Diagnosis of model error in the Met Office data assimilation system

Evolution of forecast error covariances predicted by 4D-VAR and ETKF

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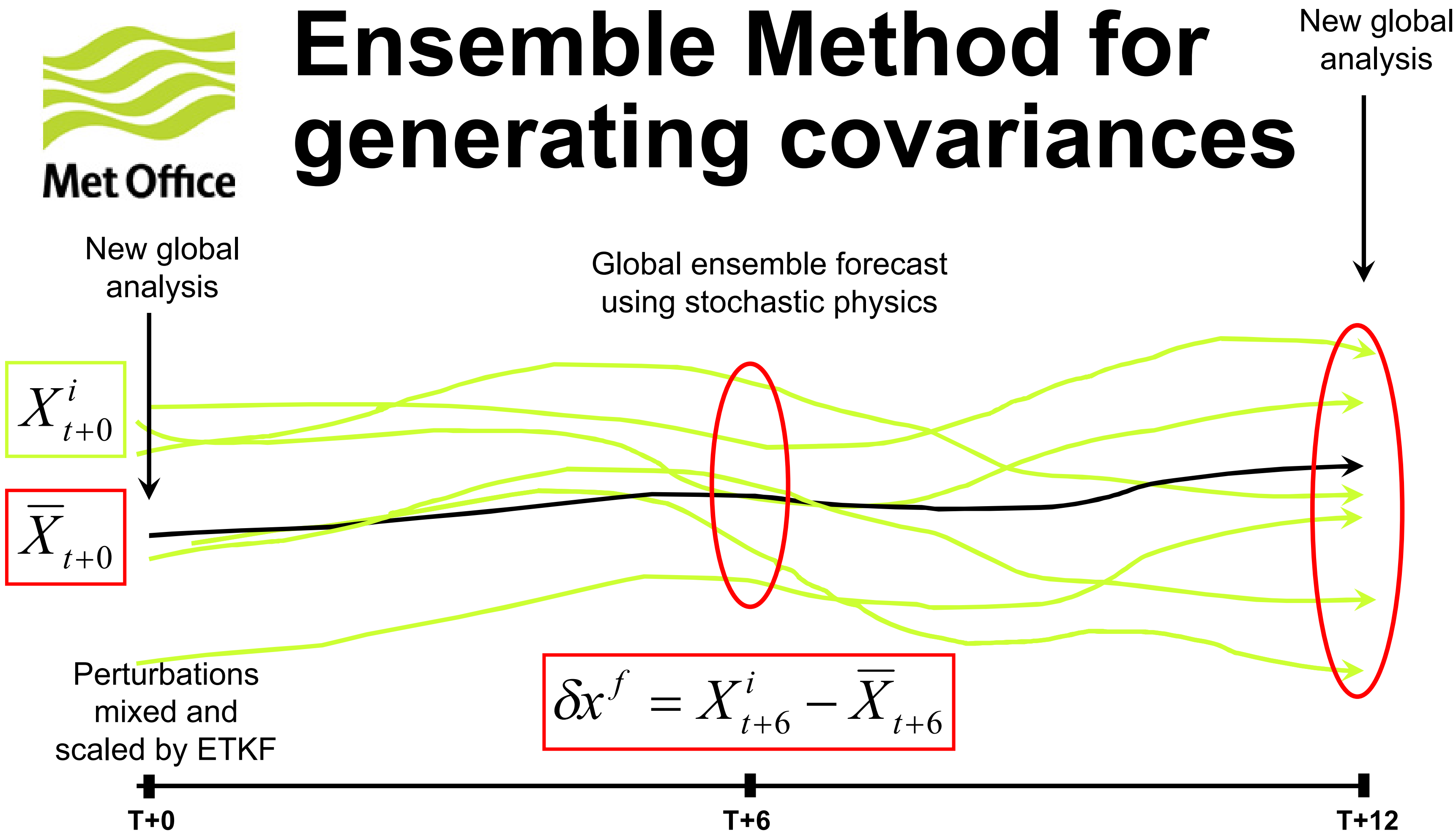
Contents

This presentation covers the following areas

- How well does the ETKF allow for Model Errors?
- How well does the Stochastic Physics describe Model Errors?
- Comparison with the Error Growth implied by 4D-VAR and with Verification figures
- Summary and Open questions

How well does the ETKF allow for Model Errors?

