Data Assimilation and Ensemble Forecasting at the Met Office: Current Status and Future Plans

Dale Barker

UMD AOSC Seminar, 14th May 2009

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Outline of Talk

1. Met. Office NWP Overview:
   - Data Assimilation and Ensembles (DAE) Section.
   - Original of NWP Improvement in past few decades (A Lorenc)
   - Future Plans.

2. Hybrid Variational/Ensemble DA in WRF: The story continues…
   - Recap on methodology.
   - Vertical localization.
   - Results from AFWA applications.

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Data Assimilation within the Met Office

- **Data Assimilation and Ensembles (DAE) Section within Forecasting R&D (260 posts).**

- **DAE (~40 posts: 25 DA + 15 ENS) made up of:**
  - **Global DA:** Pre-operational trials, DA software.
  - **Regional DA:** North Atlantic Europe (NAE) and UK domains, land surface DA.
  - **Assimilation Studies:** Obs. impacts, hybrid DA, model error.
  - **4D-Var research:** Covariance modelling, linear PF model.
  - **Assimilation Applications:** Ozone, middle-atmosphere, space weather.
  - **Ensemble Research:** MOGREPS: ETKF, stochastic physics, TIGGE, …
  - **Ensemble Products:** Tailor-made products, expanding….

- **DAE external collaborations increasing (e.g. Australia, India, Korea, …)**

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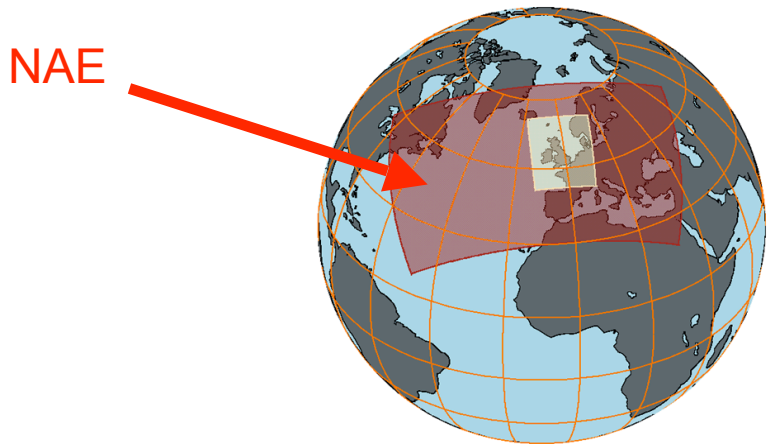
Met Office Current Configurations



- **Global 40km L50** model
  - Incremental 4D-Var
  - 90km 24m ETKF ensemble
- **Regional NAE 12km** L38 model
  - Incremental 4D-Var
  - 24km 24m L38 ETKF ensemble
- **UK 4km** model
  - Incremental 3D-Var

Met. Office Global/Regional Ensemble Prediction System (MOGREPS) became fully operational in Sep 2008 after 3 years of trials. Focus on short-range out to 72hr.

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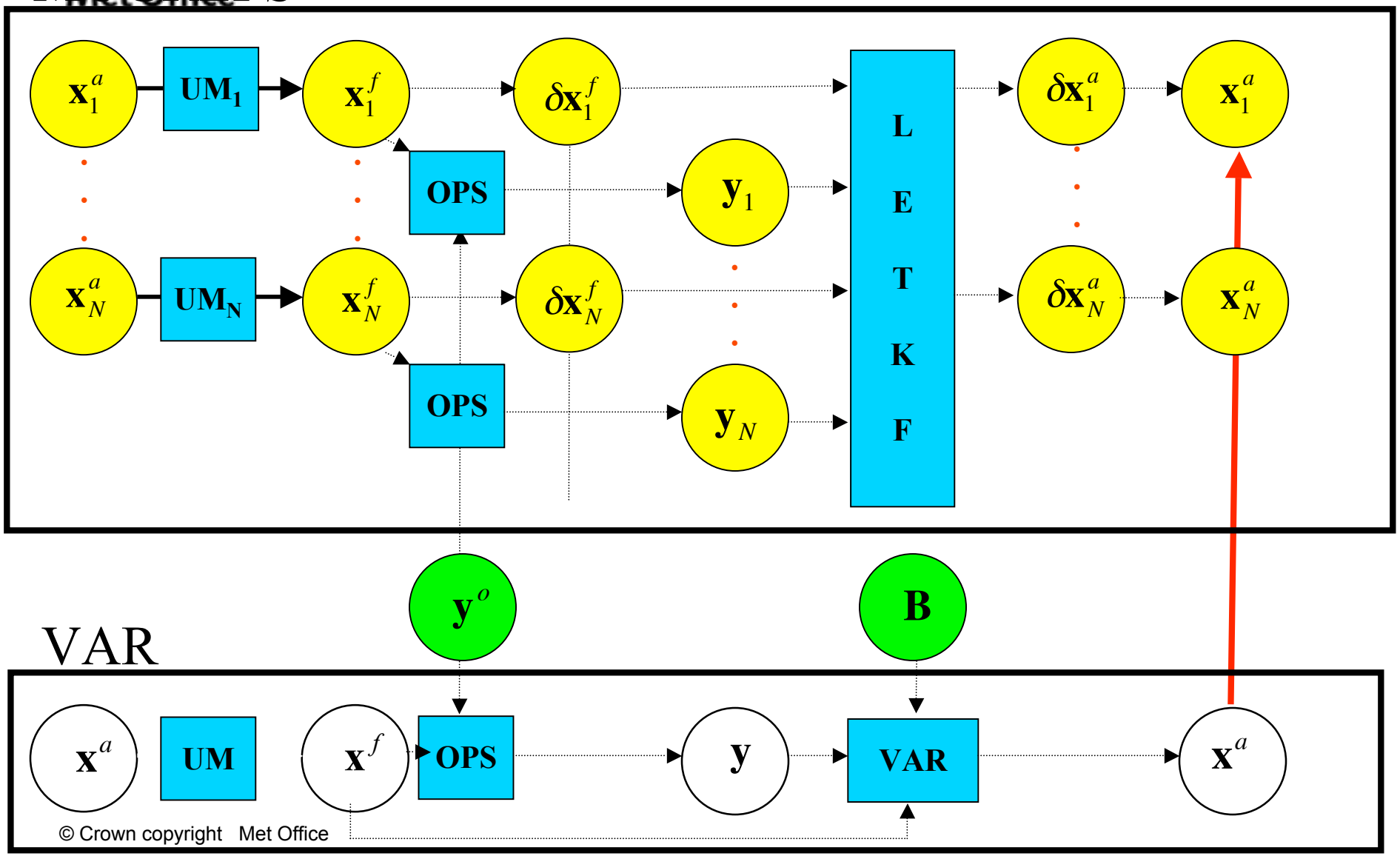
MetO Operational Global/Regional NWP

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



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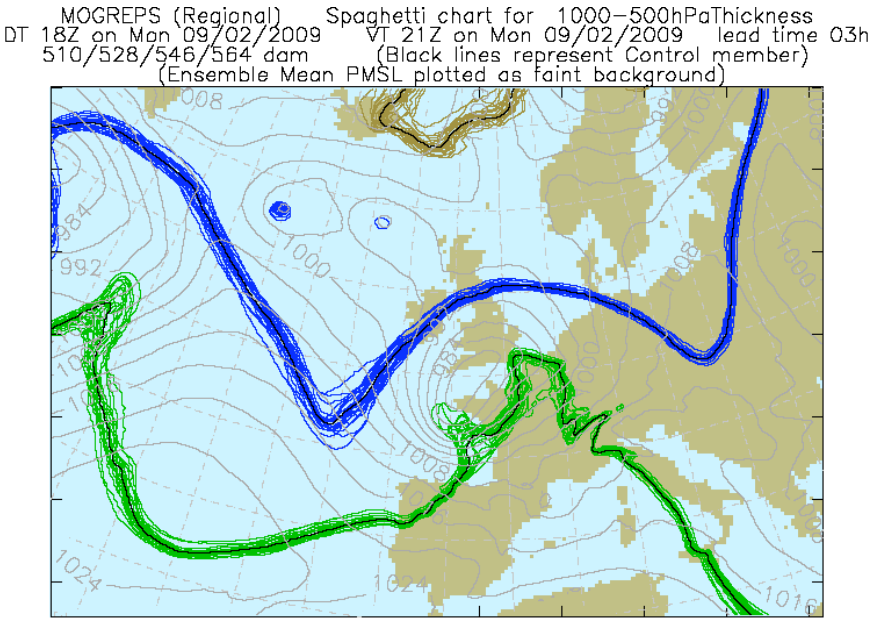
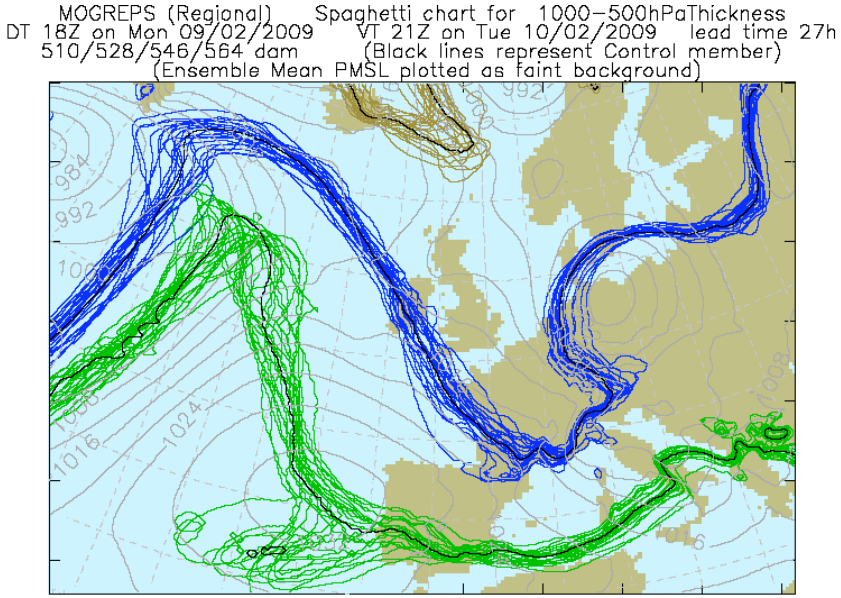
MOGREPS –general meteorological products

‘Spaghetti’ Charts





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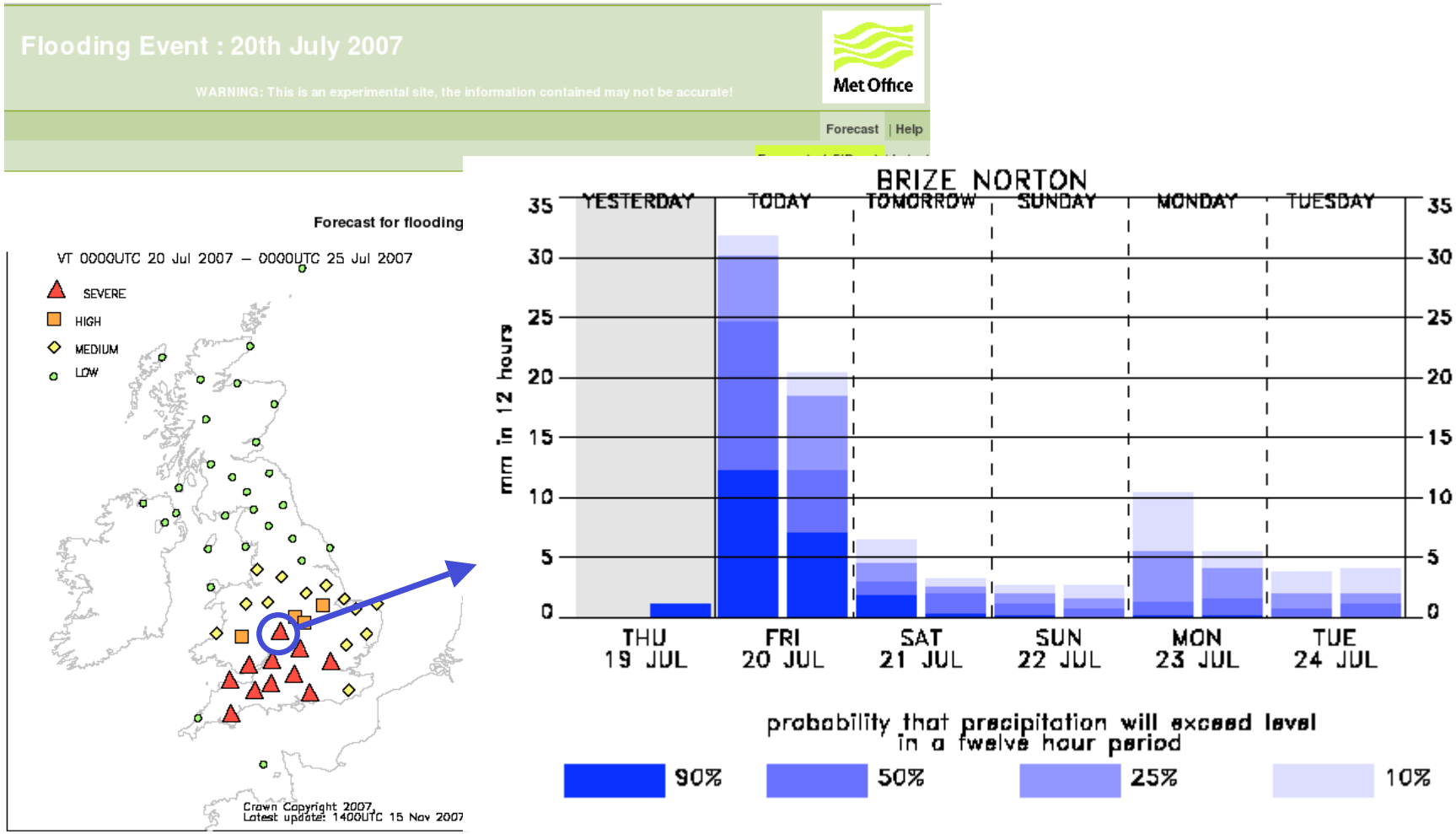
Traffic-light map with site-specific product



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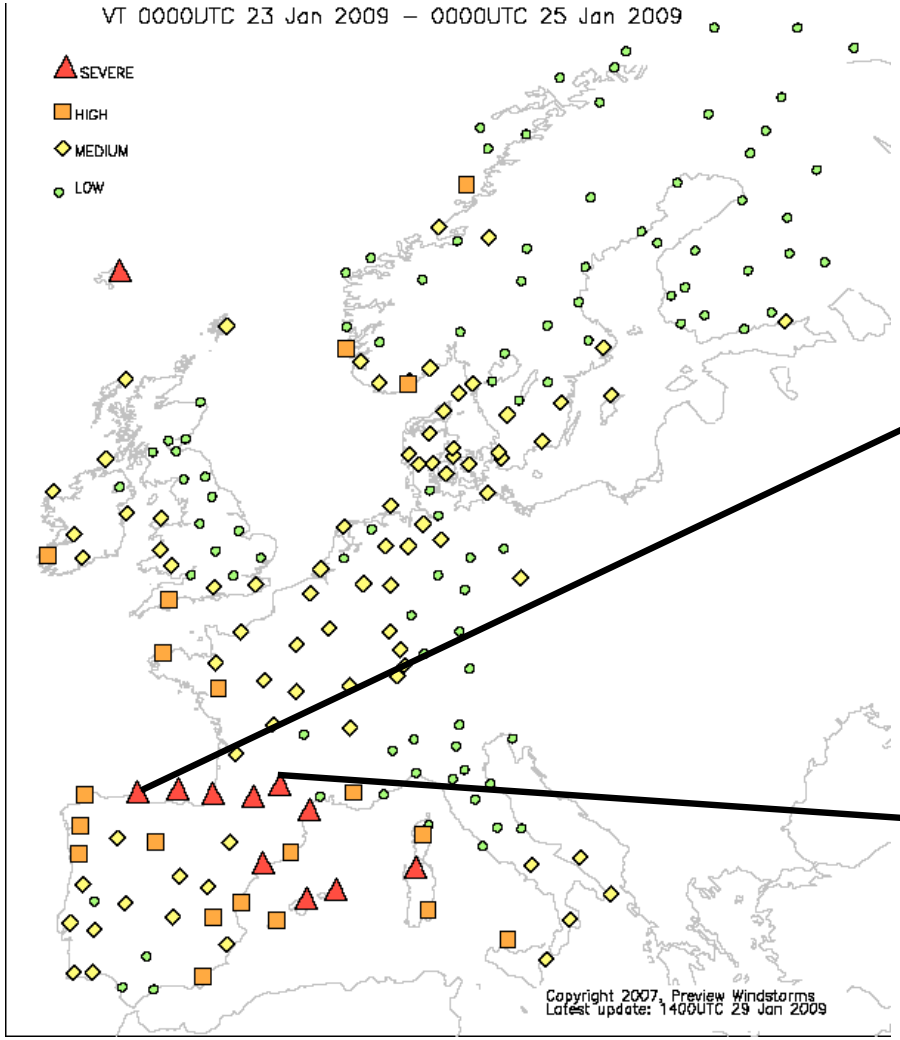
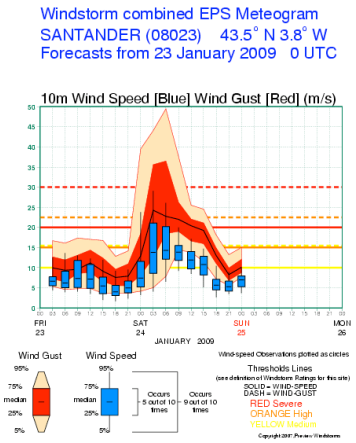
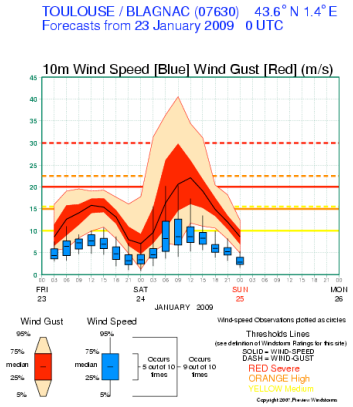
Storm in Southern Europe, 2009: Windstorms overview







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Met Office plans on IBM Power6 (~x6 NEC) in 2009

- **Global 25km L70** model
  - Incremental 4D-Var
  - 60km 24m ETKF ensemble

- **Regional NAE 12km** L70 model
  - Incremental 4D-Var (with outer-loop, cloud & ppn)
  - ~16km 24m L70 ETKF ensemble

- **UK 1.5km** model (stretched)
  - 3D-Var + nudging of ppn & cloud
  - Ensemble driven by NAE perturbations (experimental)
  - Small domain 4D-Var RUC (experimental)

