Perturbations in the ECMWF operational ensembles

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Firstly .. thank you for having brough me on board in 1991 …

- Franco
- Tim
- Cedo
- Ernst
- Robert
- Joe
- Laura
- Adrian
- Tony
- Dave B
- Dave A
- Els
- Carole
- …

Topics

1. The first years of the ECMWF ensemble: SV perturbations (1992-1998)
2. Perturbations that simulate observation and model uncertainties (1999-2010)
3. Conclusions: perturbations in the global ensembles today

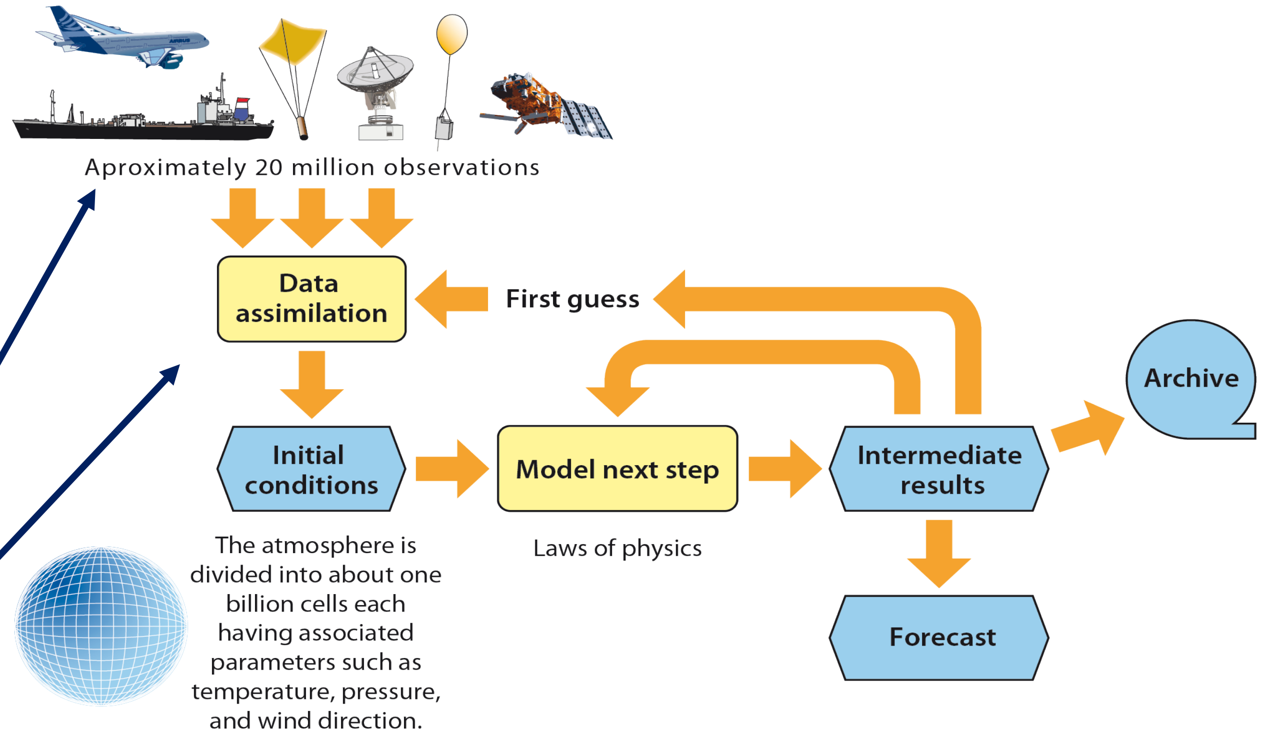
Fc errors are due to uncertainties in obs, DAs, ICs, models

The +T forecast is given by the time integration of the equation of motions:

$$f(T) = f(0) + \int_0^T F(t)dt$$

where the initial conditions $f(0)$ are computed with a data-assimilation procedure.

Forecast errors arise from obs, DA assumptions, model imperfections and approximations.



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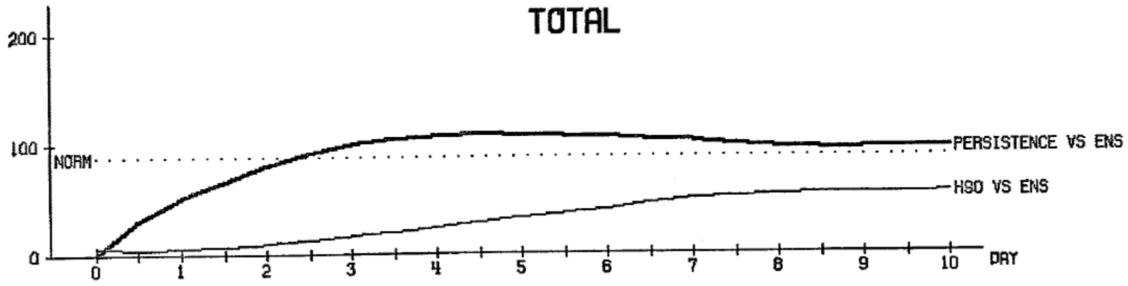
Leith (MWR 1974) and Hollingsworth (ECMWF 1979)

- *"… The averaging in Monte Carlo forecasting procedure has the effect of filtering out small scale structure for which there is little accuracy … **A Monte Carlo forecasting procedure represents a practical, computable approximation** to the stochastic dynamic forecast proposed by Epstein (1969). …" (Leith 1974)*

- *"The results of these experiments are inconclusive because of the difficulty that was experienced in having the initial geostrophic perturbations survive the initialisation procedure" (Hollingsworth 1979).*



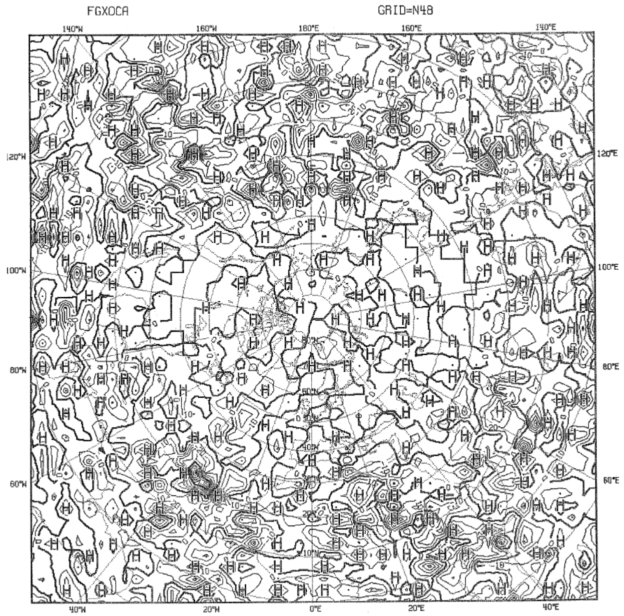


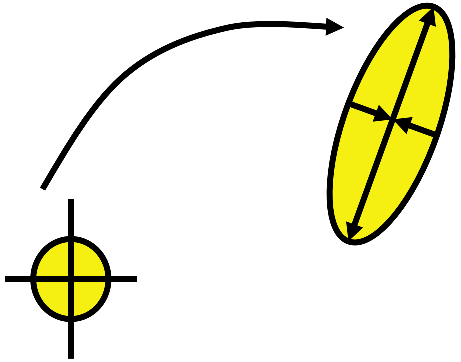
Fig. 2 Example of a perturbation geopotential height field at 500 mb.Contour interval 10 m.

