ENSEMBLE ASSIMILATION OF STRATOSPHERIC TEMPERATURE AND OZONE OBSERVATIONS IN A CHEMISTRY-CLIMATE MODEL

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Motivation

Ensemble methods are computationally expensive, but produce along-the-flow error covariances :

- can produce spatial, cross-variable, temporal error covariances.
- excellent for data-sparse regions.
- potential of improving global stratospheric winds from ozone or temperature observations

Objectives

We are experimenting stratospheric chemical and dynamical ensemble data assimilation, incorporating synthetic ENVISAT-MIPAS temperature or ozone retrievals to chemistry-climate model forecasts using an Ensemble Kalman Filter (EnKF).

We wish to explore the potential of ensemble covariances, especially chemical-dynamical ones, and their skills at constraining the atmospheric fields.

Outline

- Data assimilation system and experimental setup
- Sensitivity study on localization parameters
- Chemistry-Dynamics interaction in data assimilation cycle

Experimental setup : EnKF

EnKF with perturbed obs (Evensen, 1994; Burgers, 1998)

$$\boxed{\delta x = \mathbf{K_e}\ d}$$

$\delta x = x^a - x^f =$ analysis increments

$d = y - \mathcal{H}(x^f) =$ innovations

$\mathbf{K_e} = \mathbf{P_e^f H}^{\ \mathbf{T}}(\mathbf{H P_e^f H}^{\ \mathbf{T}} + \mathbf{R})^{-1} =$ Kalman Gain

$$\mathbf{P_e^f} = \frac{1}{\mathrm{Nens}} \sum_{m=1}^{\mathrm{Nens}} (x_m^f - \overline{x^f})(x_m^f - \overline{x^f})^T$$

$=$ sample background error-covariance matrix

$\mathbf{R} =$ observations error-covariance matrix (prescribed)

$\mathcal{H} =$ model-to-observation-space matrix

Experimental setup : CCM

CHEMISTRY-CLIMATE MODEL (CCM)

IGCM (Forster et al, 2000):

- Multilayer spectral GCM run at T21L26, lid at 0.1 hPa
- Intermediate-complexity physics parametrization
- Prescribed surface temperatures

FASTOC (Taylor and Bourqui, 2005):

- Fast surrogate chemistry scheme
- Based upon comprehensive box model by Fish and Burton (1997), with JPL02 rates.
- Timestep: 24 hrs (diurnal-averaged chemistry)
- Represented catalytic cycles: O_x, HO_x, NO_x.
- Advected species: O_x, N_2O_5, NO_x, HNO_3

Experimental setup : filter configurations

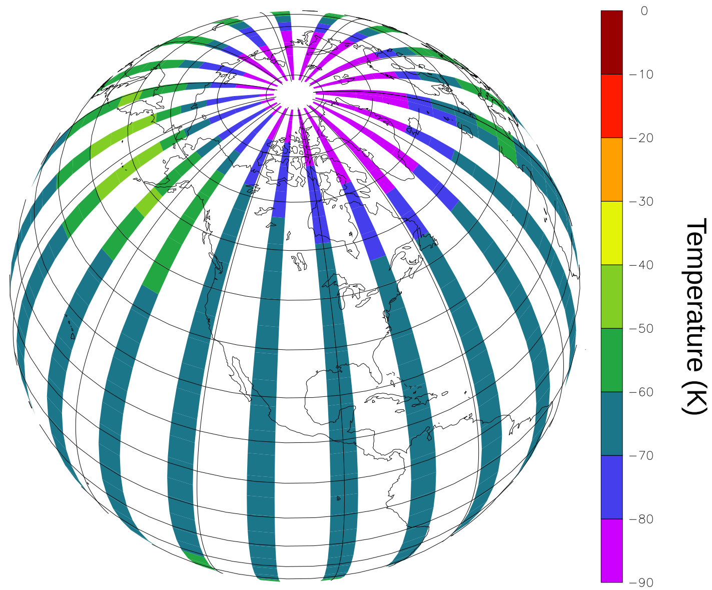
model state vector

$$\begin{pmatrix} u \\ v \\ T \\ P_s \\ Q \\ O_x \\ N_2O_5 \\ NO_x \\ HNO_3 \end{pmatrix}$$

- Initial ensemble is climatological with 128 members (Jan 1^{st} of each year)
- Twin experiment
- Perfect-model hypothesis
- Sequential Double-EnKF assimilation of observations by batches (Houtekamer & Mitchell, 2001)
- Horizontal and vertical covariance localization
- No covariance inflation
- Analysis performed every 24 hours

Experimental setup : observations

- Synthetic MIPAS-like temperature retrievals with 2K error
- Synthetic MIPAS-like ozone retrievals with 10% error
- Diagonal $\mathbf{R}$ matrix
- Obs instantaneous at 00UTC
- Vertical coverage between 4hPa and 200hPa on pressure levels
- Horizontal coverage on model grid points :



Localization

INTRODUCTION

EXPERIMENTAL SETUP

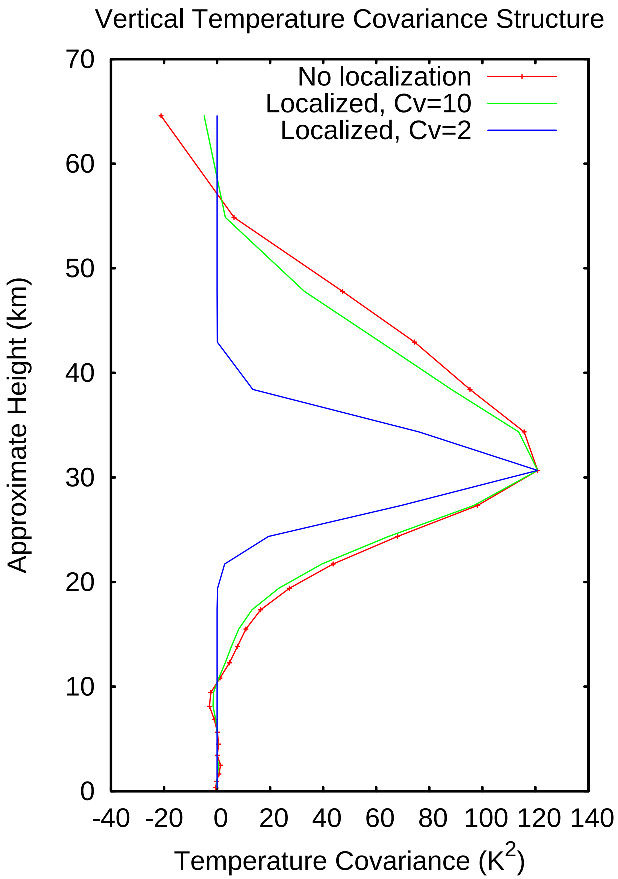
LOCALIZATION SENSITIVITY STUDY

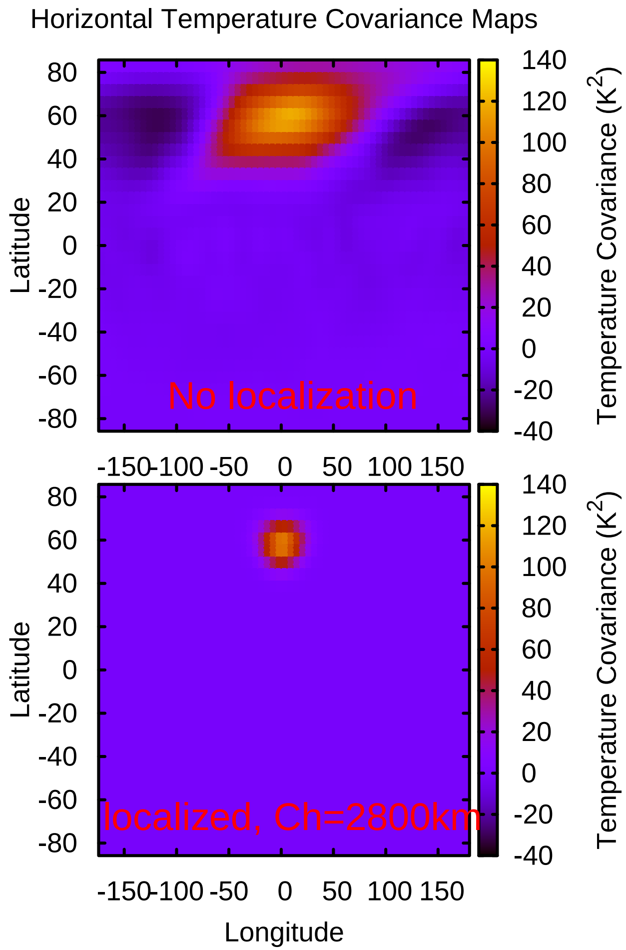
- Localization
- Sensitivity Study
- Optimal parameters
- Inflation Diagnostics