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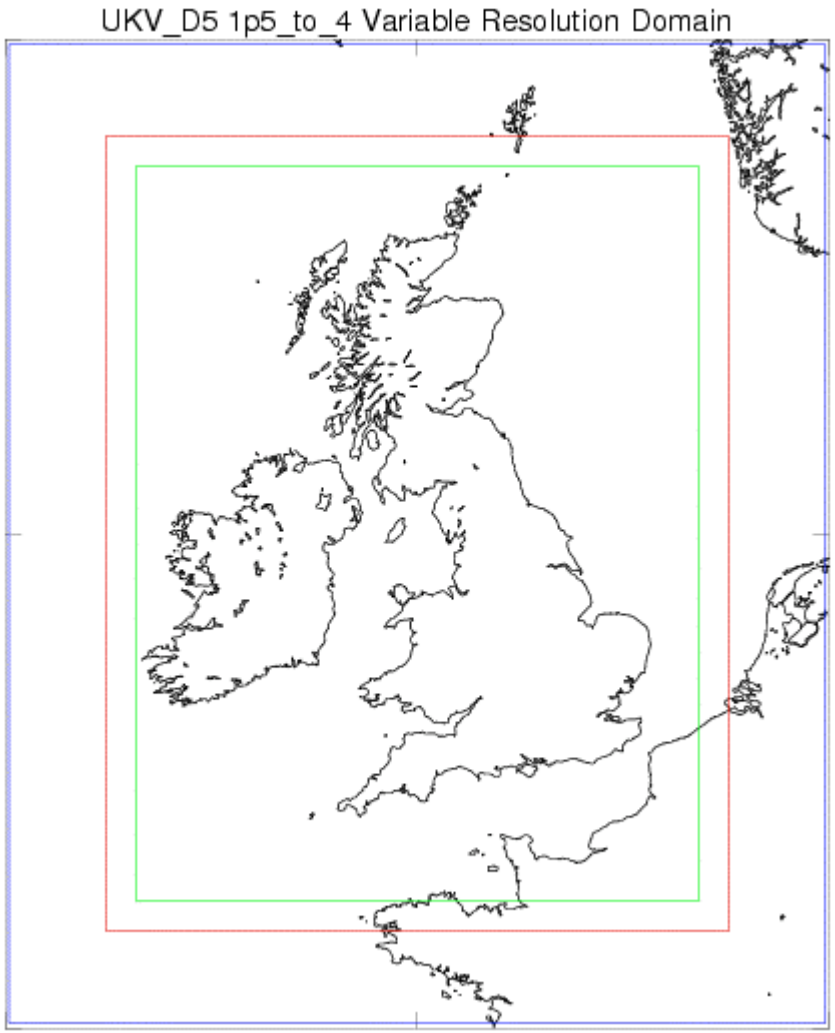
New UK 1.5km variable grid

- Outer edge of 1.5km regular grid
- Outer & Inner edge of 4*1.5km rectangular grid
- Nests in 12km NAE.
- Similar number of gridpoints as main global model.
- Better than current 4km for heavy convective precipitation (fewer false alarms).



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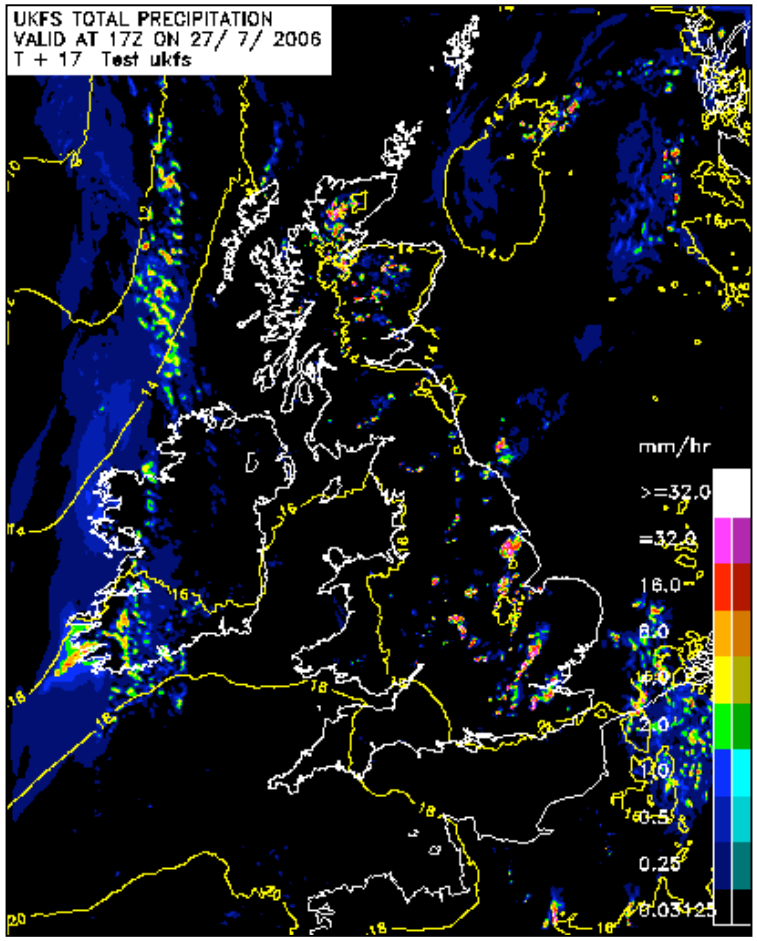
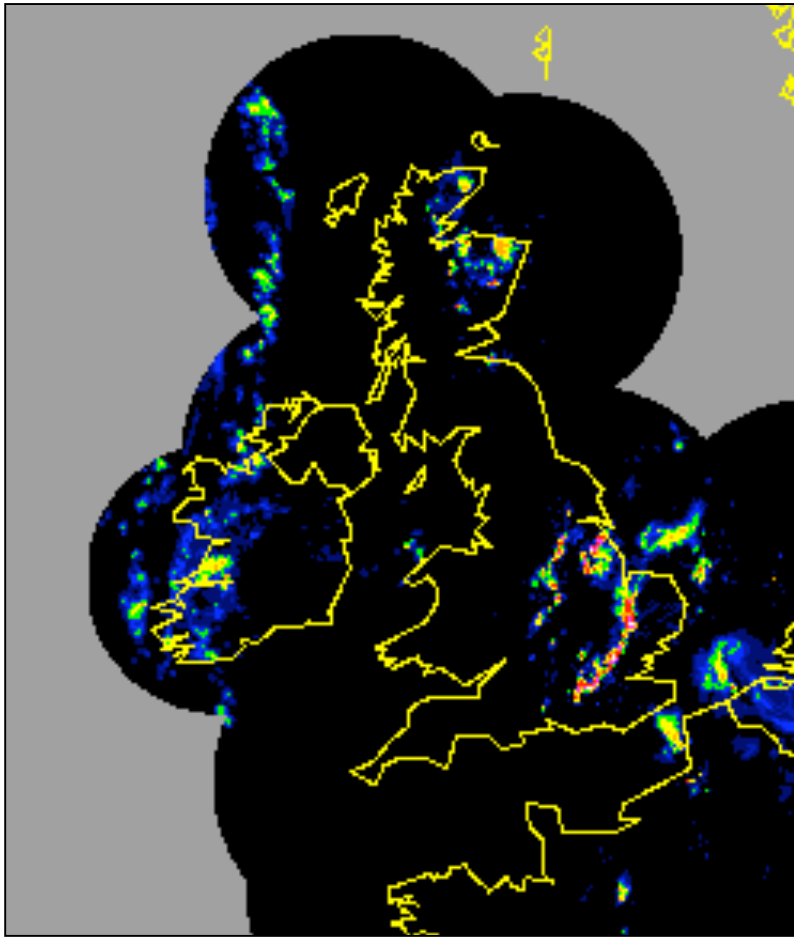
UK 1.5 km model - example



17 h Forecast 1.5 km L70
From NAE analysis
(DA will be implemented!)



Radar Composite

17 UTC
27/07/2006

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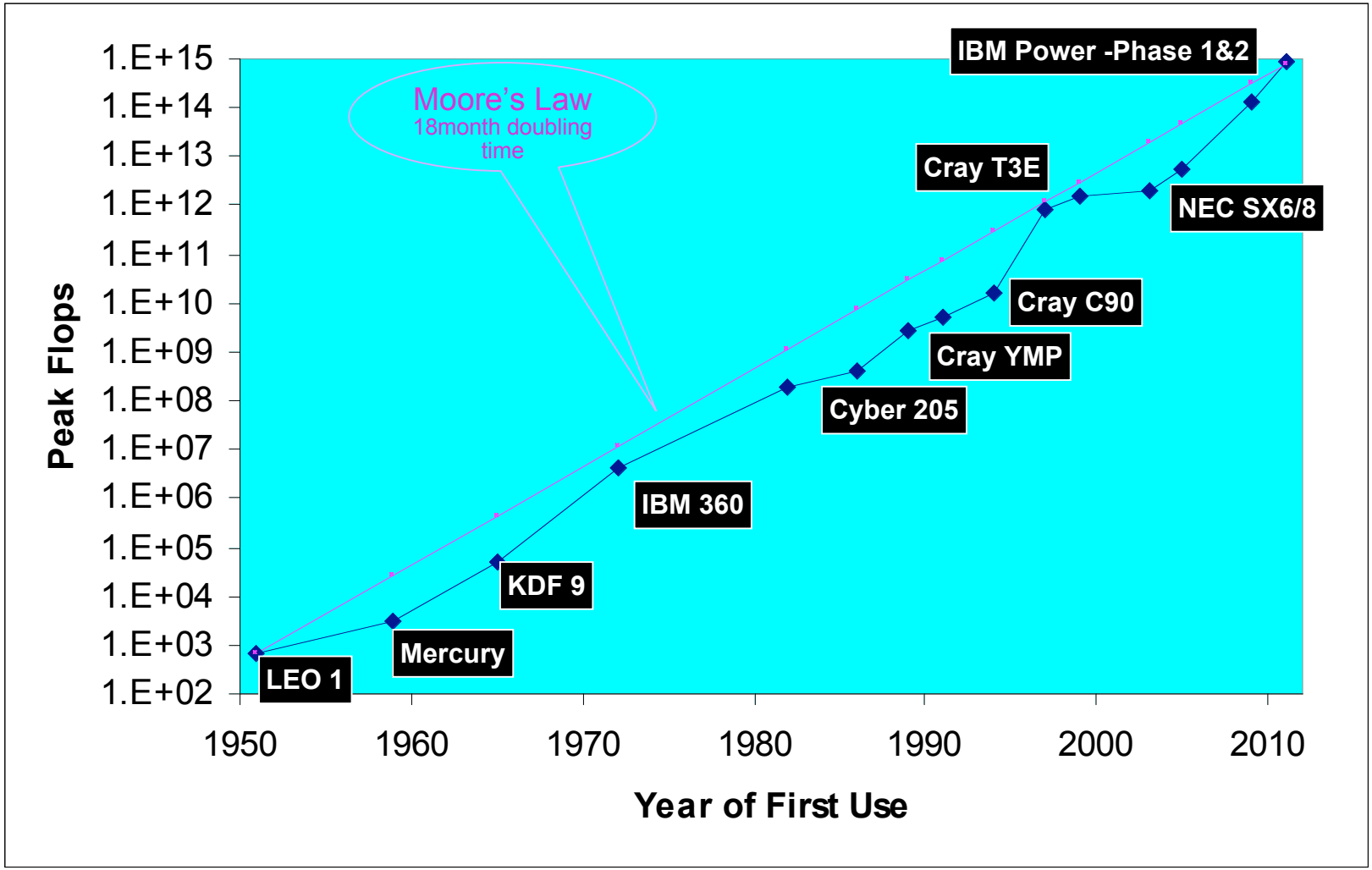
60 Years of Met Office Computers



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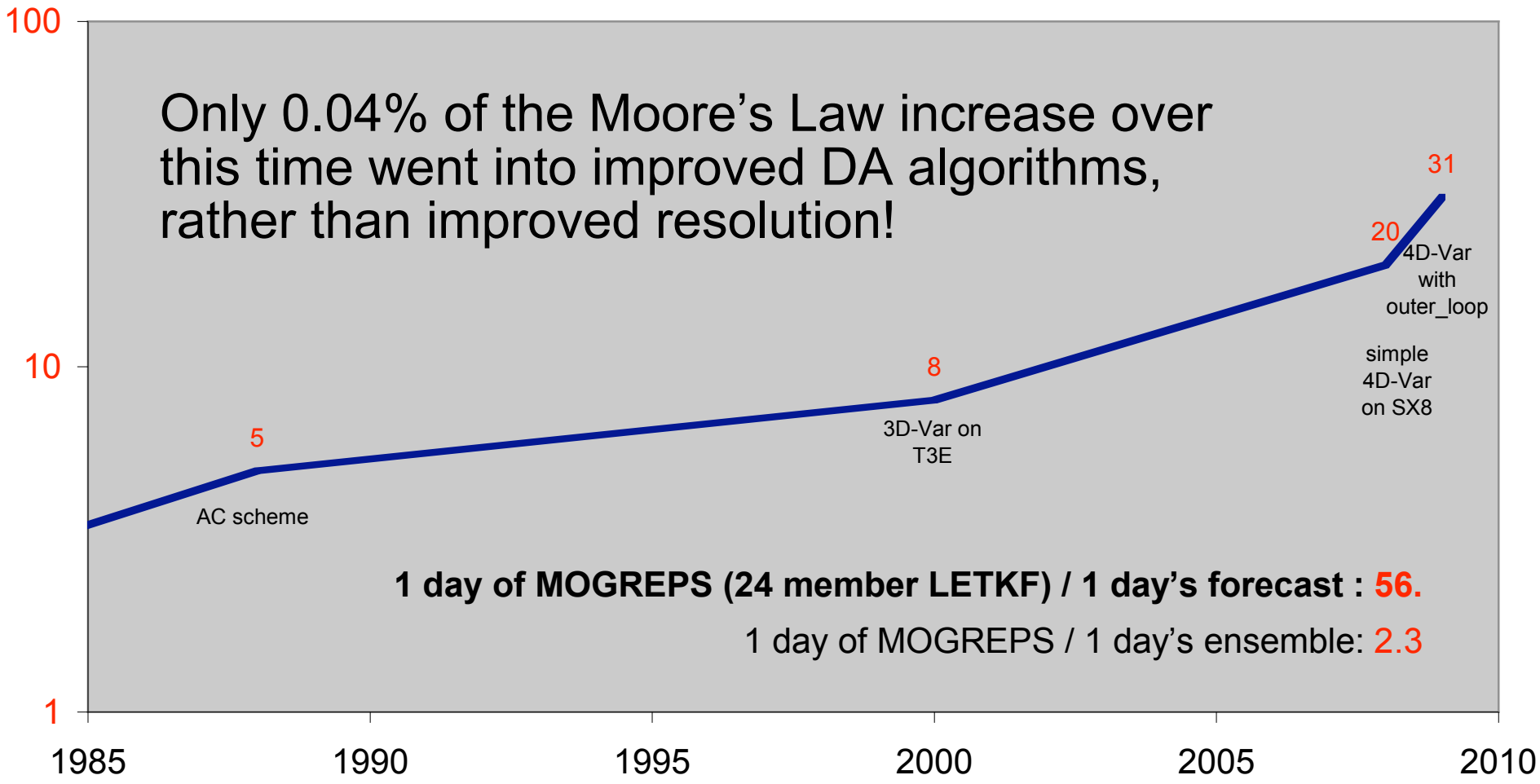
Ratio of global computer costs:

1 day's DA (total incl. FC) / 1 day's forecast.



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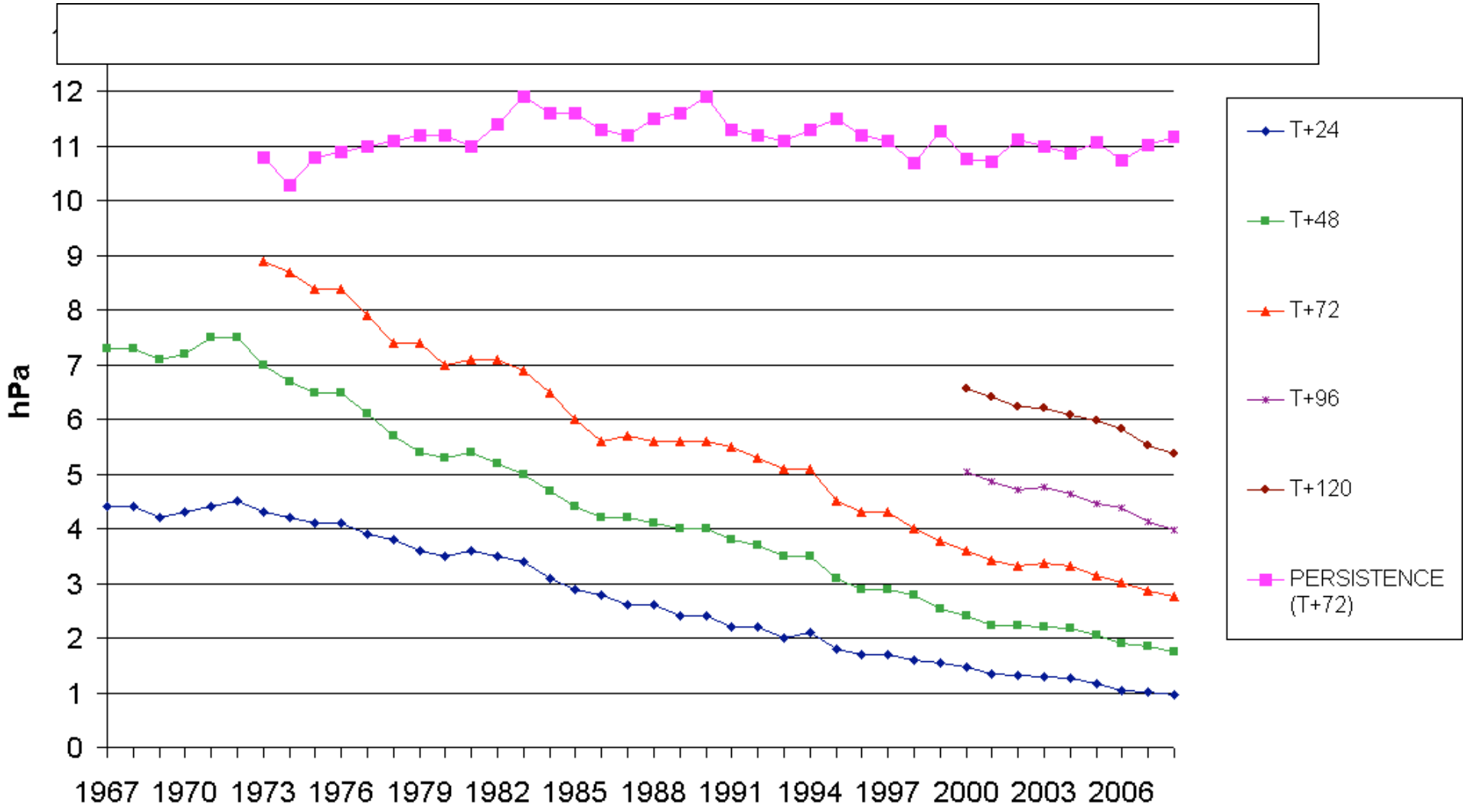
Performance Improvements

