The ECMWF Ensemble Prediction System

Design, Diagnosis and Developments

Martin Leutbecher

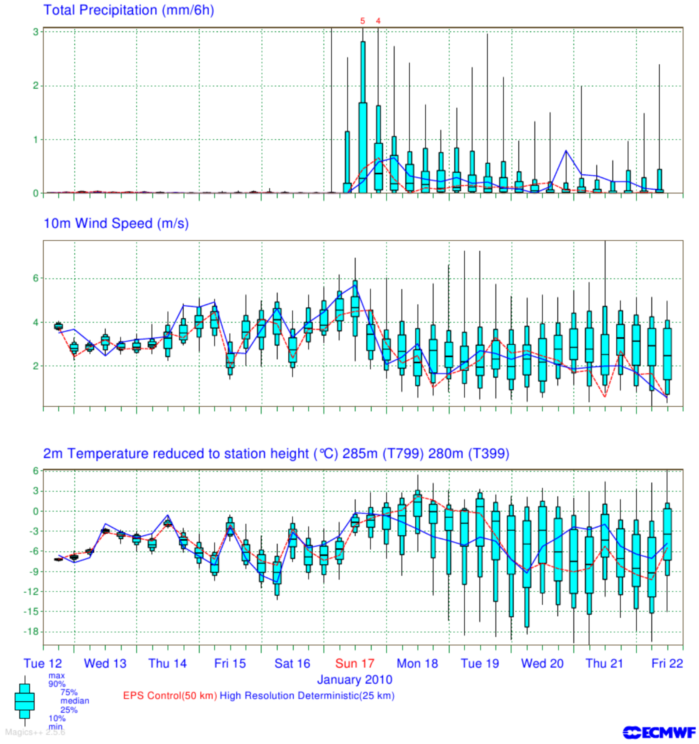
European Centre for Medium-Range Weather Forecasts

MPIPKS Dresden, January 2010

Acknowledgements: Renate Hagedorn, Linus Magnusson

Ensemble forecasting of weather

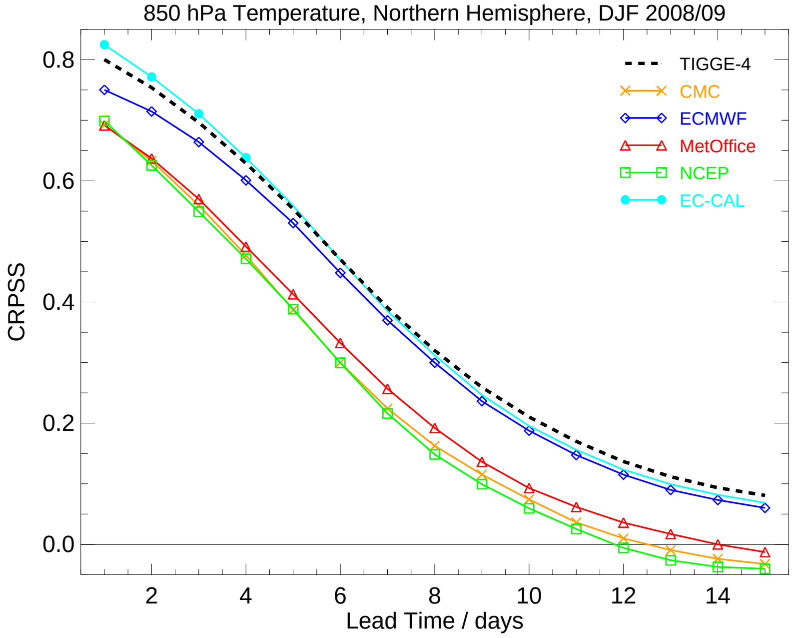
A probabilistic forecast for Dresden



The ECMWF Ensemble Prediction System (EPS)

- 50 perturbed forecasts
- forecasts start from slightly different initial conditions. Perturbations are based on singular vectors of 2-day propagator of the model.
- model tendencies are stochastically perturbed
- 2 ensembles per day at 00 and 12 UTC

Comparison with other global ensembles in TIGGE



Hagedorn et al. (2010)

Quasi-independent analysis (ERA-Interim) used for verification

Symbols indicate that differences to TIGGE-4 are statistically significant at the 1% level.

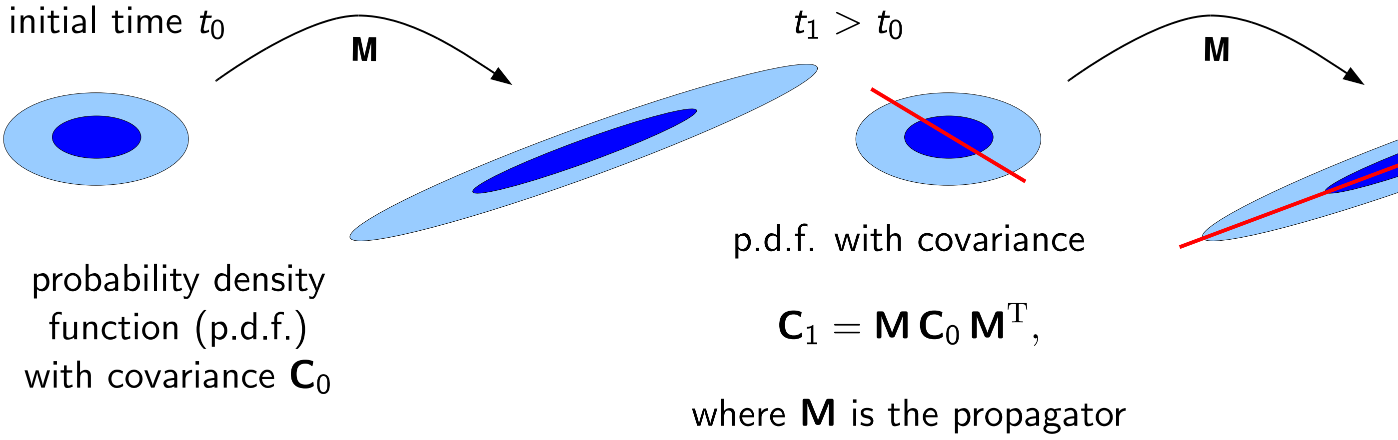
- **CRPS: C**ontinuous **R**anked **P**robability **S**core ≡ Mean Squared error of the cumulative distribution
- Converted to **skill** with CRPS of climatological distribution (1 perfect, 0 as good as climate)
- EC-CAL: Calibrated ECMWF EPS as good as multi-model TIGGE-4 (4 best ensembles in TIGGE including ECMWF)

What determines the skill of the EPS?

- Accurate centre of pdf of initial conditions: 4D-Var assimilation scheme using millions of observations every 12 hours
- Accurate forecast model: efficient and accurate dynamics, advanced parametrisations. Spatial resolution: global NWP model with 50 km (32 km from 26 Jan 2010) horizontal resolution and 62 levels up to 5 hPa
- Efficient representation of sources of uncertainty
  - Initial uncertainties: Singular vectors (SVs)
  - Model uncertainties: Stochastically perturbed parametrisation tendencies (SPPT)
- Decisions about upgrades subject to detailed diagnostics . . .

EPS Design: Representation of Initial Uncertainties

- not all initial condition perturbations grow vigorously
- perturb only those directions of the state space that are dynamically the most sensitive in a linear sense



initial time t_0

$\mathbf{M}$

$t_1 > t_0$

$\mathbf{M}$

probability density function (p.d.f.) with covariance $\mathbf{C}_0$

p.d.f. with covariance

$$\mathbf{C}_1 = \mathbf{M}\,\mathbf{C}_0\,\mathbf{M}^{\mathrm{T}},$$

where $\mathbf{M}$ is the propagator

- a suitable singular-value-decomposition of the propagator of the NWP model yields such perturbations ("singular vectors (SVs)")

EPS Design: Initial Uncertainties (2)

- Initial pdf represented by a Gaussian in the space spanned by the leading $O(100)$ SVs in a state space with dimension $O(10^7)$
- Norms (linear transformations of state space) are required to define a physically meaningful SVD
- The appropriate initial-time norm is based on the initial error covariance matrix
  - If initial error cov. matrix $\mathbf{P}_a$ was used in SVD, the SVs evolve into leading eigenvectors of (a linear and perfect model estimate of) the forecast error covariance matrix
  - If we had access to $\mathbf{P}_a$ we could use it directly to define the pdf.
  - In the operational system the so-called total energy norm is used as proxy
  - A more sophisticated estimate of the analysis error covariances based on the Hessian of the 4D-Var cost function as been tried . . . (Barkmeijer et al 1998,1999, Lawrence et al 2009).