CHEMISTRY-DYNAMICS INTERACTION

CONCLUSIONS

Localization: $\rho_v \circ \rho_h \circ \mathbf{P}^{\mathbf{f}}$





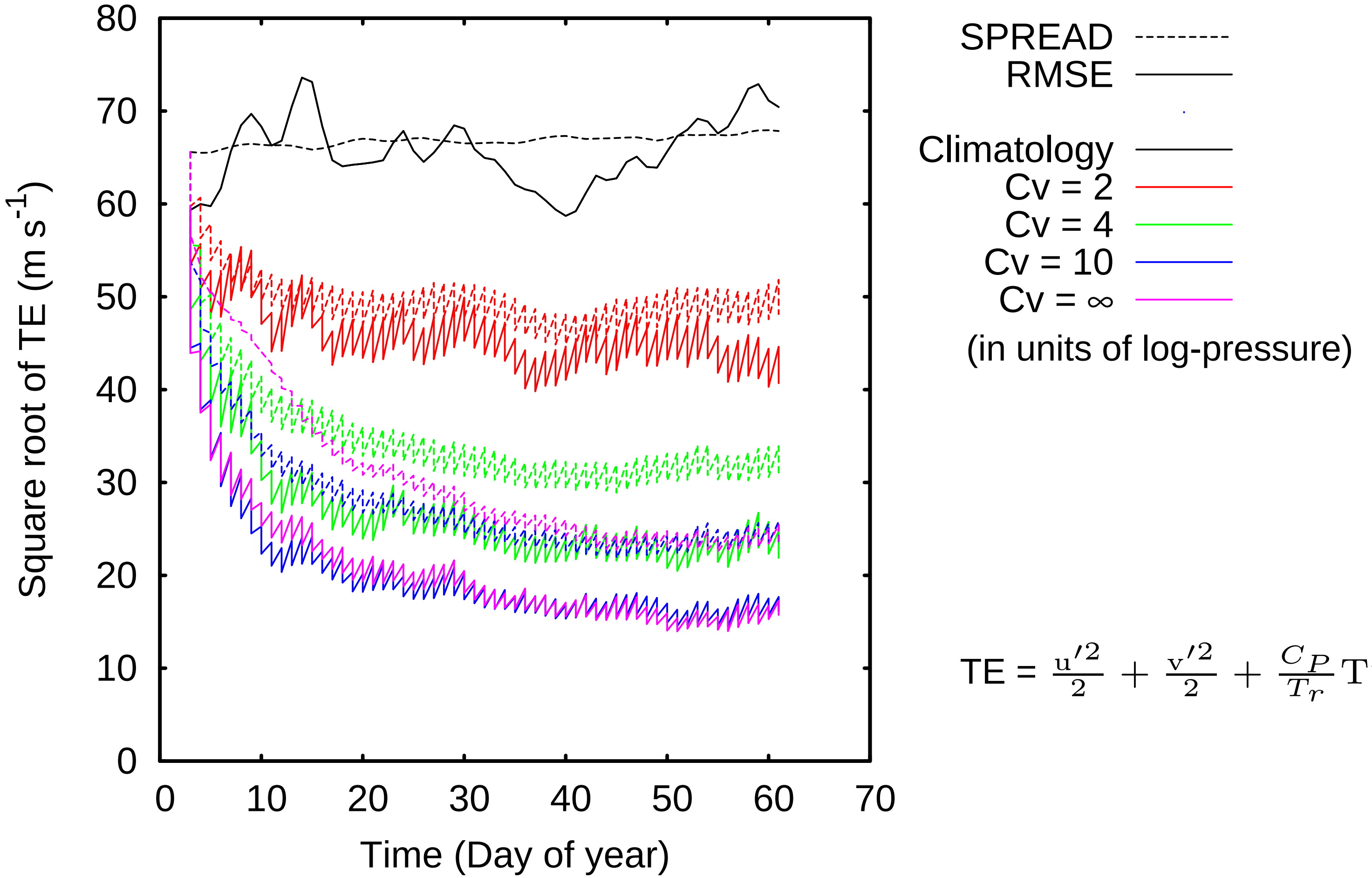
+ Reduce sampling noise, increase rank of $\mathbf{P}^{\mathbf{f}}$

- Introduce imbalance

Sensitivity Study

Sensitivity to vertical and horizontal decorrelation length parameters C_v and C_h in temperature assimilation case:

Sensitivity to vertical localization ($C_h = 2800$ km)

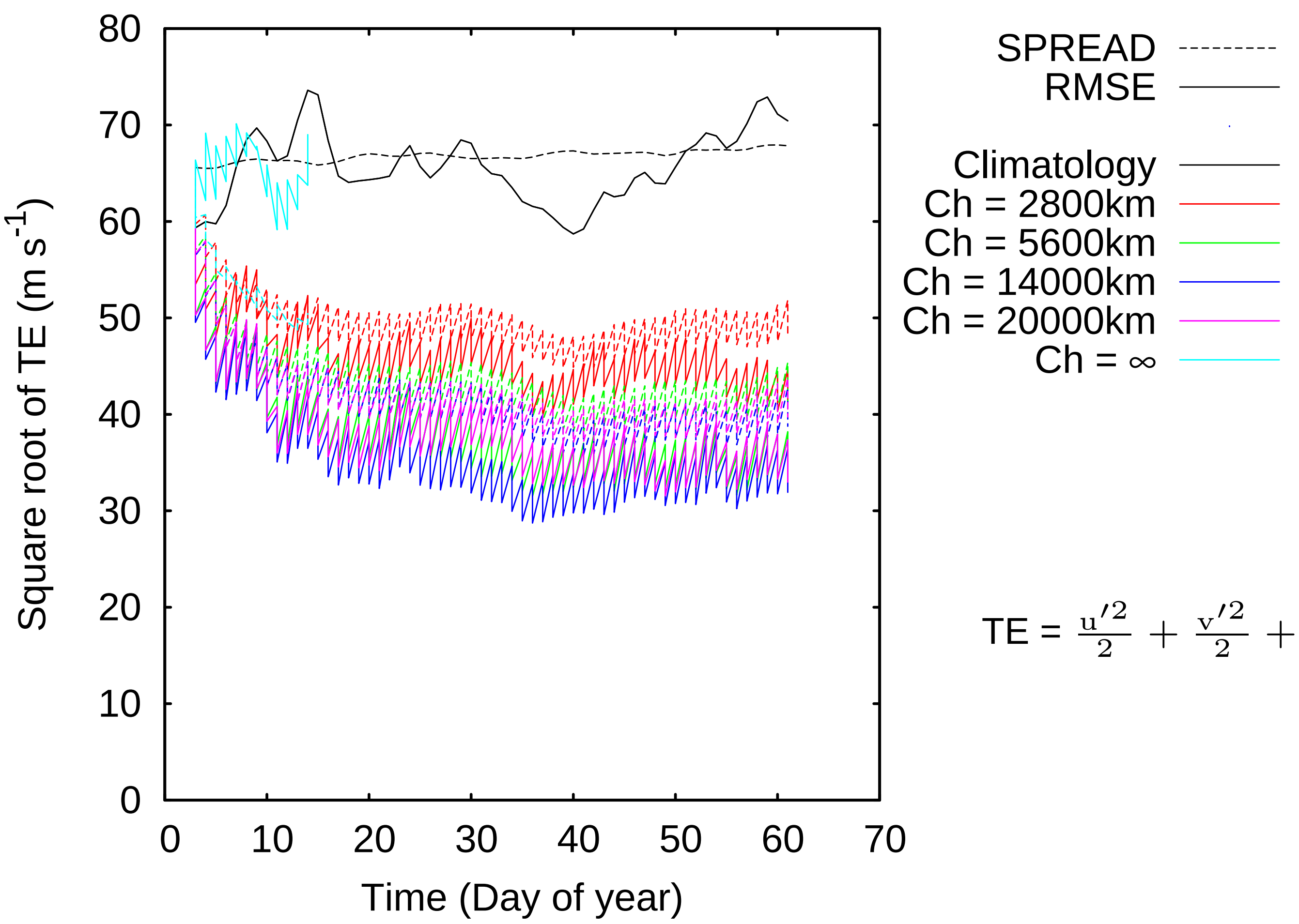


$$TE = \frac{u'^2}{2} + \frac{v'^2}{2} + \frac{C_P}{T_r}T'^2 + R\,T_r\left(\frac{P_s'}{P_r}\right)^2$$