"Improved by about a day per decade"



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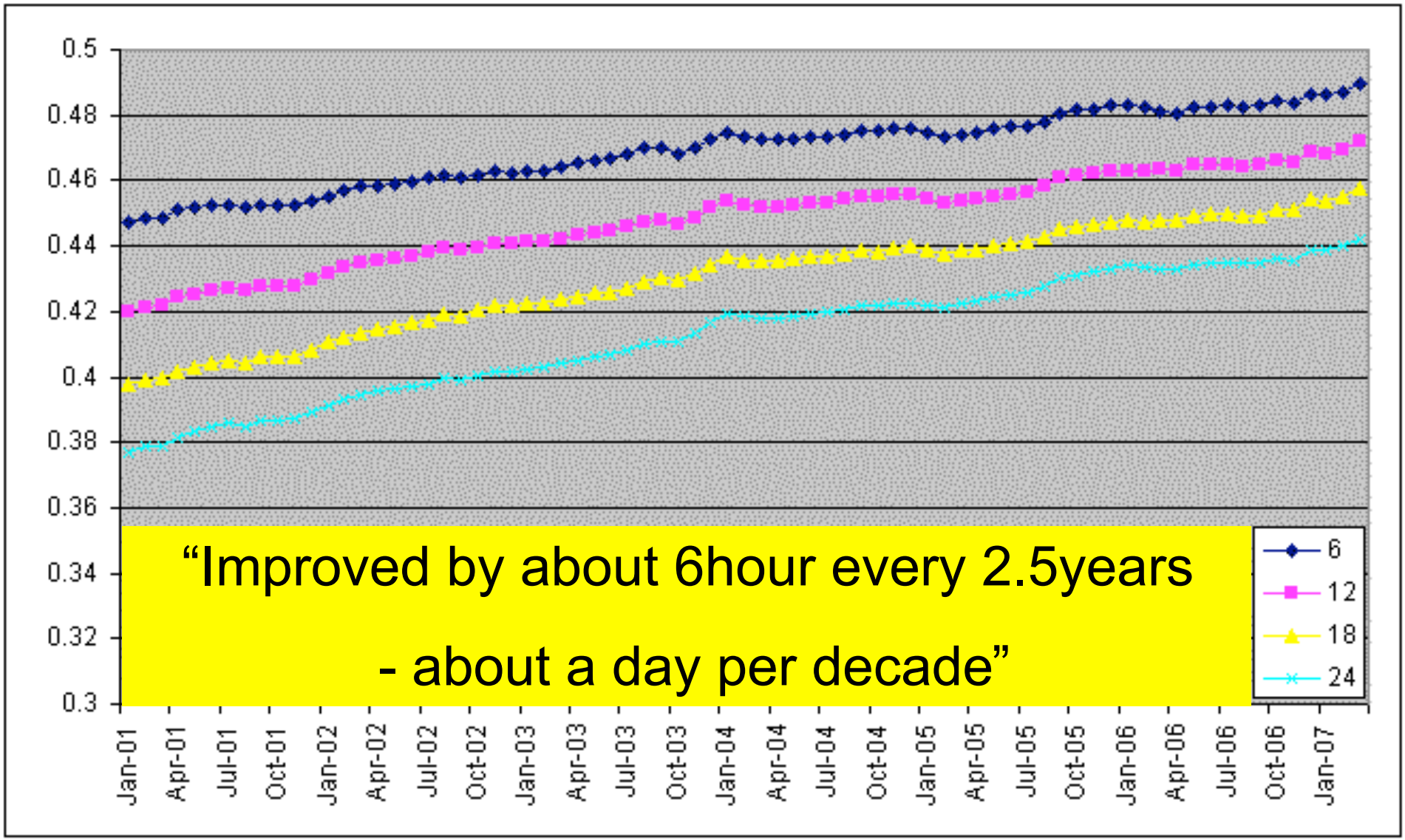
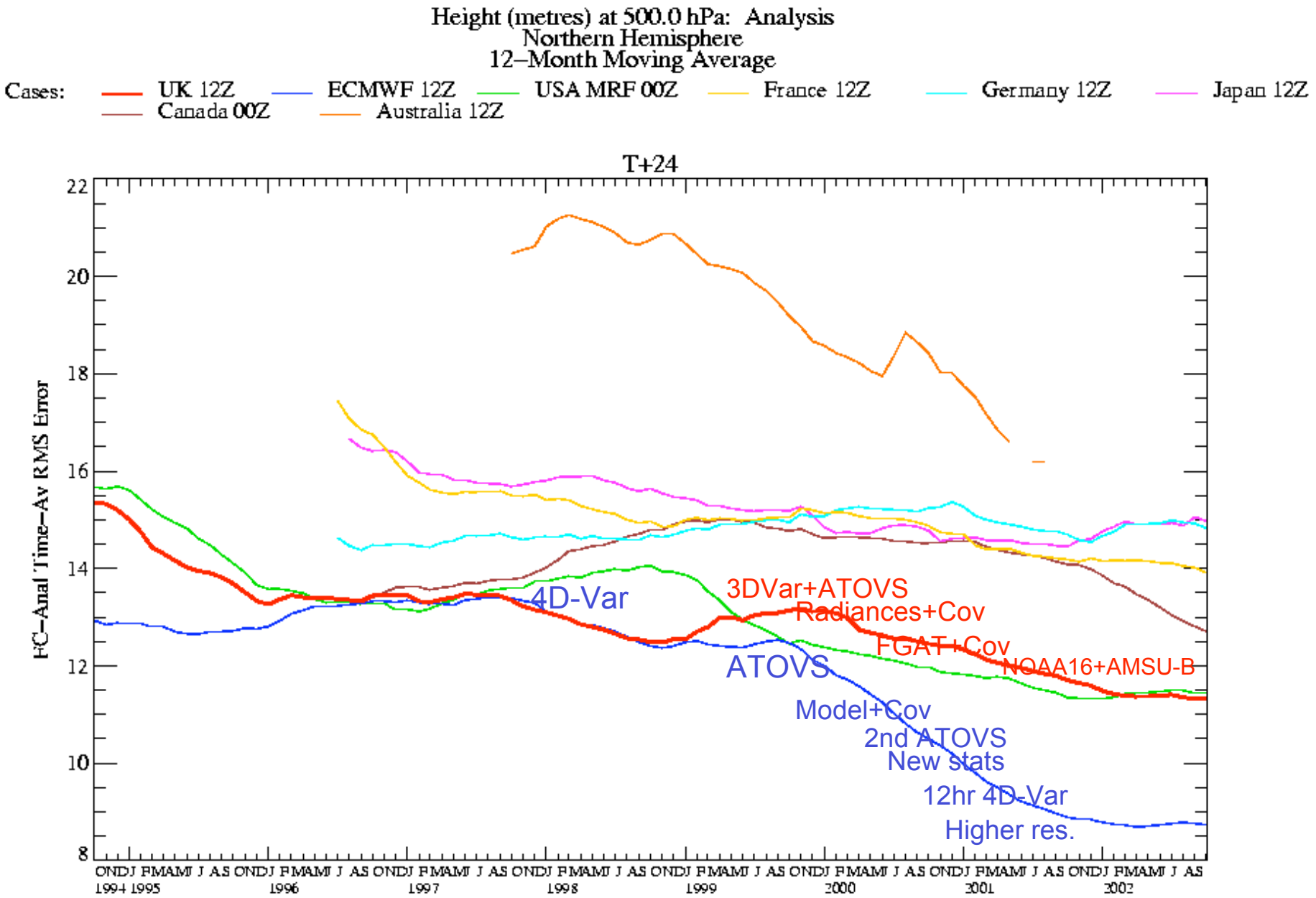
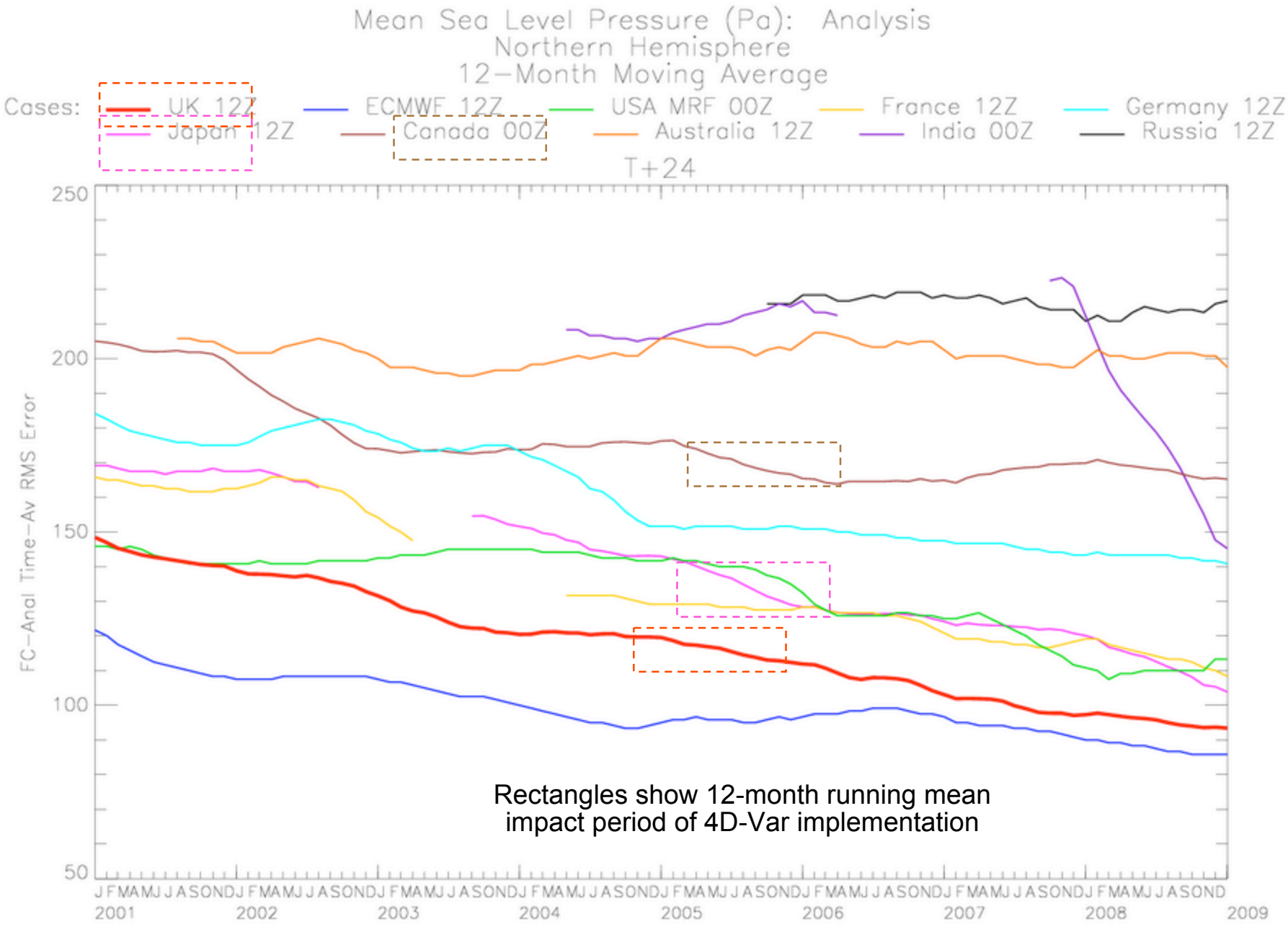
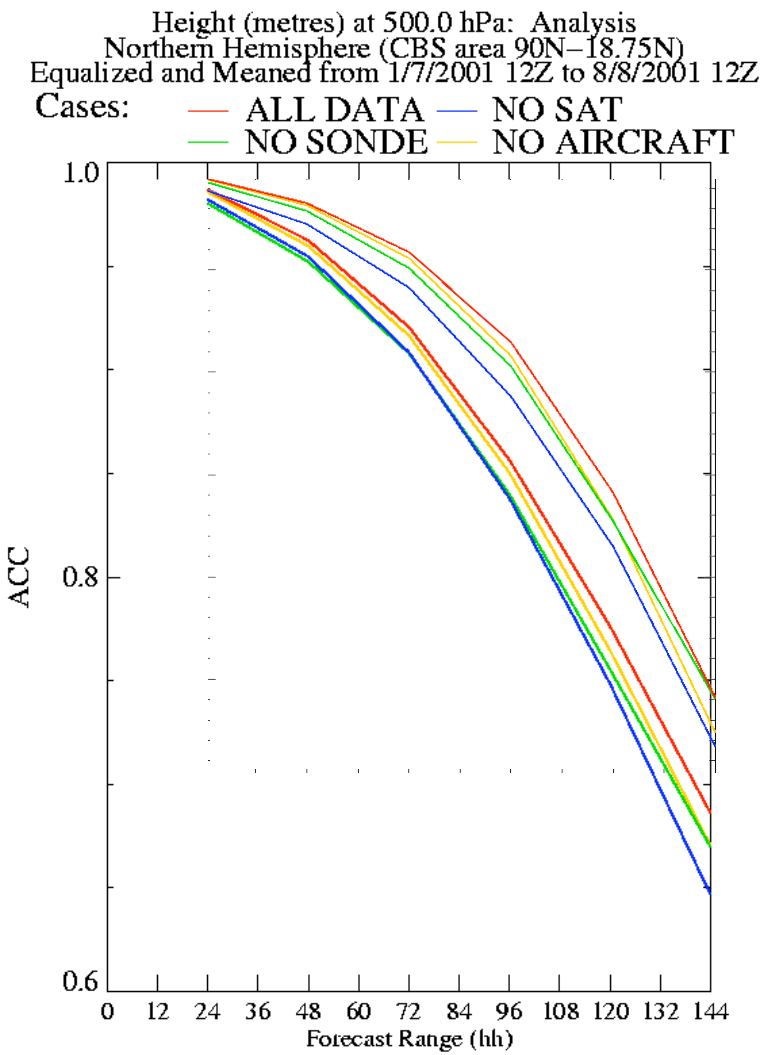
UK Index Improvement: skill scores vs UK SYNOPS for T wind ppn cloud visibility




Height (metres) at 500.0 hPa: Analysis
Northern Hemisphere
12–Month Moving Average
Cases:
UK 12Z
ECMWF 12Z
USA MRF 00Z
France 12Z
Germany 12Z
Japan 12Z
Canada 00Z
Australia 12Z
T+24
HC–Anal Time–Av RMS Error
22
20
18
16
14
12
10
8
ONDJ FMAMJ J AS ONDJ FMAMJ J AS ONDJ FMAMJ J AS ONDJ FMAMJ J AS ONDJ FMAMJ J AS ONDJ FMAMJ J AS ONDJ FMAMJ J AS ONDJ FMAMJ J AS
1994 1995 1996 1997 1998 1999 2000 2001 2002
4D-Var
3DVar+ATOVS
Radiances+Cov
FGAT+Cov
NOAA16+AMSU-B
ATOVS
Model+Cov
2nd ATOVS
New stats
12hr 4D-Var
Higher res.


Mean Sea Level Pressure (Pa): Analysis
Northern Hemisphere
12-Month Moving Average
Cases:
UK 12Z
ECMWF 12Z
USA MRF 00Z
France 12Z
Germany 12Z
Japan 12Z
Canada 00Z
Australia 12Z
India 00Z
Russia 12Z
T+24
FC-Anal Time-Av RMS Error
250
200
150
100
50
J F M A M J J A S O N D
2001
2002
2003
2004
2005
2006
2007
2008
2009
Rectangles show 12-month running mean
impact period of 4D-Var implementation

Change in OSE results 2001-2007. N-hem 500hPa height ACC.



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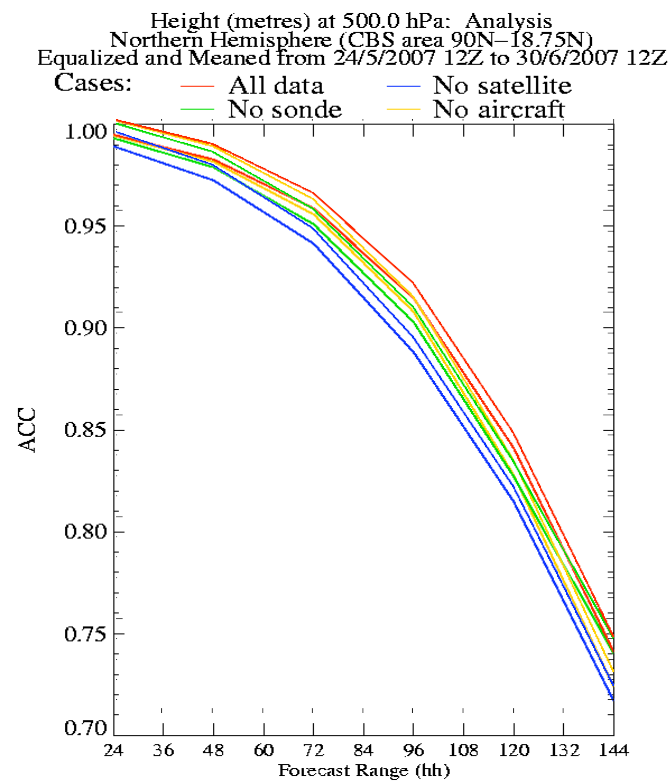

Not the same period,
so only make qualitative comparisons!

Richard Dumelow

Conclusions

1) ~Two orders of magnitude increase in computer power per decade….

2) …has led to an extra day improvement in global/UK scores every decade.

3) Bulk of cost increase taken up by NWP model (e.g. resolution, physics, ensembles. Relative DA cost only ~x3 in 20 yrs.

4) Evidence that recent improvements in model/DA larger than combined impact of all satellite data.