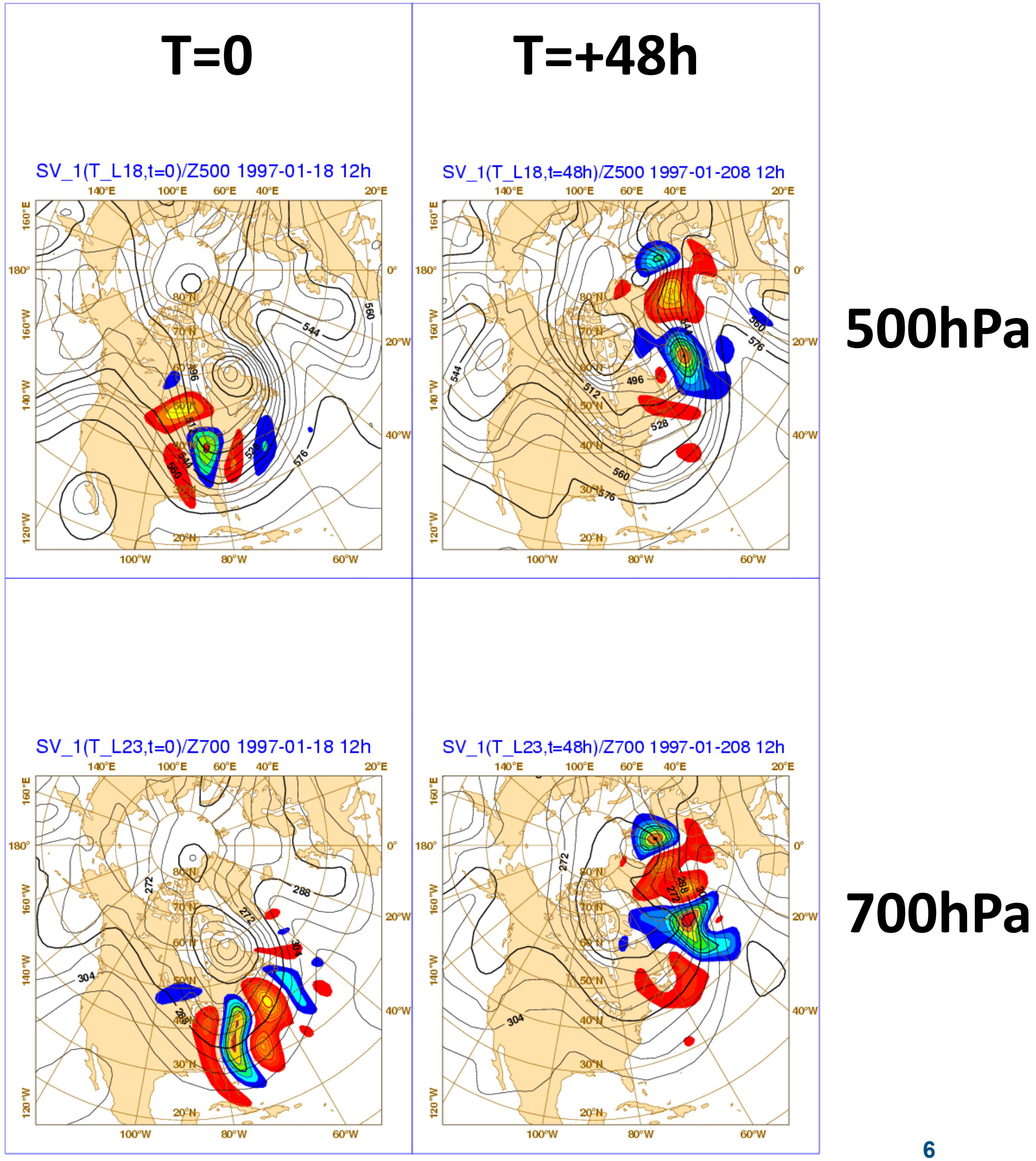
…. so we decided to test SVs in our ensemble

Singular vectors identify the perturbations with the fastest (total energy) growth over a 2-day period.

They are computed solving an eigenvalue problem:

$$E_0^{-1/2} L^* E L E_0^{-1/2} v = \sigma^2 \upsilon$$

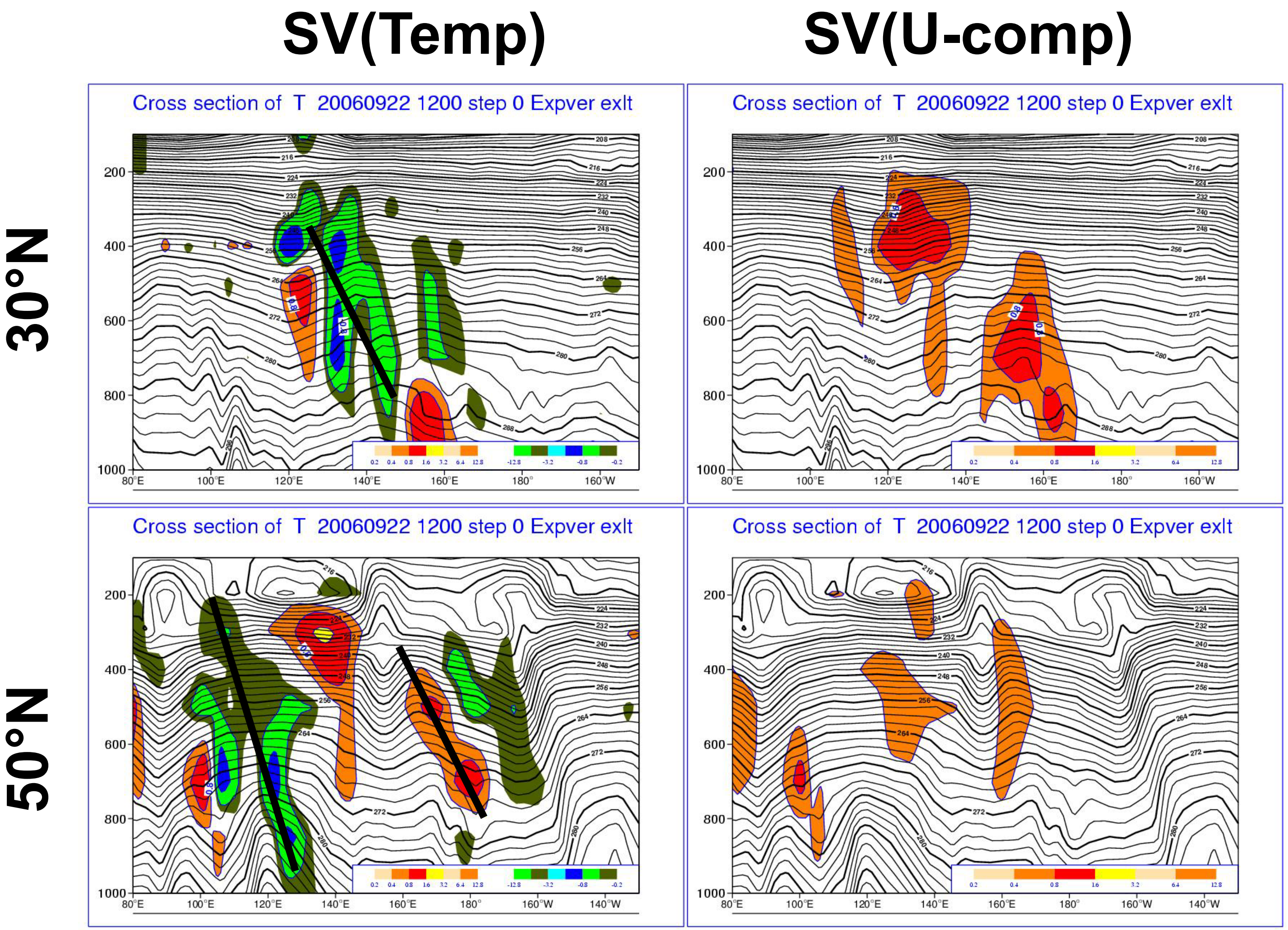




The SVs key characteristics (Tellus 1993; JAS 1995)

Singular vectors:

- are spatially localized;
- have a larger component in potential than kinetic energy
- show a westward tilt with high, typical of baroclinically unstable structures.



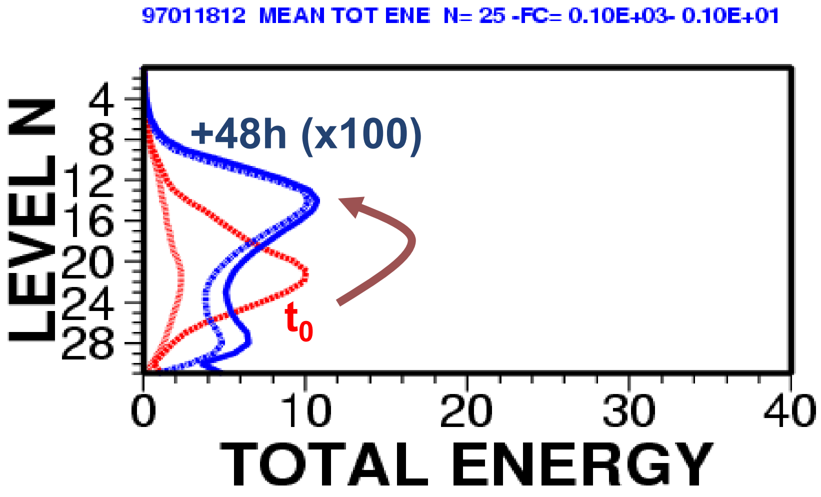
The SVs key characteristics (Tellus 1993; JAS 1995)

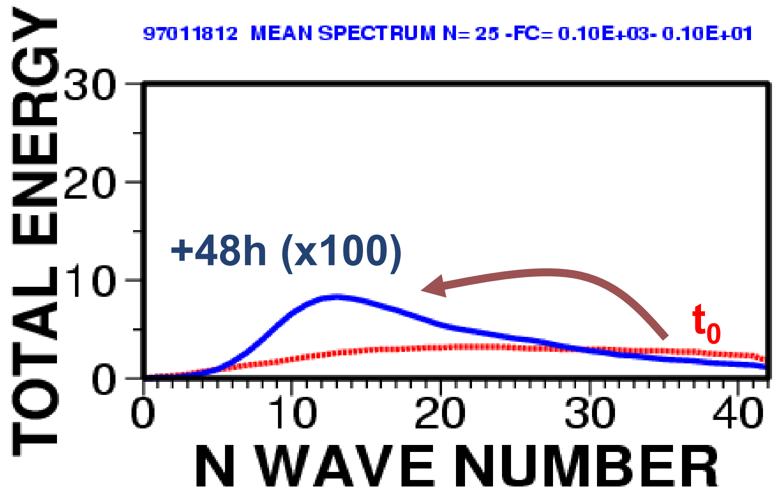
At initial time, they have most of their (potential) energy on the small scales.