Sensitivity Study

Sensitivity to vertical and horizontal decorrelation length parameters C_v and C_h in temperature assimilation case:

Sensitivity to horizontal localization ($C_v = 2$ units)



$$\text{TE} = \frac{u'^2}{2} + \frac{v'^2}{2} + \frac{C_P}{T_r}T'^2 + R\,T_r\left(\frac{P'_s}{P_r}\right)^2$$

Optimal parameters

Time-averaged SPREAD and RMSE of square-root of TE (ms^{-1}):

temperature assimilations

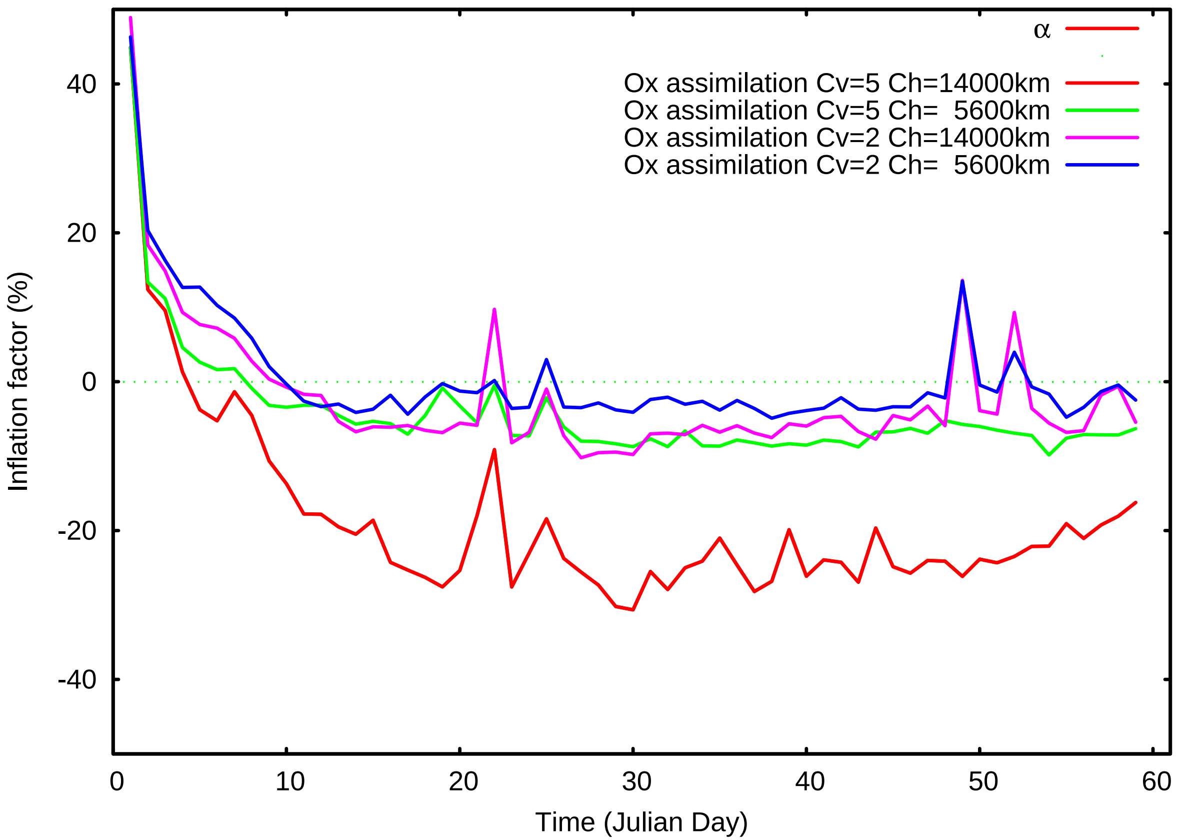
	$C_v = 2$	$C_v = 4$	$C_v = 10$
$C_h = 2800$ km	46.8 $\pm$ 0.9 42.6 $\pm$ 1.4	30.6 $\pm$ 1.3 22.7 $\pm$ 1.5	23.9 $\pm$ 1.7 16.3 $\pm$ 1.4
$C_h = 5600$ km	40.1 $\pm$ 1.0 33.7 $\pm$ 1.6		
$C_h = 14000$ km	38.0 $\pm$ 1.4 31.3 $\pm$ 1.4		14.3 $\pm$ 1.1 9.2 $\pm$ 1.5
$C_h = 20000$ km	38.6 $\pm$ 1.0 34.0 $\pm$ 1.6		

SPREAD $\pm$ σ
RMSE $\pm$ σ

ozone assimilations

	$C_v = 2$	$C_v = 4$	$C_v = 10$
$C_h = 2800$ km	48.2 $\pm$ 0.9 41.6 $\pm$ 3.7	26.6 $\pm$ 1.7 18.2 $\pm$ 1.7	21.5 $\pm$ 2.3 14.1 $\pm$ 1.7
$C_h = 5600$ km	39.6 $\pm$ 1.5 31.8 $\pm$ 2.5	17.3 $\pm$ 2.3 10.9 $\pm$ 1.8	13.8 $\pm$ 2.3 8.9 $\pm$ 1.9
$C_h = 14000$ km	33.7 $\pm$ 1.7 28.8 $\pm$ 2.4	13.3 $\pm$ 1.9 9.5 $\pm$ 2.4	10.1 $\pm$ 1.7 8.6 $\pm$ 3.1
$C_h = 20000$ km	33.7 $\pm$ 1.7 32.5 $\pm$ 2.3		

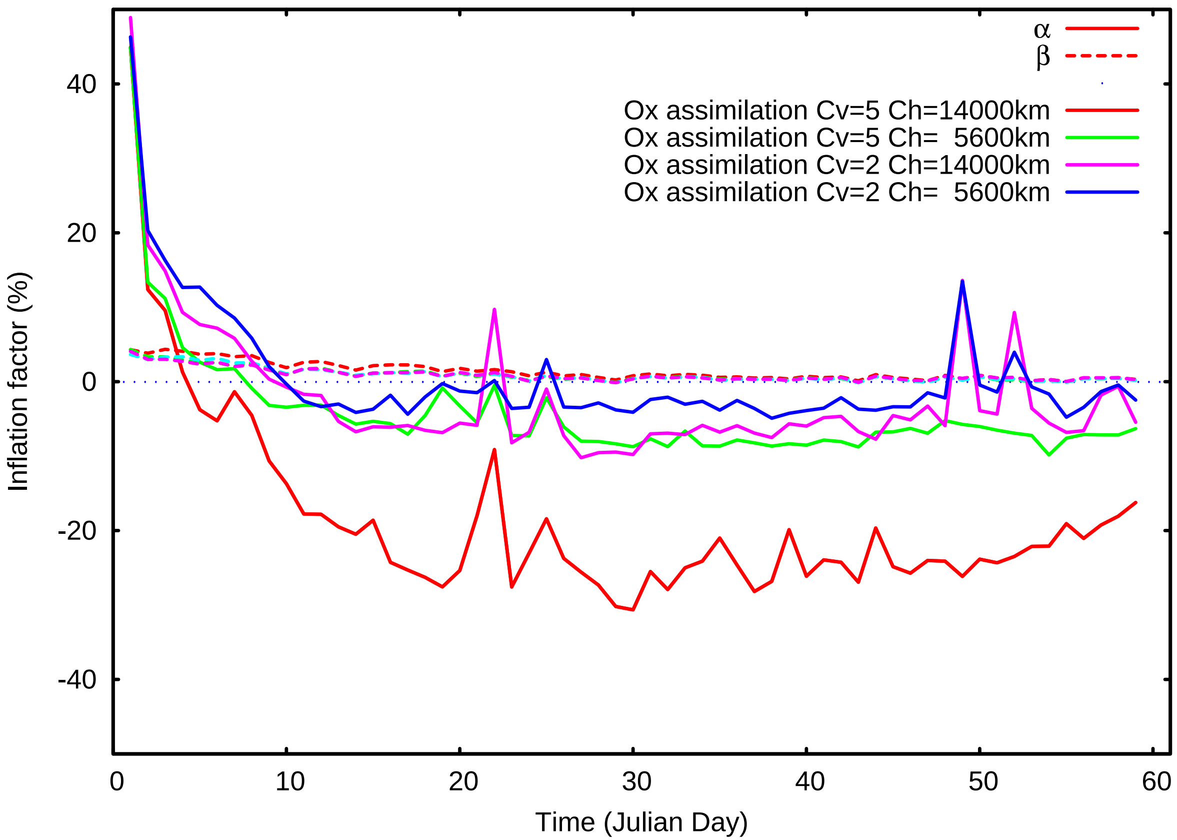
Inflation Diagnostics



$$\alpha = \frac{\mathrm{Tr}(\mathbf{H}\mathbf{P}^{\mathbf{f}}\mathbf{H}^{\mathbf{T}})}{\mathrm{Tr}(<(\mathcal{H}(x^a)-\mathcal{H}(x^f))(y-\mathcal{H}(x^f))^T>)}$$