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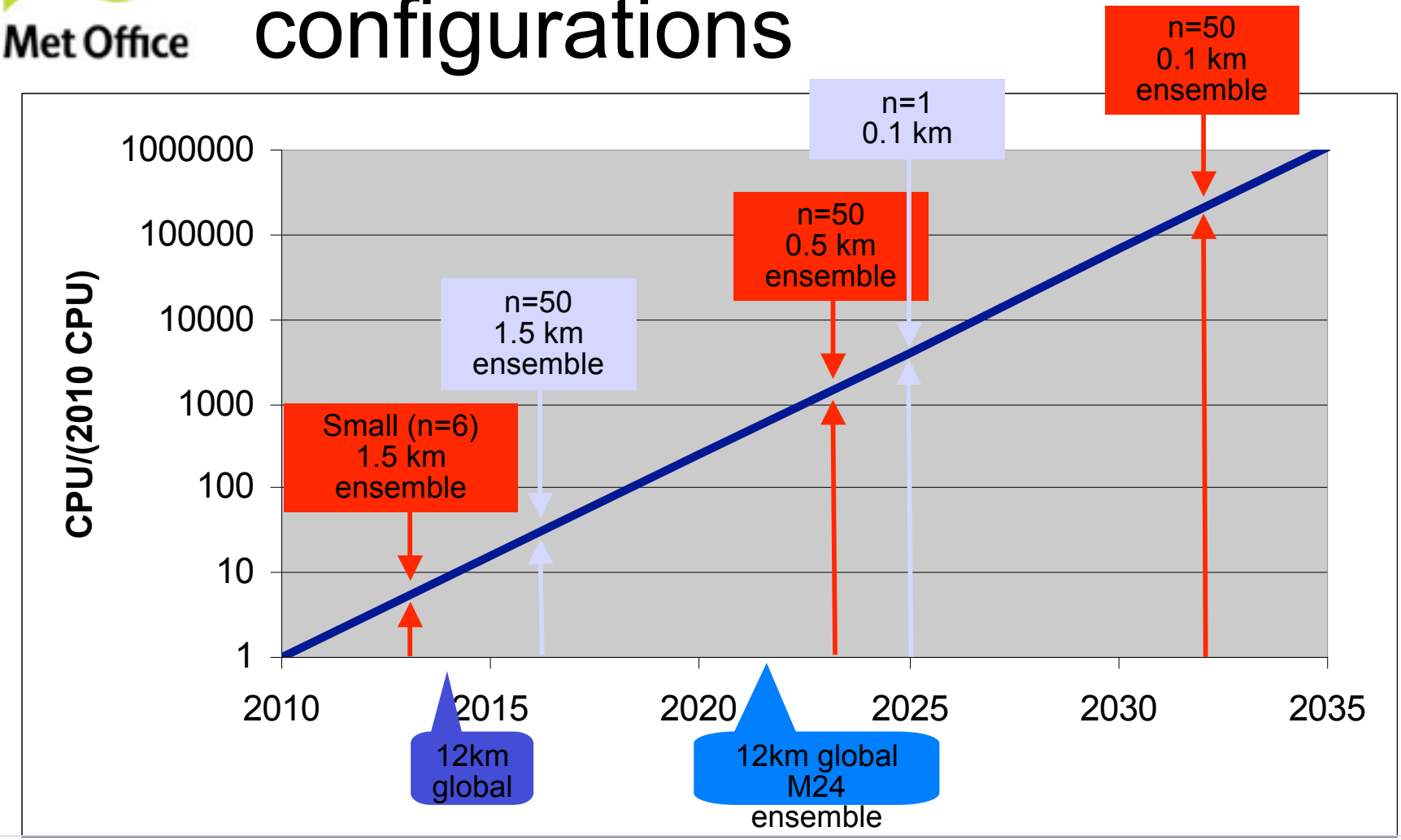
Possible UK model configurations



Assumes Moore's Law continues with 15 month doubling time

Pete Clark

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Outline of Talk

1. Met. Office NWP Overview:
   - Data Assimilation and Ensembles (DAE) Section.
   - Original of NWP Improvement in past few decades (A Lorenc)
   - Current Status and Future Plans.

2. Hybrid Variational/Ensemble DA in WRF: The story continues…
   - Recap on methodology.
   - Vertical localization.
   - Results from AFWA applications (Meral Demirtas).

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Motivation

1) Accurate specification of forecast errors vital for modern DA.

2) 4D-Var has been successfully used to model forecast error evolution, but limited by linearity assumption and static J_b.

3) Ensemble-based forecast error flow-dependent and derived from nonlinear forecasts, but suffer from sampling errors.

4) Hybrid variational/ensemble DA systems represent a promising practical way forward for operations.

5) Still many other issues to deal with, e.g. model error, spread/skill, non-Gaussianity, sample size, etc.

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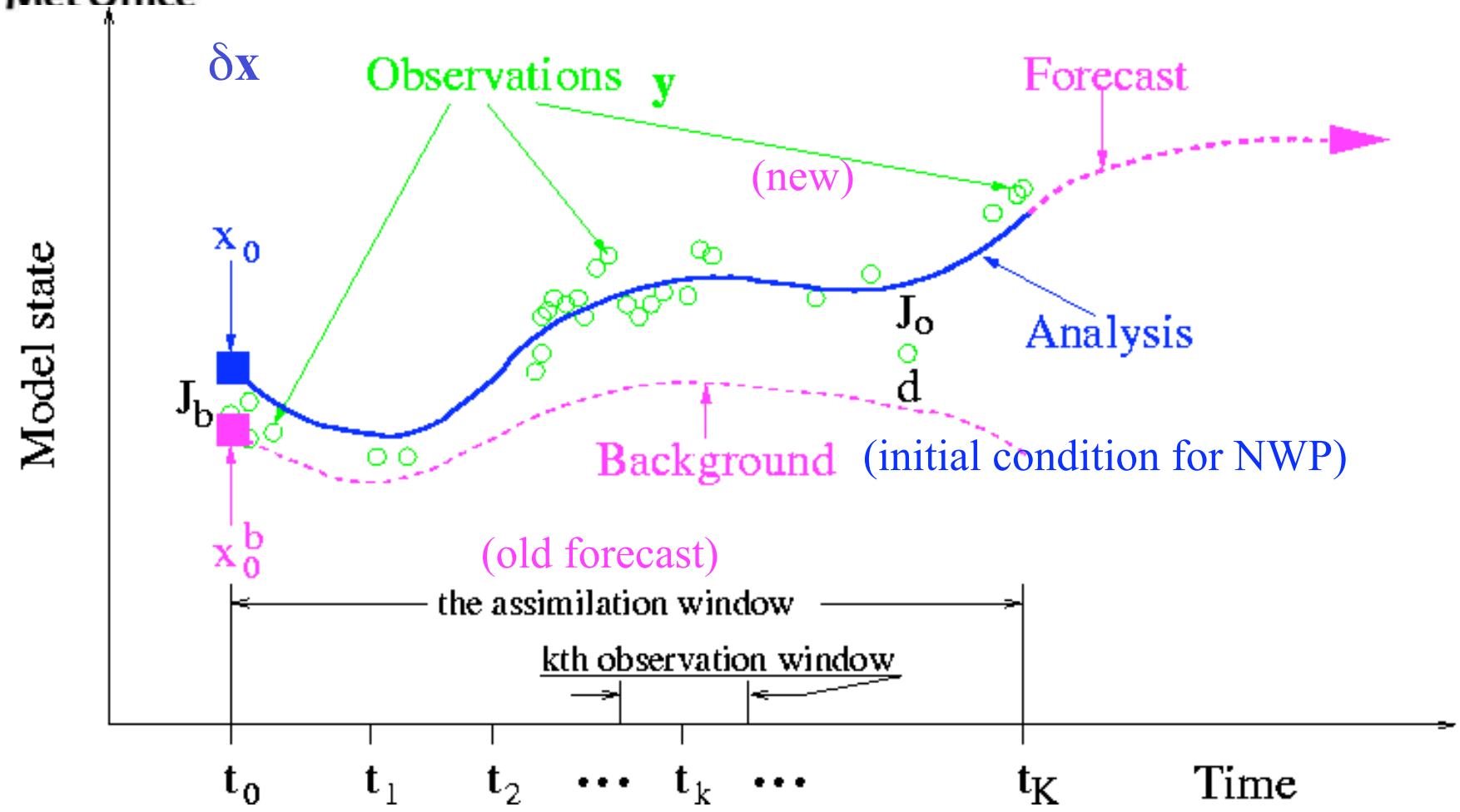
4D Variational Data Assimilation



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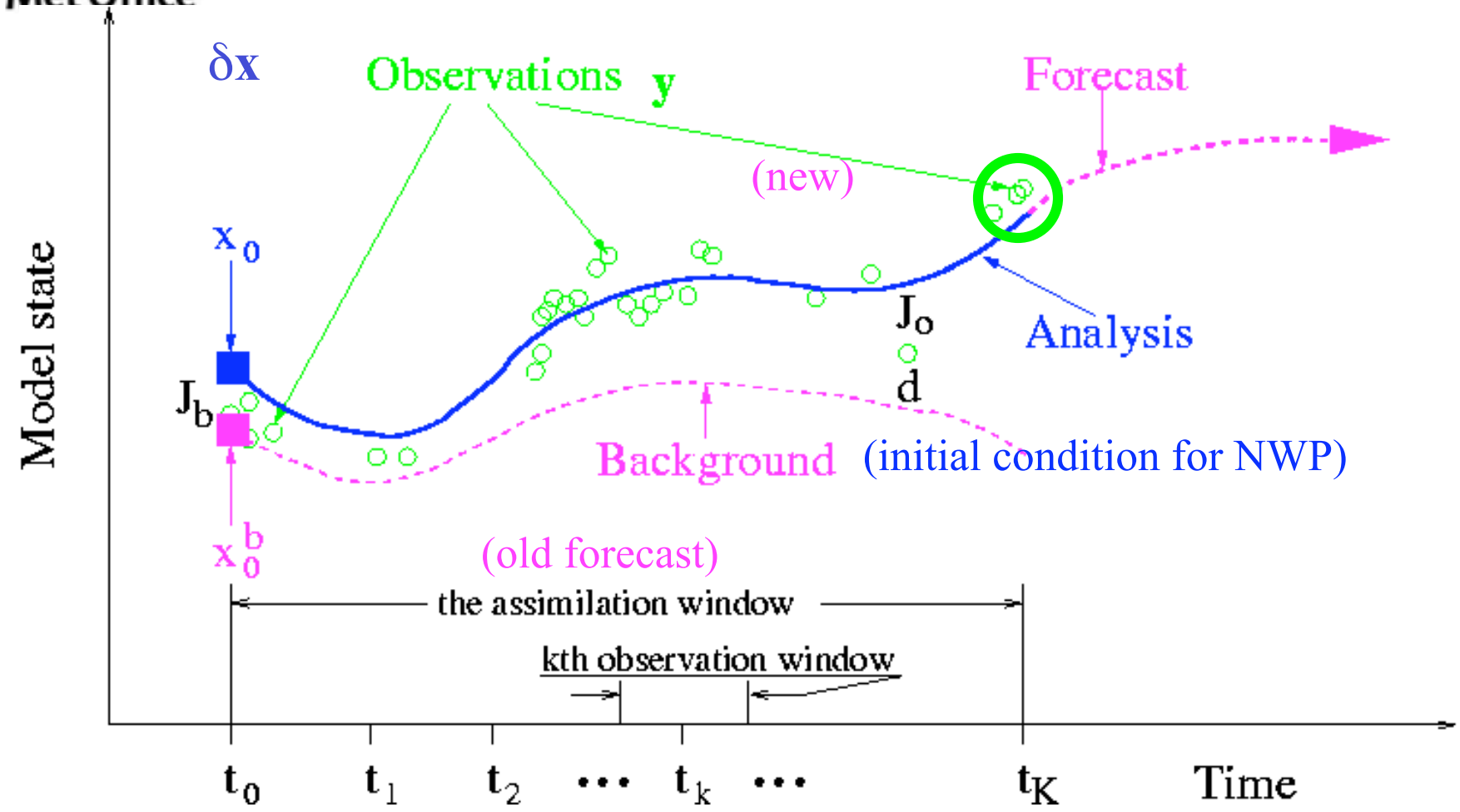
4D Variational Data Assimilation



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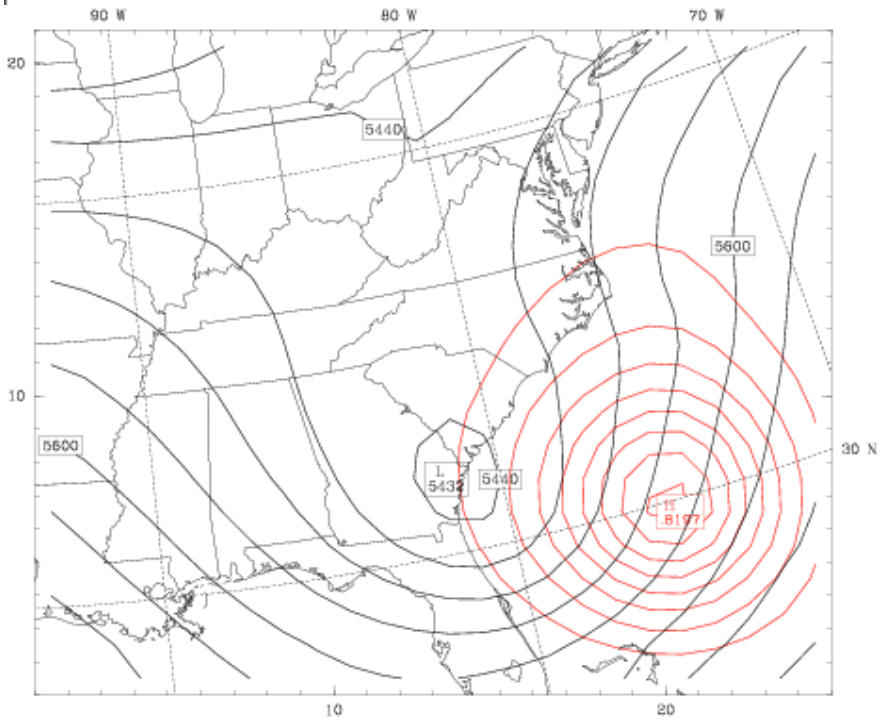
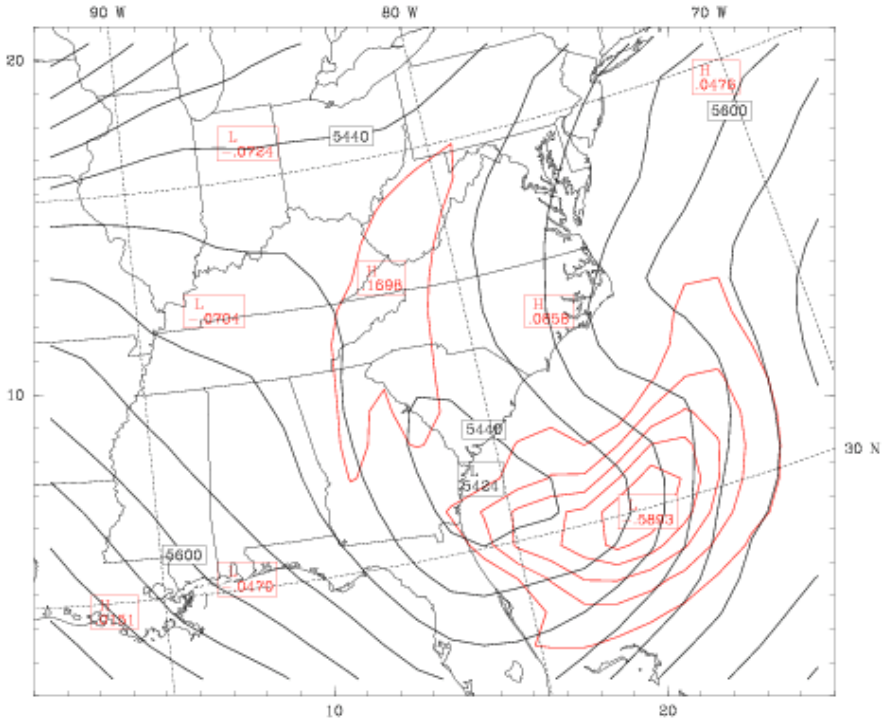
WRF-Var: 3/4D-Var Single Observation Test (observation at end of time window)



3D-Var



4D-Var

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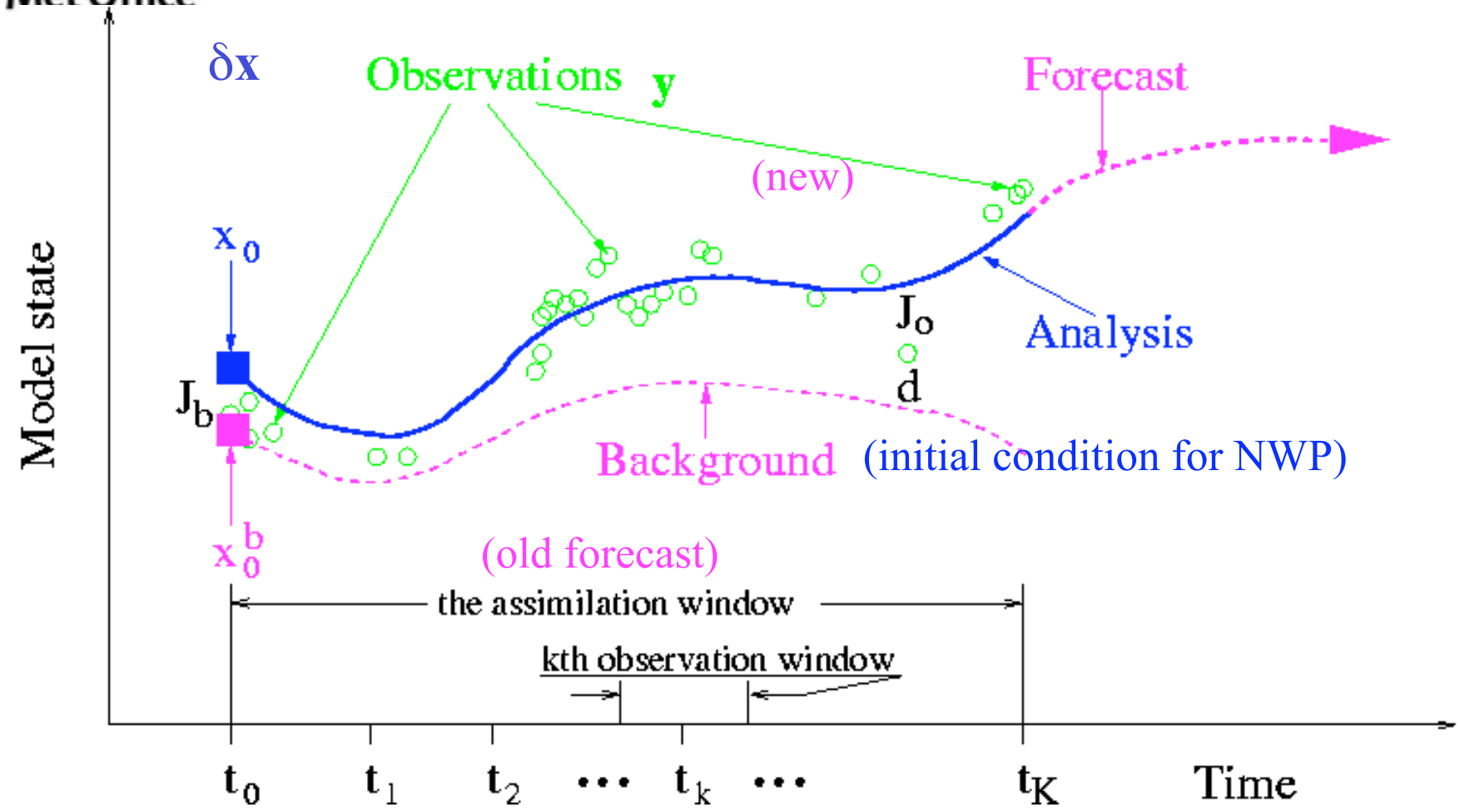
4D Variational Data Assimilation