As they grow, potential energy is transformed into kinetic energy.

Energy flows from the smaller to the larger scales.

In the vertical, perturbations propagate from the lower to the upper levels.





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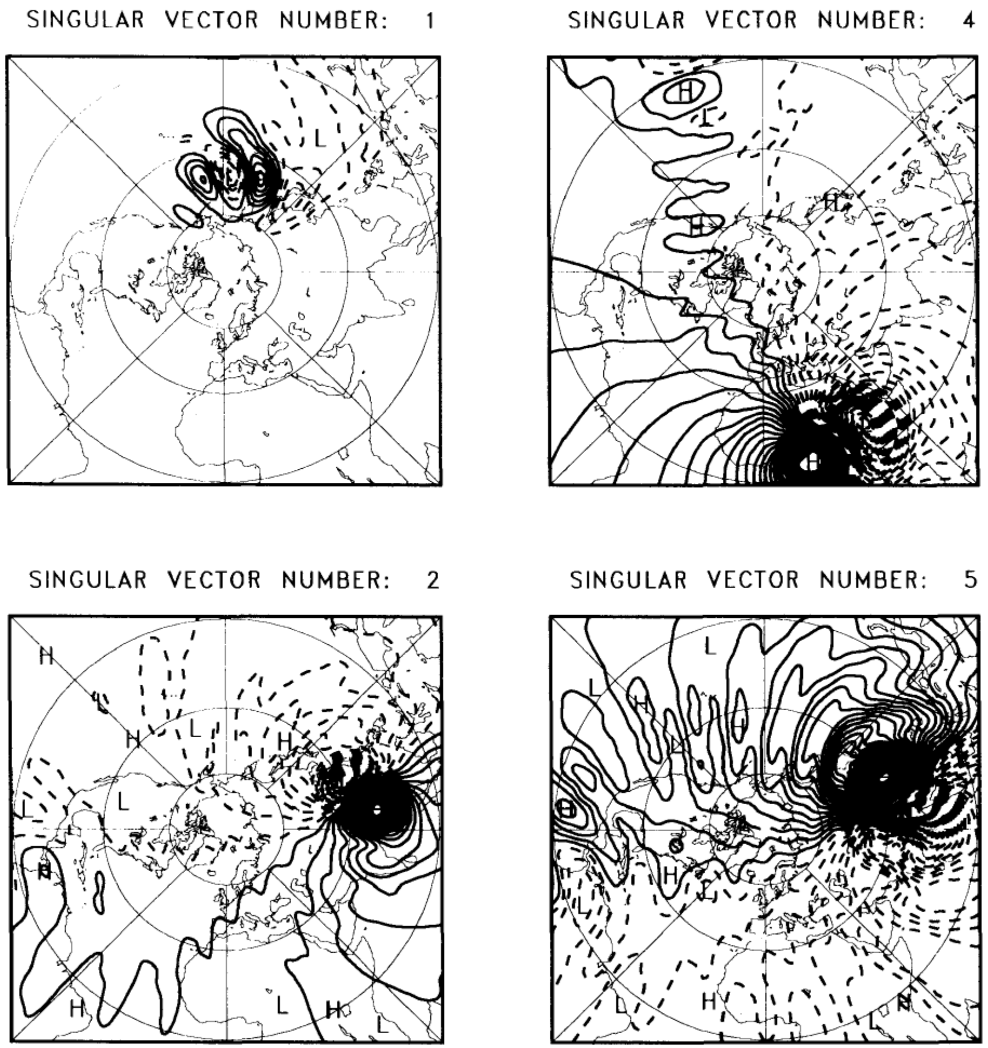
Problems due to the absence of a PBL (Tellus 1993)

R. BUIZZA ET AL.

Some SVs are almost completely confined to the lowest model levels and are "non-meteorological" in character (as it will be shown in Section 6, these structures do not grow in a model with a parameterization of boundary layer dissipation). They have a very strong baroclinic structure as can be detected from the temperature fields (not shown), with a positive perturbation at one level, negative at the following one, then positive again. The "meteorological" SVs have more realistic structures (in the sense that they have a structure not associated with the vertical discretization), with maximum amplitude in the region of the mid-latitude jet streams. The growth of the "non-meteorological" surface structures occurs probably because of the absence of a PBL physics in the version of the IFS used. These per-

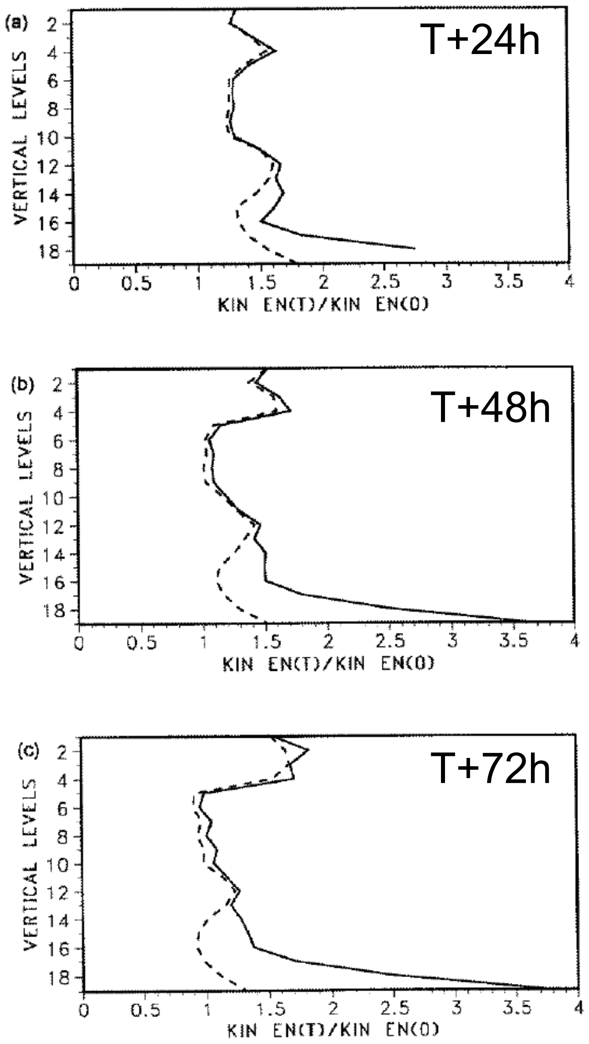


The LIN/ADJ surface drag & vert diffusion (QJRMS 1994a)

R. BUIZZA

The adjoint technique has been applied to the computation of the fastest-growing perturbations of a primitive-equation model. A very simple parametrization of the planetary boundary-layer turbulent processes has been implemented in the nonlinear, tangent and adjoint versions of a primitive-equation model. Experiments have been performed to study the impact of the scheme on the nonlinear evolution of the basic state, and on the definition of the unstable sub-space of the system, i.e. the sub-space generated by the first N SVs.

The scheme has proved to be capable of simulating the main turbulent mechanisms, although its crudeness can be shown by detailed comparisons with more complex schemes. It has been clearly shown that the introduction of the scheme is necessary to inhibit the growth of 'non-meteorological' structures close to the surface. This result implies that the identification of realistic optimal perturbations cannot be achieved by using only the adiabatic part of numerical weather-prediction models. If optimal perturbations are used to construct the initial conditions for the ensemble prediction system, the scheme helps in identifying structures representative of error growth in the nonlinear model.