$$\beta = \frac{\mathrm{Tr}(\mathbf{R})}{\mathrm{Tr}(<(y-\mathcal{H}(x^a))(y-\mathcal{H}(x^f))^T>)}$$

Inflation Diagnostics



$$\alpha = \frac{\mathrm{Tr}(\mathbf{HP^fH^T})}{\mathrm{Tr}(<(\mathcal{H}(x^a) - \mathcal{H}(x^f))(y - \mathcal{H}(x^f))^T>)}$$

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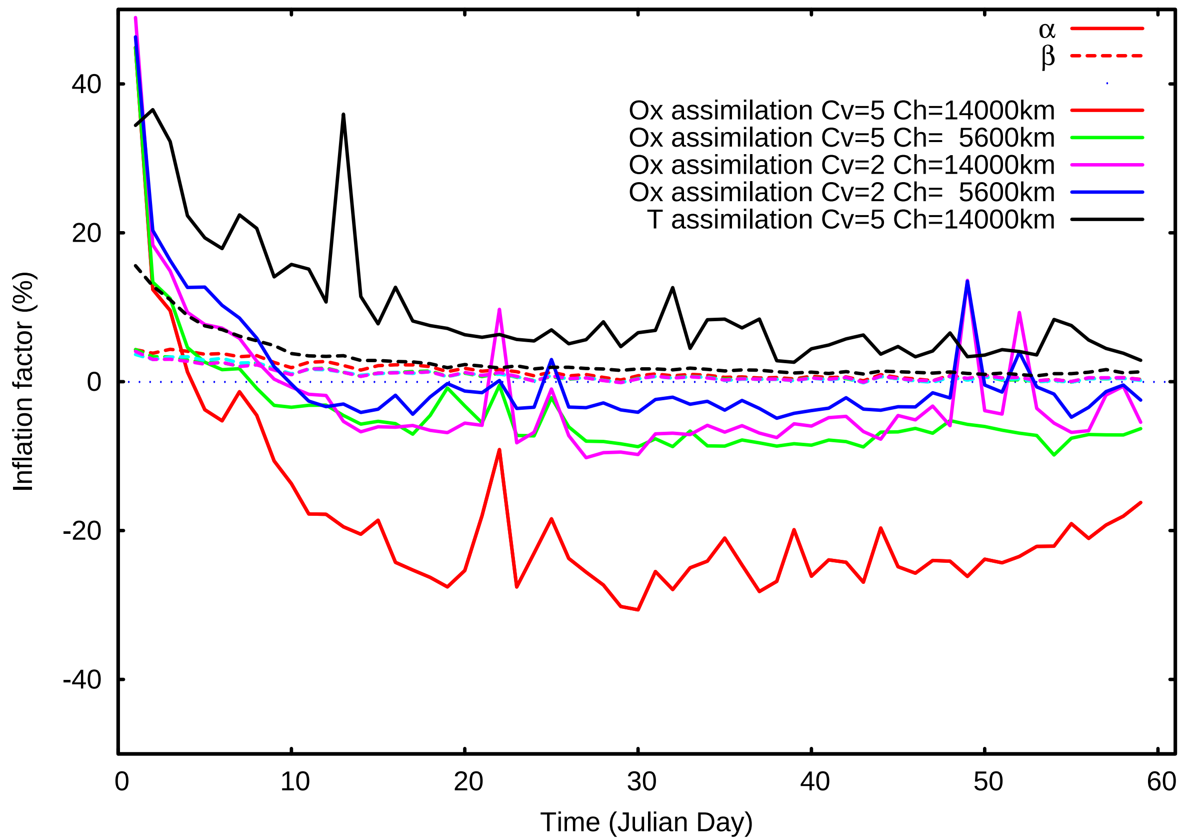
Inflation Diagnostics



$$\alpha = \frac{\mathrm{Tr}(\mathbf{H}\mathbf{P}^{\mathbf{f}}\mathbf{H}^{\mathbf{T}})}{\mathrm{Tr}(<(\mathcal{H}(x^a)-\mathcal{H}(x^f))(y-\mathcal{H}(x^f))^T>)}$$

$$\beta = \frac{\mathrm{Tr}(\mathbf{R})}{\mathrm{Tr}(<(y-\mathcal{H}(x^a))(y-\mathcal{H}(x^f))^T>)}$$

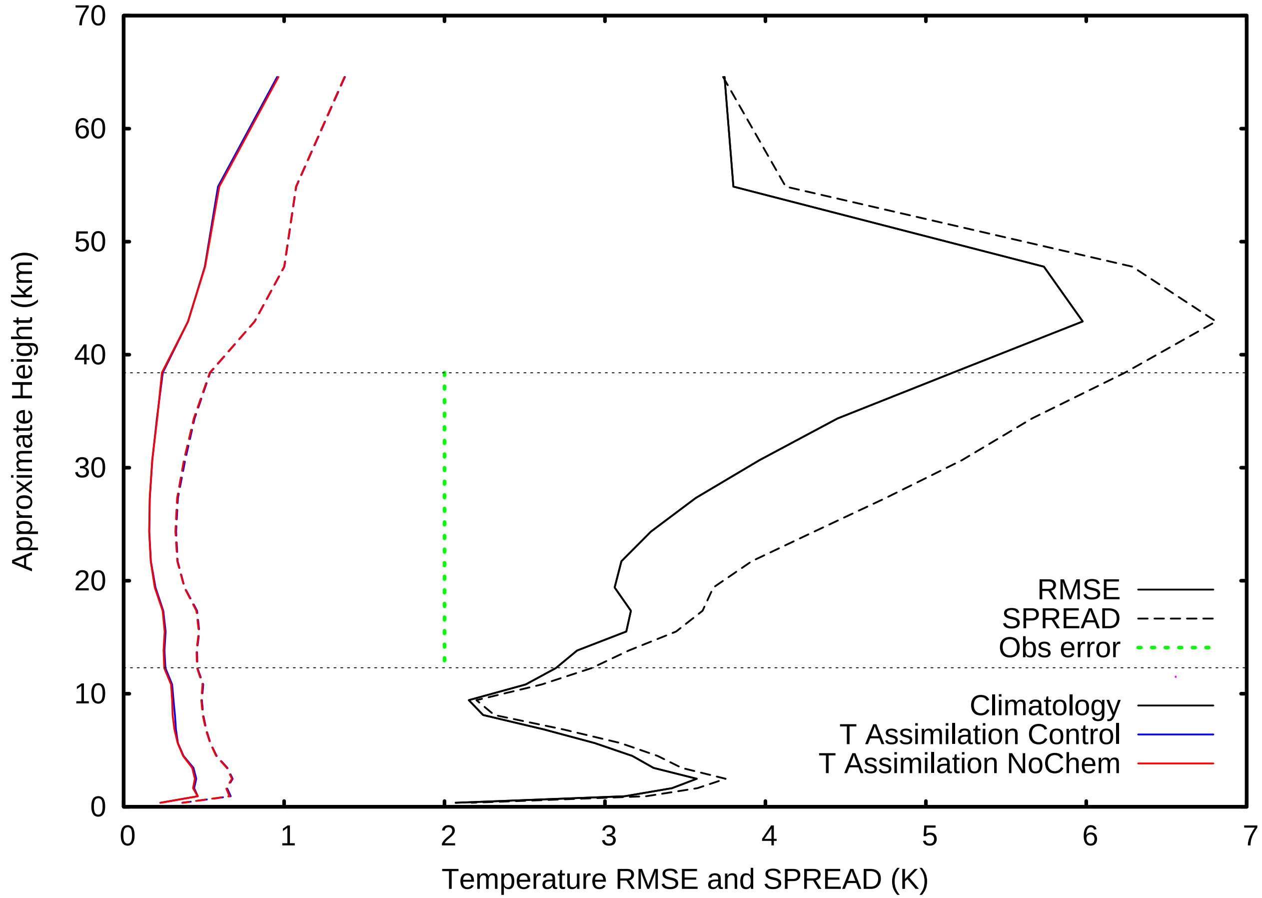
Chemistry-dynamics interaction

Experiments

- “Control” temperature assimilation
- “NoChem” temperature assimilation :
  no temperature-chemistry cross-covariances
- “Control” ozone assimilation
- “NoDyn” ozone assimilation :
  no ozone-dynamics cross-covariances