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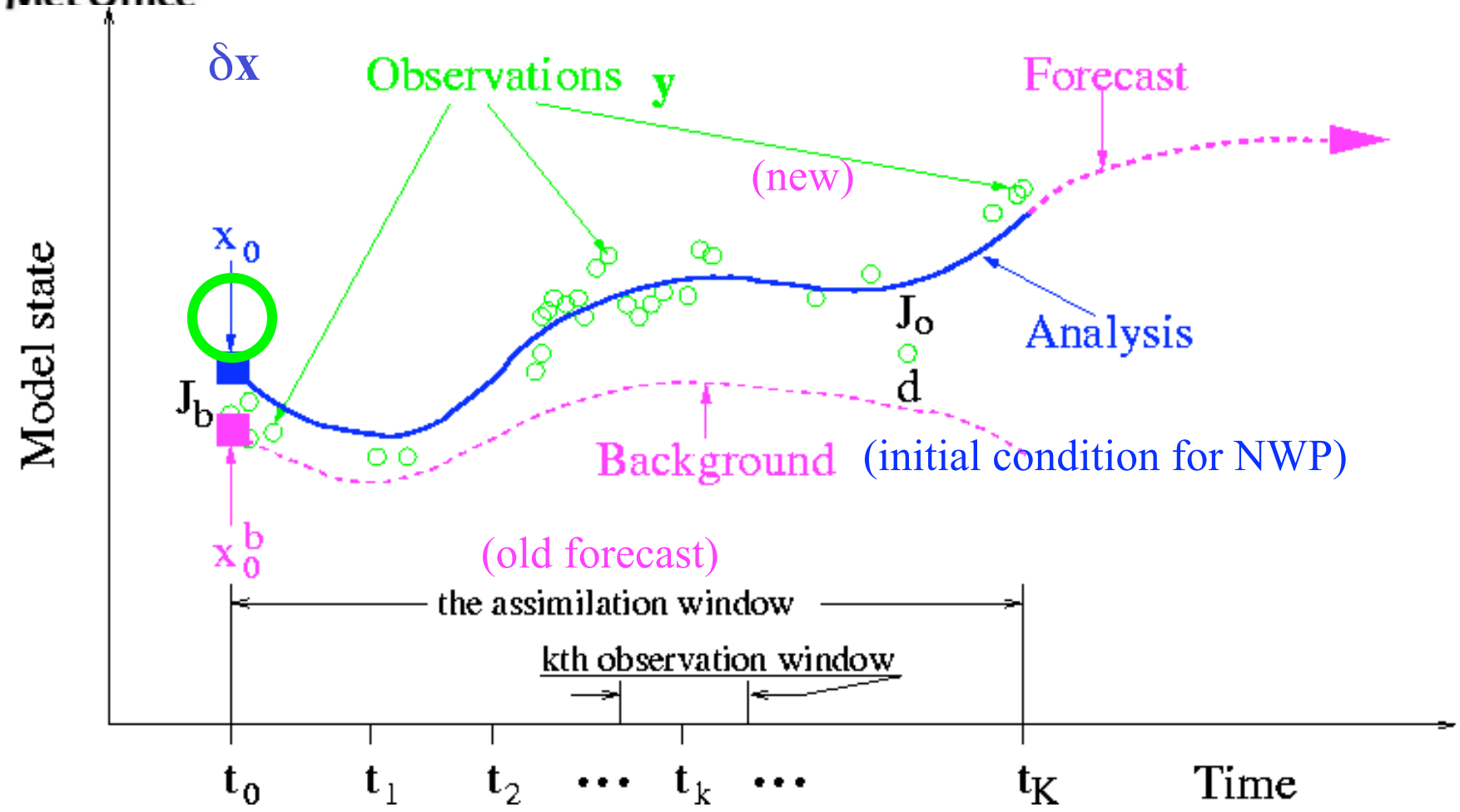
4D Variational Data Assimilation



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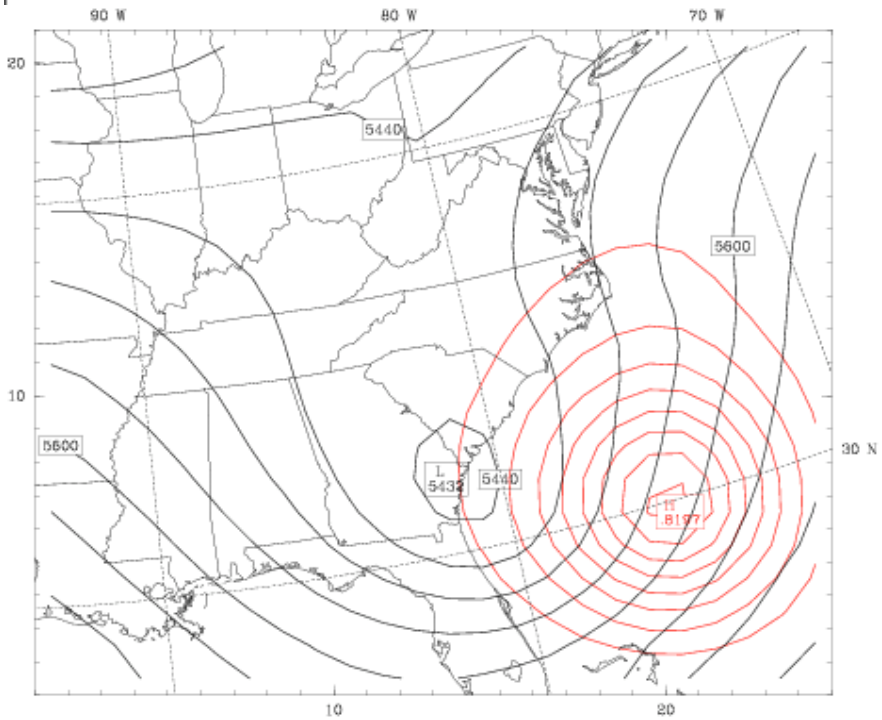
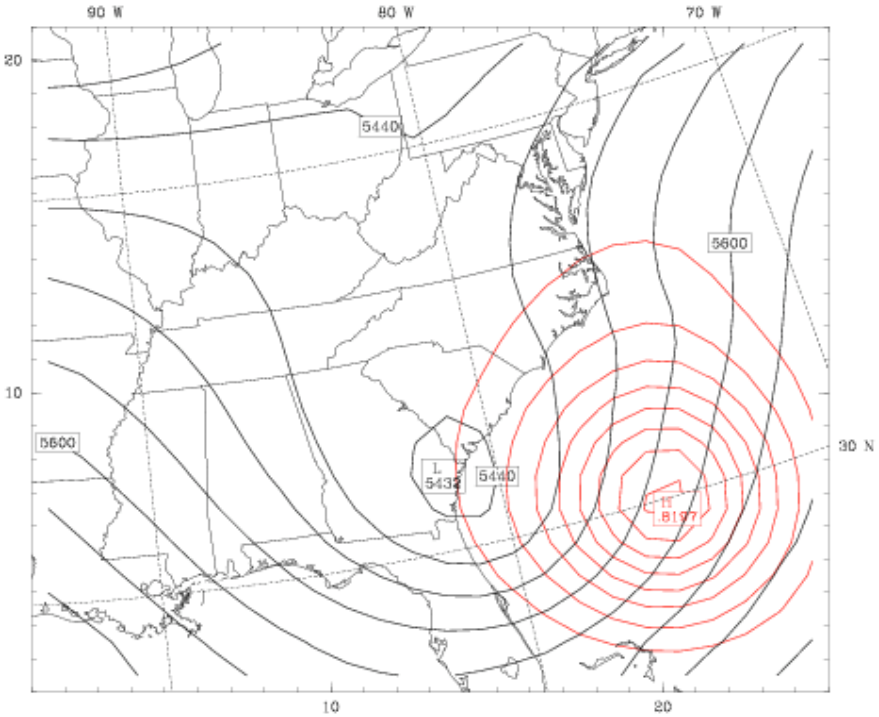
WRF-Var: 3/4D-Var Single Observation Test (observation at start of time window)



3D-Var



4D-Var

4D-Var introduces no flow-dependence for observations at analysis time

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Flow-Dependent Ensemble-Based Forecast Error Covariances

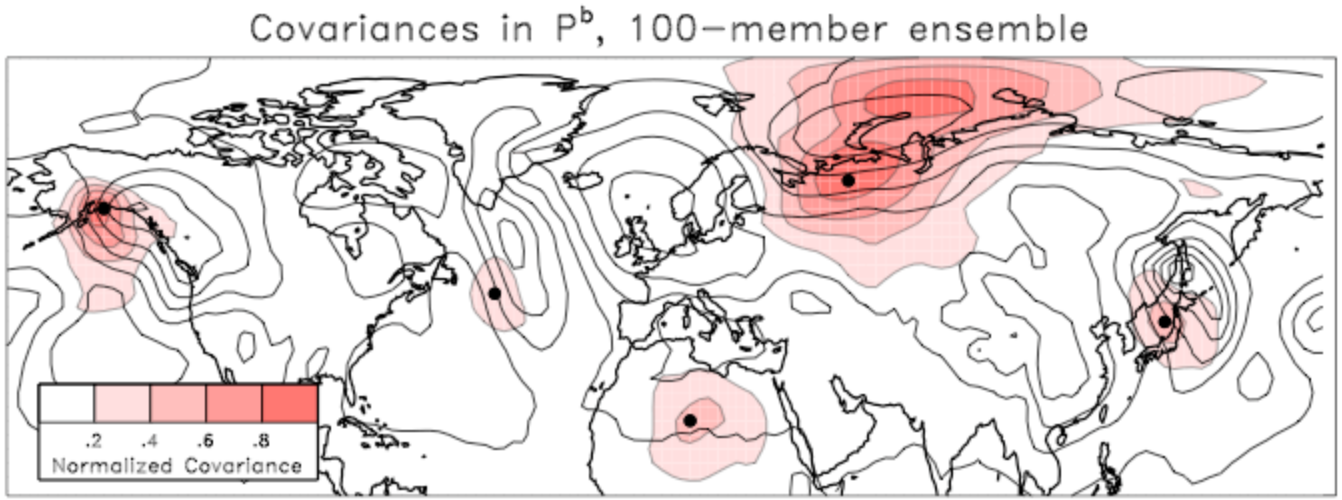

Figure 2. Background-error covariances (colors) of sea-level pressure in the vicinity of five selected observation locations, denoted by dots. Covariance magnitudes are normalized by the largest covariance magnitude on the plot. Solid lines denote ensemble mean background sea-level pressure contoured every 8 hPa.

From Hamill (2006)

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Lorenz 96 Model OSSE: Analysis Error, N=10

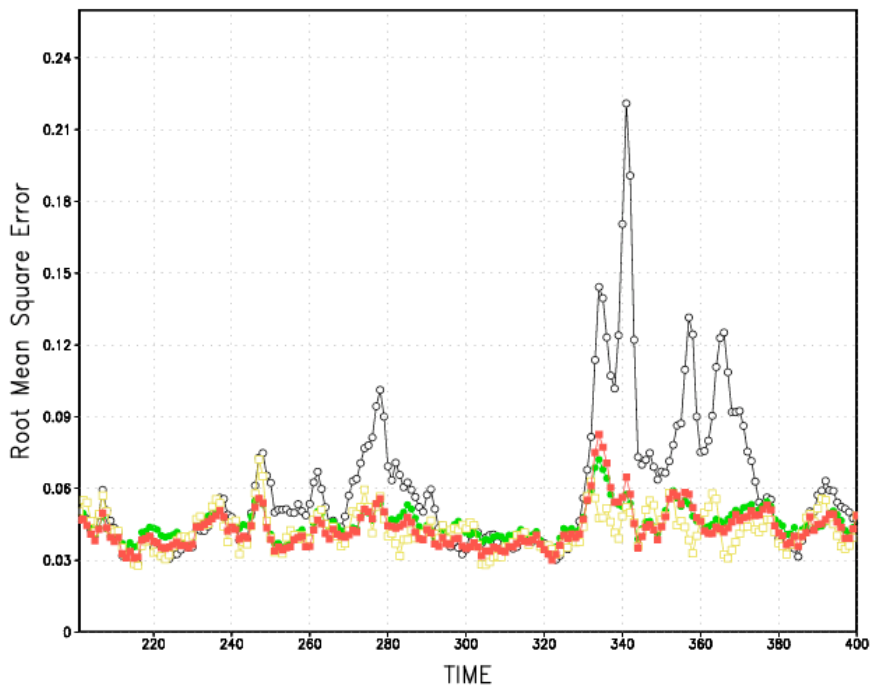
Root Mean Square Analysis Error (x100)

β	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Hybrid	4.59	4.21	4.33	**4.19**	4.46	4.32	4.37	4.86	5.00	5.20	5.70

EnKF

Optimal β=0.3

3D-Var



3D-Var

β=0.3

β=0.7

EnKF

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Example Hybrid Result: ETKF/3D-Var (Etherton and Bishop 2004)

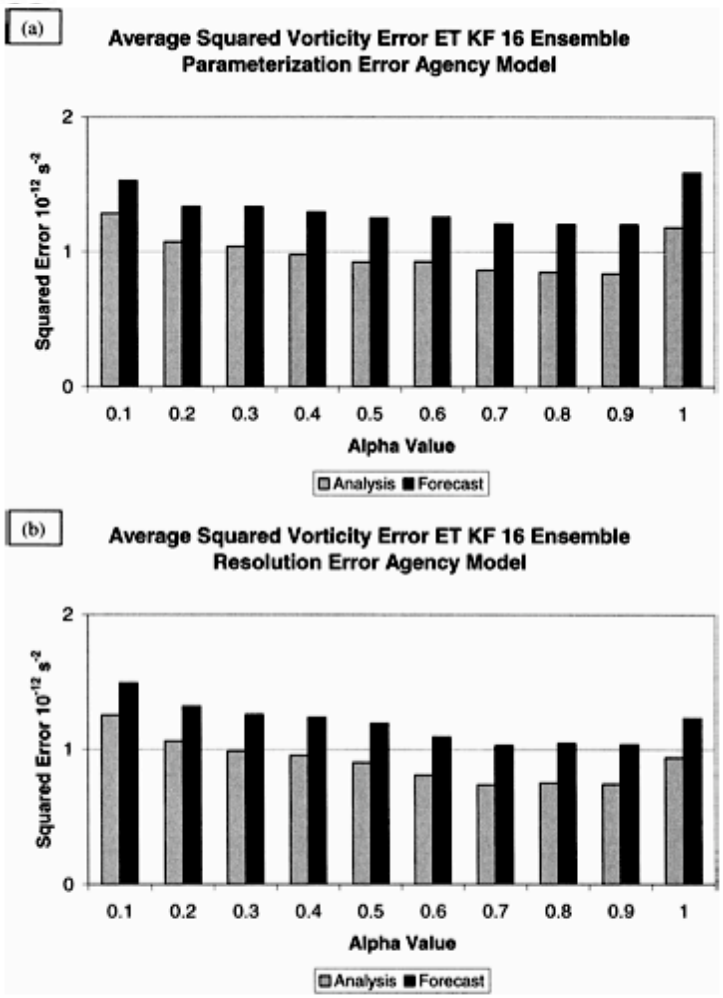

FIG. 5. The daily average squared vorticity error as a function of the parameter alpha ($\alpha = 0$ being pure ETKF, $\alpha = 1$ being pure 3DVAR) for when the agency's forecast model had (a) parameterization error or (b) resolution error. A 16-member ETKF-generated ensemble was used for the construction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

- Barotropic vorticity model.
- ETKF not localized.
- 3D (not 4D)-Var.
- Optimal mix of Var/Ens covariance ~70/30%.

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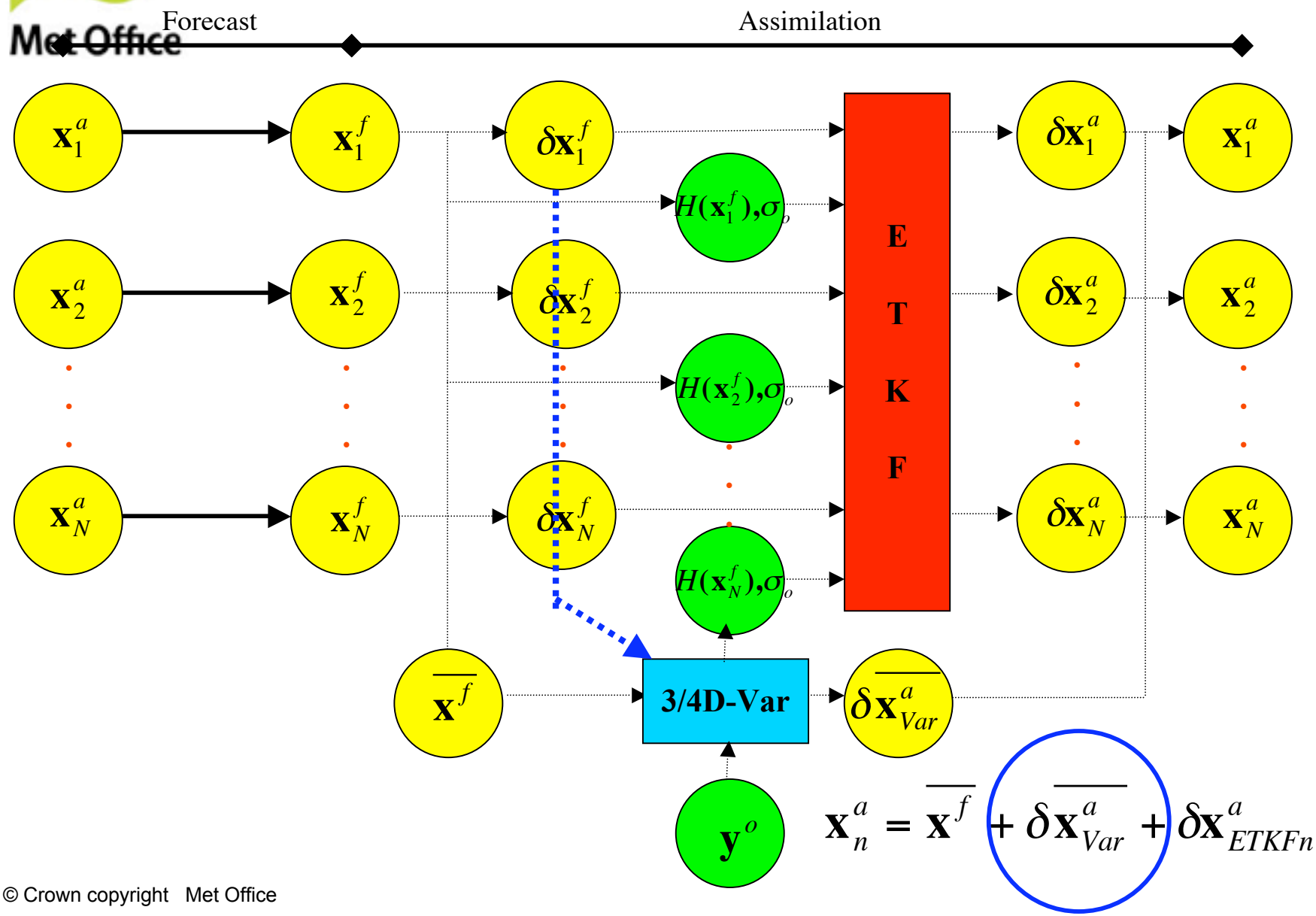
Cycling WRF/WRF-Var/ETKF System (Hybrid DA)



$$\mathbf{x}_n^a = \overline{\mathbf{x}^f} + \delta\overline{\mathbf{x}_{Var}^a} + \delta\mathbf{x}_{ETKFn}^a$$

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Variational Data Assimilation

- Minimization of cost function (-log(pdf)), e.g. Gaussian pdfs imply quadratic cost function $J = J_b + J_o$:

$$J_b\left[\mathbf{x}(t_0)\right] = \frac{1}{2}\left[\mathbf{x}(t_0) - \mathbf{x}^b(t_0)\right]^T \mathbf{B}_o^{-1}\left[\mathbf{x}(t_0) - \mathbf{x}^b(t_0)\right]$$

$$J_o\left[\mathbf{x}(t_0)\right] = \frac{1}{2}\sum_{i=0}^{n}\left[\mathbf{y}_i - \mathbf{y}_i^o\right]^T \mathbf{R}_i^{-1}\left[\mathbf{y}_i - \mathbf{y}_i^o\right]$$

- $\mathbf{B_0}$ is an *a priori* weight matrix estimating the error covariance of $\mathbf{x^b}$.