Ensemble Method for generating covariances



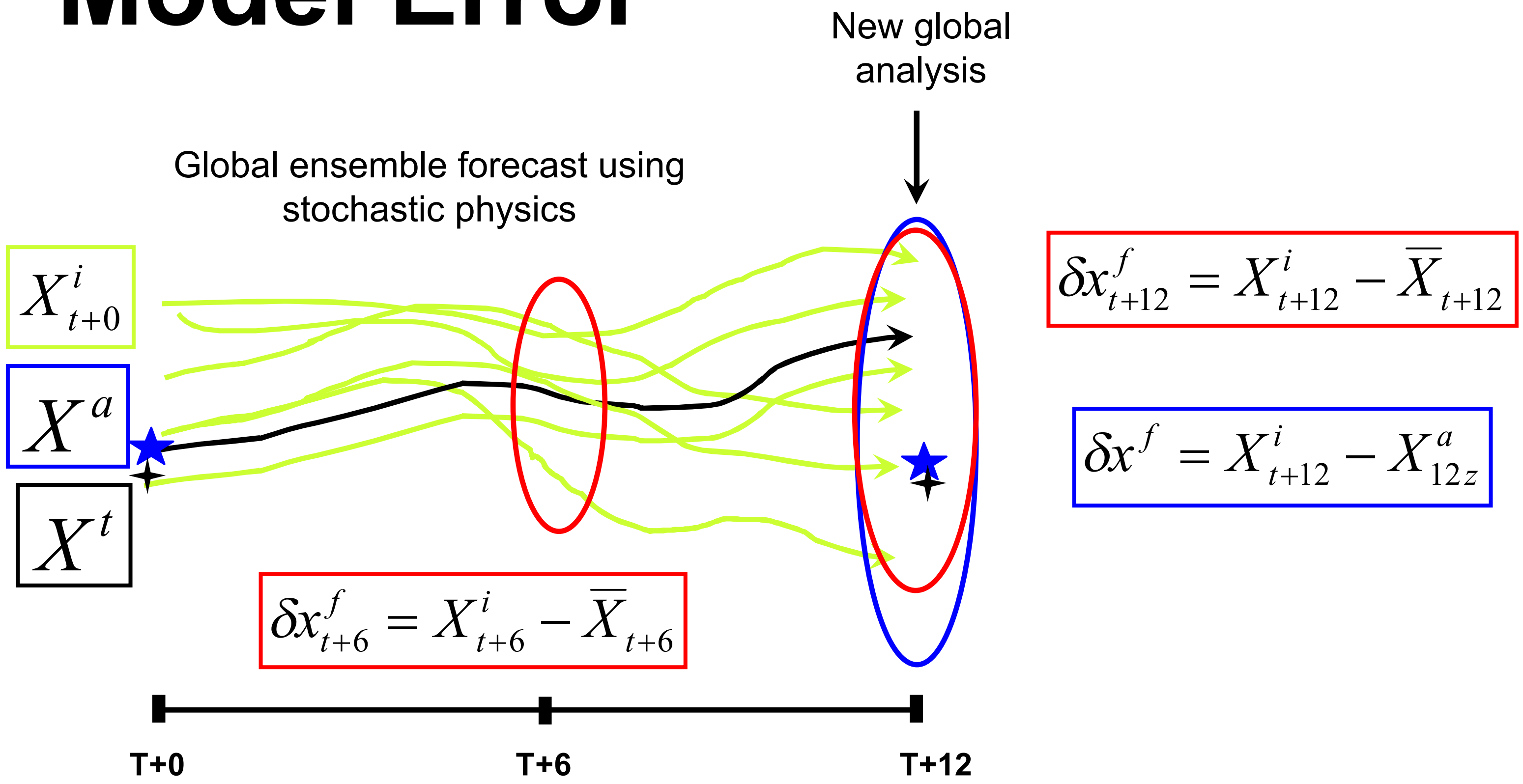
As proxy for background error, use differences between the forecast members of the ensemble and their ensemble mean forecast.

MOGREPS tuning method

- ❖ The variance in an ensemble generated by an ETKF is often smaller than required
- ❖ To overcome this problem MOGREPS uses a variable inflation factor to ensure that the ensemble spread matches the error in the ensemble mean forecast (*)
- ❖ At T+12h the ensemble spread is calibrated to match the ensemble mean error (ensemble mean – analysis, assuming analysis = truth)
- ❖ Therefore the ETKF is tuned so that the ensemble spread includes the model error evolution!

(*) Bowler et al., The MOGREPS short-range ensemble prediction system (2008)

Perturbation Growth versus Model Error



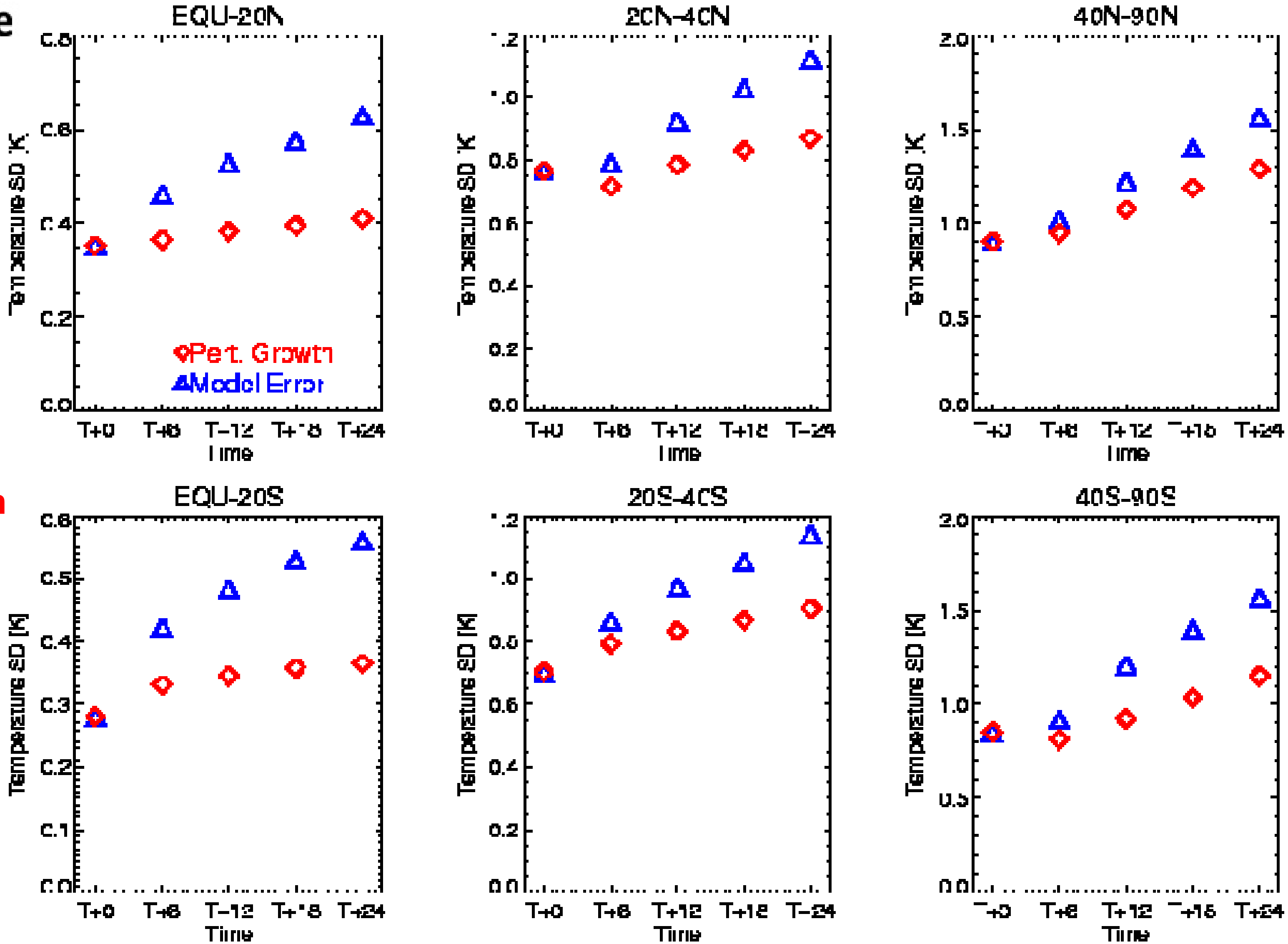
Perturbation Growth + Tuning = $X^i_{t+12} - \overline{X}_{t+12}$