Localisation problems …

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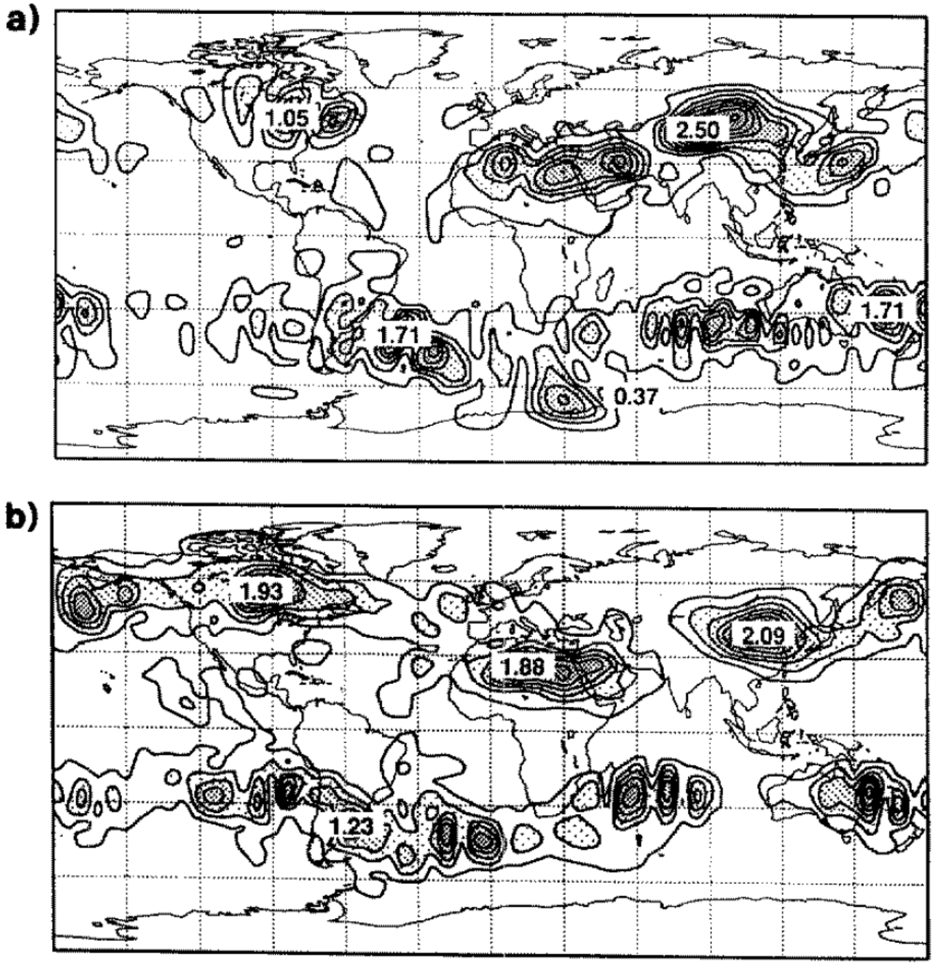
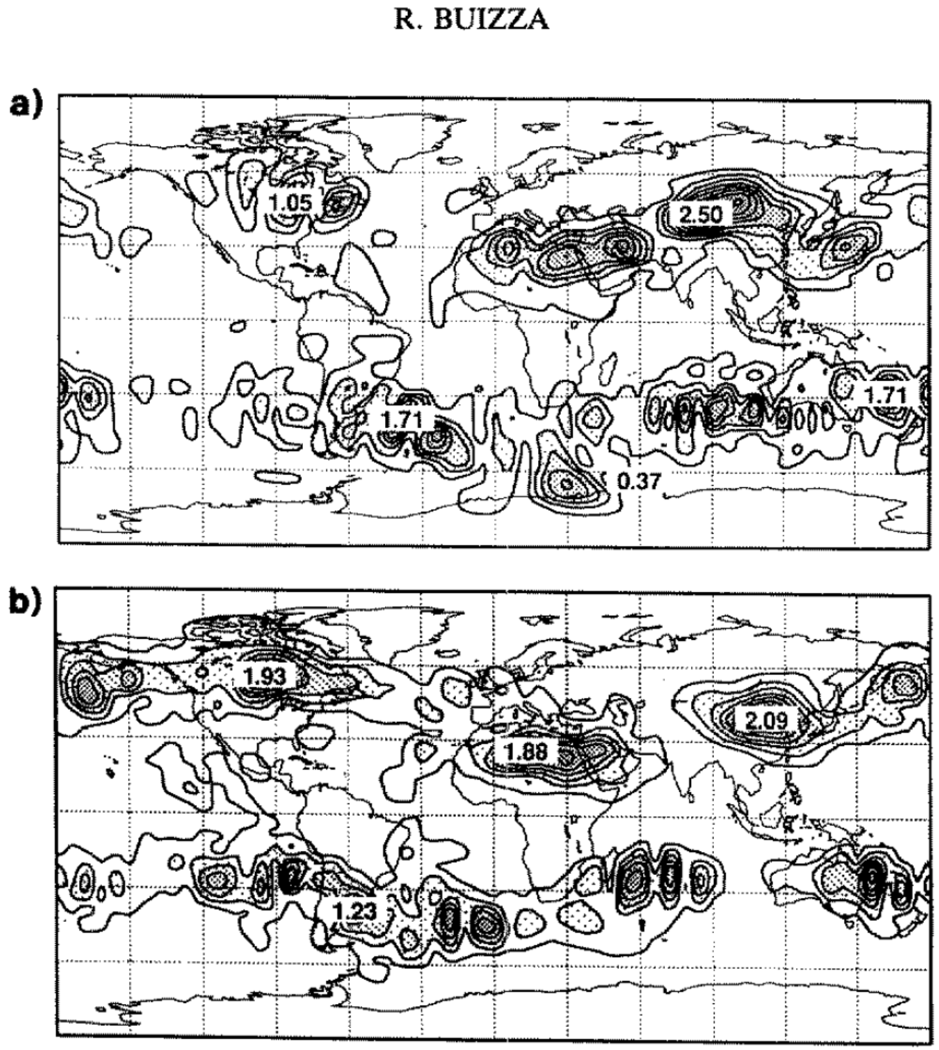
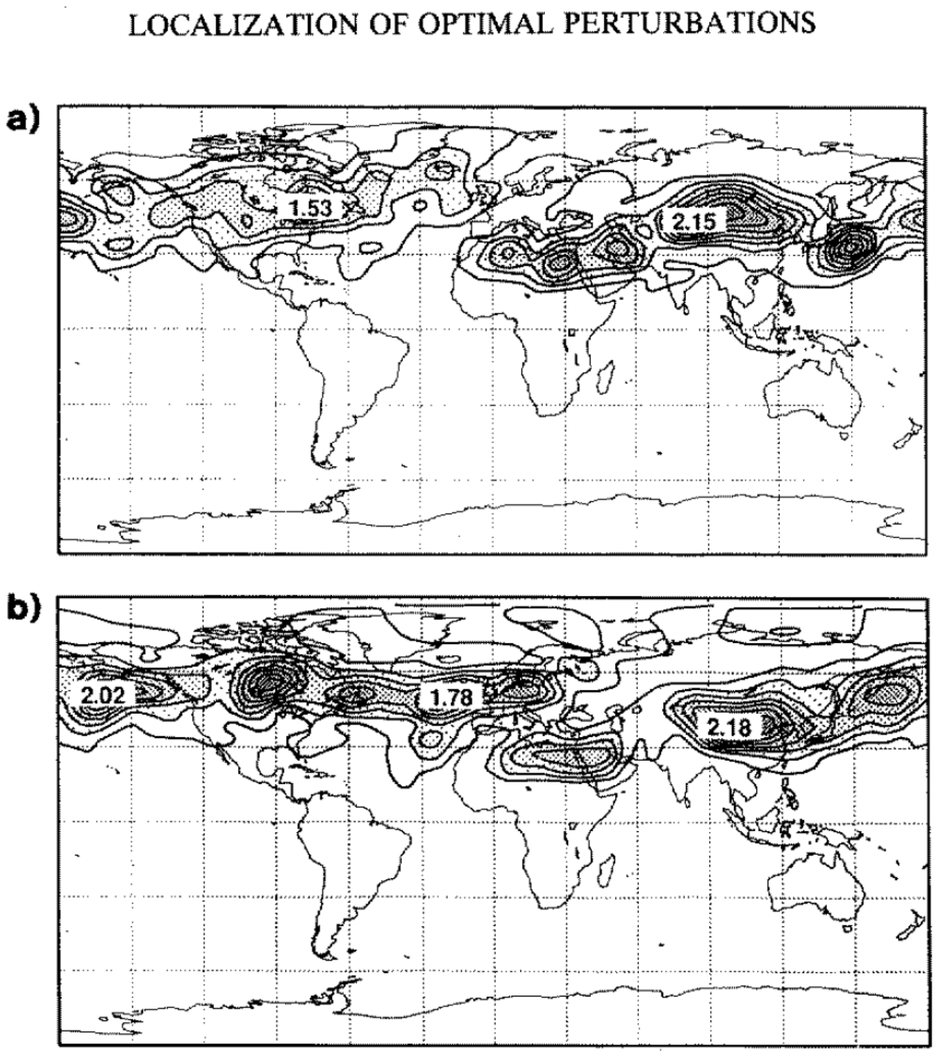