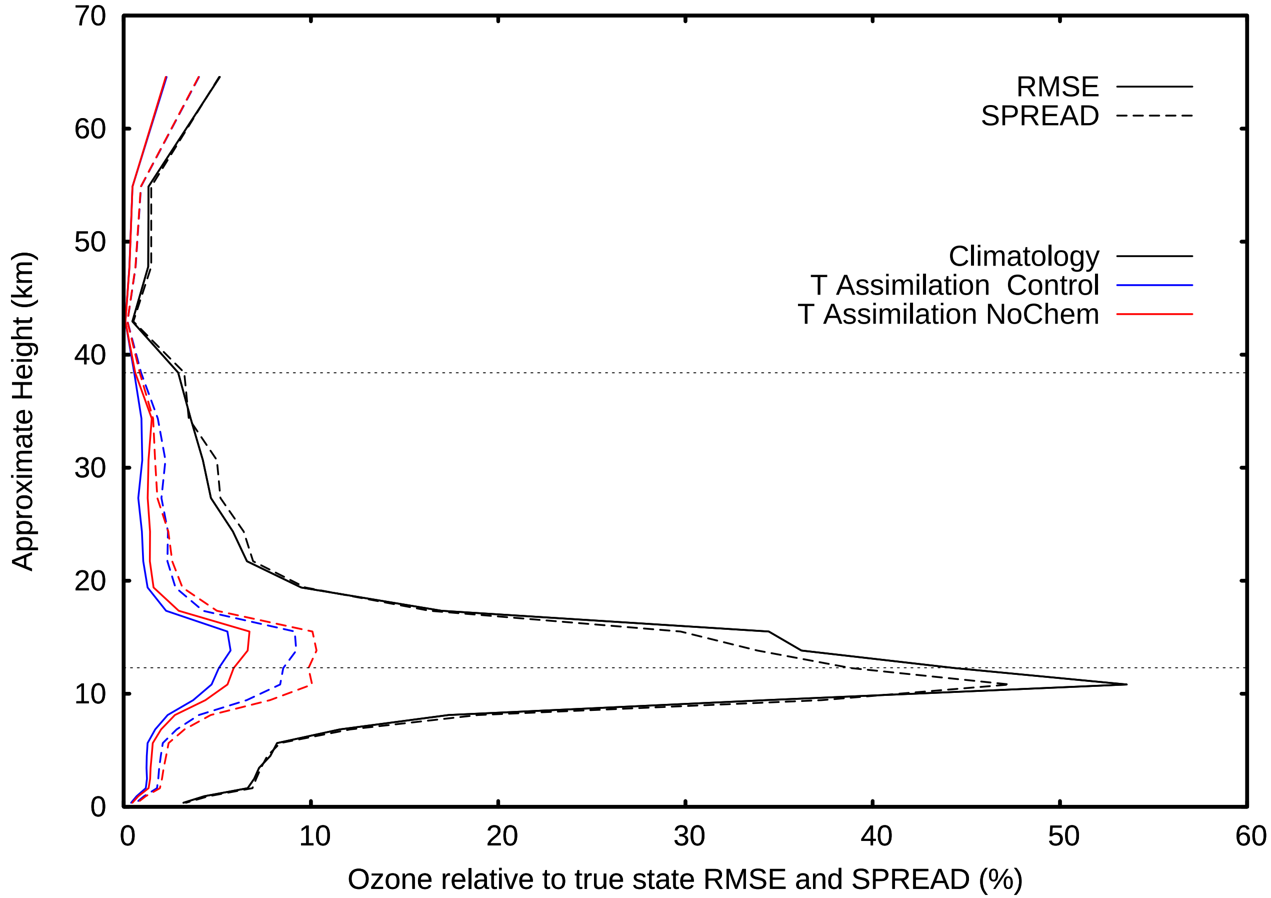
Simulation are run for 60 day. We take time averages over the last 45 days of RMSE and SPREAD and we analyze them for each variable and scenario.

T assimilation : effect on T analysis



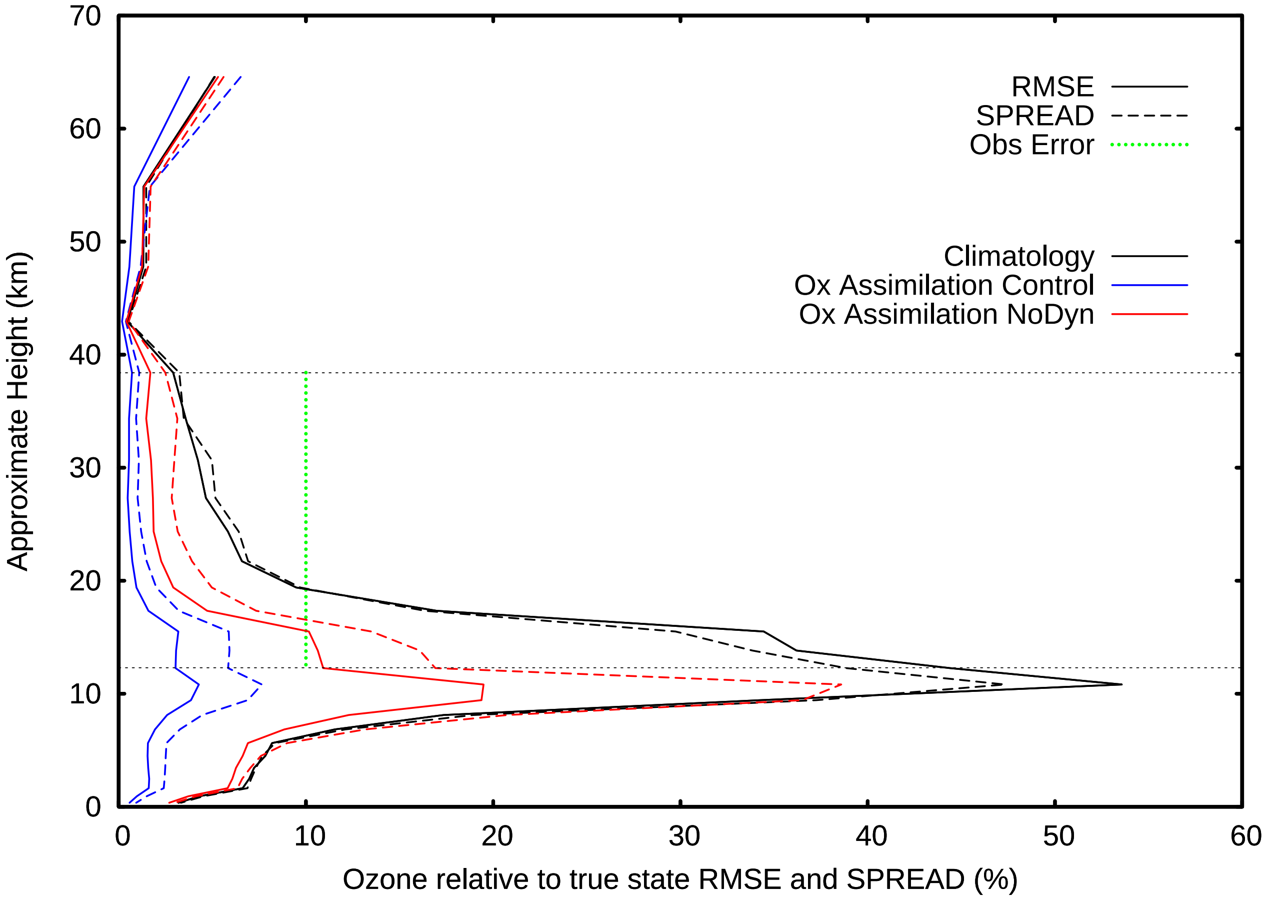
→ useless T-Chem covariances or ineffective radiation ?