Singular vectors of the propagator

Consider the SVD of the scaled propagator $\mathbf{D}^{1/2}\mathbf{M}\mathbf{C}_0^{1/2}$ for the initial time norm and final time norm

$$\|\mathbf{x}\|_i^2 = \mathbf{x}^\mathrm{T}\mathbf{C}_0^{-1}\mathbf{x}, \qquad \|\mathbf{x}\|_f^2 = \mathbf{x}^\mathrm{T}\mathbf{D}\mathbf{x}$$

The singular value decomposition of the scaled propagator is

$$\mathbf{D}^{1/2}\mathbf{M}\mathbf{C}_0^{1/2} = \widetilde{\mathbf{U}}\mathbf{S}\widetilde{\mathbf{V}}^\mathrm{T} \tag{1}$$

Here, **S** is the diagonal matrix containing the decreasing singular values $\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_N$. Orthonormal matrices $\widetilde{\mathbf{U}}$ and $\widetilde{\mathbf{V}}$ contain the non-dimensional left and right singular vectors, respectively (as column vectors). In the usual physical coordinates, we refer to the singular vectors as

$$\begin{array}{rl} \text{initial SVs} & \mathbf{V} = \mathbf{C}_0^{1/2}\widetilde{\mathbf{V}} \\ \text{normalised evolved SVs} & \mathbf{U} = \mathbf{D}^{-1/2}\widetilde{\mathbf{U}} \end{array}$$

The leading SVs evolve into the leading eigenvectors of the fc error cov. matrix $\mathbf{C}_1$

$$\mathbf{C}_1 = \mathbf{M}\mathbf{C}_0\mathbf{M}^\mathrm{T} = \mathbf{U}\mathbf{S}^2\mathbf{U}^\mathrm{T}. \tag{2}$$

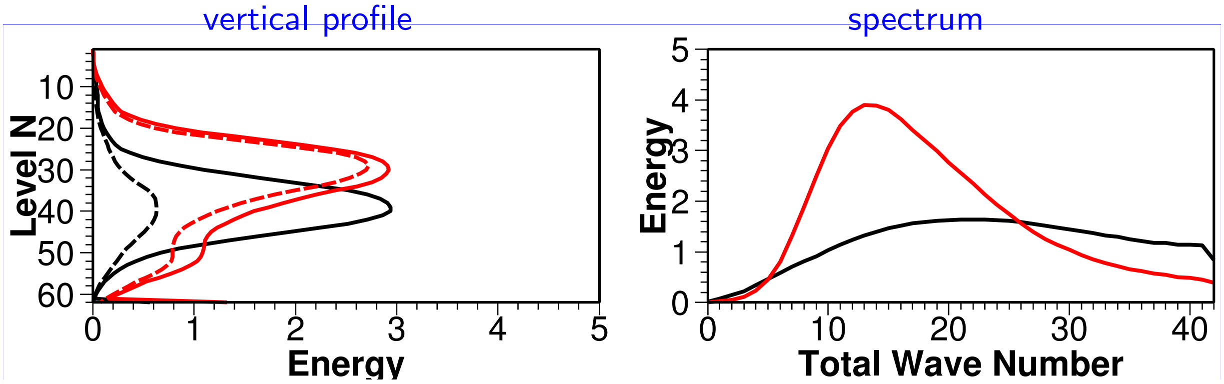
Singular vectors in the operational ECMWF EPS

- $t_\mathrm{opt} \equiv t_1 - t_0 = 48$ h
- resolution: T42 (300 km)
- **Extra-tropics:** 50 SVs for N.-Hem. (30°–90°N) + 50 for S.-Hem.(30°–90°S). Tangent-linear model with vertical diffusion and surface friction only.
- **Tropical cyclones:** 5 singular vectors per region targeted on active tropical depressions/cyclones. Up to 6 such regions. Tangent-linear model with representation of diabatic processes (large-scale condensation, convection, radiation, gravity-wave drag, vert. diff. and surface friction).
- **Localisation** is required to avoid that too many leading singular vectors are located in the dynamically more active winter hemisphere. Also required to obtain (more slowly growing) perturbations associated with tropical cyclones.

  In order to optimise perturbations for a specific region simply replace the propagator **M** in the equations by **PM**, where **P** denotes the projection operator which sets the state vector ($T, u, v, \ln p_\mathrm{sfc}$ in grid-point space) to zero outside the region of interest and is the identity inside it.

Upward and upscale growth of singular vectors

average energy of the leading 50 singular vectors
initial time (× 50), **final time t =48 h (× 1)**
━━: total energy; ━ ━: kinetic energy
Northern hemisphere extra-tropics, 2006032100



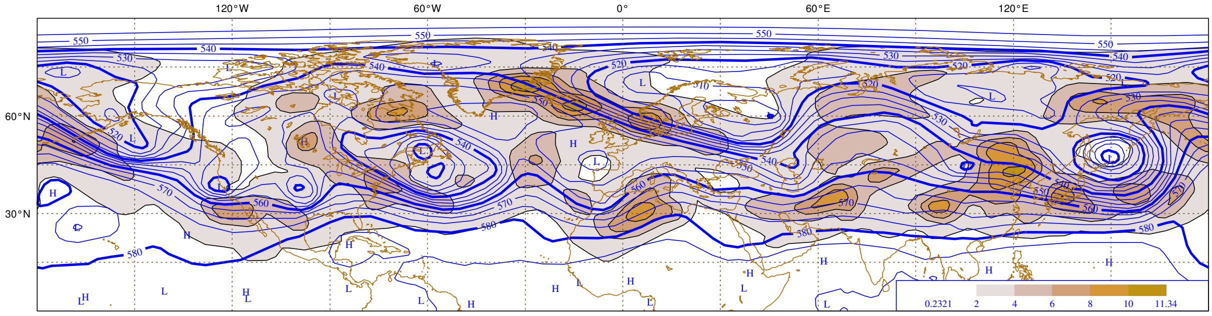
200 hPa ↔ level 20   300 hPa ↔ level 27
500 hPa ↔ level 35   700 hPa ↔ level 42
850 hPa ↔ level 48   925 hPa ↔ level 52

wave number	wave length
5	8000 km
10	4000 km
20	2000 km
40	1000 km

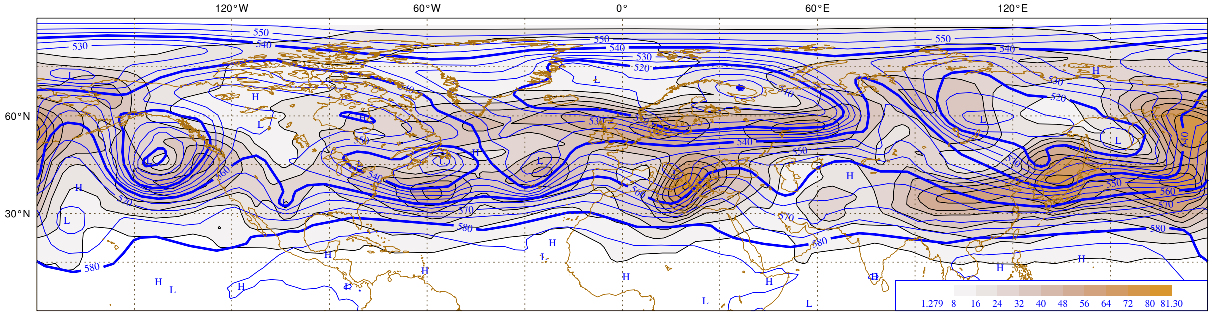
see also Buizza and Palmer (1995) and Lawrence et al (2009)

Regional distribution of Northern Hem. SVs

square root of vertically integrated total energy of SV 1–50 (shading)
500 hPa geopotential (contours)
initial singular vectors, 21 March 2006, 00 UTC



evolved singular vectors, 23 March 2006, 00 UTC

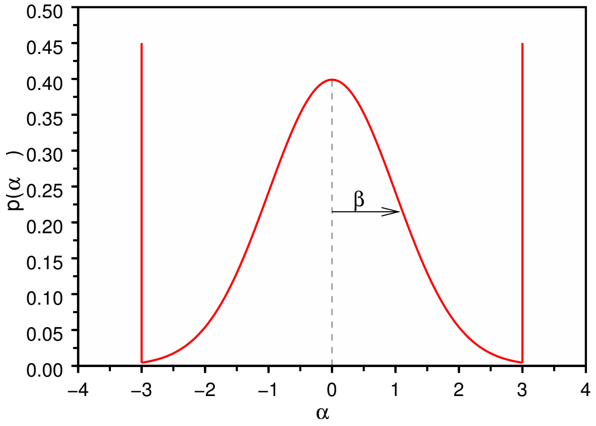


Initial condition perturbations

- Initial condition uncertainty is represented by a (multi-variate) Gaussian distribution in the space spanned by the leading singular vectors
- The perturbations based on a set of singular vectors $\mathbf{v}_1, \ldots, \mathbf{v}_m$ are of the form

$$\mathbf{x}_j = \sum_{k=1}^{m} \alpha_{jk} \mathbf{v}_k \qquad (3)$$

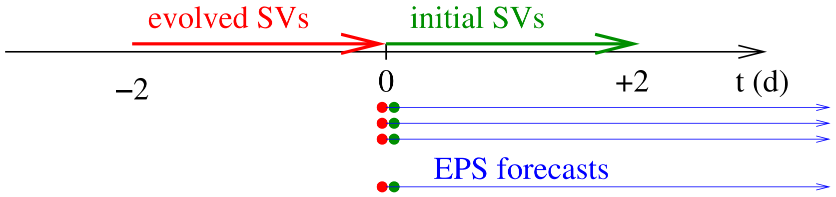
- The α_{jk} are independent draws from a truncated **Gaussian distribution**.



- The width of the distribution is set so that the spread of the ensemble matches the root-mean square error in an average over many cases ($\beta \approx 10$).
- The Gaussian is truncated at ± 3 standard deviations to avoid numerical instabilities for extreme values ($\alpha = 10\sigma$ is unlikely but possible).

Initial condition perturbations (2)

- For the **extra-tropical perturbations**, the leading 50 initial singular vectors and the leading 50 evolved singular vectors are combined (in each hemisphere)



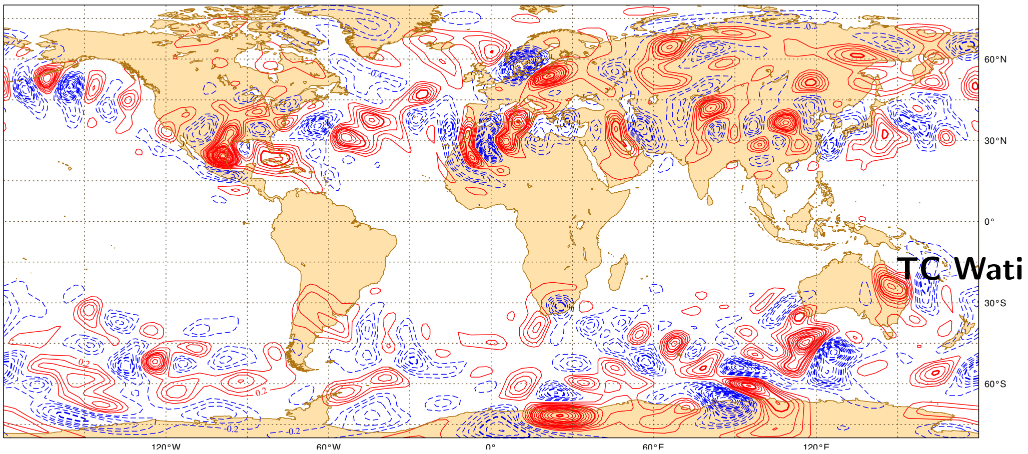
- For each of the (up to 6) optimisation regions **targeted on a tropical cyclone**, the leading 5 initial singular vectors are combined.
- To make sure that the ensemble mean is centred on the unperturbed analysis a **plus-minus symmetry** has been introduced:
  - coefficients for members 1, 3, 5, . . . , 49 are sampled,
  - the perturbation for members 2, 4, 6, . . . 50 is set to minus the perturbation of the member $j-1$ ($\mathbf{x}_j = -\mathbf{x}_{j-1}$).