Without LPO

Localisation problems were solved with a LPO (QJRMS 1994b)



Without LPO



With LPO (30ºN<lat<75ºN)

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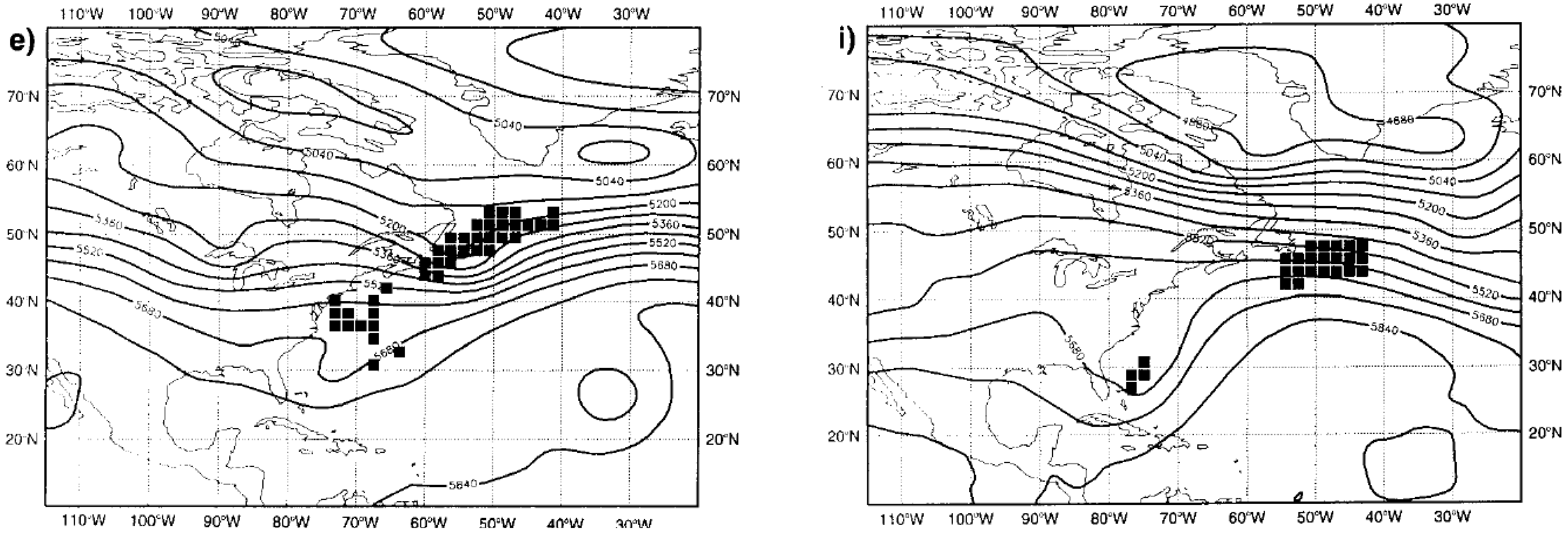
The LPO allowed us to compute targeted SVs (JAS 1999)

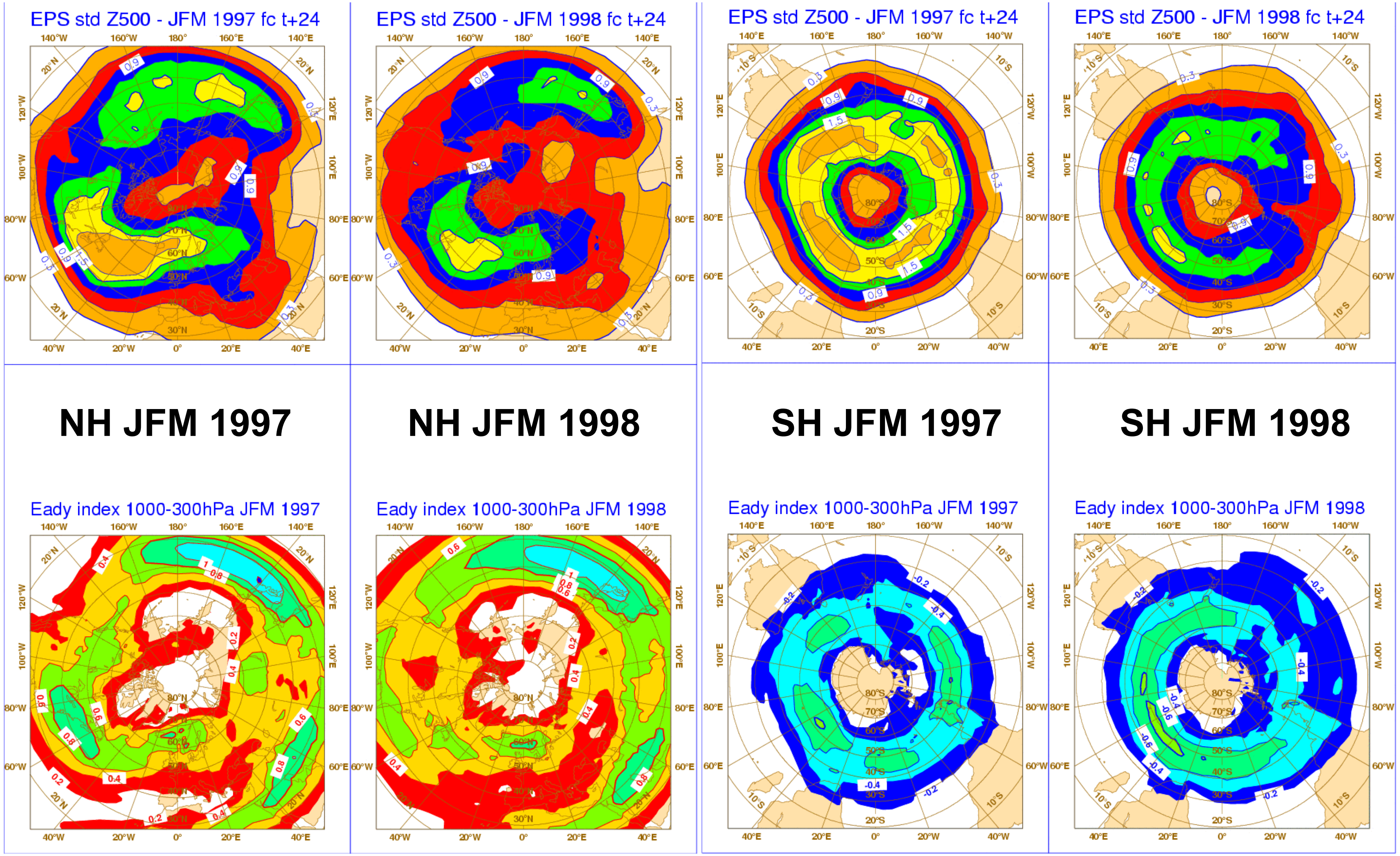


What do SVs tell us about the atmosphere? (JAS 1995)

SVs localized in areas of baroclinic instability, as seen by comparing the ENS std with the Eady index (*Hoskins and Valdes* 1990:

$$\sigma_E = 0.31 \frac{f}{N} \frac{du}{dz}$$

(with static stability N and wind shear computed using the 300- and 1000-hPa potential temperature and wind).



Which metric is the most appropriate? (JAS 1998)

In this paper, energy, enstrophy, and streamfunction variance were all considered as candidate metrics for singular vector calculations. From two independent sets of calculations based on analyses, and short-range forecast data, it was shown that of these three choices, energy is the most appropriate metric for the predictability problem. More accurate estimates of the AECM can in principle be obtained from variational and Kalman filter data assimilation techniques.