T assimilation : effect on $\mathrm{O_x}$ analysis



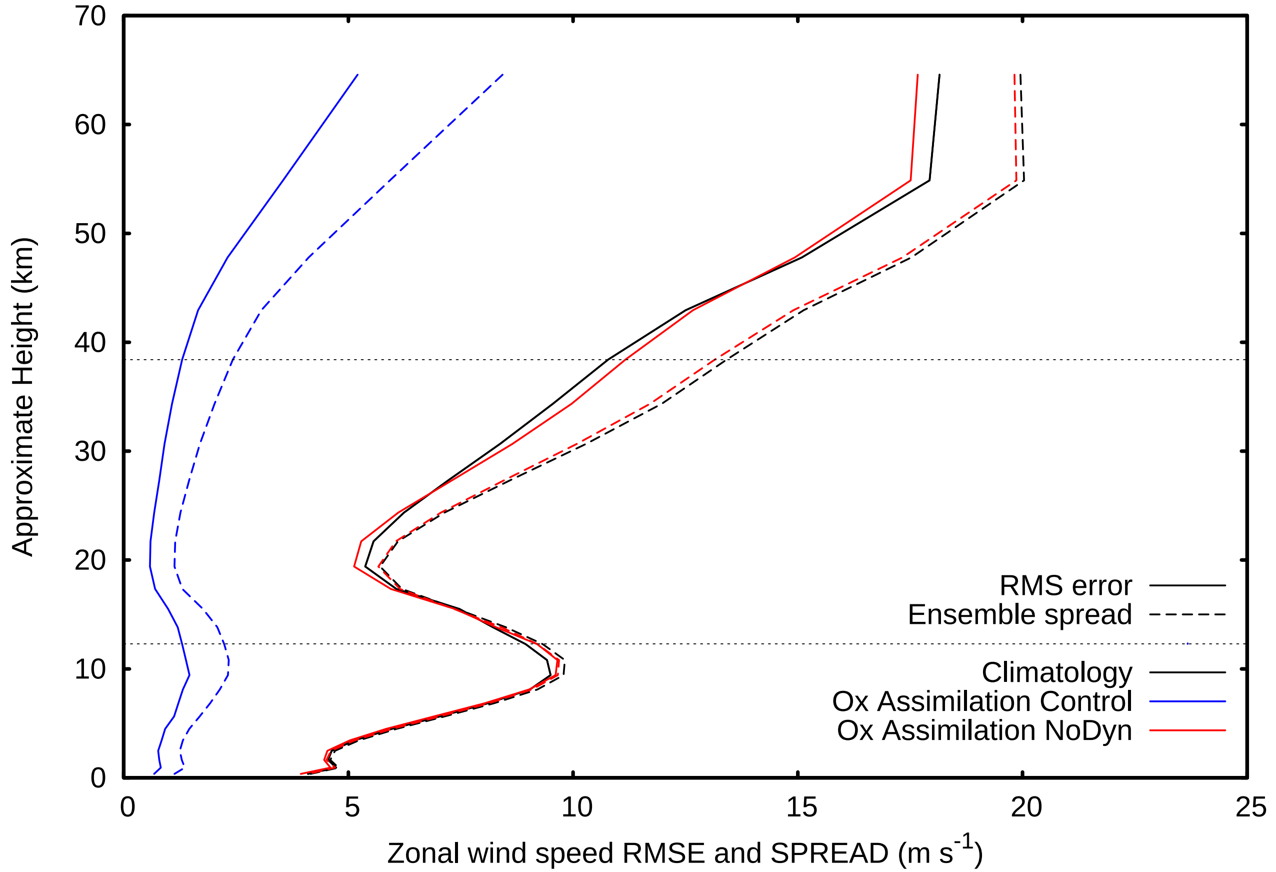
$\longrightarrow$ T autocovariances reduce most of the error, but T-chem covariances are useful as well.

O_x assimilation : effect on O_x analysis



→ Both chemical and chemical-dynamical covariances reduce the RMSE.

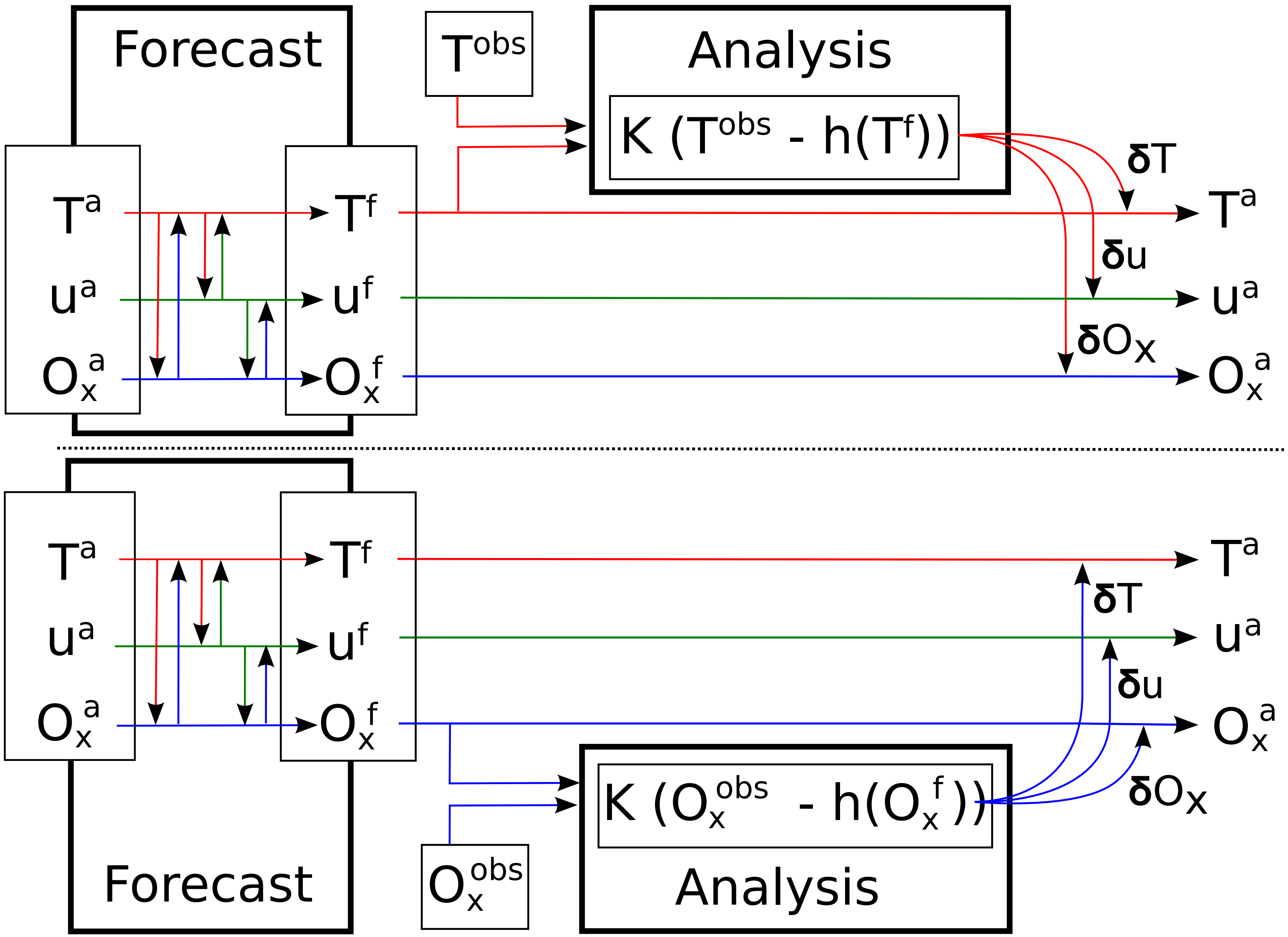
O_x assimilation : effect on u analysis



→ Radiation is not effective.

→ Chemical-Dynamical covariances constrain well the RMSE.