Perturbation Growth + Model Error = $X^i_{t+12} - X^a_{12z}$

$X^a \approx X^{truth}$

Temperature Error Growth at 500hPa (Model Error vs Pert. Growth)

Model Error
Pert. Growth



Model Error and Perturbation Growth: Summary

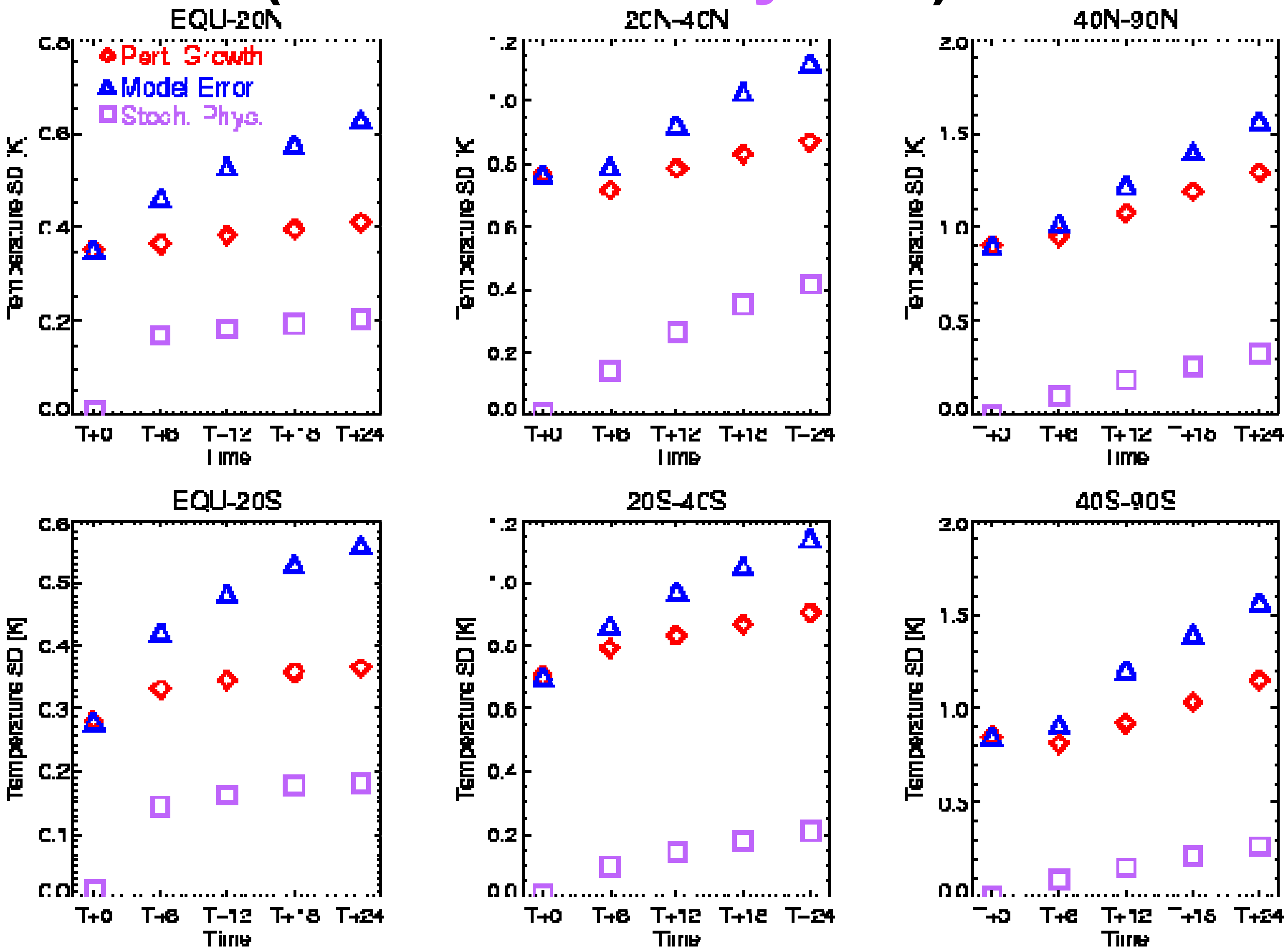
- The ensemble perturbations growth includes model errors because the ETKF is tuned so that the ensemble spread matches the ensemble mean error
- The Model Error in the ensemble is correctly tuned in the extra-tropics troposphere for the Northern Hemisphere but <u>not everywhere else</u> (Temperature at 500hPa)

How well does the Stochastic Physics describe the Model Error?