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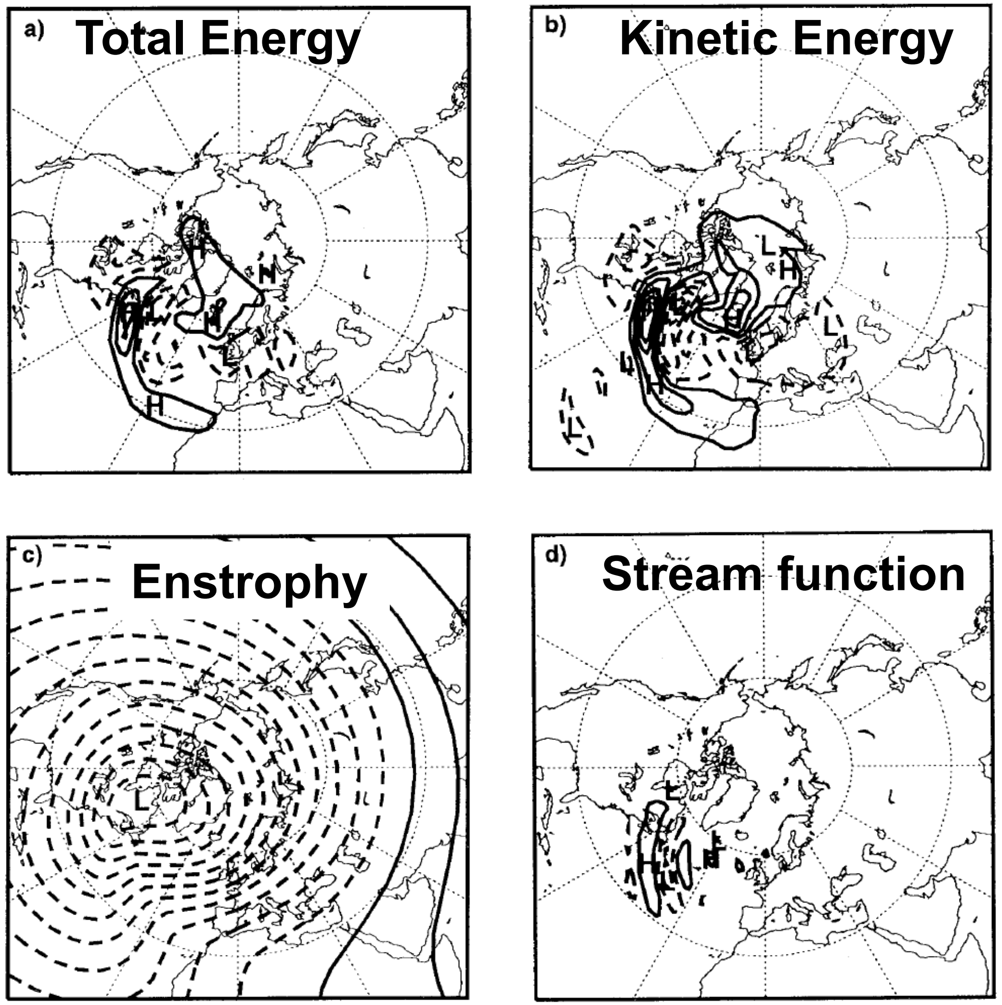

Fig. 1. Streamfunction of dominant 48-h singular vector at initial time on a model level near 500 hPa optimized for energy growth in the target area 30°–80°N, 30°W–10°E. Initial time 1200 UTC 5 December 1994. Metric used: (a) total energy, (b) kinetic energy, (c) enstrophy, (d) streamfunction variance. See Fig. 2 caption for information about contour intervals.

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1992 > 1998: the first version of the ECMWF Ensemble

In the first years of development of the ECMWF ensemble, we:

- *Focused on initial perturbations;*
- *Decided to follow a 'selecting sampling' strategy based on SVs;*
- *Investigated the role of SVs in explaining the atmospheric dynamics;*
- *Explored the role of metrics, resolution, optimization time interval;*
- *Improved linear and adjoint physics;*
- *Designed tools to improve reliability;*
- *Assessed the sensitivity to resolution and membership.*

By exchanging results and ideas with the other two operational global ensemble groups (NCEP Washington, MSC Canada), ***we understood that we had to improve the way we simulated observation and model uncertainties****.*

Topics

1. The first years of the ECMWF ensemble: SV perturbations (1992-1998)
2. Perturbations that simulate observation and model uncertainties (1999-2010)
3. Conclusions: perturbations in the global ensembles today

Are total-energy SVs the best perturbations? (QJRMS 1999)

Total energy SVs identify the perturbations with the fastest total energy growth over a 2-day period:

$$E_0^{-1/2} L^* E L E_0^{-1/2} \overrightarrow{v_j} = \sigma_j^2 \overrightarrow{v_j}$$

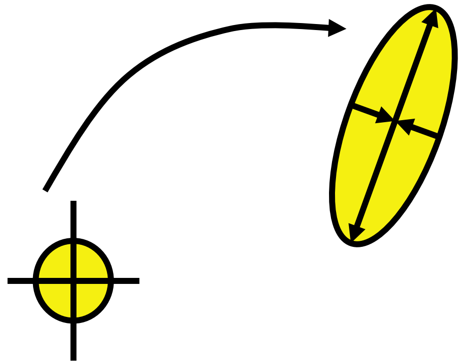
They are not sensitive to observation/analysis errors.

Barkmejier et al (1999) developed a method to take into account analysis error statistics, by using the **Hessian of the DA cost function** as initial-time norm:

$$C^{-1/2} L^* E L C^{-1/2} \overrightarrow{v_j} = \sigma_j^2 \overrightarrow{v_j}$$

$$C = B^{-1} + H^T R^{-1} H$$

where B and R are the background and observation errors



3D-Var Hessian and TE SVs (QJRMS 1999)

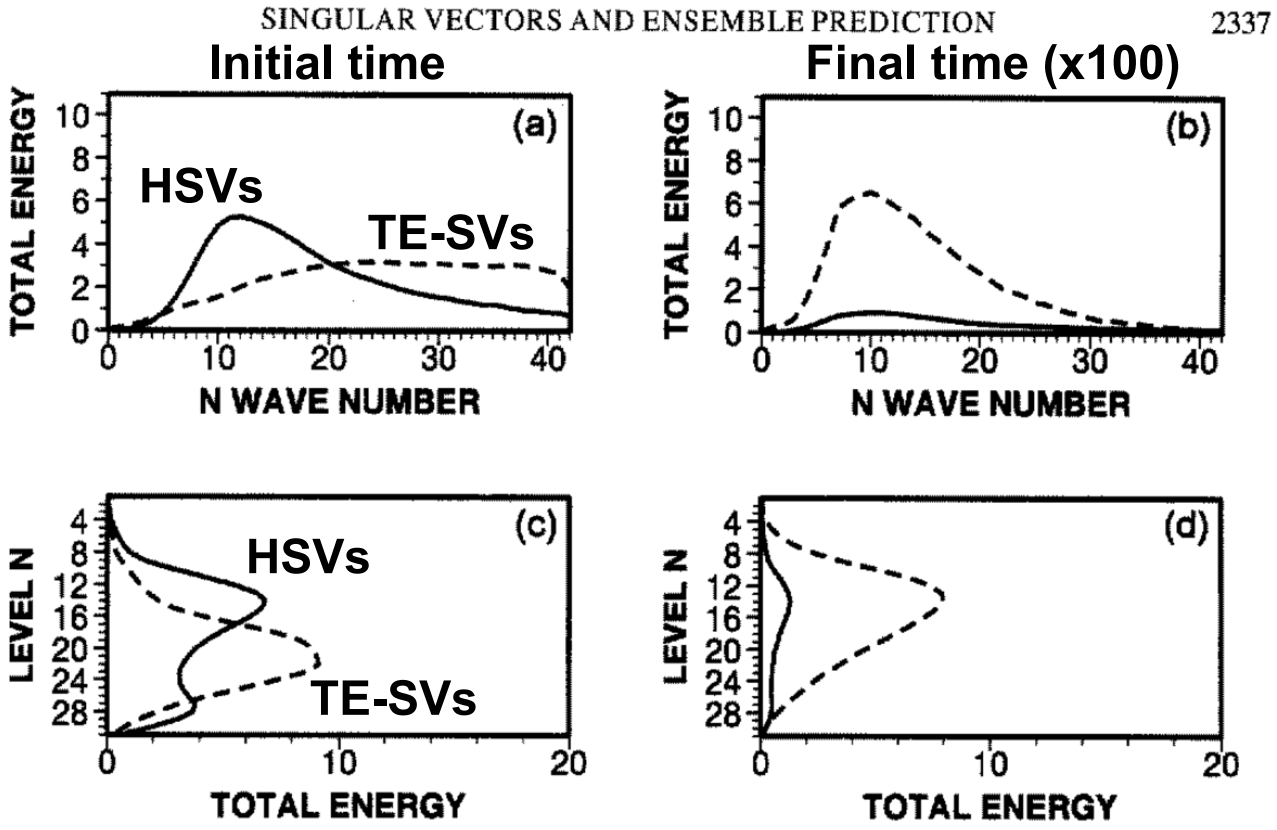


Figure 1. (a) and (b) The total energy spectrum, and (c) and (d) the vertical distribution of the total energy spectrum, of total energy singular vectors and Hessian singular vectors respectively. Values at initial (final) time are given by dashed (solid) lines. At initial time the total energy (m^2s^{-2}) has been multiplied by a factor of 100.