Schematics:



Forecast
T^obs
Analysis
K (T^obs - h(T^f))
T^a
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Forecast
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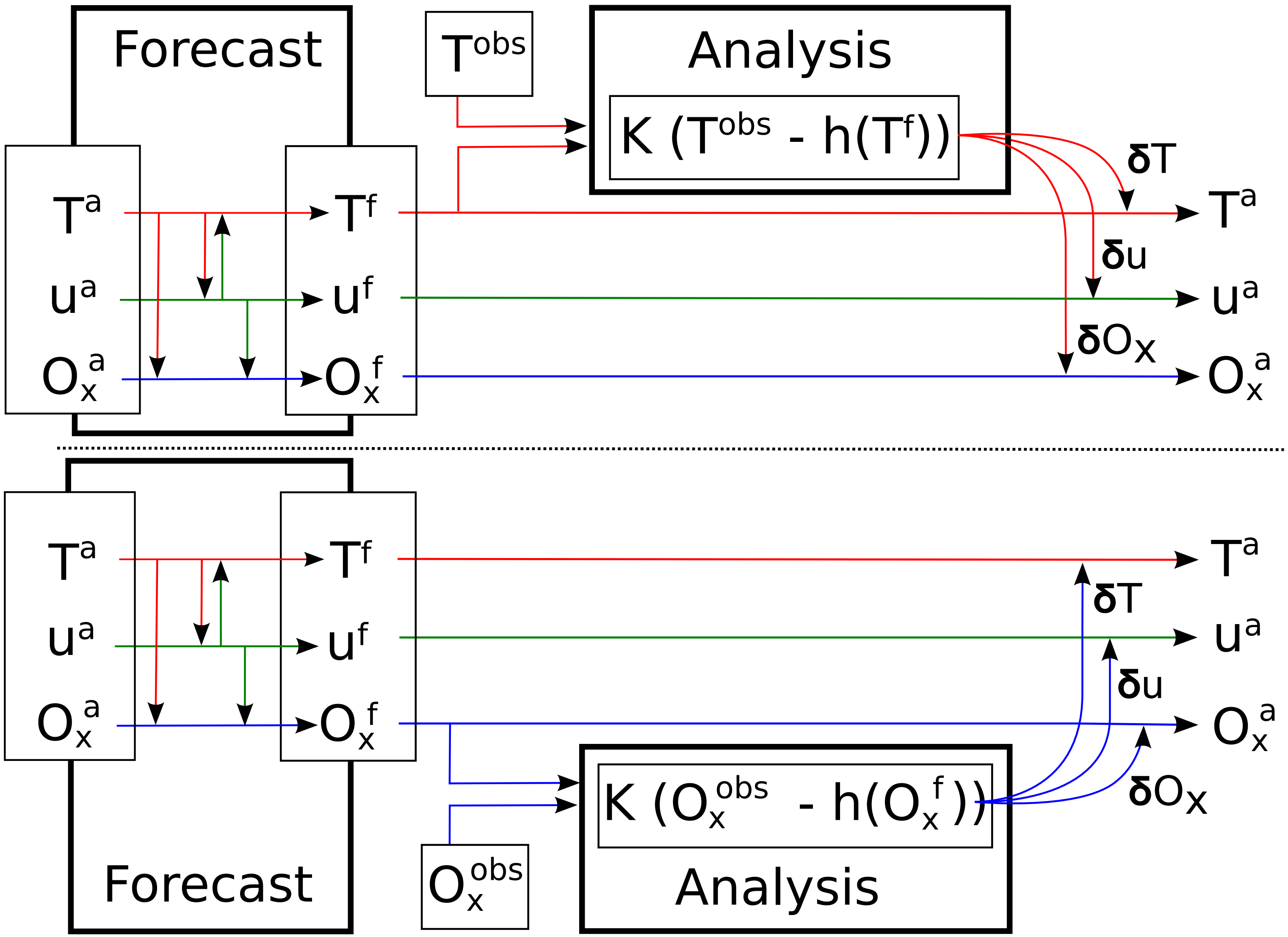
Schematics:



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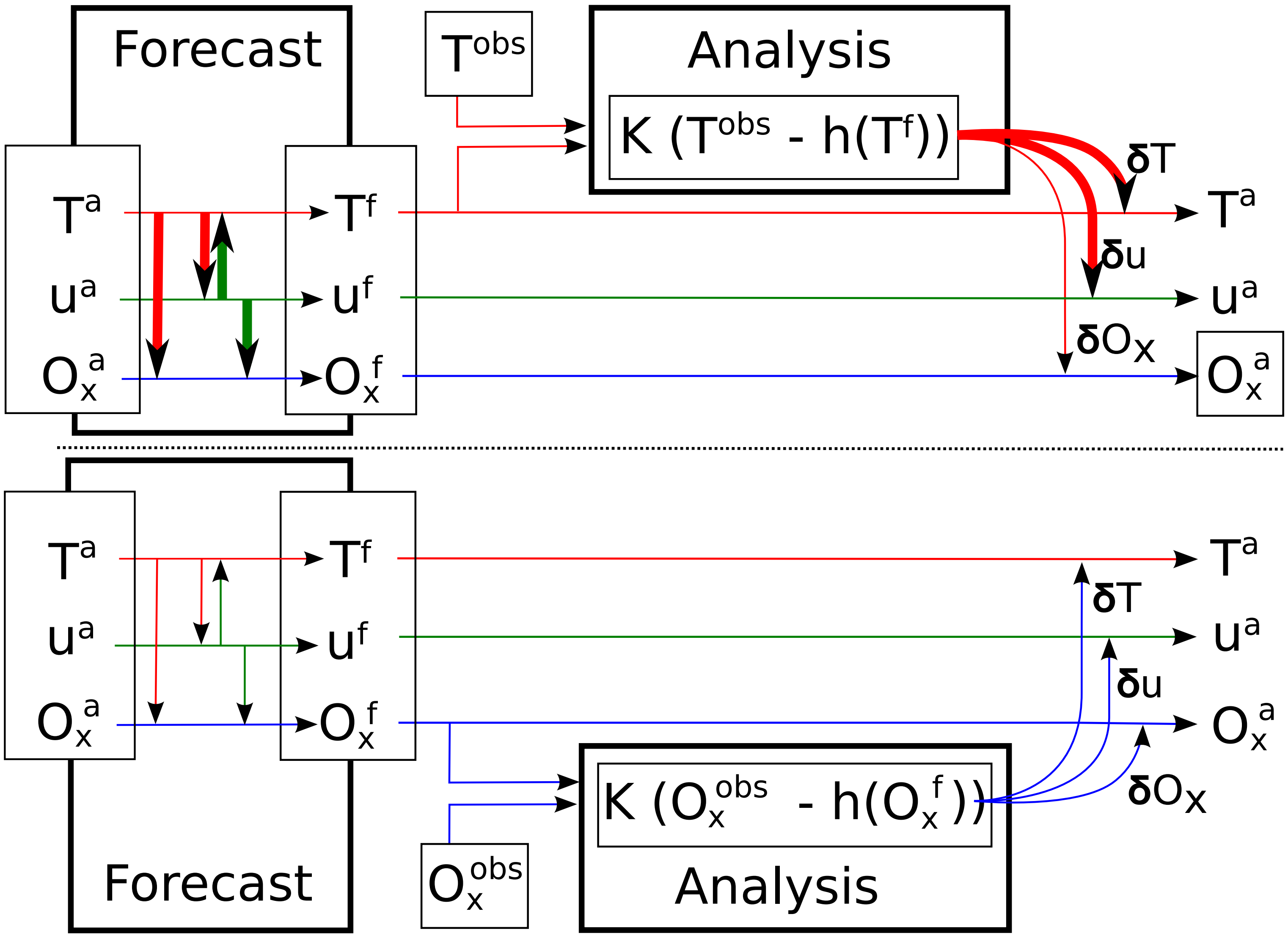

