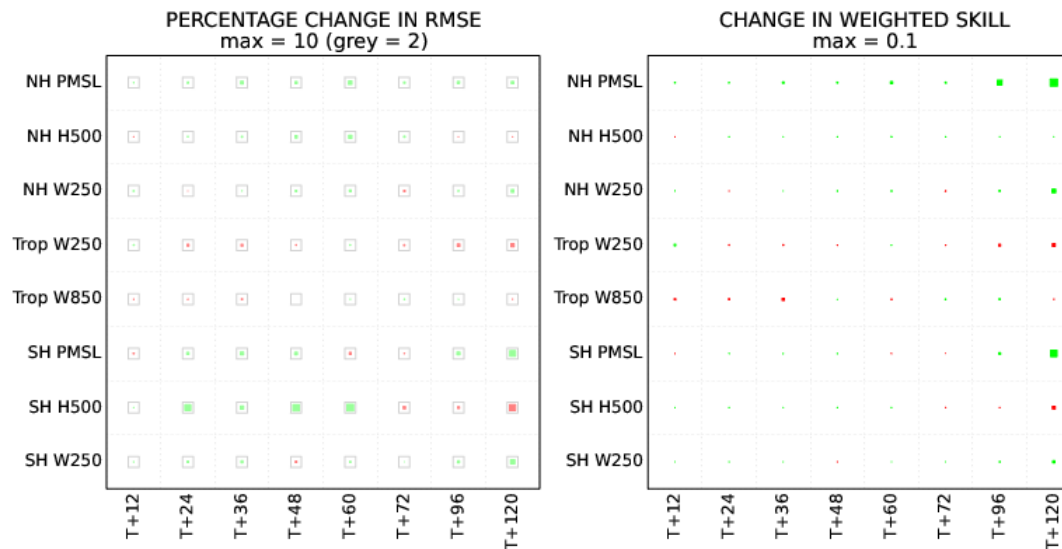
With correction

— Accumulated mass-divergence from the top of the model.

Hybrid-4DEnVar trials at KMA

Correction to columnar mass-divergence

- Diagnostics show a significant improvement in balance.
(E.g. projection on 4DVar J_c term reduced by around 75%.)
- Control trial:** 4DEnVar, 30% $\mathbf{B}_c$ / 70% $\mathbf{B}_e$, 176 error modes.
- Results:**



Change to index:
+0.131 %

- Basically neutral.** (Imbalances normally well-controlled by other methods.)
- Well-justified scientifically, so correction will probably be used routinely.

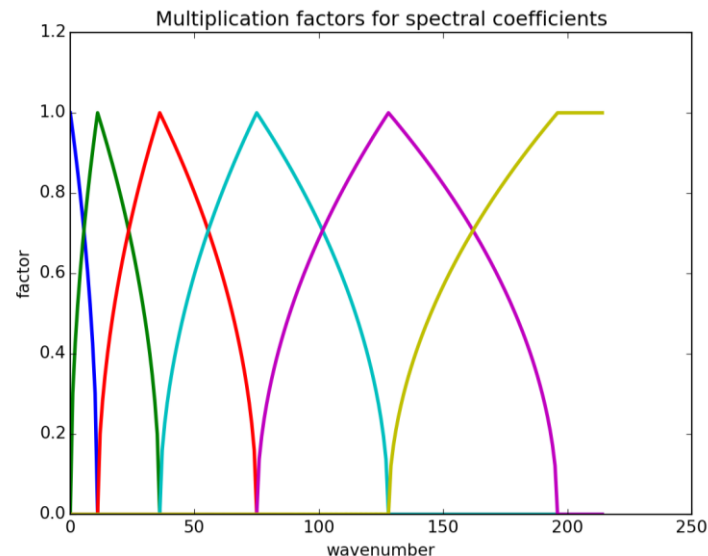
Hybrid-4DEnVar trials at KMA

Horizontal “waveband” localisation

- Buehner (2012), MWR “**Evaluation of a Spatial/Spectral Covariance Localization Approach for Atmospheric Data Assimilation**”:
 - Correlations decrease with distance between horizontal wavenumbers, so split ensemble error modes into wavebands and assume they are uncorrelated.
 - Apply shorter localisation scales to shorter-scale bands.
 - Performance improvement in hybrid-3DVar with 48 members, similar to improvement from doubling the ensemble size to 96 members.
- Waveband localisation coded into Met Office 4DEnVar system and trialed with the following settings:

Band: Scale (km)

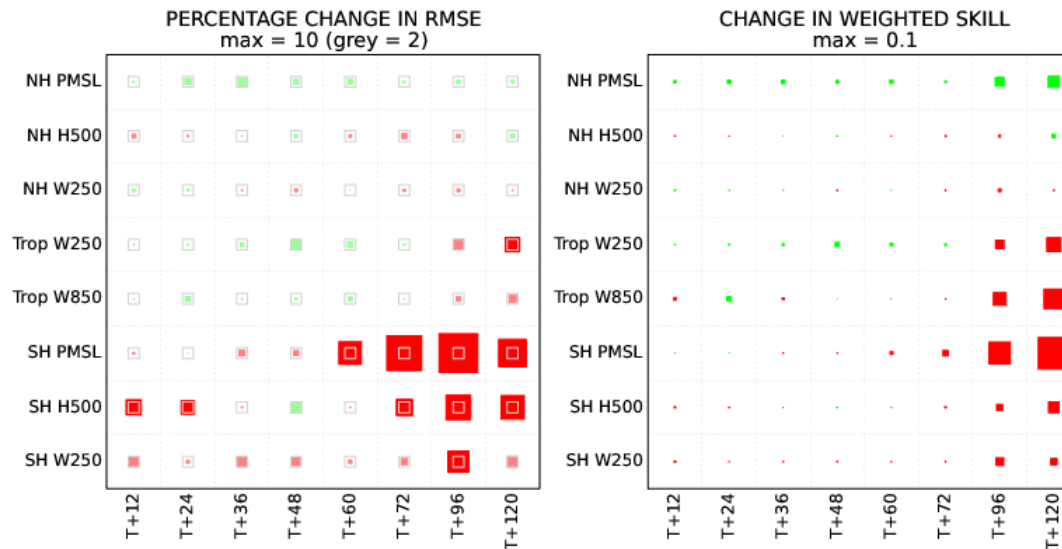
- 1: 80063
- 2: 4710
- 3: 1160
- 4: 600
- 5: 600
- 6: 600



Hybrid-4DEnVar trials at KMA

Horizontal “waveband” localisation

- Control trial: 4DEnVar, 30% B_c / 70% B_e , 176 error modes.