- $\mathbf{R_i}$ is the observation error covariance matrix for observation y^o at time *i*.

- Direct calculation of J_b and J_o impossible for NWP problems ($\mathbf{B_0}$, $\mathbf{R}$ are matrices of dimension 10^7). Therefore many practical simplifications required.

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Hybrid Variational/Ensemble Data Assimilation

- Hybrid 3/4D-Var analysis increments updated in minimization by

$$\delta\mathbf{x}_0 = \delta\mathbf{x}_{0d} + \delta\mathbf{X}_f \bullet \mathbf{a}$$

- Flow-dependence is constrained by an additional cost-function J_α, i.e.

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

- W_b and W_α are weights of climatological/flow-dependent errors in hybrid.
- Forecast error variance conservation: $\frac{1}{W_b} + \frac{1}{W_\alpha / \sigma_\alpha^2} = 1$
- Define empirical alpha covariance matrix $\mathbf{A} = \sigma_\alpha^2\mathbf{A}_c$

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Benefits Of Hybrid Var/Ensemble DA

Benefits for Variational DA:

- Introduces flow-dependent initial PDF in 3/4D-Var.
- Explicit coupling between moisture/temp/wind fields (tropics, high-res).
- Easily incorporated in Var framework.
- Relatively cheap (if properly preconditioned and compressed).
- Can't do worse – flexible weighting of variational/ensemble covariances.

Benefits for Ensemble DA:

- Hybrids more robust for small ensemble sizes and large model error.
- Makes use of Var's ability to treat all observations simultaneously.
- Nonlinear QC possible (serial filter can't do that by itself).
- Ensemble used for covariance modeling only - can still run high-res. mean.

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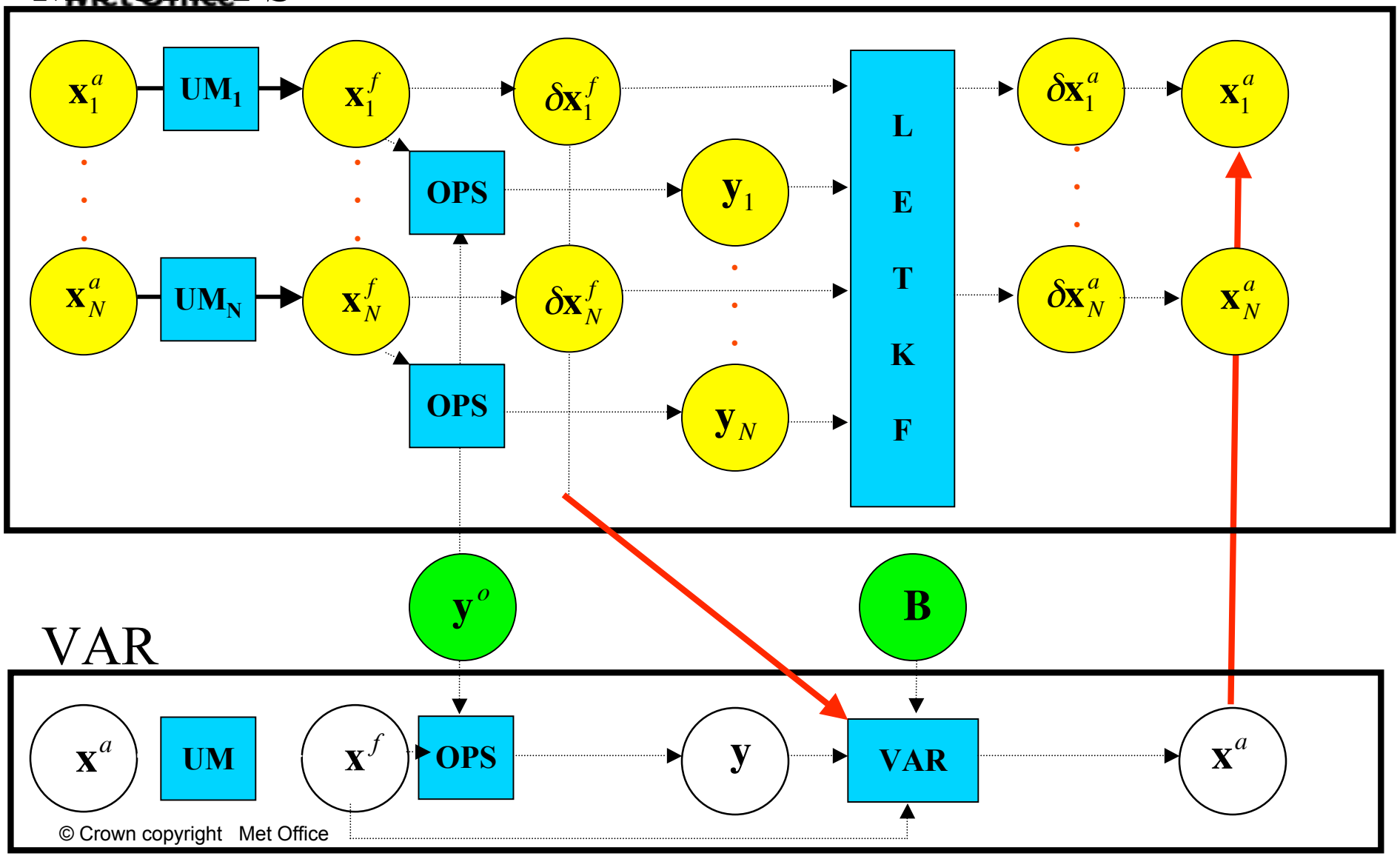
Met. Office 4D-Var/LETKF Hybrid System

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



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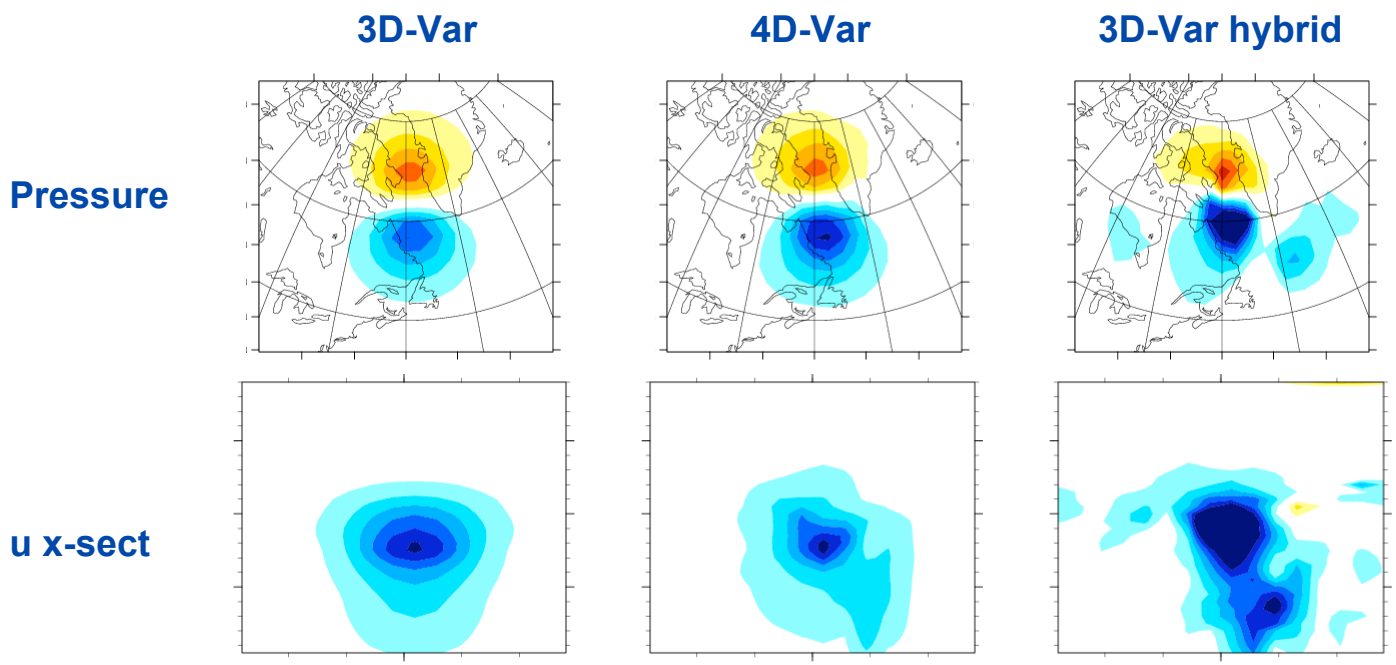
Coupled Variational/Ensemble DA At The Met. Office (Adam Clayton)

- **3D-Var**: Observational information spread using static, quasi-isotropic covariances calculated from climatological statistics.
- **4D-Var**: Static covariances implicitly evolved by linear model.
- **Hybrid VAR**: 3D or 4D-Var covariances combined with (localised) covariances calculated directly from an ensemble.

Response to single u observation



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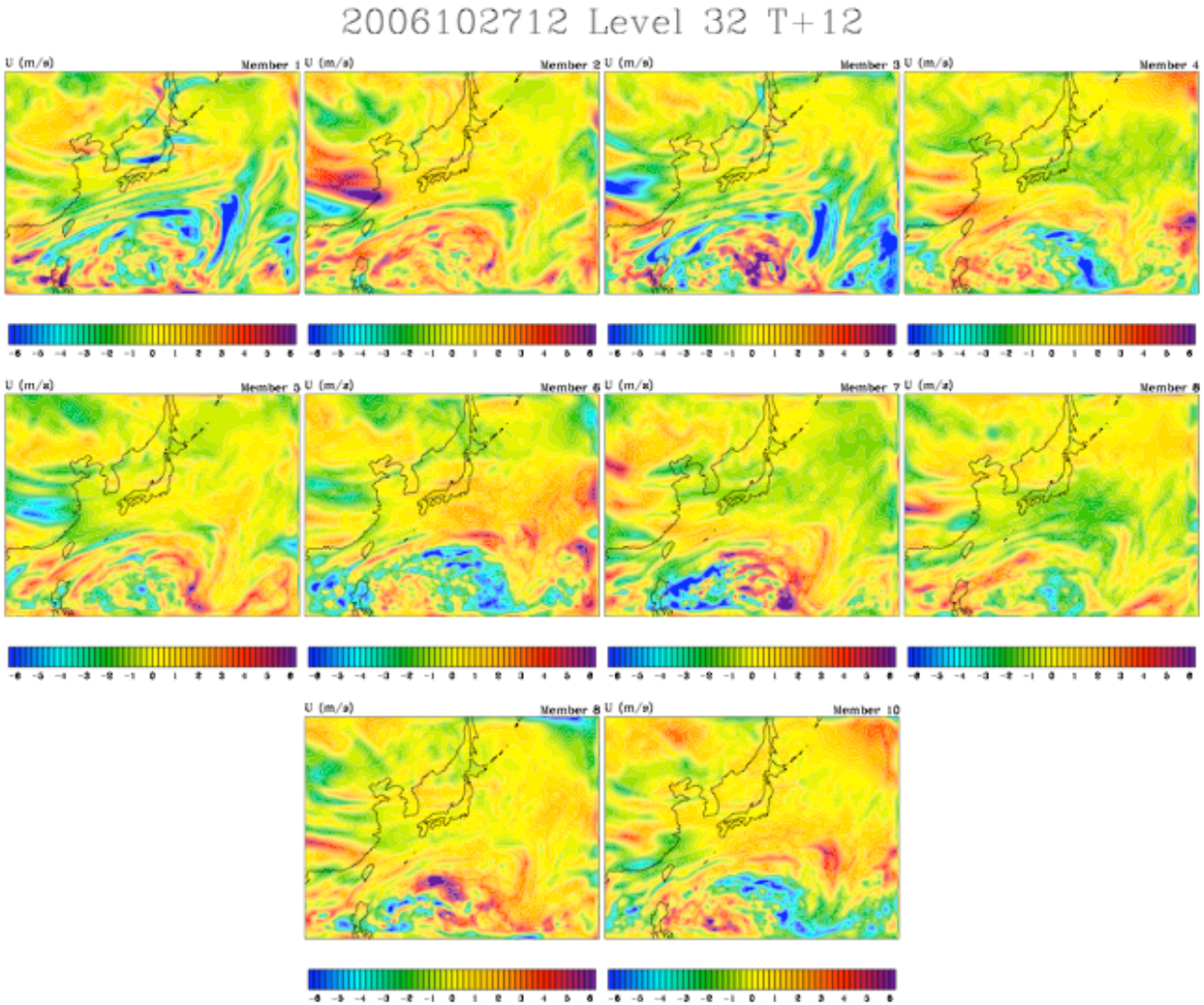
US Air Force Weather Agency: E. Asia Theater u250hPa Ensemble Perturbations (N=10)



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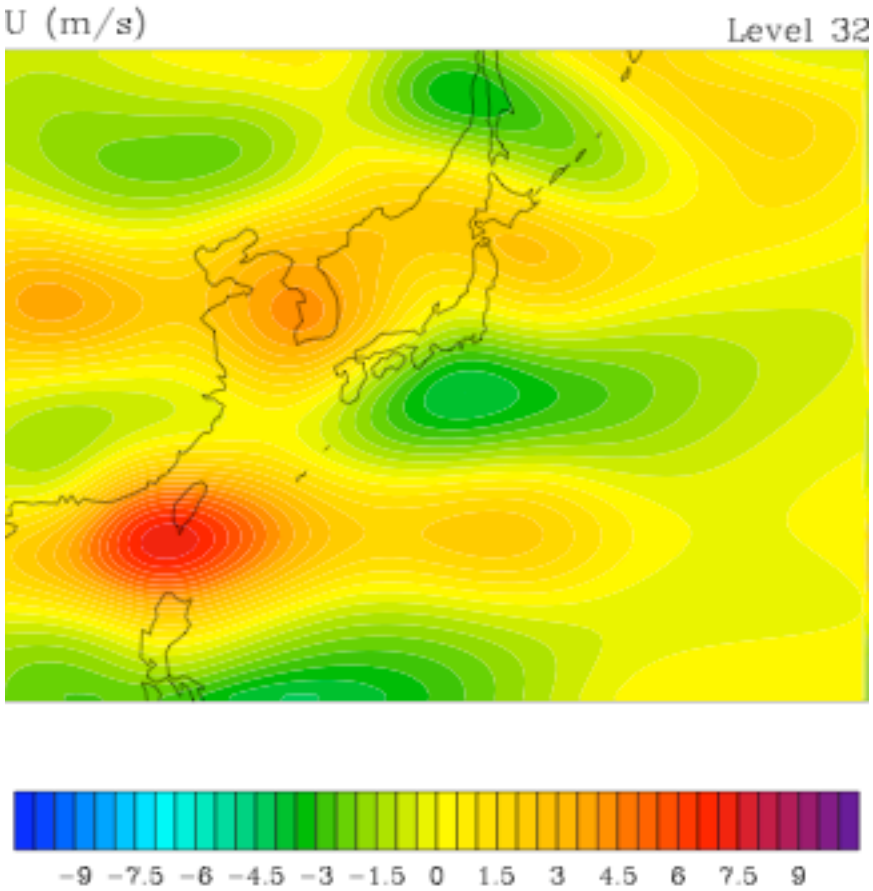
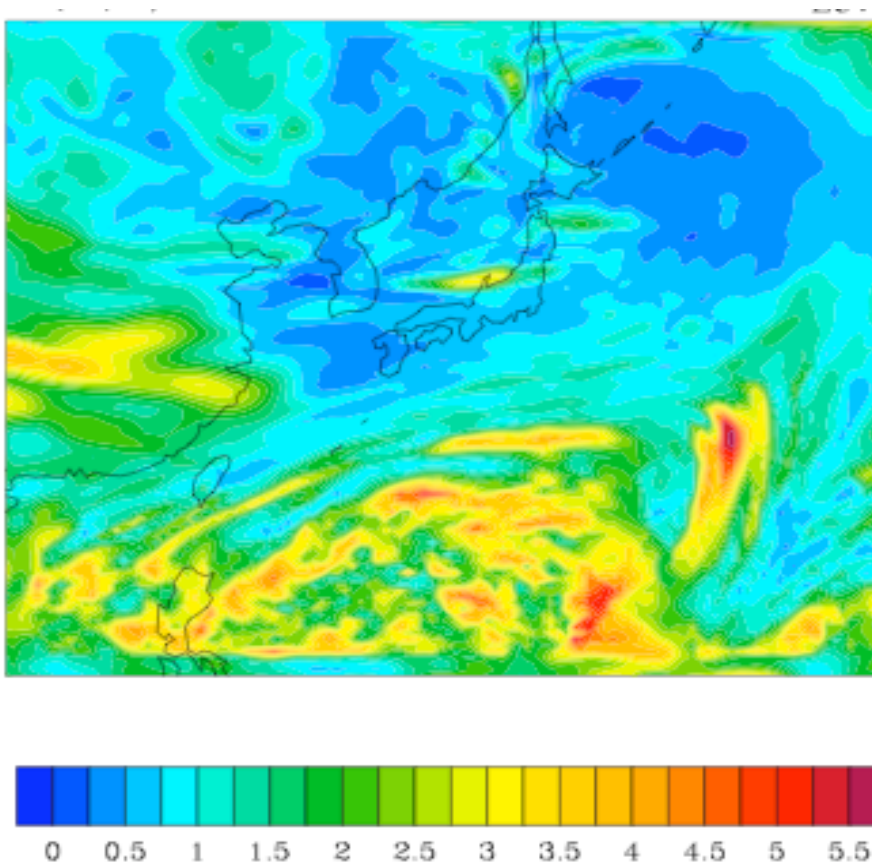
WRF-Var (3D-Var) 2006102800 Analysis