Note: The sign of a singular vector itself is arbitrary.

Initial condition perturbation for member 5

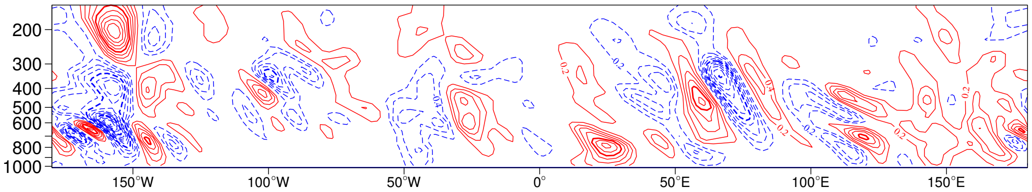
Temperature (every 0.2 K); 21 March 2006, 00 UTC

at ≈ 700 hPa



TC Wati

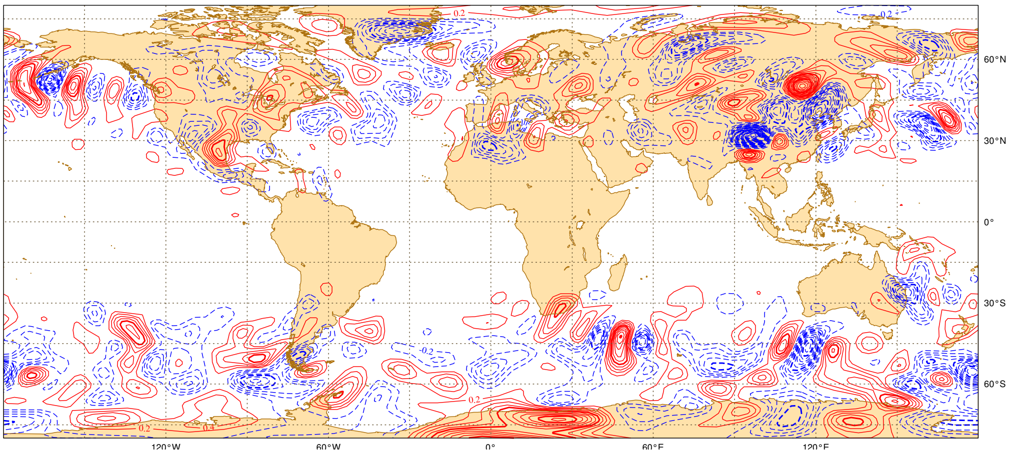
at 50°N



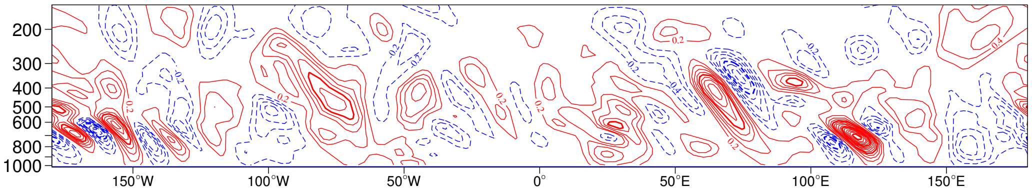
Initial condition perturbation for member 50

Temperature (every 0.2 K); 21 March 2006, 00 UTC

at ≈ 700 hPa



at 50°N

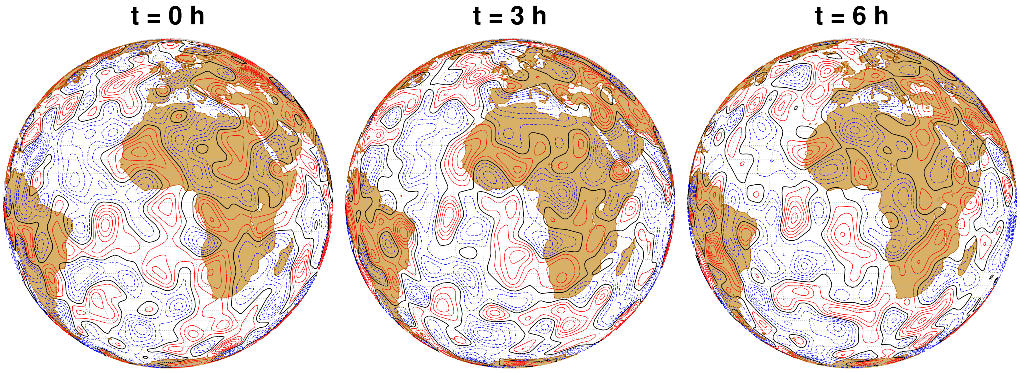


EPS Design: Representation of Model Uncertainties

- Model uncertainties are represented by stochastically perturbed parametrisation tendencies (SPPT)
- Original scheme developed by Buizza et al (1999, "stochastic physics")
- Revised scheme outlined below (see Palmer et al, 2009, for details)

Perturbed parametrized tendencies

- Tendency perturbation: $\Delta X_p = (1 + r)\Delta X_0$,
  where ΔX_0 denotes the unperturbed tendency of u, v, T, q
- Random pattern r given by AR(1) processes in spectral space

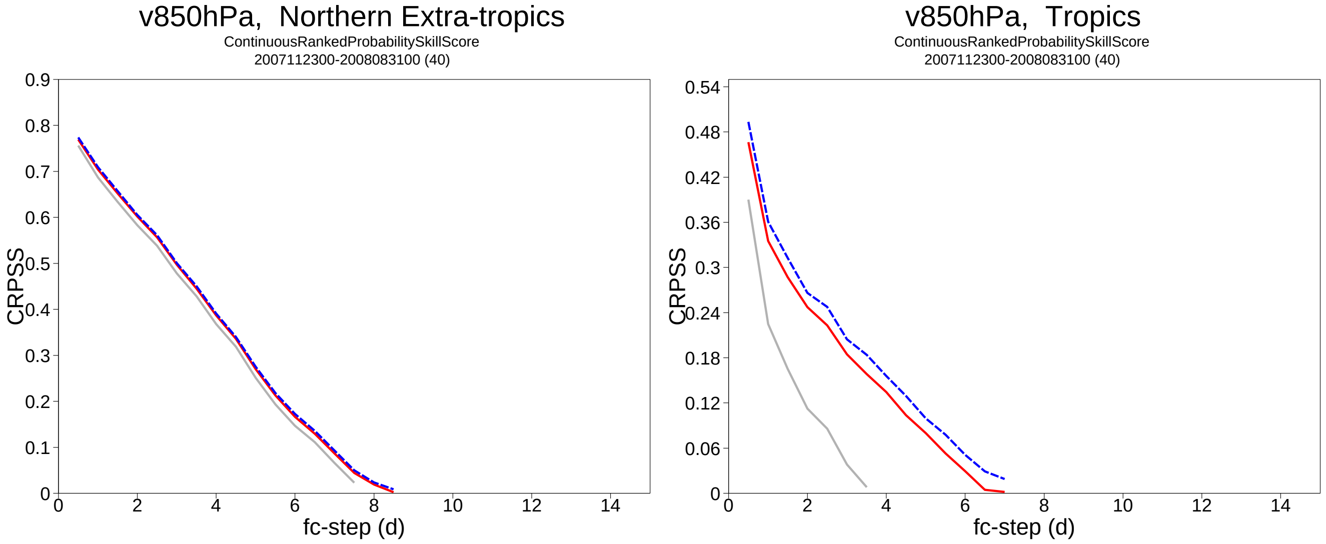


- Decorrelation scales: 500 km (horizontal), 6 h
- Distribution of r is Gaussian with stdev 0.5 in grid point space
- No perturbations in stratosphere and close to the surface

EPS skill and SPPT

CRPSS of Meridional Wind Component at 850 hPa

Northern Extratropics 20°–90°N   Tropics 20°S–20°N



— No tendency perturbations

— Buizza et al (1999)

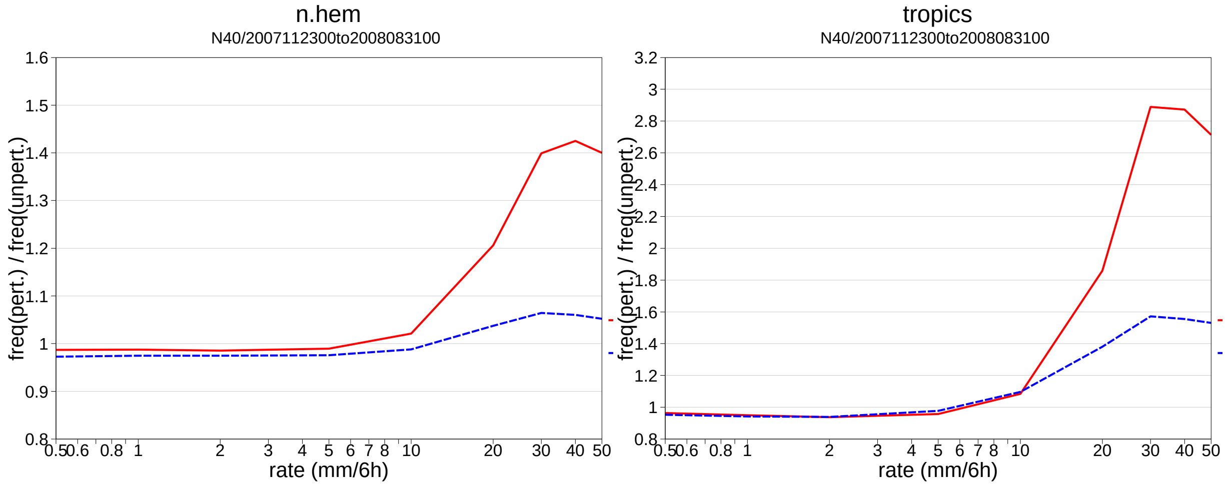
- - - revision (2009)