MOGREPS Stochastic Physics

- ❖ MOGREPS includes a Stochastic Physics scheme in order to represent the effects of model uncertainties (and not to generate noise to increase the ensemble spread).
- ❖ The scheme perturbs randomly a selected group of parameters (e.g. large-scale precipitation, convection, boundary layer and gravity-wave drag).
- ❖ The initial condition perturbations are a combination of the ETKF perturbations and the model perturbations coming from the Stochastic Physics scheme
- ❖ In order to estimate the Stochastic Physics contribution only, the ETKF initial condition perturbations have been switched off.

Temperature Error Growth at 500hPa (Stochastic Physics)



Model Error
Pert. Growth
Stoch. Phys

Unbalanced/Total Pressure at 500hPa (Stochastic Physics)

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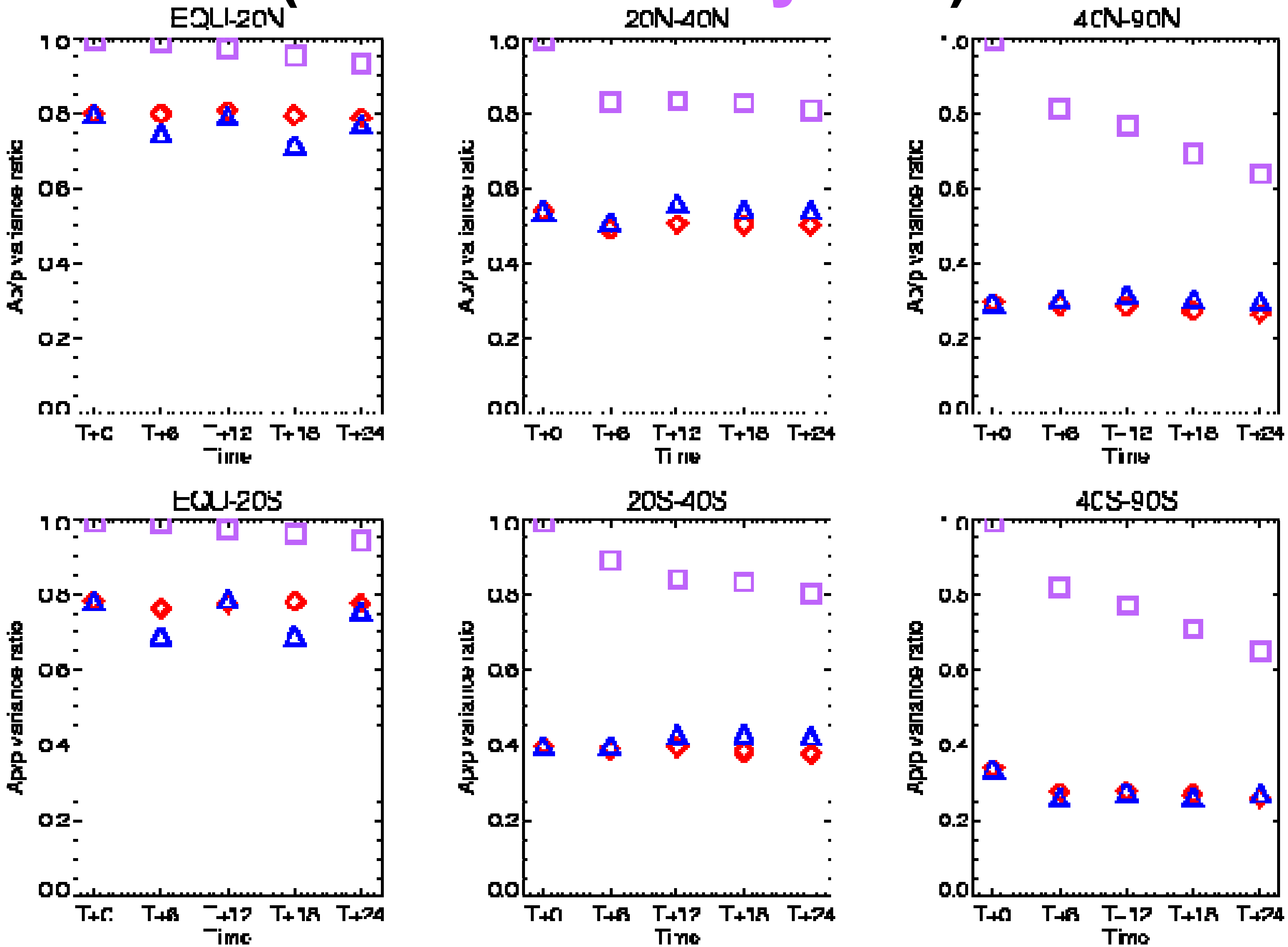
Model Error
Pert. Growth
Stoch. Phys



Stochastic Physics: Summary

- The contribution from the Stochastic Physics is small as expected (of the order of 10% for Temperature at 500hPa in the tropics and extra-tropics, while higher in the equatorial regions)
- The Stochastic Physics perturbations seem to contribute mainly to the <u>unbalanced</u> part of the increments when they are the only initial condition perturbations (i.e. Ap/p at 500hPa),while when added to the ETKF perturbations the initial conditions are still in balance

Comparison with the Error Growth implied by 4D-VAR and with Verification figures

Ensemble versus 4D-VAR error growth (1)

- Error growth using the ***Non-Linear*** model (UM) starting from ETKF perturbations when ensemble spread is calculated against the <u>ensemble mean</u> – **Pert. Growth**
- Error growth using the ***Non-Linear*** model (UM) starting from ETKF perturbations when ensemble spread is calculated against the <u>analysis</u> – **Model Error**
- Error growth implied by 4D-VAR using the ***Linear*** model (PF) as evolution operator starting from a <u>random sample</u> of **B** – **4D-VAR**:
  - evolution of the initial condition errors (**$\mathbf{MBM}^T$**) which in principle should not include any systematic errors
  - the random sample of the initial condition errors is calculated by using the **Randomisation Method**

Temperature Error Growth at 500hPa (4D-VAR using Randomisation of B)