U250 Analysis Increment



U250 Ensemble Spread

Control (no hybrid)

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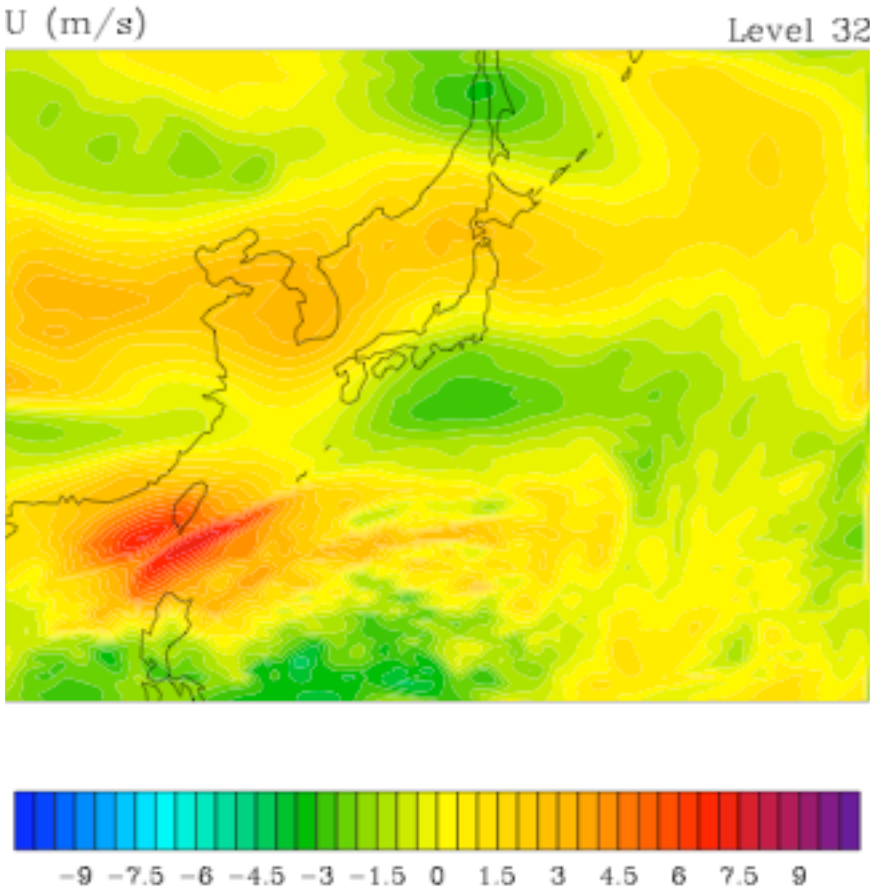
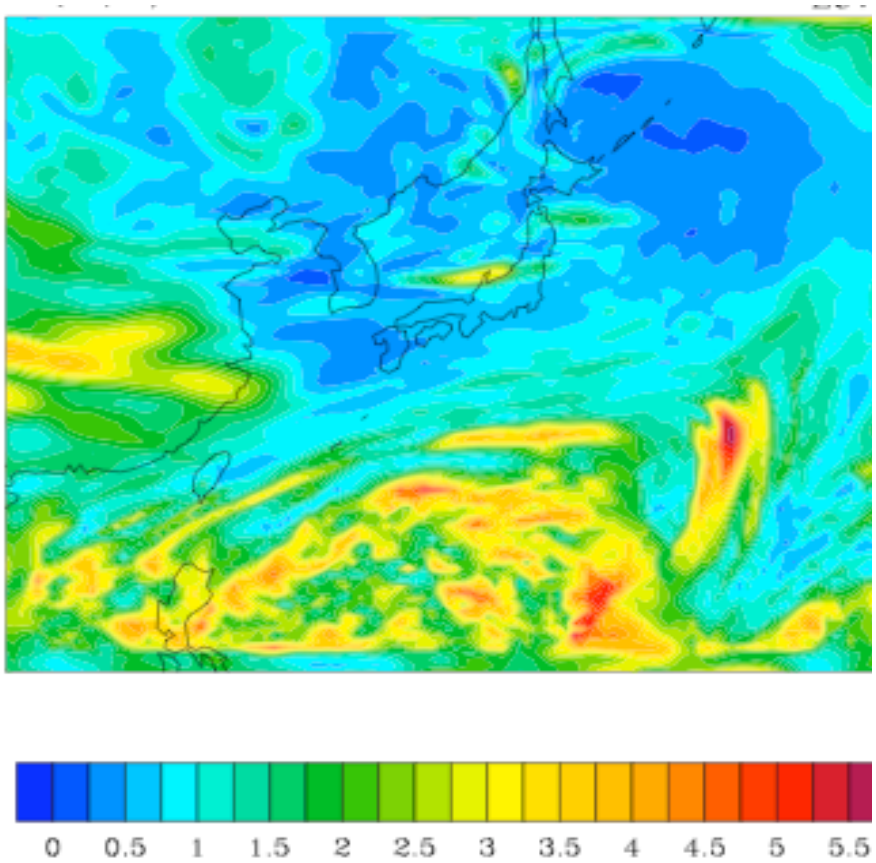
WRF-Var (Hybrid) 2006102800 Analysis



U250 Analysis Increment



U250 Ensemble Spread

$W_e=2$, $W_b=2$

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Vertical Covariance Localization

- Spurious sampling error not confined to horizontal error correlations.

- Hybrid alpha CVs can be made 3D to damp vertical correlations.

- Two approaches considered for specifying vertical localization function

  a) Empirical function (as in horizontal).

  b) Use vertical background error covariances to define localization.

- Initial studies use method a).

- Learn from data compression of EOFs to reduce size of alpha CV.

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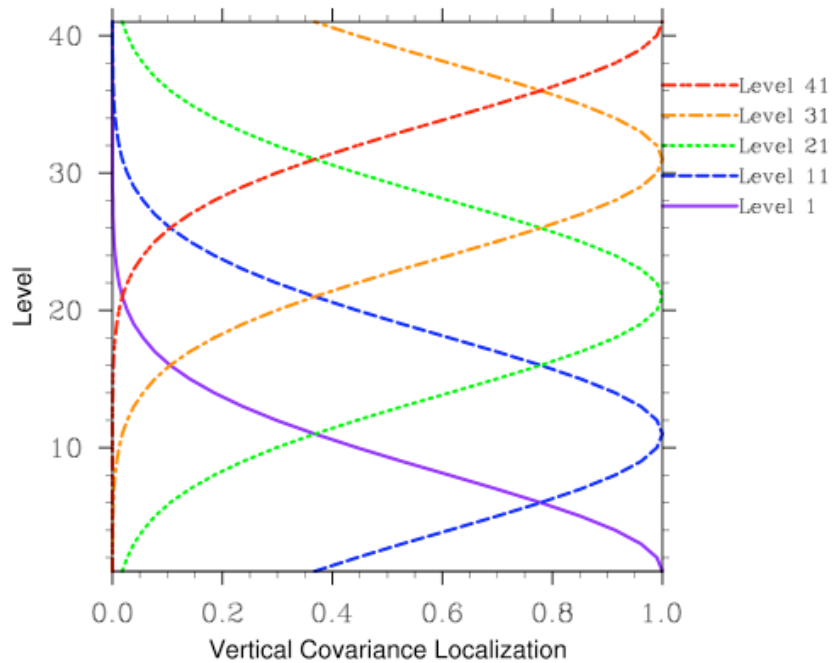
Empirical Vertical Covariance Localization

Apply Gaussian Vertical Covariance Localization:

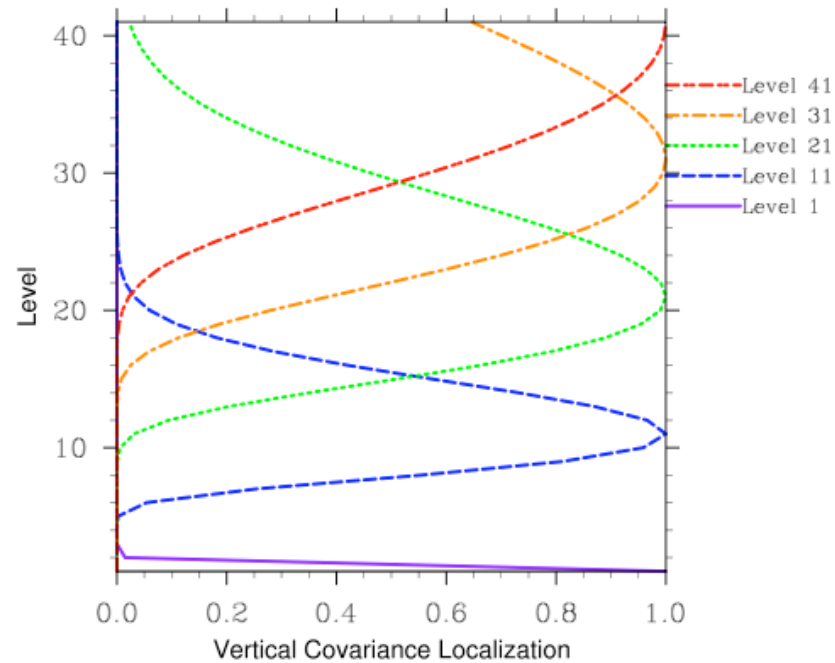
$$\rho(k - k_c) = \exp\left[-\left(k - k_c\right)^2 / L_c^2\right]$$

Example 1:
Constant Localization Scale



$$L_c = 10$$

Example 2:
Vertically-Dependent Localization Scale



$$L_c = 20k_c / 41$$

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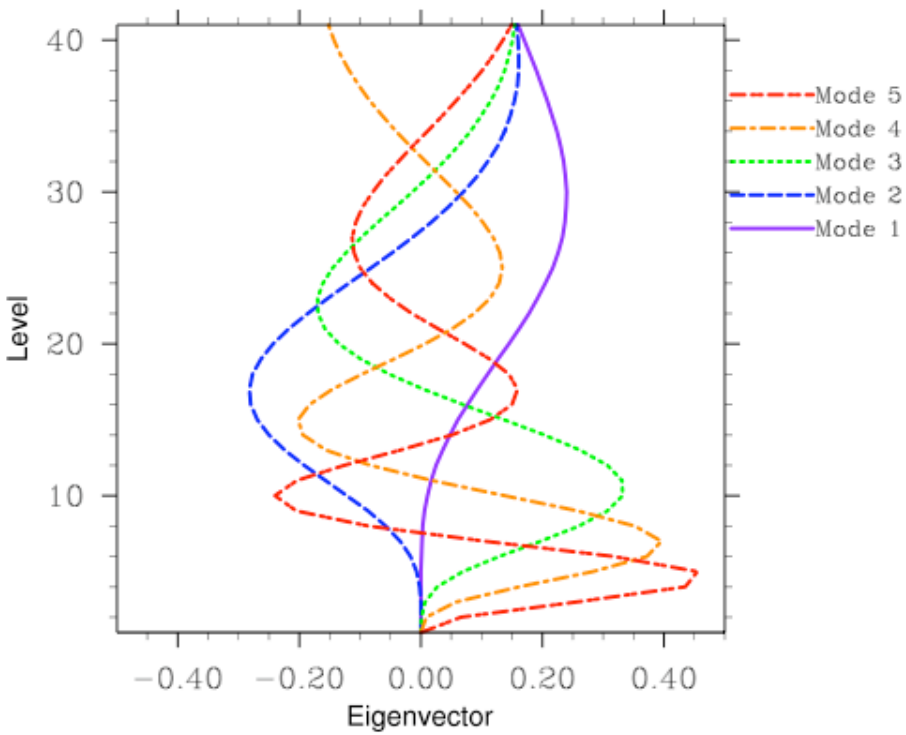
Covariance Localization Decomposition

Example: Gaussian Localization with variable localization scale:

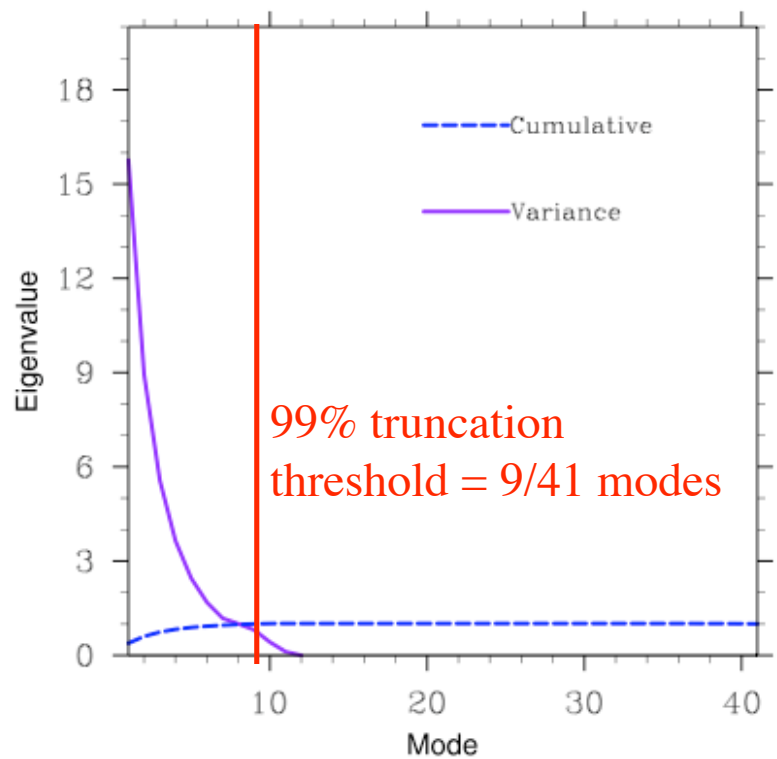
$$\rho(k - k_c) = \exp\left[-\left(k - k_c\right)^2 / L_c^2\right]$$

$$L_c = 20 k_c / 41$$

Eigenvectors



Eigenvalues



Conclusion: 75% data compression via use of EOFs for covariance localization

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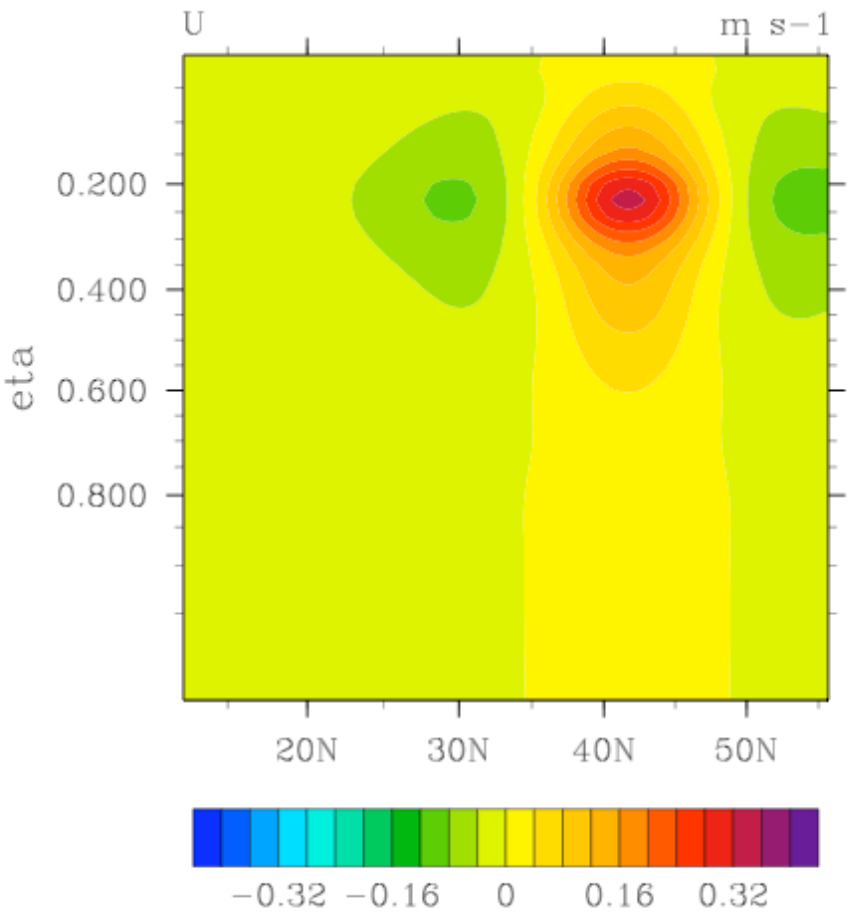
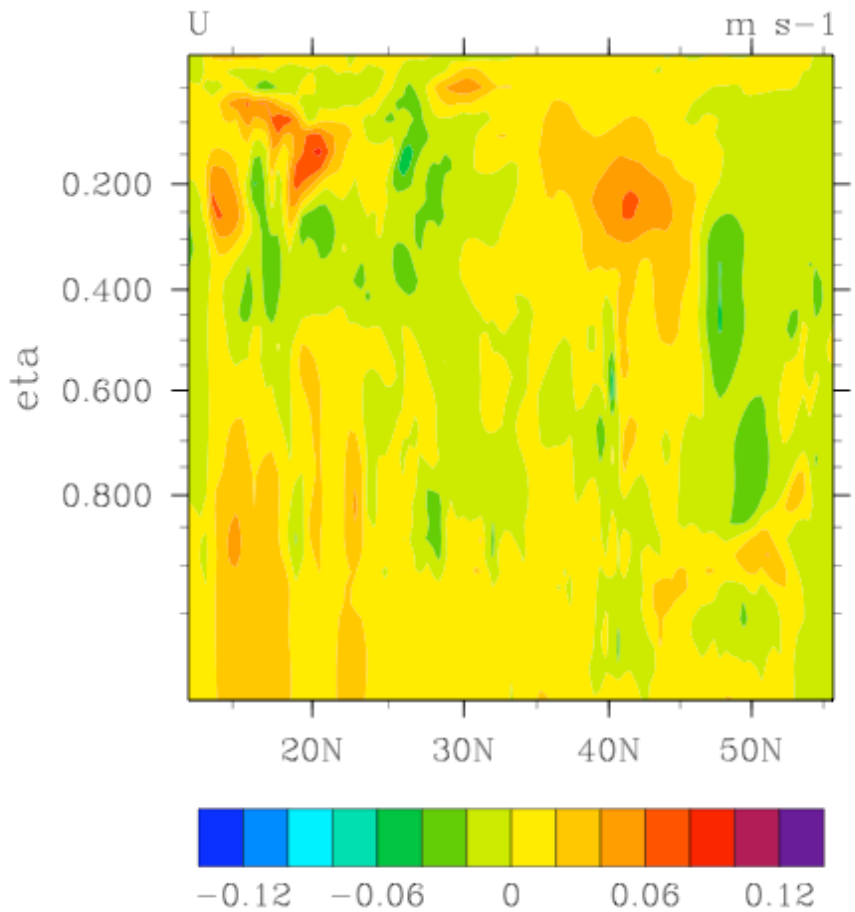
WRF-Var Hybrid Single ob test (250hPa u, O-B=1m/s, sigma_o=3.3m/s)