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Stochastic simulation of model uncertainties (QJRMS 1999)

Following the Canadian example, in 1999 ECMWF introduced a stochastic method to simulate model uncertainties :

$$f_j(T) = f_j(0) + \int_0^T [F(t) + \delta F(t)]dt$$

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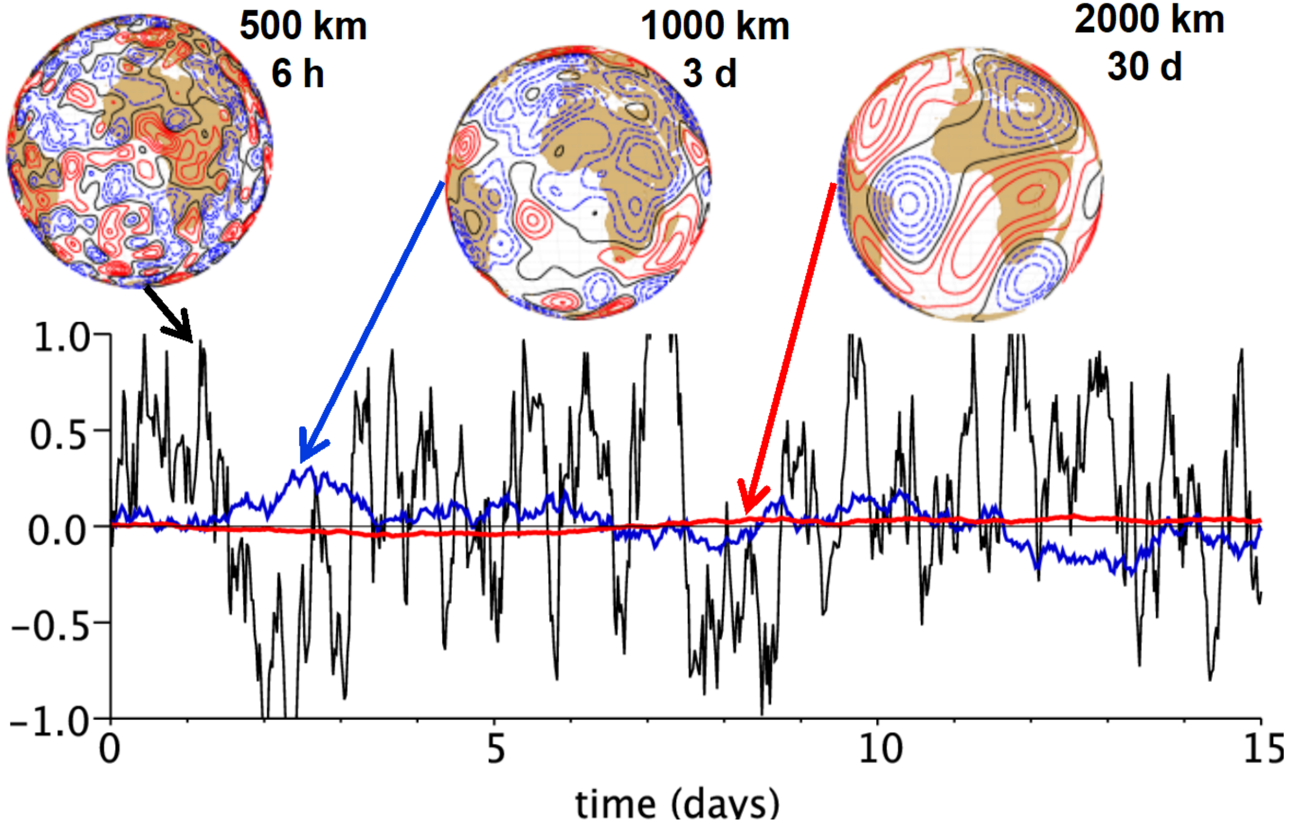
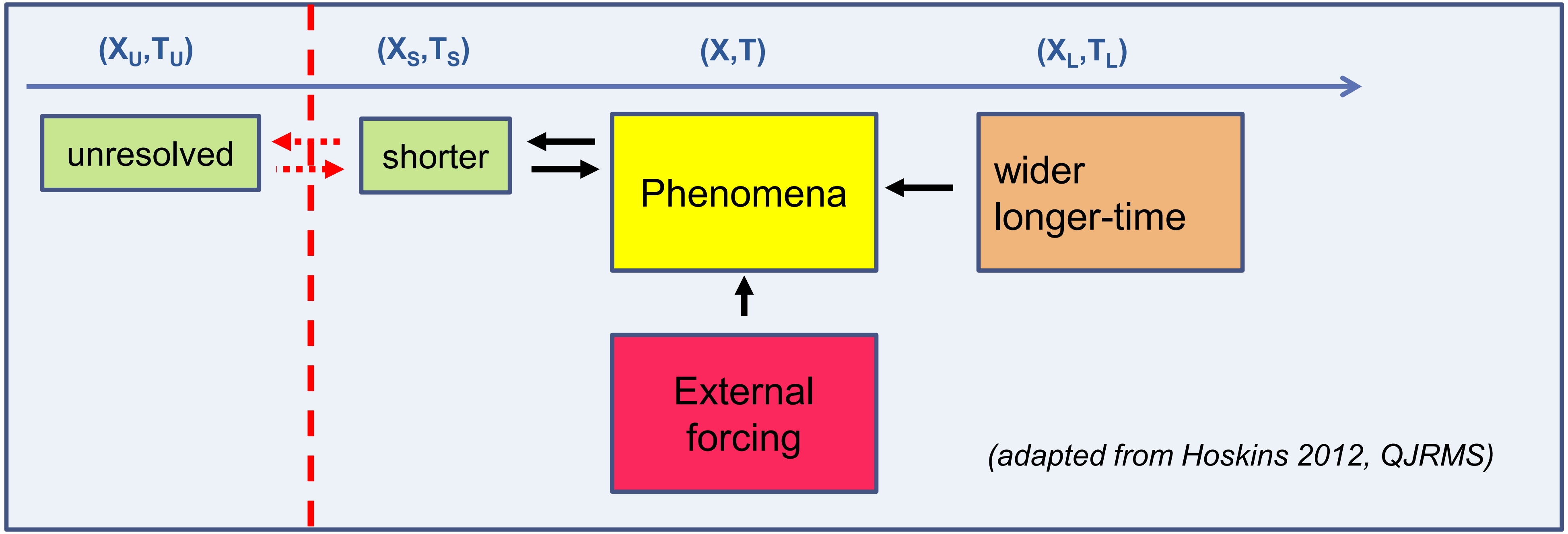
In the scheme, the total tendency due to parameterized processes is stochastically perturbed.

The original scheme was later improved with the introduction of multi-scales (Palmer et al 2005).



How can we simulate the effects of the unresolved scales?



Two stochastic schemes to simulate model error (QJRMS 2005)

After the introduction of SPPT and SKEB, the ECMWF ensemble perturbed equations included two terms :

$$e_j(d,T) = e_j(d,0) + \int_0^T [A(e_j,t) + P(e_j,t) + \underline{\delta P_j(e_j,t)}]dt$$

$$\delta P_j(\lambda,\varphi,p) = r_j(\lambda,\varphi)P_j(\lambda,\varphi,p) + F_\Psi(\lambda,\varphi,p)$$