SPPT revision and the tail of the precipitation distribution

CDF of 6-hourly precipitation estimated from 2000 10-day forecasts

$$\frac{\text{precipitation frequency in forecasts with SPPT}}{\text{precip. frequency in fcs. without tendency pertns.}}$$

Northern Extratropics 20°–90°N   Tropics 20°S–20°N



— Buizza et al (1999)   - - - revision (2009)

Diagnosis

Comparison of SV-based perturbations with other initial perturbations

- Focus on 3 recent studies
- Model and unperturbed initial state based on operational NWP system
- Comparison using the same forecast model (IFS of ECMWF) and the same unperturbed initial state (operational ECMWF analysis)
- Comparisons
  - Bred vectors ↔ singular vectors
  - Ens. Transform Pertns. ↔ Random States ↔ SVs
  - Short-range forecast errors ↔ SVs

Comparison of ensembles using bred vectors and singular vectors

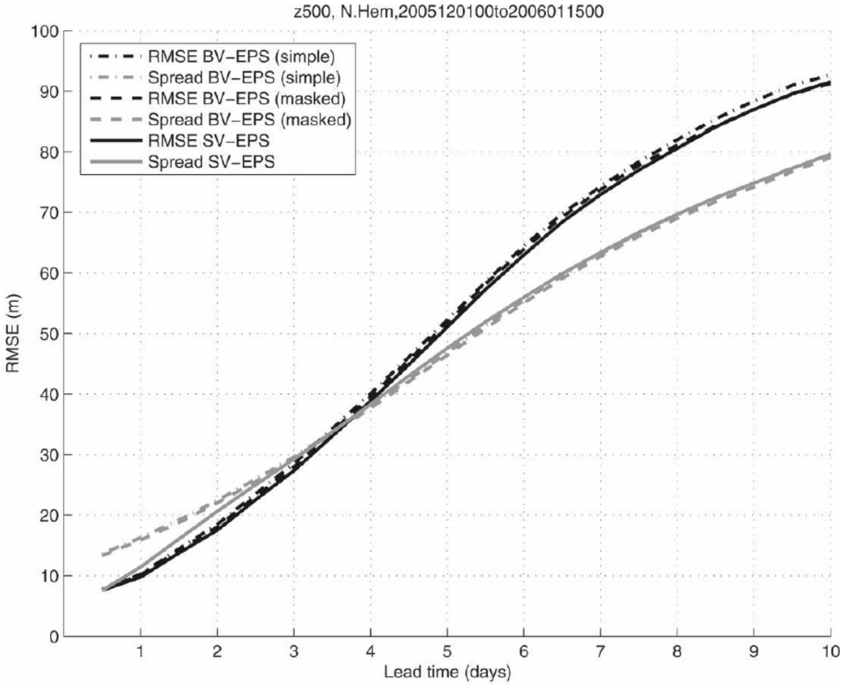
Magnusson, Leutbecher and Källén (2008, MWR)

- Bred vectors:
  - rescaling every 6-hours
  - 2 flavours: global rescaling, regionally varying rescaling (“masked”)
  - 18 perturbed ICs from adding/subtracting 9 independent BVs to analysis
  - ensemble spread tuned to get same spread at Day 3 as SV ensemble
- Singular vectors: operational ECMWF configuration

- T_L255L40 (80 km, 40 levels up to 10 hPa)
- 18 members, model cycle 31r1
- Buizza et al (1999) tendency perturbations
- 46 cases; period: 1 December 2005 – 15 January 2006

Ensemble standard deviation and Ens. Mean RMS error

500 hPa height

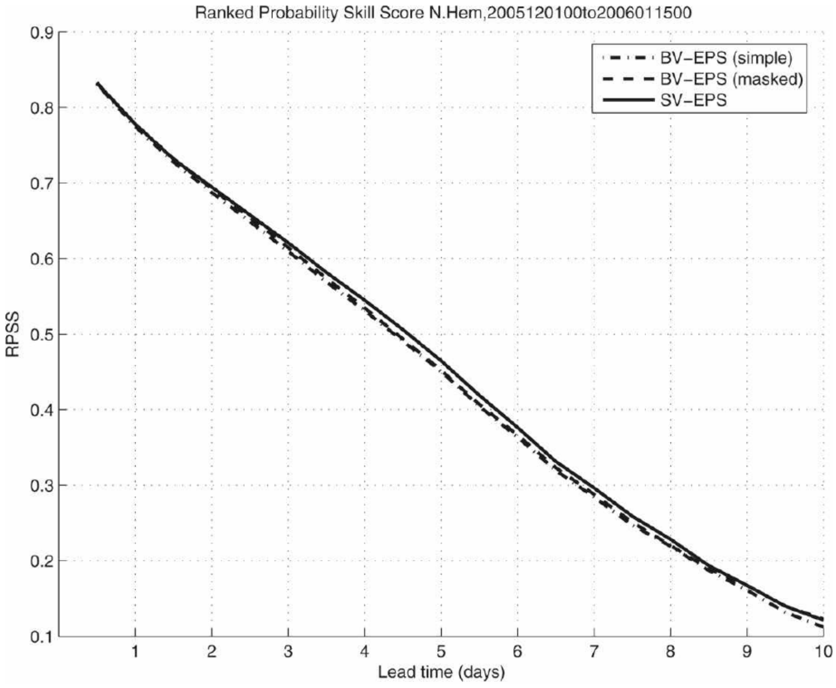


← RMSE

← Spread

Discrete Ranked Probability Skill Score

500 hPa height



Scaled differences of random states and Ens. Transform

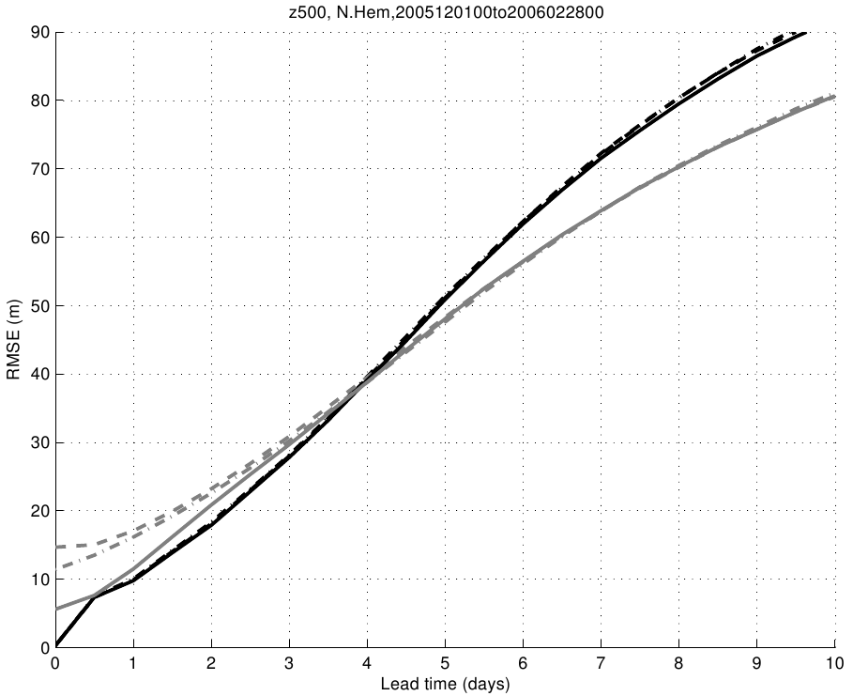
Magnusson, Nycander and Källén, 2009, Tellus

- Random Perturbation Fields
  - scaled difference between randomly selected states
  - scaling factor (~ 0.1) tuned to get similar spread as SV ensemble at Day 3 (Z500, N-Hem)
- Ensemble Transform with rescaling (NCEP's current method)
  - Ensemble Transformation every 6-hours
  - 20 perturbed ICs from adding/subtracting 10 ET perturbations to analysis
  - ensemble spread tuned to get same spread at Day 3 as SV ensemble
- Singular vectors: operational configuration as described earlier

- T_L255L40 (80 km, 40 levels up to 10 hPa)
- 20 members, model cycle 31r1
- Buizza et al (1999) tendency perturbations
- 90 cases; period: 1 December 2005 – 28 February 2006

Ensemble standard deviation and Ens. Mean RMS error

500 hPa height



← RMSE

← Spread

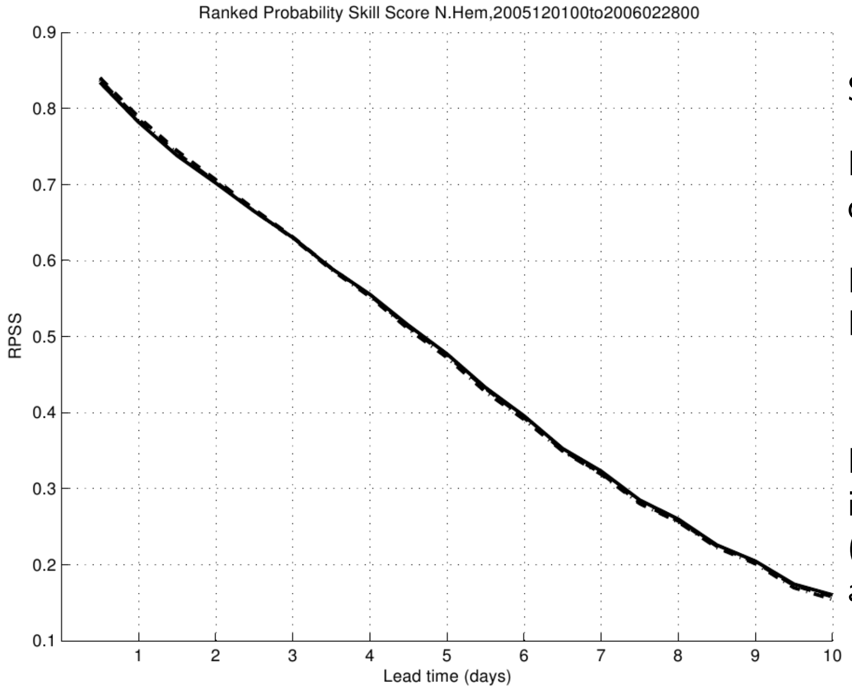
Singular vectors: solid

Ens. Transform: dash-dotted

Random Field Perturbations: dashed

Discrete Ranked Probability Skill Score

850 hPa temperature



Singular vectors: solid

Ens. Transform: dash-dotted

Random Field Perturbations: dashed

However, SVs better initially in terms of Z500 (overdispersion of ET and RPF).