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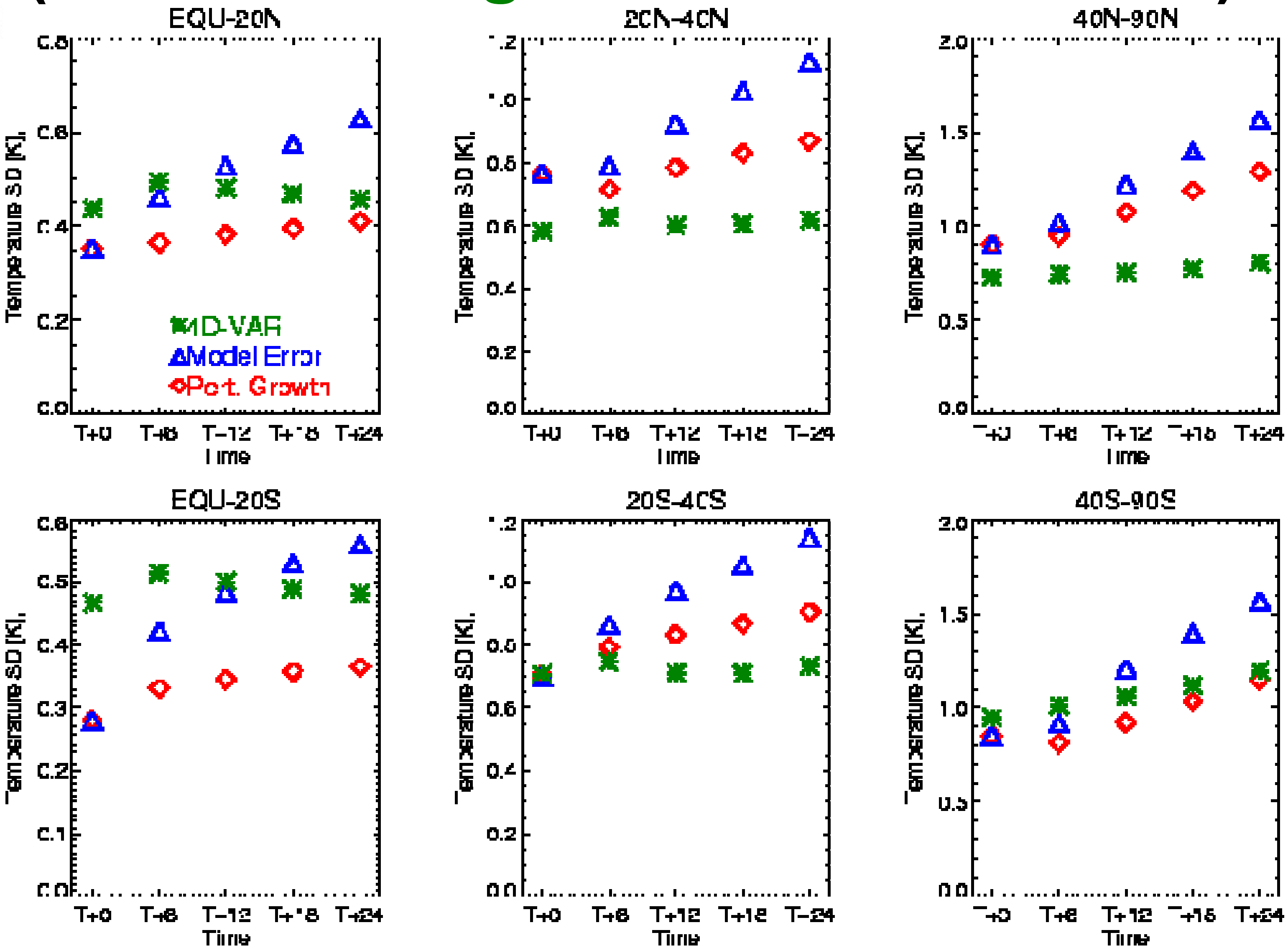


4D-VAR
Model Error
Pert. Growth

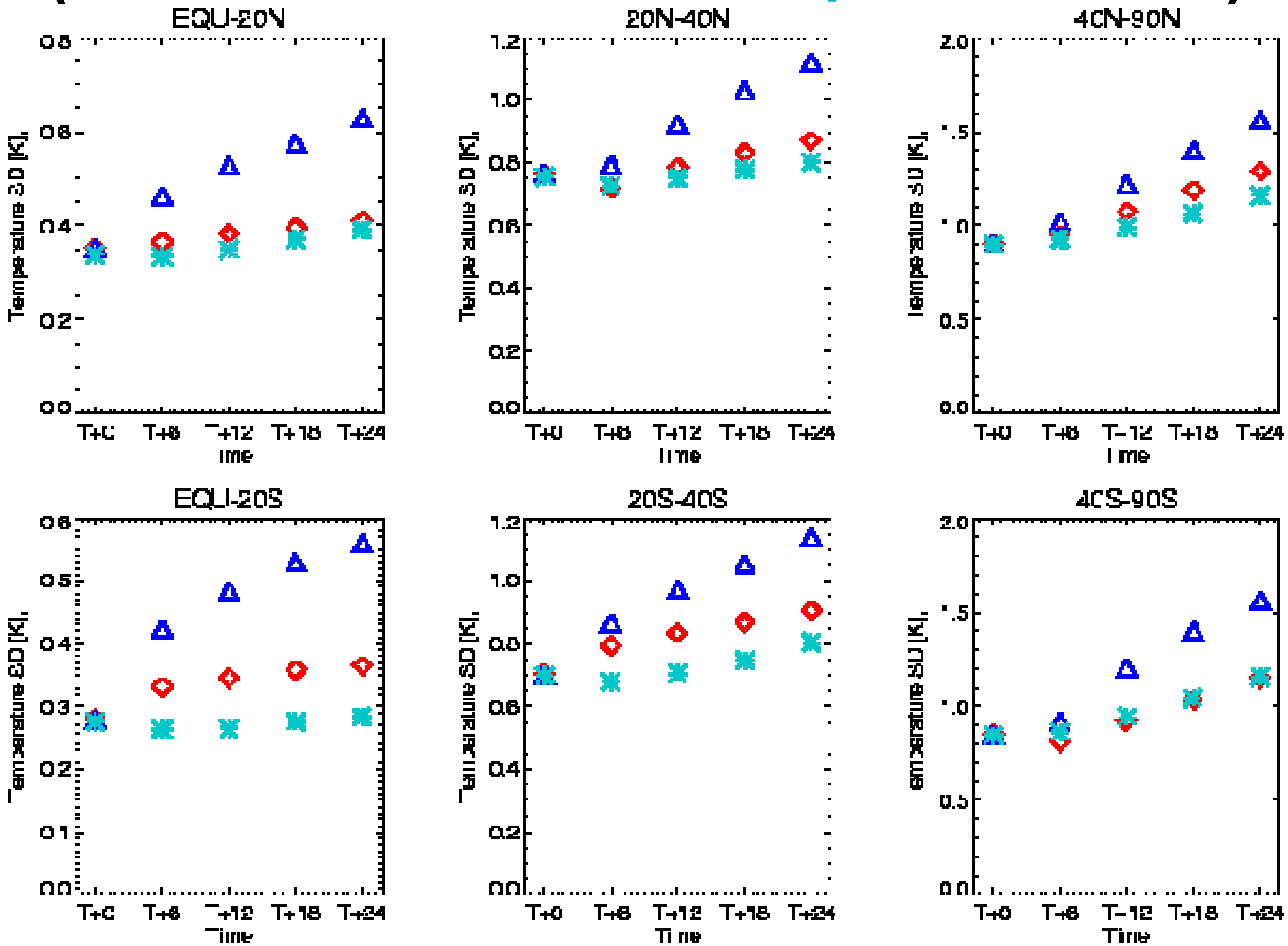
Ensemble versus 4D-VAR error growth (1): Summary