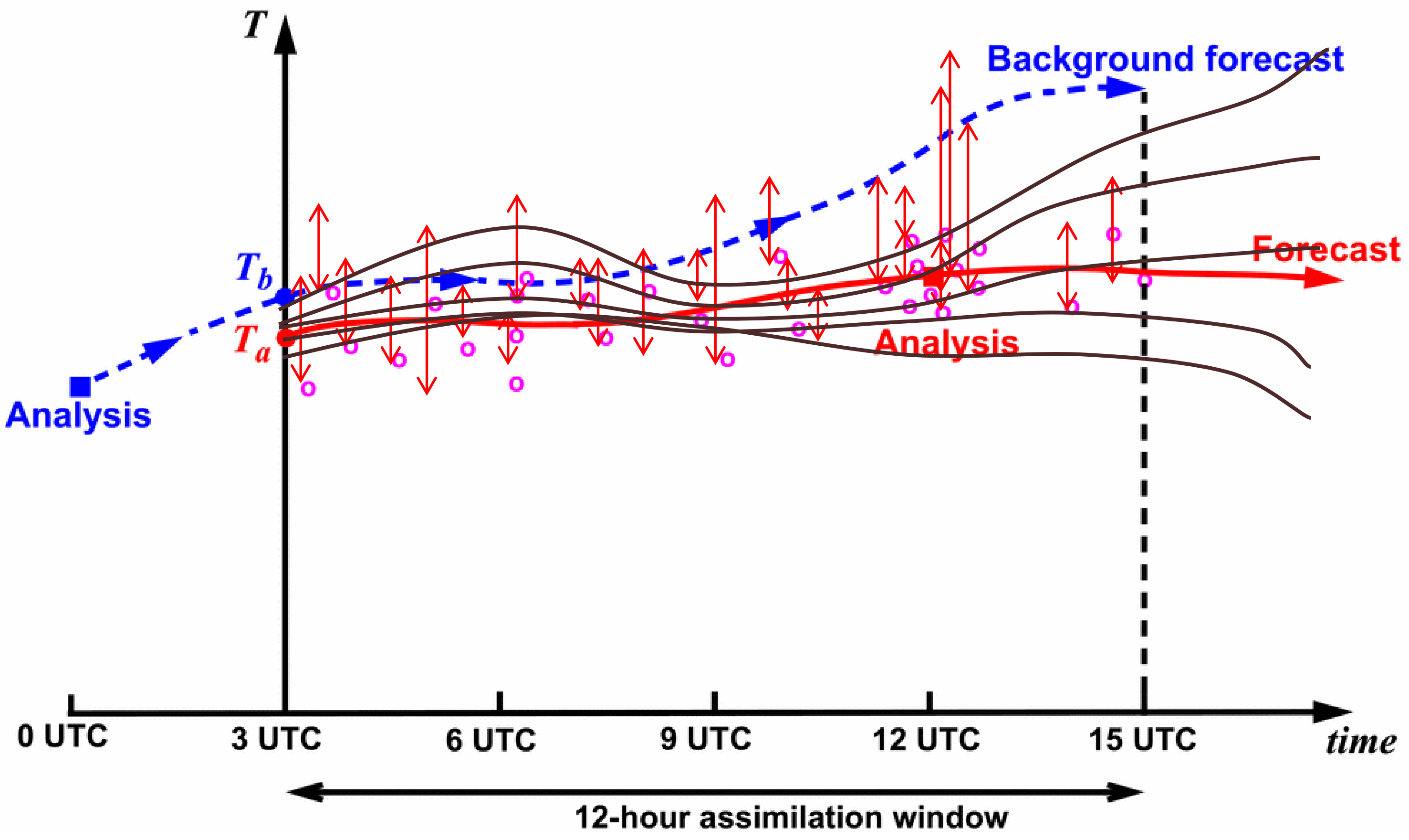
SPPT: Stochastically Perturbed Parameterized Tendencies
(to represent uncertainty associated with parameterisations)

SKEB: Stochastic Kinetic Energy Backscatter
(to represent unresolved upscale energy transfer)

The ECMWF Ensemble of Data Assimilations (QJRMS 2000)

The ensemble of data assimilations (EDA) has been designed to simulate obs-errors (obs are randomly perturbed) and model uncertainty (with stochastic schemes) in the assimilation cycle.

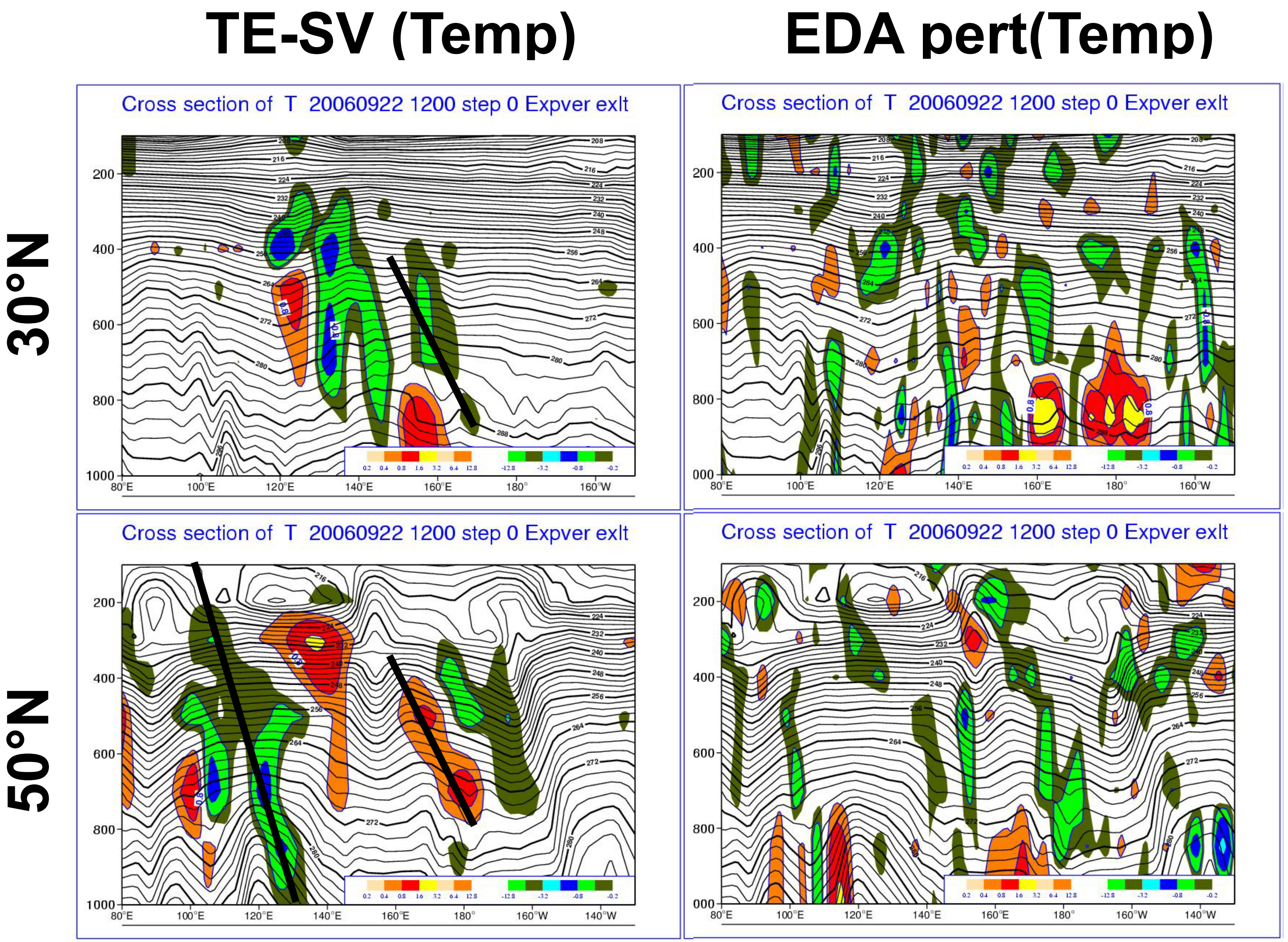
Since 2010, perturbations computed from the EDA has been used with SVs to simulate initial (and model) uncertainties).



The EDA-based perturbations

EDA-based perturbations have different characteristics than SVs:

- include smaller scales;
- are less localized in space;
- have a similar amplitude in potential and kinetic energy;



Topics

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Further ensemble configuration changes after 2010

Today, **synoptic-scale (T42) targeted SVs** are still used, combined with **EDA-based perturbations** to simulate the initial uncertainties. An upgraded version of the **stochastic scheme SPPT** is used to simulate model uncertainties.

Throughout the years, ensembles have benefitted from upgrades in the model, the assimilation procedure, and the number and quality of the observations,

Further changes in the ensemble configuration include improvements in the initial SVs and in the model stochastic scheme; coupling to the NEMO ocean model and seamless merging with the monthly; forecast length extension to 46 days; use of an ensemble of ocean analyses to simulate ocean initial uncertainties

Today, consistent/seamless ensembles are operationally used in analyses, reanalyses, medium-range, monthly and seasonal forecasts.

Today: 3 classes of schemes are used to simulate initial unc

The schemes used today in the global ensembles can be classified in 3 classes:

a) **Lagged** - Based on the hypothesis that time-lagged analyses have the statistics of analysis errors	▪ Lagged Average Forecast
b) **Kalman** – Inspired by the Kalman Filter	▪ Ensemble Kalman Filter ▪ Ensemble Transformed Kalman FIlter ▪ ET with Rescaling ▪ Ensemble Data Assimilation
c) **Reduced sampling** - Inspired by the analysis cycle and trying to identify leading error-growth directions	▪ Bred vectors ▪ Singular vectors (SVs) ▪ EOF ▪ STOCH perturbations

Today: 4 classes of schemes are used to simulate model unc

The schemes used today in the global ensembles can be classified in 4 classes:

	Random Perturbed Parameters	Stochastic Perturbed Parameterization Tendencies	Stochastic Convective Vorticity	Stochastic Total Perturbed Tendencies
BMRC Australia (*)				
CMA-BCC China				
CPTEC Brazil				
ECCC Canada				
ECMWF Europe				
JMA Japan				
KMA Korea				
MF France				
NCEP US				
MO U.K. (*)				

Thank you very much …