Nonmodal perturbation growth in the atmosphere

Lorenz (1969, 1984)

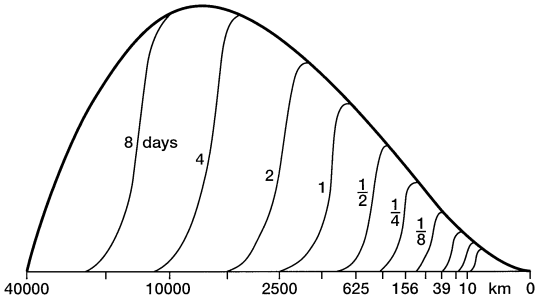
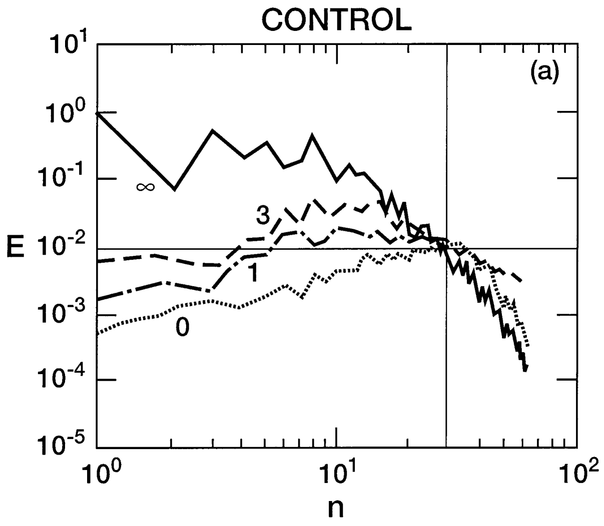


FIG. 1. Growth of errors initially confined to smallest scales, according to a theoretical model Lorenz (1984). Horizontal scales are on the bottom, and the upper curve is the full atmospheric motion spectrum.

Tribbia & Baumhefner (2004)



Initial perturbations based on short-range forecast errors

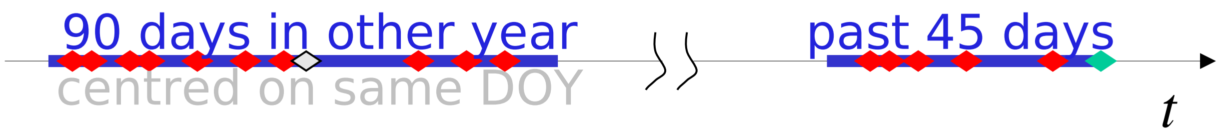
Previous work

- Mureau, Molteni & Palmer (1993)
    - assimilation method: Optimum Interpolation
    - model T63
    - initial perturbations based on 6-hour errors from past 30 days & Gram-Schmidt-orthonormalisation
    - conclusion: SV perturbations are superior
- revisit with a state-of-the-art system
- methodology here slightly different

Initial perturbations based on short-range forecast errors

Methodology

- simple: use what is in the archive, avoid interpolation
- remove systematic component of error
- define set X of short-range forecast errors or lagged forecast differences valid for the season (00 and 12 UTC control forecast fields)



- compute mean error(s) μ_{00}, μ_{12} from set X
- sample 25 realisations ϵ_j from X, subtract mean, scale

$$x_j = \alpha(\epsilon_j - \mu)$$

- add and subtract x_j from unperturbed analysis → 50 perturbed ICs

Here: $\mathbf{x}$ includes the dry upper air model state: vorticity, divergence, T, $\log(p_{sfc})$

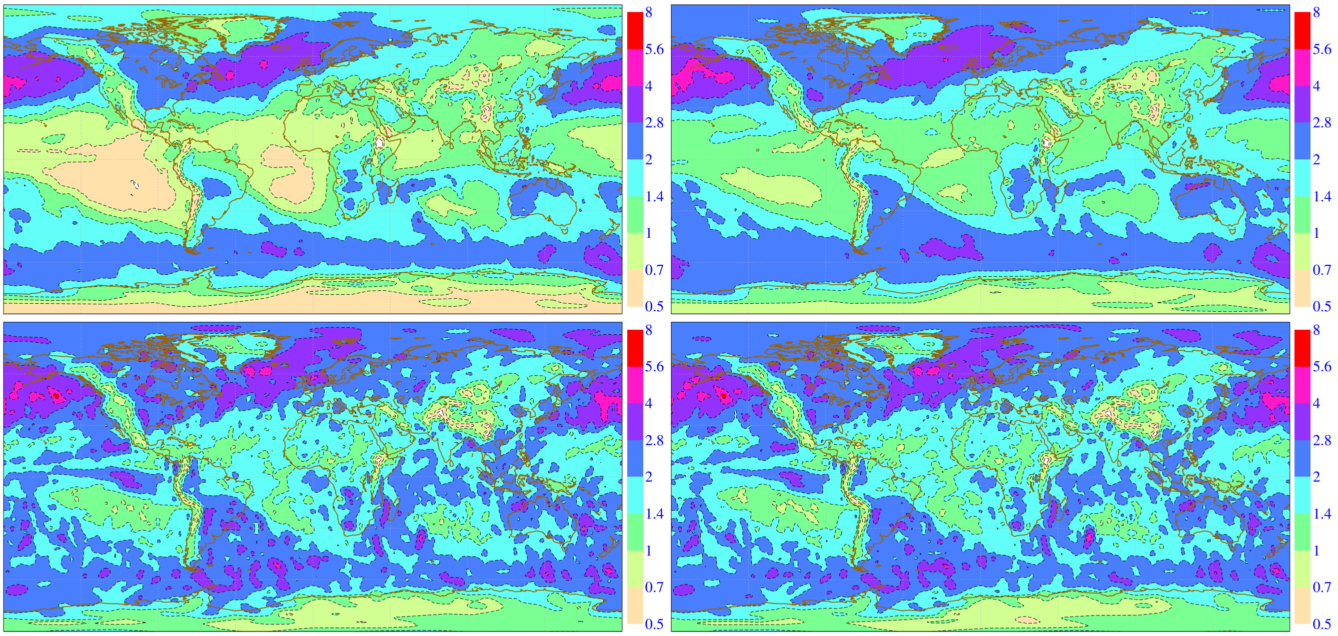
Initial perturbations based on short-range forecast errors

Experiments

- Experiments T_L255L62, cycle 32r3
- Buizza et al (1999) stochastically perturbed parametrisation tendencies
- initial perturbations:
  - operational singular vector configuration
  - sampling of (unscaled) 24-hour forecast errors
- 50 cases in NDJF2008 (every other day)
- Additional experiments:
  - 12-hour, 48-hour forecast errors
  - lagged fc differences (48 h – 24 h)
  - spectrally filtered forecast errors

Time mean spread vs. RMSE of Ens. mean

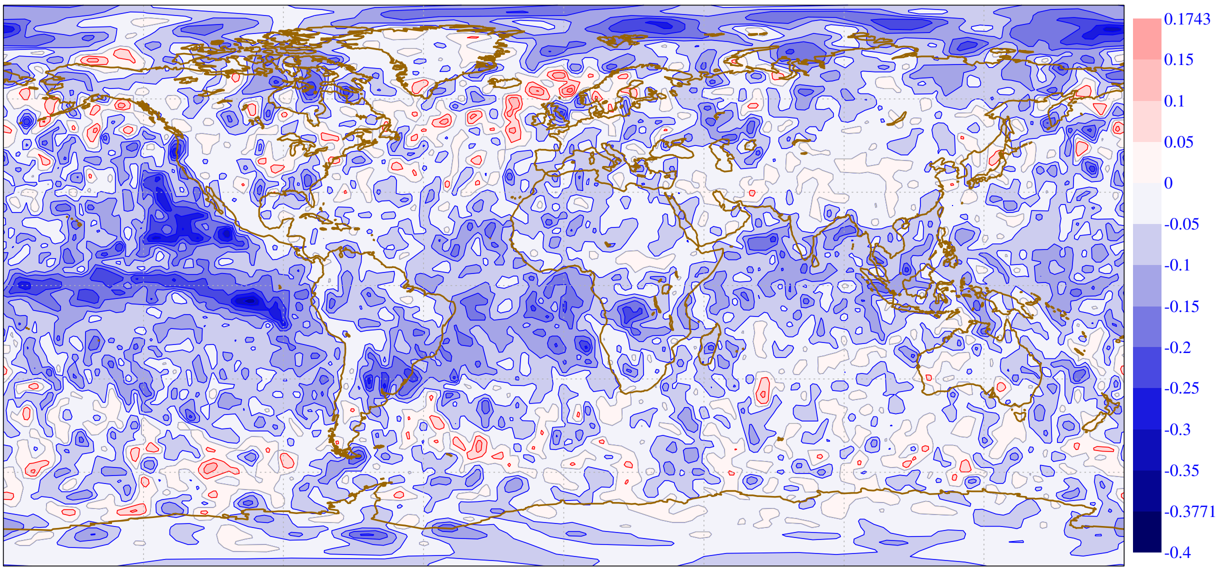
Meridional wind component ($\mathrm{m\,s^{-1}}$) at 850 hPa, t=48 h



singular vector init. perts. 24-hour fc. error init. perts.

top: ens. stdev.; **bottom:** ens. mean RMS error; 50 cases: 23 Nov '07–29 Feb '08
T_L255, 32r3, unscaled 24-hour FCEs