- Ensemble and 4D-VAR error growths are comparable in the tropics, while 4D-VAR initial condition error does not grow as much as ensemble spread
    - the effect of the ensemble tuning must be relevant
- We expect that the Linear model grows faster than the Non-Linear model, but the Randomisation Method selects a random sample of growing modes while the ETKF selects the fastest growing modes
- The Linear model should exaggerate the growth but the random sample of initial condition errors does not pick up the most rapidly growing structure
    - locally the error grows significantly in time

Ensemble versus 4D-VAR error growth (2)

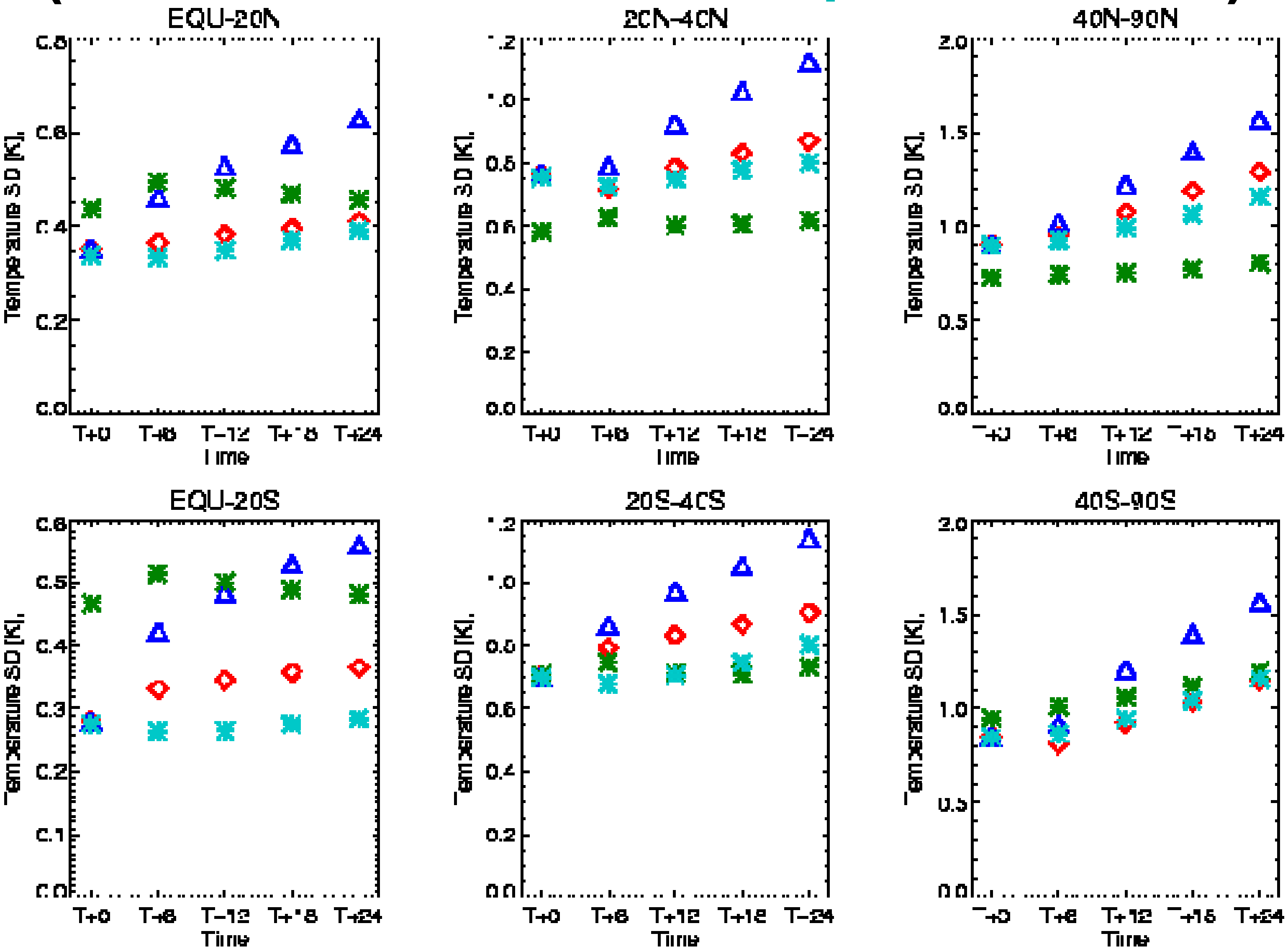
- Error growth using the *Non-Linear* model (UM) starting from ETKF perturbations when ensemble spread is calculated against the ensemble mean – **Pert. Growth**
- Error growth using the *Non-Linear* model (UM) starting from ETKF perturbations when ensemble spread is calculated against the analysis – **Model Error**
- Error growth implied by 4D-VAR using the *Linear* model (PF) as evolution operator starting from a random sample of **B** – **4D-VAR**
- Error growth using the *Linear* model (PF) as evolution operator starting from ETKF initial condition perturbations with covariance $\mathbf{P}^a$ – **Linear ETKF**
    - evolution of the initial condition errors ($\mathbf{M}\mathbf{P}^a\mathbf{M}^T$)