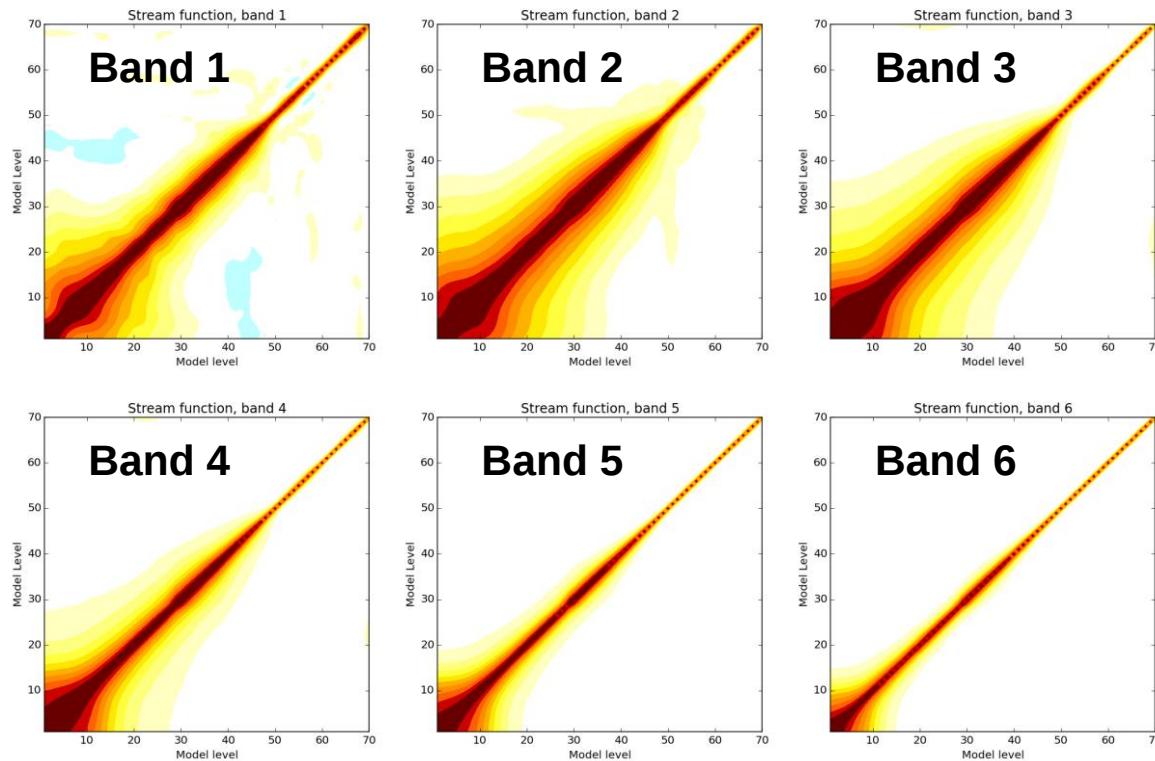
Change to index:
-0.530 %

- Poor performance in SH.
- Neutral or better overall in NH and Tropics.

Hybrid-4DEnVar trials at KMA

Horizontal “waveband” localisation

- **Aside:** Should we have different vertical localisation for each waveband?
- Global-average stream function vertical correlations for each band:

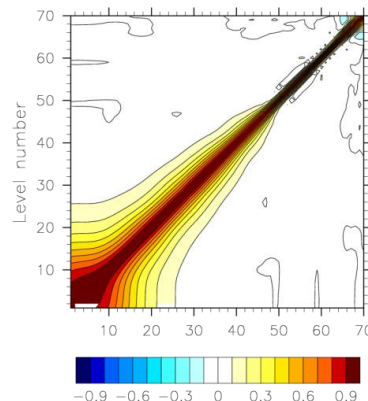




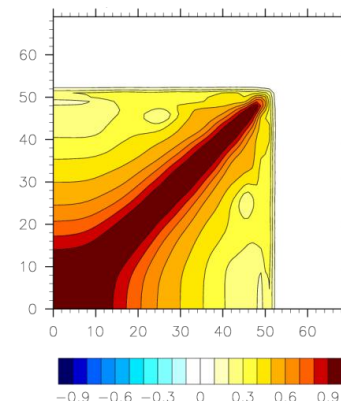
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“Optimal” vertical localisation

- Currently modify vertical stream function correlations to get localisation covariance:

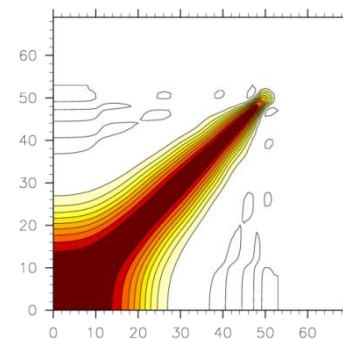
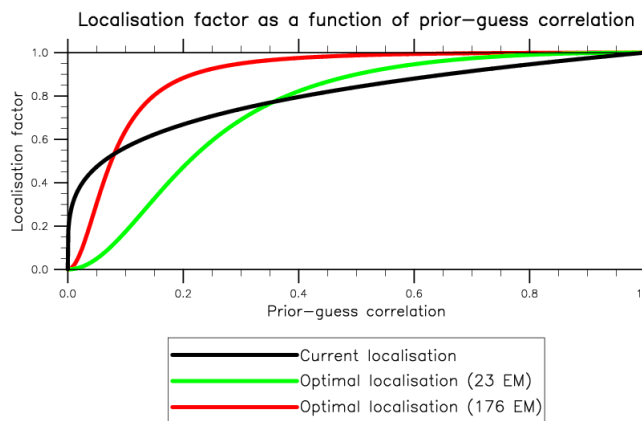


Streamfunction correlations



Localisation covariance

- “Optimal” localisation theory* suggests a different modification:



New localisation covariance
(for 23 error modes)

- Yet to be tried in 4DEnVar, but could be used with waveband localisation.

* Flowerdew (2015), Tellus: “Towards a theory of optimal localisation”



Future work

- Decision point for future development: **October 2015.**
- 4DEnVar
 - Continue work on waveband localisation.
 - Expand testing of “wrong-time” modes.
 - ...
- En-4DEnVar
 - System basically complete. Now being tuned.
- **July:** Tests of final configurations, with 200 member ensembles.



Thanks for listening