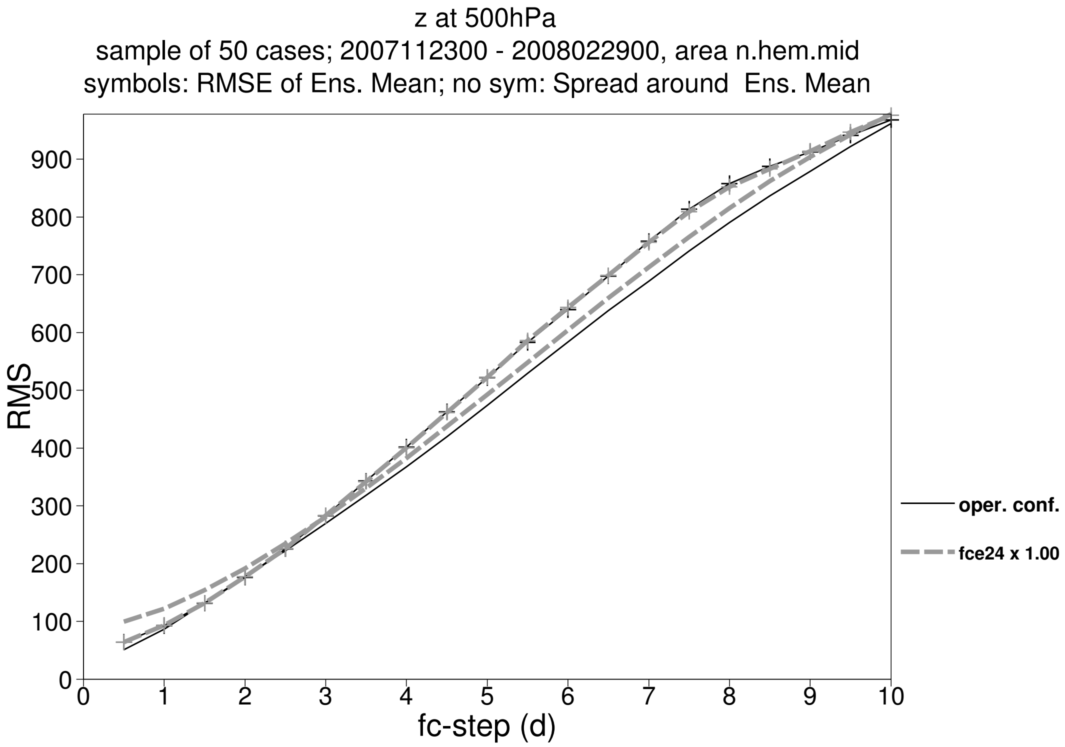
Meridional wind component ($\mathrm{m\,s^{-1}}$) at 850 hPa, t=48 h



- CRPS (Continuous Ranked Probability Score ≡ mean squared error of the cumulative distribution)
- Blue means EPS based on short-range forecast errors is more skilful.
- 50 cases: 23 Nov 2007 – 29 Feb 2008

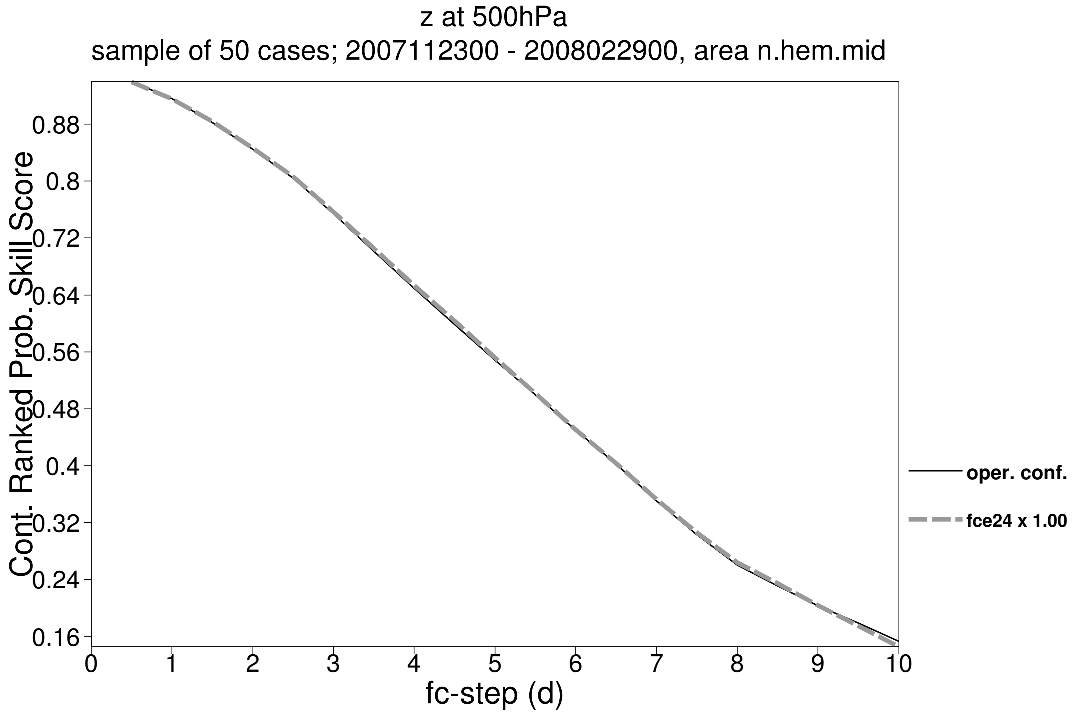
Ensemble Mean RMSE & Ensemble Standard Deviation

500 hPa geopotential, Northern Mid-latitudes 35°–65°N



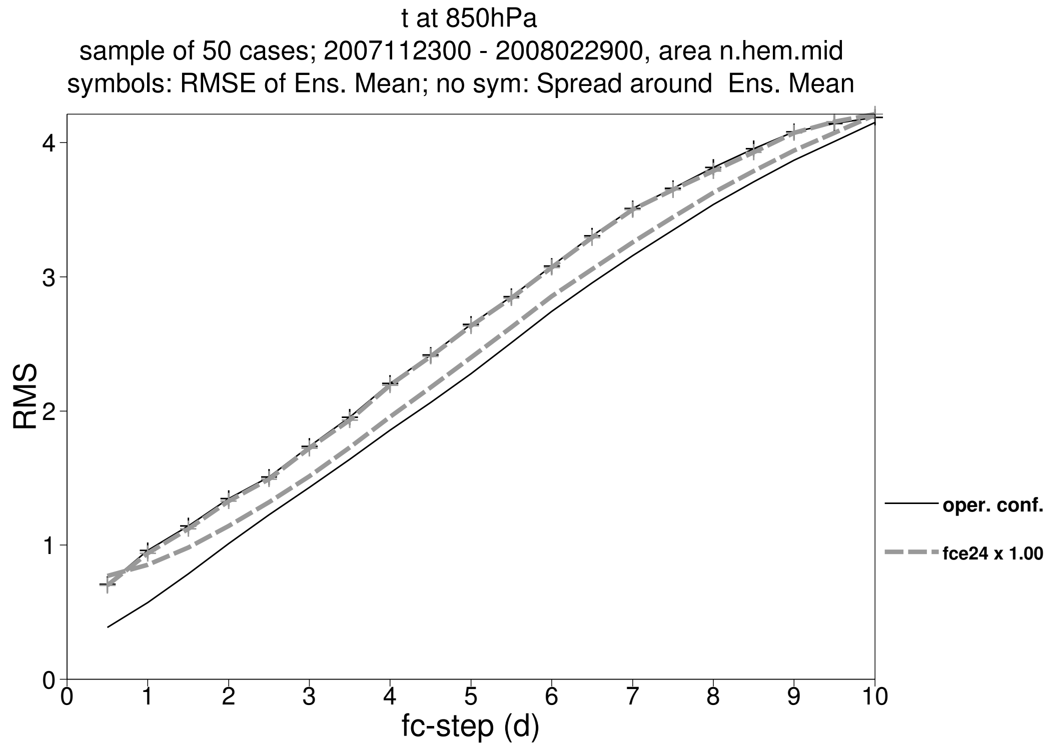
Continuous Ranked Probability Skill Score

500 hPa geopotential, Northern Mid-latitudes 35°–65°N



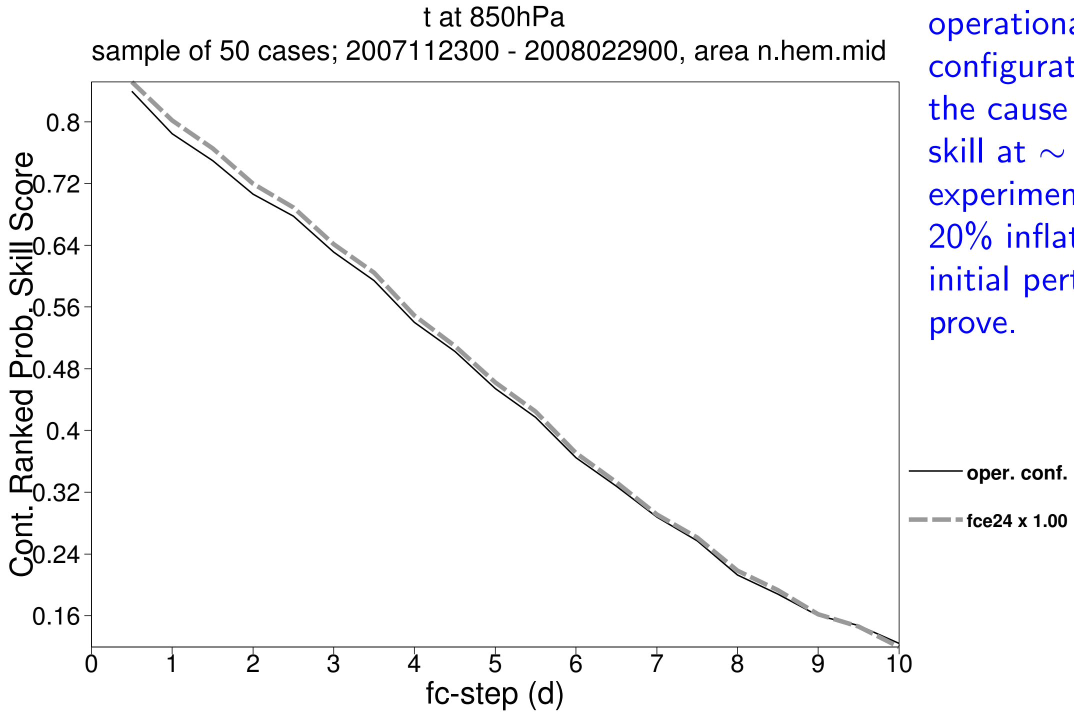
Ensemble Mean RMSE & Ensemble Standard Deviation