Temperature Error Growth at 500hPa
(Linear evolution of ETKF perturbations)



Model Error
Pert. Growth
Linear ETKF

Temperature Error Growth at 500hPa
(Linear evolution of ETKF perturbations)



4D-VAR
Model Error
Pert. Growth
Linear ETKF

Ensemble versus 4D-VAR error growth (2): Summary

- We expect the linear evolutions of ETKF perturbations to be similar to the ensemble spread evolution
- Differences for EQU- 20S and 20S- 40S regions could be explained by:
  - resolution
  - physics (more active convection – Dec 2006)
  - non-linearity
- For Linear ETKF evolution the model error is missing, only tuning effect is present.
- Linear evolution of ETKF perturbations and 4D-VAR show similar growth in the SH, while ETKF shows more growth in NH where it is properly tuned to match the ensemble mean error

Ensemble and 4D-VAR versus Verification figures

- Error growth using the *Non-Linear* model (UM) starting from ETKF perturbations when ensemble spread is calculated against the <u>analysis</u> – **Model Error**

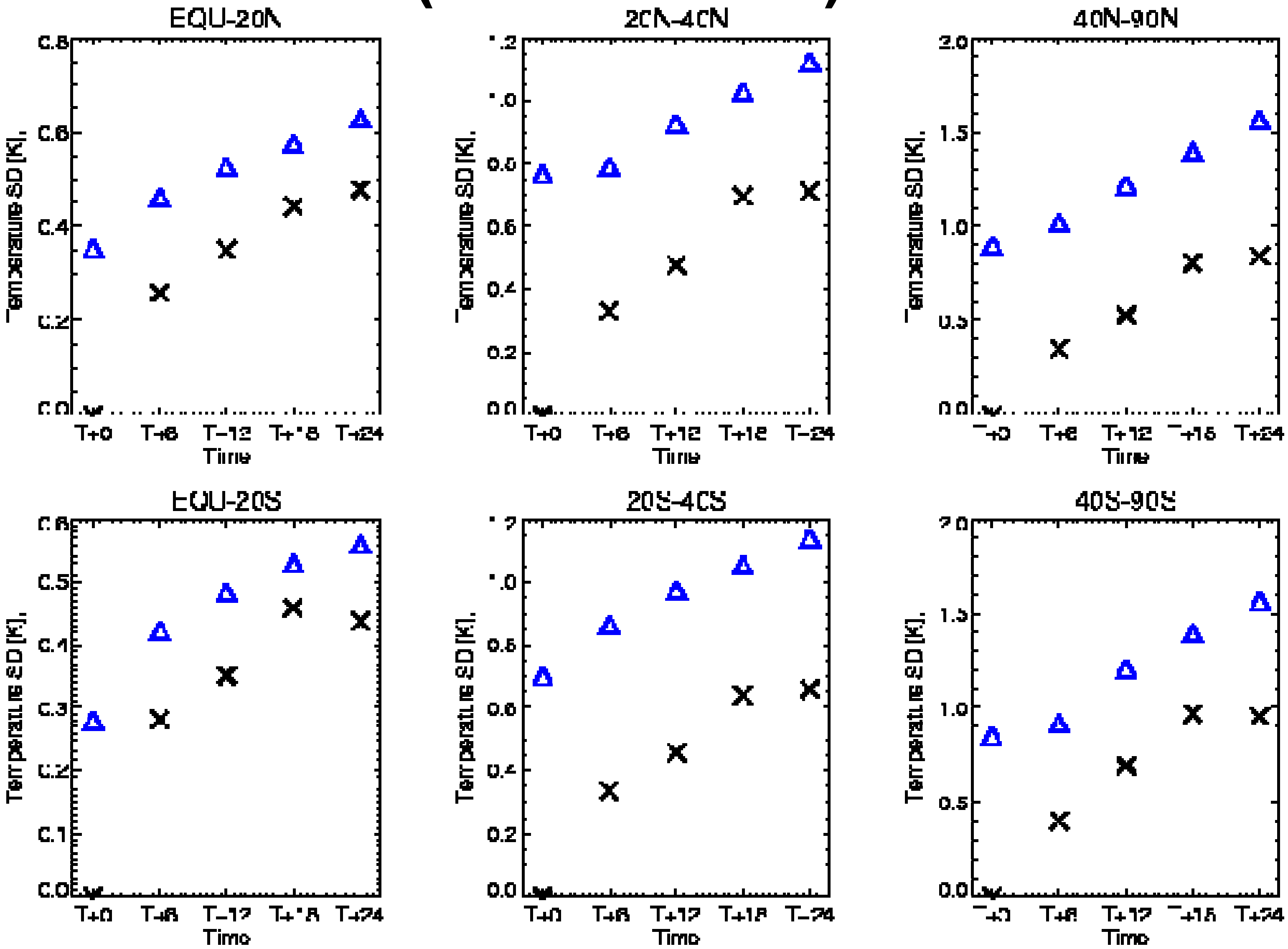
- Error growth implied by 4D-VAR using the *Linear* model (PF) as evolution operator starting from a <u>random sample</u> of **B** – **4D-VAR**