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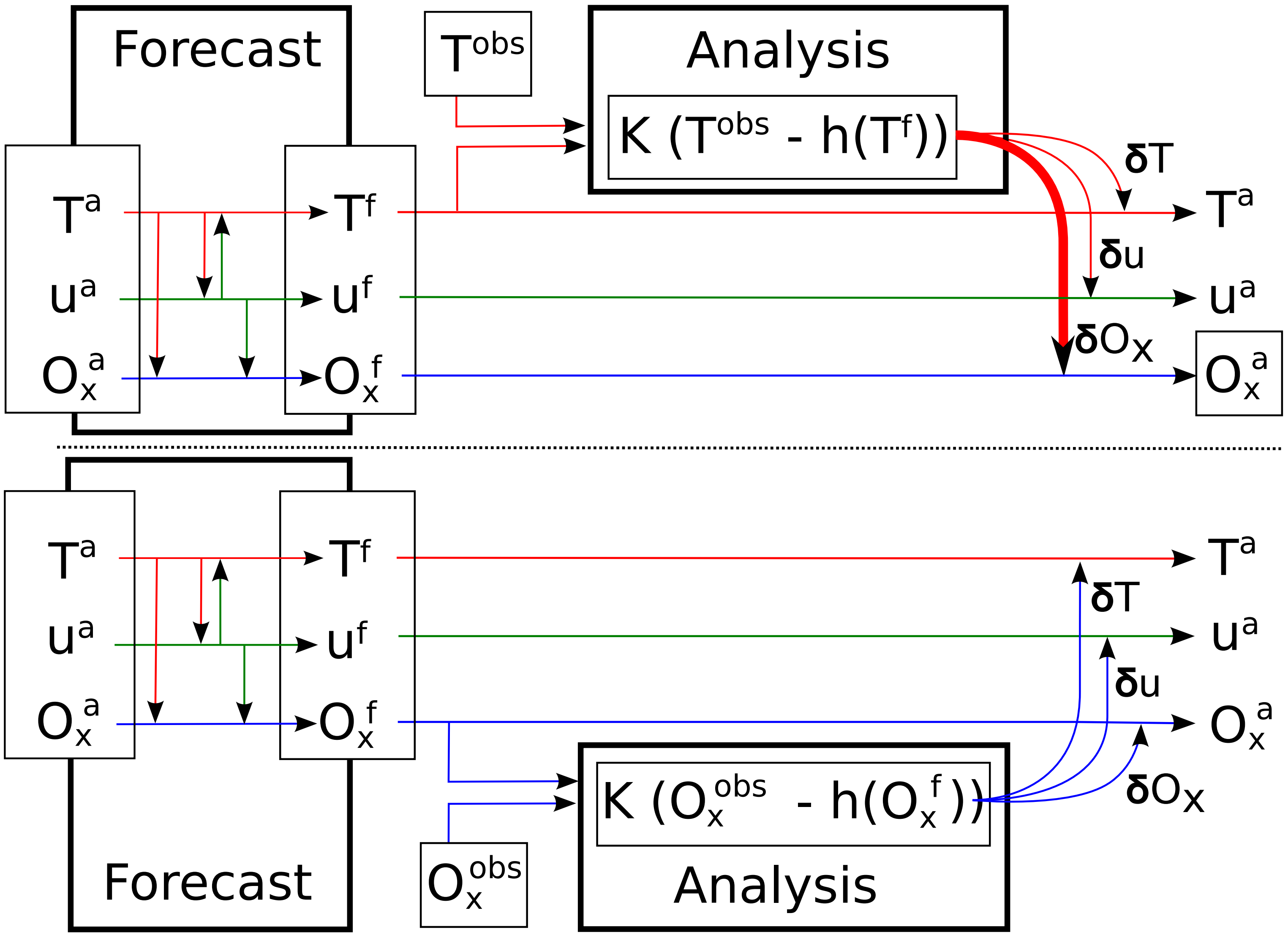

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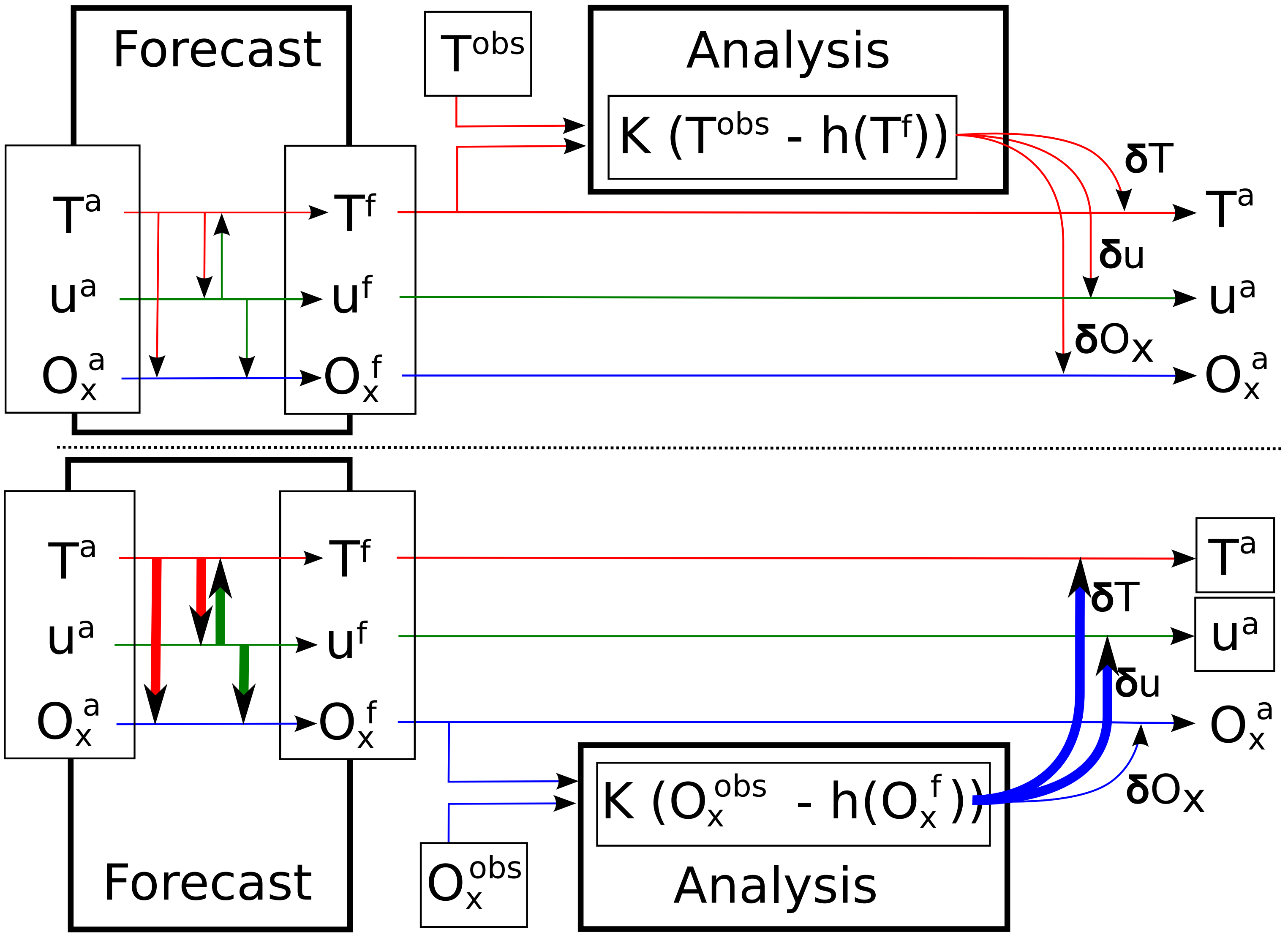

Forecast
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Summary

LOCALIZATION :

- Optimal simulations have very long localization parameters for temperature covariances ($C_h = 14000$ km and $C_v = 10$ units of log-pressure).
- Shorter localization for ozone covariances ($C_h = 5600$ km and $C_v = 4$).
- "Superoptimal" assimilation (RMSE < SPREAD) $\rightarrow$ noisy covariances but reduced likelihood of filter divergence.

CHEMISTRY-DYNAMICS INTERACTION :

- On daily timescales, radiation can not transfer chemical increments into dynamical ones.
- $\mathrm{T} - \mathrm{O_x}$ covariances permit to slightly improve the ozone analysis.
- $\mathrm{O_x} - \mathrm{u}$ and $\mathrm{O_x} - \mathrm{T}$ covariances permit to constrain wind motion during ozone assimilation.

Future work

- Relative importance of $\mathrm{O_x - u}$ and $\mathrm{O_x - T}$ covariances in constraining the dynamics.
- Assimilate asynchronous observations : Ensemble Kalman Smoother (EnKS)
- Other flavours of ensemble data assimilation : ensemble square-root filter.

THANKS !

ANY FEEDBACK IS HIGHLY APPRECIATED