850 hPa temperature, Northern Mid-latitudes 35°–65°N



Continuous Ranked Probability Skill Score

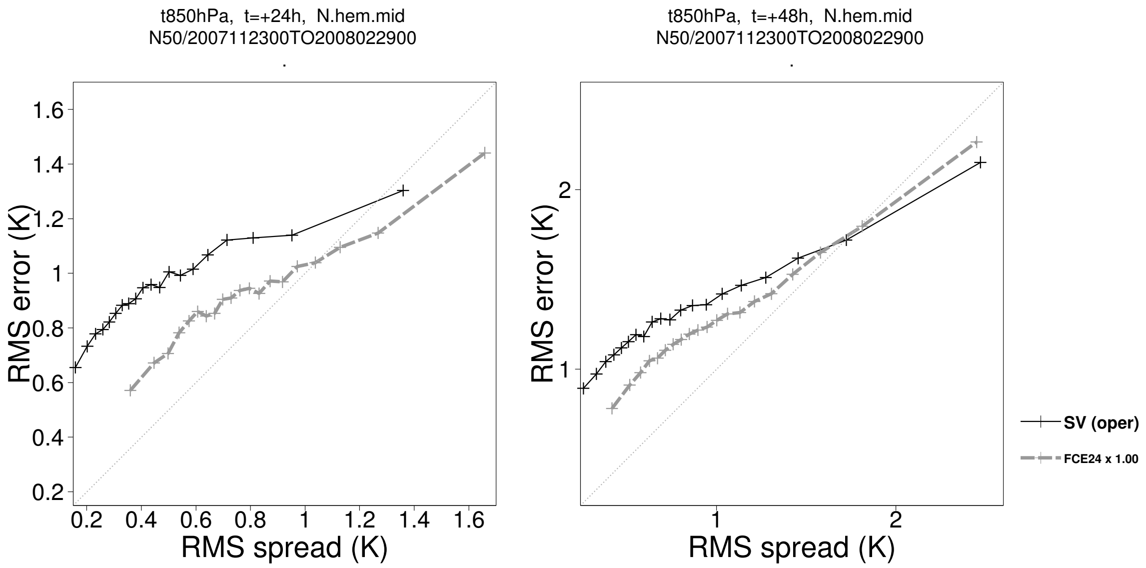
850 hPa temperature, Northern Mid-latitudes 35°–65°N



Lower spread of operational configuration is *not* the cause of lower skill at ∼ D1–3 as experiments with 20% inflated SV initial perturbations prove.

Spread-reliability

850 hPa temperature, Northern Mid-latitudes 35°–65°N

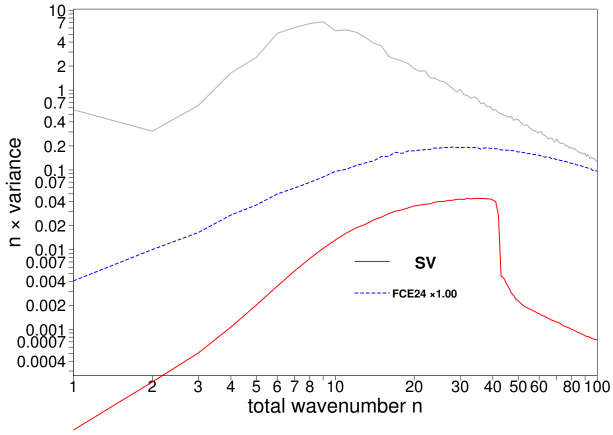


- stratify pairs of RMSE and spread by predicted spread
- 1 pair (spread, RMSE) for each grid point and each initial time
- compute RMSE and spread in 20 equally populated bins

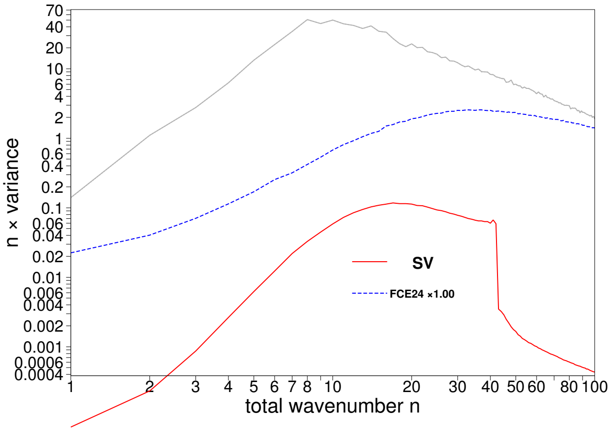
Which scales are the most important?

Initial perturbation variance spectra

Temperature
700 hPa



Rotational wind component
700 hPa



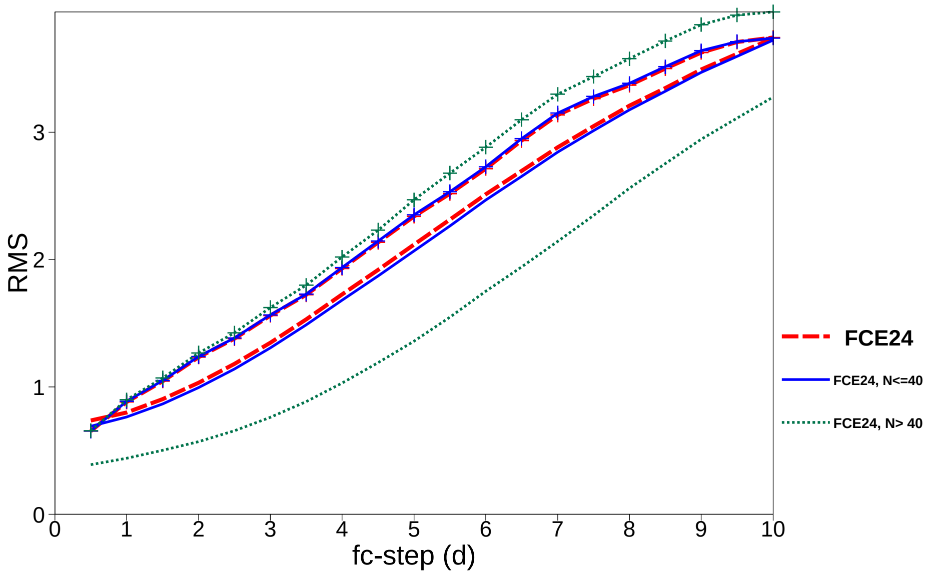
- 20 cases: 23 Nov – 31 Dec 2007
- full fields (analyses, grey)

Spectrally filtered forecast errors

Ensemble dispersion

t850hPa, Northern Extra-tropics

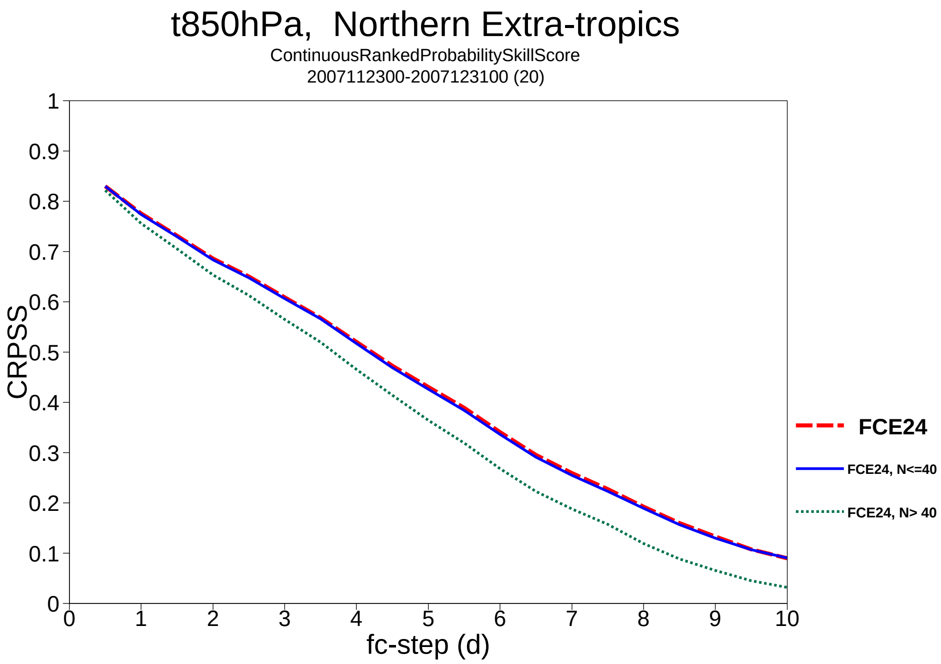
spread_em, rmse_em
2007112300-2007123100 (20)