Vertical Cross Section (note different contour ranges)



W_b=1



W_b=11, W_α=1.1, No Vert. Loc

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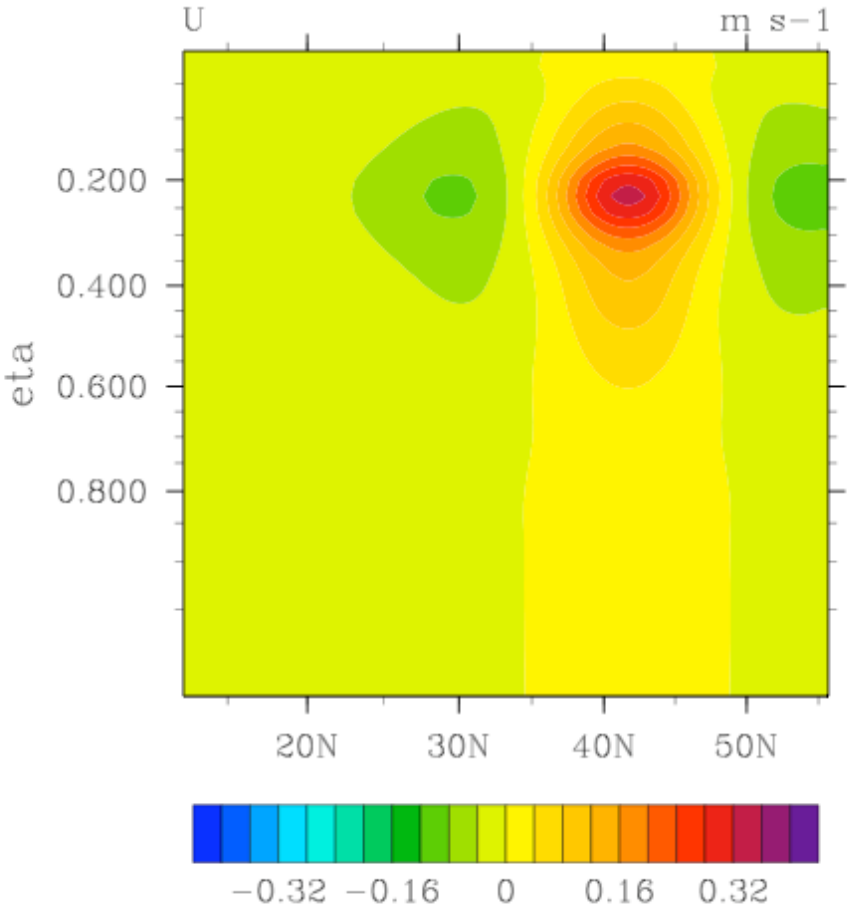
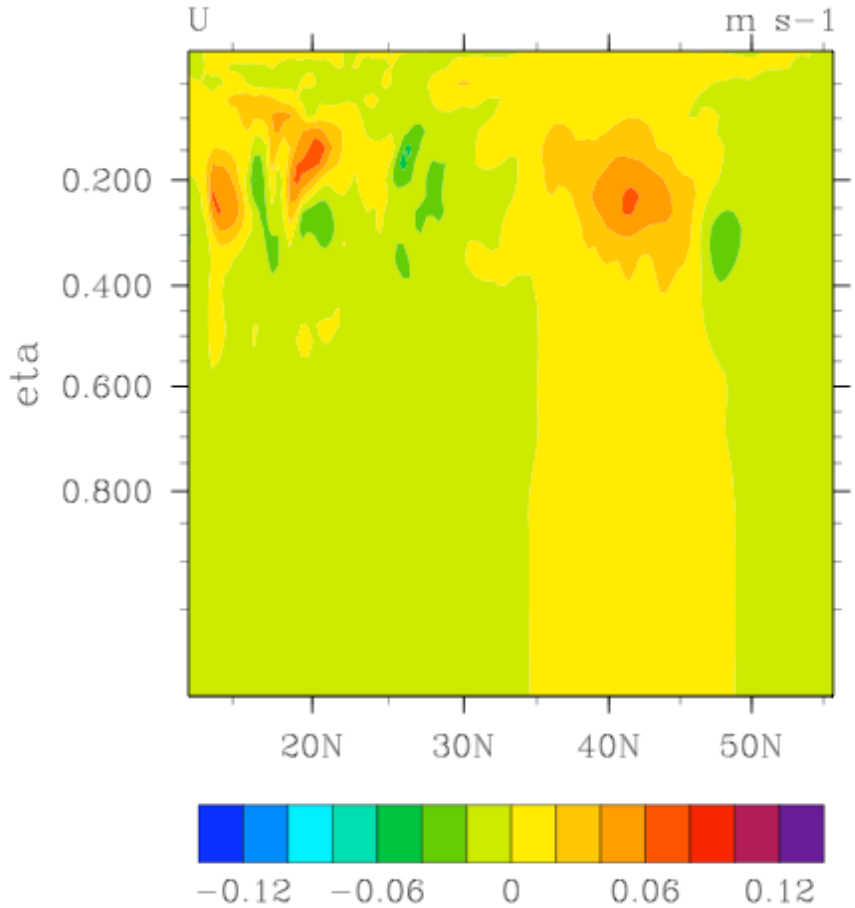
WRF-Var Hybrid Single ob test (250hPa u, O-B=1m/s, sigma_o=3.3m/s)

Impact of Vertical Localization $L_c = 10k_c / 41$



W_b=1



W_b=11, W_α=1.1, With Vert. Loc

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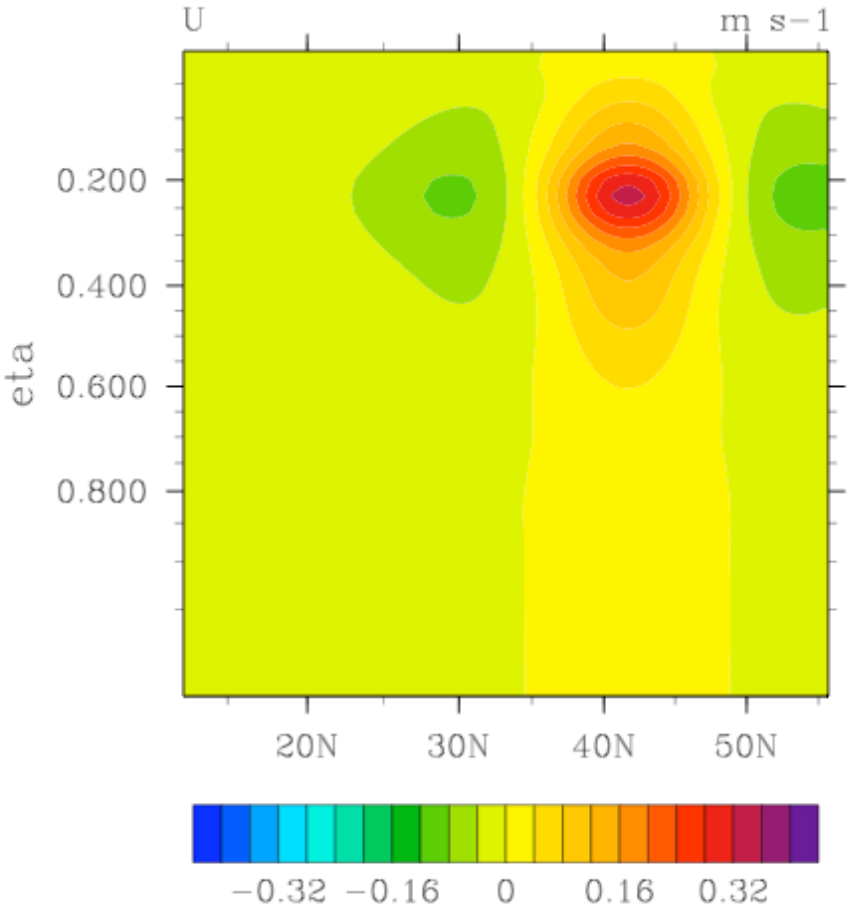
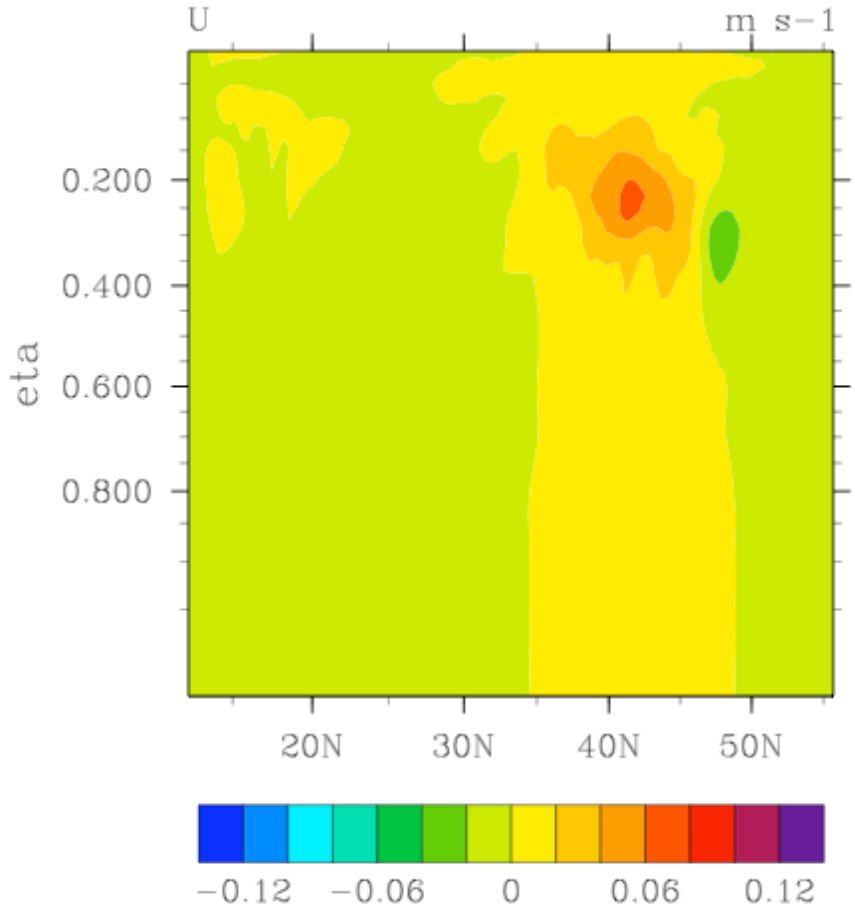
WRF-Var Hybrid Single ob test (250hPa u, O-B=1m/s, sigma_o=3.3m/s)

Impact of More Stringent Horizontal Localization (500km radius)



W_b=1



W_b=11, W_α=1.1, With Vert. Loc

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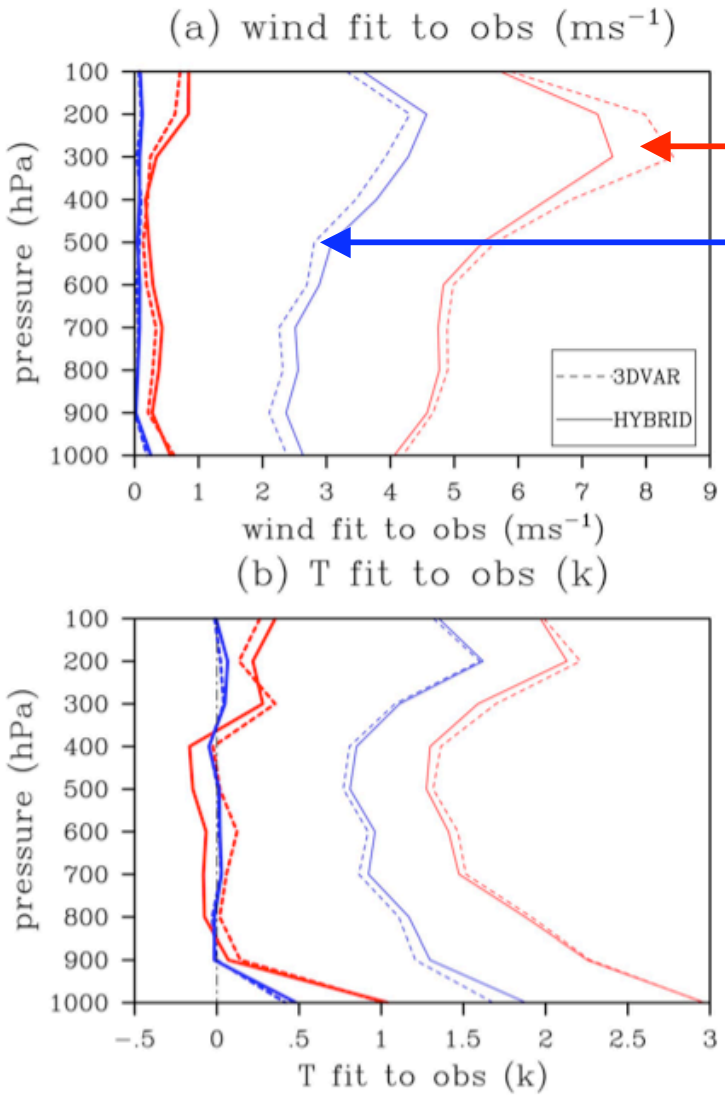
Hybrid 1-Month Real-Data (Sonde) Trial (Wang, Barker, Hamill and Snyder 2008b)



RMS 12hr Fcst Fit to Sonde

RMS Analysis Fit to Sonde

- 200km resolution US domain. Sondes only.
- 3D-Var analysis fits observations more closely.
- Hybrid forecast fits observations more closely.

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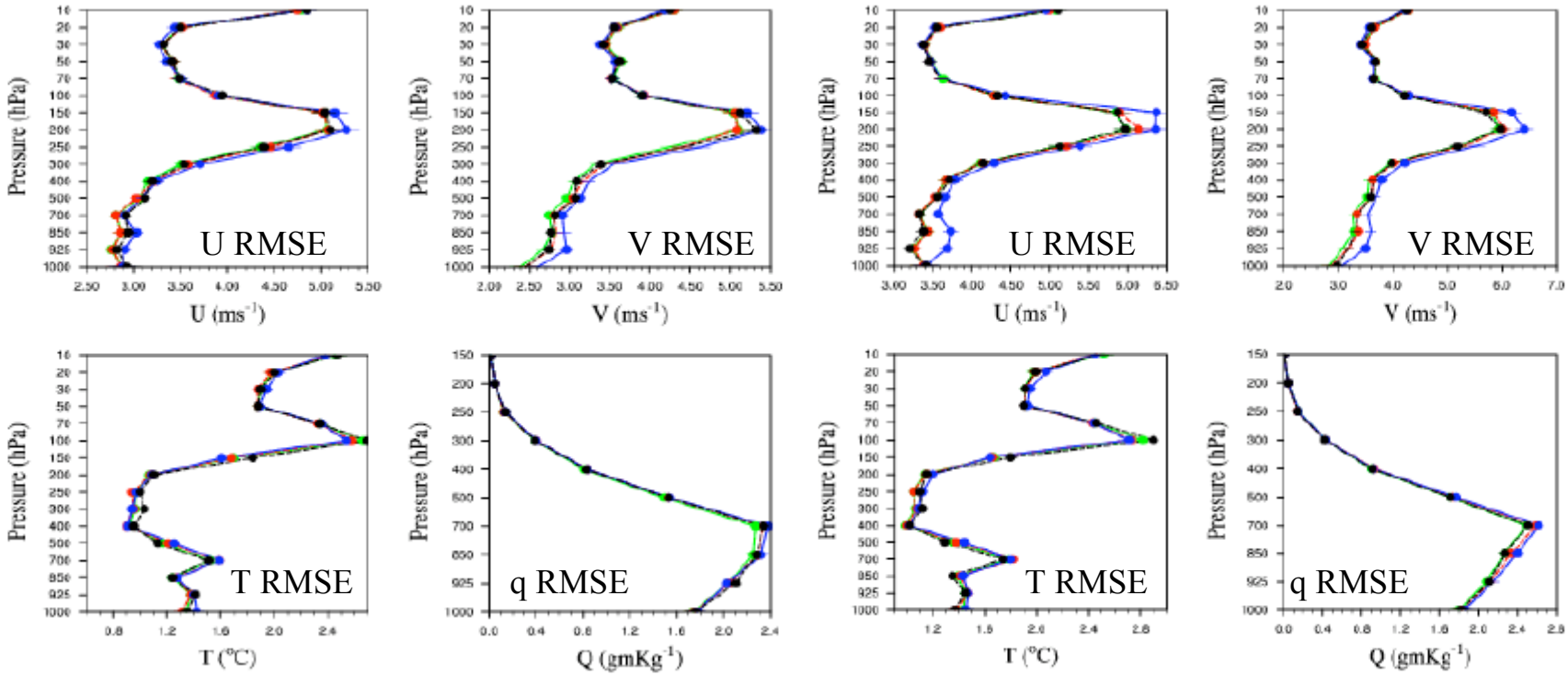
WRF-Var Hybrid Trial: October 2006 (Verification against observations)

Meral Demirtas, NCAR (2009)

- 15km resolution AFWA E. Asian domain. All obs.

T+24 **T+48**



Hybrid **Hybrid_mod** **Hybrid_mod+QC_ENS** **3DVAR**

Conclusion: Significant impact of hybrid on T+24/48 forecasts (mainly wind)

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Outline of Talk

1. Met. Office NWP Overview:
   - Data Assimilation and Ensembles (DAE) Section.
   - Original of NWP Improvement in past few decades (A Lorenc)
   - Current Status and Future Plans.

2. Hybrid Variational/Ensemble DA in WRF: The story continues…
   - Recap on methodology.
   - Vertical localization.
   - Results from AFWA applications (Meral Demirtas).

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