- Error growth of the deterministic forecast averaged over a large number of cases (one month) – **Verification**

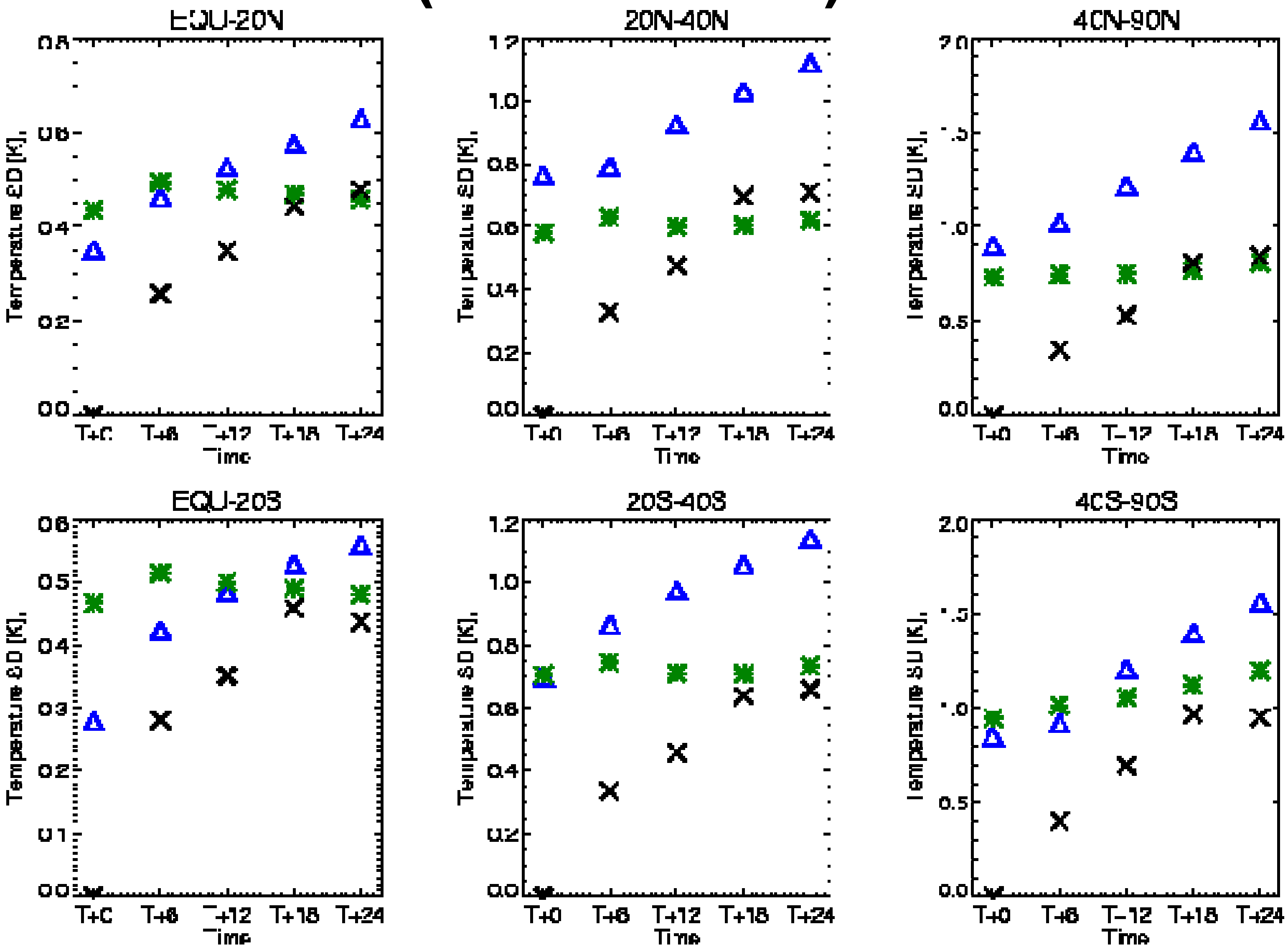
  - it describes the **climatological** error

Temperature Error Growth at 500hPa (Verification)

Verification
Model Error



Temperature Error Growth at 500hPa (Verification)



Verification
Model Error
4D-VAR

Ensemble and 4D-VAR vs Verification: Summary

- Verification error is smaller than Model Error ensemble spread: offset due to lack of ensemble spread in the Verification error since it represents a single estimate of the forecast error averaged over a month.

- The implicit growth in 4D-VAR is different from both the Model Error ensemble spread and the verification error.

- Verification error is also smaller than 4D-VAR error although 4D-VAR should not include any systematic errors either:

  - <u>but</u> **B** is calculated by using the NMC method (difference of forecasts valid at the same time) which includes the model error – the NMC method contradicts 4D-VAR assumption of zero mean initial condition error!

Summary & Open Questions

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- The MOGREPS is correctly tuned in the extra-tropics NH but not everywhere else.
- The contribution from the Stochastic Physics is small as expected and seems to contribute mainly to the unbalanced part of the increments.
- MOGREPS and 4D-VAR error growths are comparable in the tropics, while 4D-VAR does not grow as much as the ensemble spread.
- Linear evolution of ETKF perturbations is similar to the ensemble spread evolution as expected (differences are due to resolution and physics) and shows more growth in NH where the ETKF is properly tuned.
- Verification error is smaller than Model Error ensemble spread: does **B** represent the error of a single forecast time or the error of large number of cases?
- The implicit growth in 4D-VAR is very different from true evolution of **B,** i.e. from the Model Error ensemble spread, should it be?