- T_L255, 20 cases: 23 Nov – 31 Dec 2007
- (unscaled) 24-hour forecast errors

Spectrally filtered forecast errors

Probabilistic skill

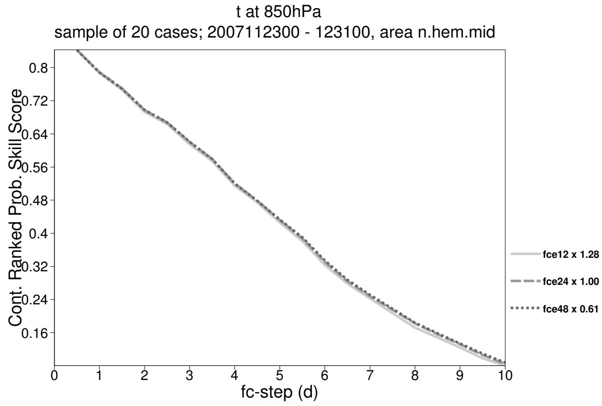


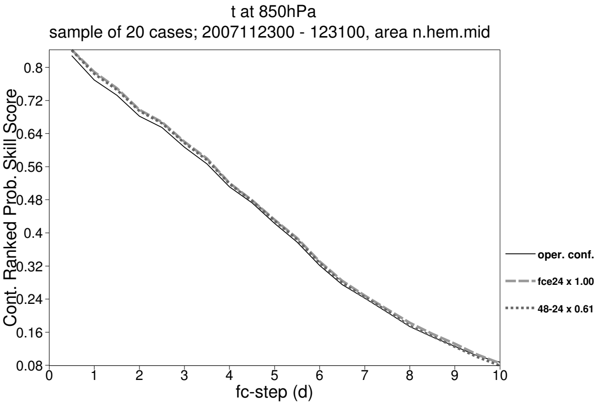
- T_L255, 20 cases: 23 Nov – 31 Dec 2007
- (unscaled) 24-hour forecast errors

---

other proxys for initial uncertainty

- Experiments
  - 12-hour forecast errors (×1.28)
  - 24-hour forecast errors (×1.00)
  - 48-hour forecast errors (×0.61)
  - 48−24-hour forecast differences (×0.61, NMC-method)
- Scaling factors: exponential growth model with error doubling time of 1.4 d (cf. Simmons and Hollingsworth, 2002)
- Results based on 20 cases Nov–Dec 2007 (T_L255, cycle 32r3)





Projection of initial perturbations on singular vectors

Method

- The singular vectors are orthonormal with respect to the total energy metric
$$\mathbf{v}_j^{\mathrm{T}}\mathbf{E}\mathbf{v}_k = \delta_{jk}$$
- Any initial perturbation $\mathbf{x}$ can be written as

$$\mathbf{x} = \sum_{j=1}^{N} \alpha_j \mathbf{v}_j + \mathbf{x}_\perp, \qquad \text{where}$$

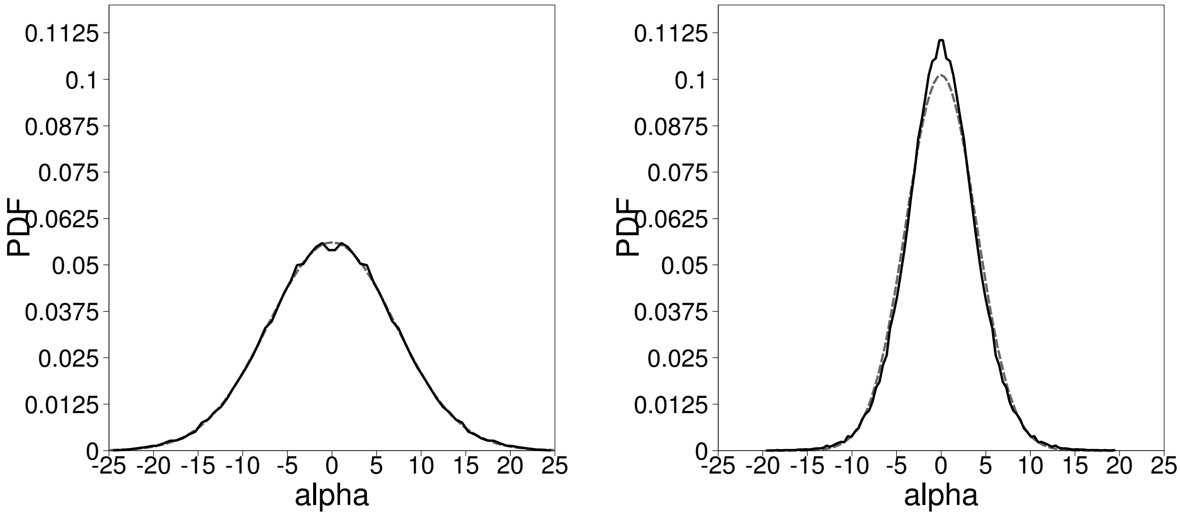
$$\alpha_j = \mathbf{x}^{\mathrm{T}}\mathbf{E}\mathbf{v}_j \quad \text{and} \quad \mathbf{x}_\perp^{\mathrm{T}}\mathbf{E}\mathbf{v}_j = 0$$

- For the operational EPS configuration the α-s are independent & normally distributed.
- What is the distribution of α-s for the short-range forecast errors?

Projection of initial perturbations on singular vectors

Results

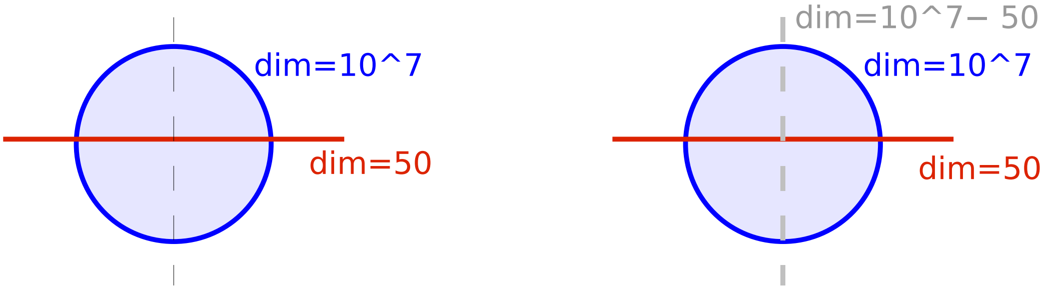
SVs ($\gamma = 0.014$), $\sigma_\alpha = 6.9$ 24-hour FCE ($\times 1.0$), $\sigma_\alpha = 3.9$



- 20 cases: 23 Nov – 31 Dec 2007
- leading 50 northern extra-tropical SVs
- $50 \times 50 \times 20 = 5 \times 10^4$ coefficients

A schematic of the initial uncertainty representations

model's phase space



Developments

- Resolution upgrade . . . 50 km → 32 km (Jan 2010)
- Evolved singular vectors ⟶ perturbations from a 10-member ensemble of perturbed 4D-Vars
  - perturbed obs.
  - perturbed SSTs
  - perturbed tendencies (SPPT)

  see Buizza et al. (2008)
- Stochastically Perturbed Parameterization Tendency (SPPT) scheme upgraded (Sep 2009)
- Stochastic backscatter scheme to represent uncertainty due to missing variability on the near-gridscale
- Multi-scale version of SPPT $r = \sum_{k=1}^{L} r_k$ where the r_k differ in terms of variance, spatial and temporal correlation scales

Conclusions

- TIGGE and calibrated ECMWF ensemble
  - Multi-model based on four best ensembles can improve on the best single-model, the ECMWF EPS
  - Reforecast-calibrated ECMWF EPS comparable or superior these multi-model predictions
- Representing model uncertainty can improve the skill of ensemble predictions (in particular in the tropics)
- Probabilistic skill of various flow-dependent initial perturbation methodologies is very similar:
  - bred vectors ≈ Ens. Transform ≈ singular vectors

Conclusions (II)

- Flow-independent initial perturbations based on past short-range forecast errors lead to an ensemble that is as skilful as or better than SV-based system in terms of traditional probabilistic skill measures
- Short-range forecast errors have a significant projection on the space of the leading singular vectors; in addition, they perturb also in the $10^7 - 50$ other directions
- However,
  - initially somewhat overdispersive
  - unrealistic initial perturbations can occur due to flow-independence. Technique not applicable without some prior filtering
- Expected that ensemble data assimilation techniques will be (eventually) superior to a simple flow-independent perturbation technique (work in progress)

References

- Barkmeijer, Jan, Martin Van Gijzen and François Bouttier, 1998: Singular vectors and estimates of the analysis-error covariance metric. *Quart. J. Royal Met. Soc.*, **124**, 1695–1713
- Barkmeijer, J., R. Buizza and T. N. Palmer, 1999: 3D-Var Hessian singular vectors and their potential use in the ECMWF Ensemble Prediction System. *Quart. J. Royal Met. Soc.*, **125**, 2333–2351
- Buizza, R. and T. N. Palmer, 1995: The Singular-Vector Structure of the Atmospheric Global Circulation. *J. Atmos. Sci.*, **52**, 1434-1456
- Buizza, R., M. Miller and T. N. Palmer, 1999: Stochastic representation of model uncertainties in the ECMWF Ensemble Prediction System. *Quart. J. Royal Met. Soc.*, **125**, 2887–2908
- Buizza, Roberto, Martin Leutbecher and Lars Isaksen, 2008: Potential Use of an Ensemble of Analyses in the ECMWF Ensemble Prediction System. *Quart. J. Royal Met. Soc.*, **134**, 2051–2066
- Hagedorn, Renate, Roberto Buizza, Thomas M. Hamill, Martin Leutbecher and T. N. Palmer, 2010: Comparing TIGGE multi-model forecasts with reforecast-calibrated ECMWF ensemble forecasts. submitted to *Mon. Wea. Rev.*
- Magnusson, Linus, Martin Leutbecher and Erland Källén, 2008: Comparison between Singular Vectors and Breeding Vectors as Initial Perturbations for the ECMWF Ensemble Prediction System. *Mon. Wea. Rev.*, **136**, 4092–4104
- Magnusson, Linus and Jonas Nycander and Erland Källén, 2009: Flow-dependent versus flow-independent initial perturbations for ensemble prediction. *Tellus*, **61A**, 194–209
- Lawrence, A. R., M. Leutbecher and T. N. Palmer, 2009: The characteristics of Hessian singular vectors using an advanced data assimilation scheme. *Quart. J. Royal Met. Soc.*, **135**, 1117–1132
- Palmer, T.N., R. Buizza, F. Doblas-Reyes, T. Jung, M. Leutbecher, G.J. Shutts, M. Steinheimer and A Weisheimer, 2009: Stochastic parametrization and model uncertainty. *ECMWF Tech. Memo.*, **598**