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

Thomas Milewski and Michel Bourqui

McGill University

thomas.milewski@mail.mcgill.ca

Objectives and Context

To study the transfer of information from the observed variable, chemical or dynamical, to the full model state.

This transfer from the observation innovations to the full model state can be :

- DIRECT: during the analysis step, through the background error-covariances.
- INDIRECT: through the subsequent forecast balancing of newly-analyzed model variables.

Specifically, we are assimilating a limited number of stratospheric temperature or ozone observations using ensemble techniques, which produce "along-the-flow" multivariate background error-covariances, allowing for efficient DIRECT impact of observations on the model state.

Outline

- EnKF-CCM system
- Chemical-dynamical interaction
- Ensemble Kalman smoother

ENSEMBLE KALMAN FILTERING with a CHEMISTRY CLIMATE MODEL

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

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

$\mathbf{K_e} = \mathbf{P_e^f H}^{\ \mathbf{T}}(\mathbf{HP_e^f H}^{\ \mathbf{T}} + \mathbf{R})^{-1} =$ 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: $\mathrm{O_x}$, $\mathrm{HO_x}$, $\mathrm{NO_x}$.
- Advected species: $\mathrm{O_x}$, $\mathrm{N_2O_5}$, $\mathrm{NO_x}$, $\mathrm{HNO_3}$

Experimental setup : filter configurations

model state vector

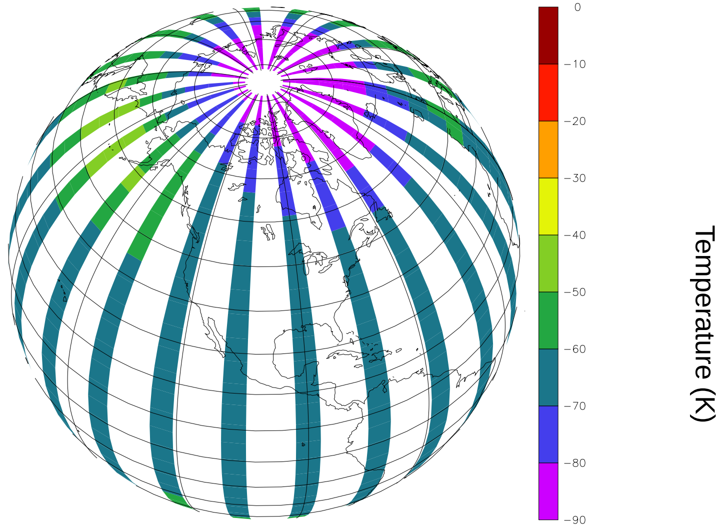
$$\begin{pmatrix} \mathrm{u} \\ \mathrm{v} \\ \mathrm{T} \\ \mathrm{P_s} \\ \mathrm{Q} \\ \mathrm{O_x} \\ \mathrm{N_2O_5} \\ \mathrm{NO_x} \\ \mathrm{HNO_3} \end{pmatrix}$$

- 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)
- Separate horizontal and vertical covariance localization parameters for ozone and temperature covariances
- No covariance inflation
- Analysis performed every 24 hours

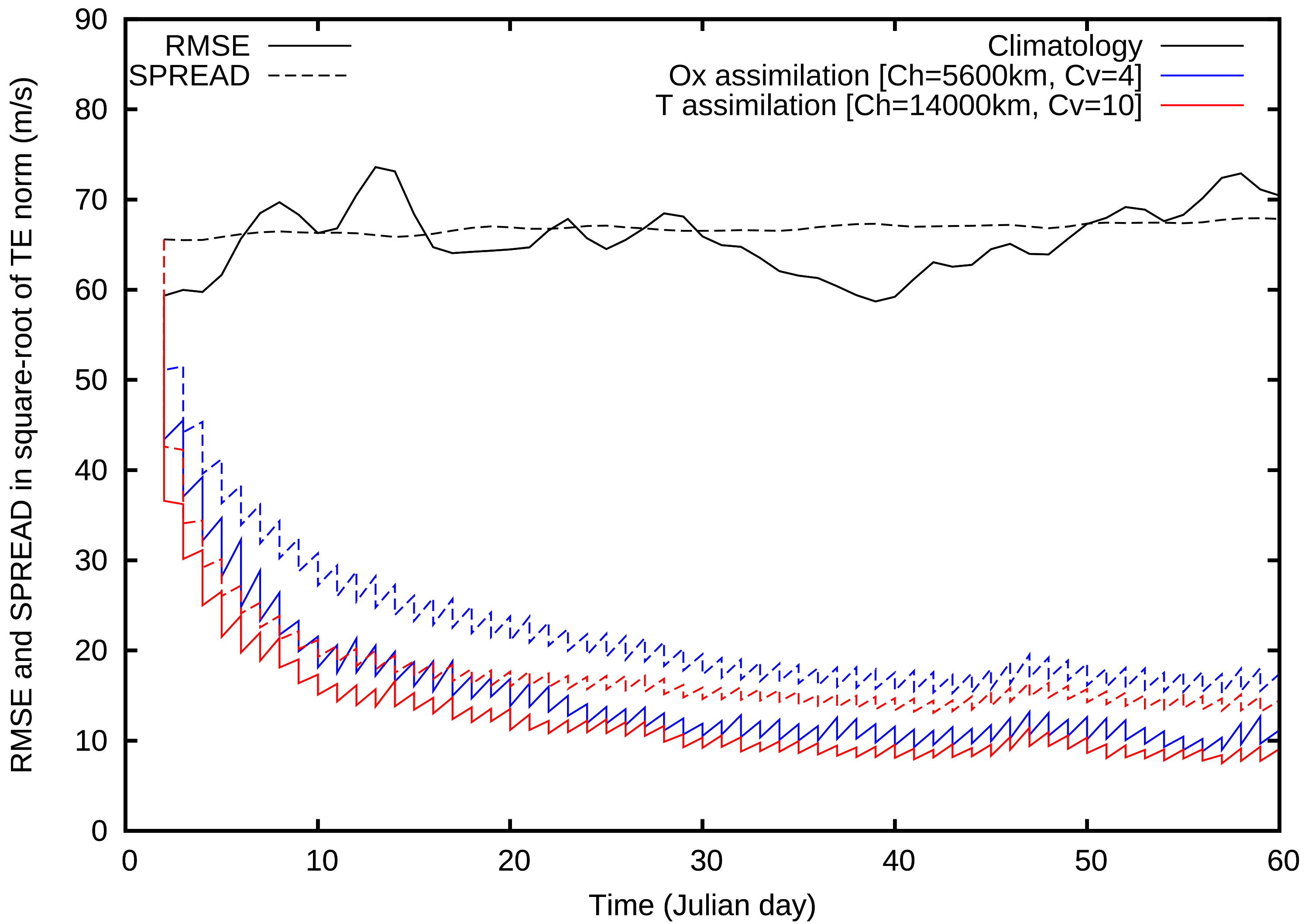
Experimental setup : observations

- 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 :



Evolution of Optimal Simulation: Total Energy



$$TE = \frac{u'^2}{2} + \frac{v'^2}{2} + \frac{C_p}{T_{ref}} T'^2 + R_\alpha T_{ref} \left(\frac{P_s'}{P_{ref}} \right)^2$$

Evolution of Optimal Simulation: Ozone

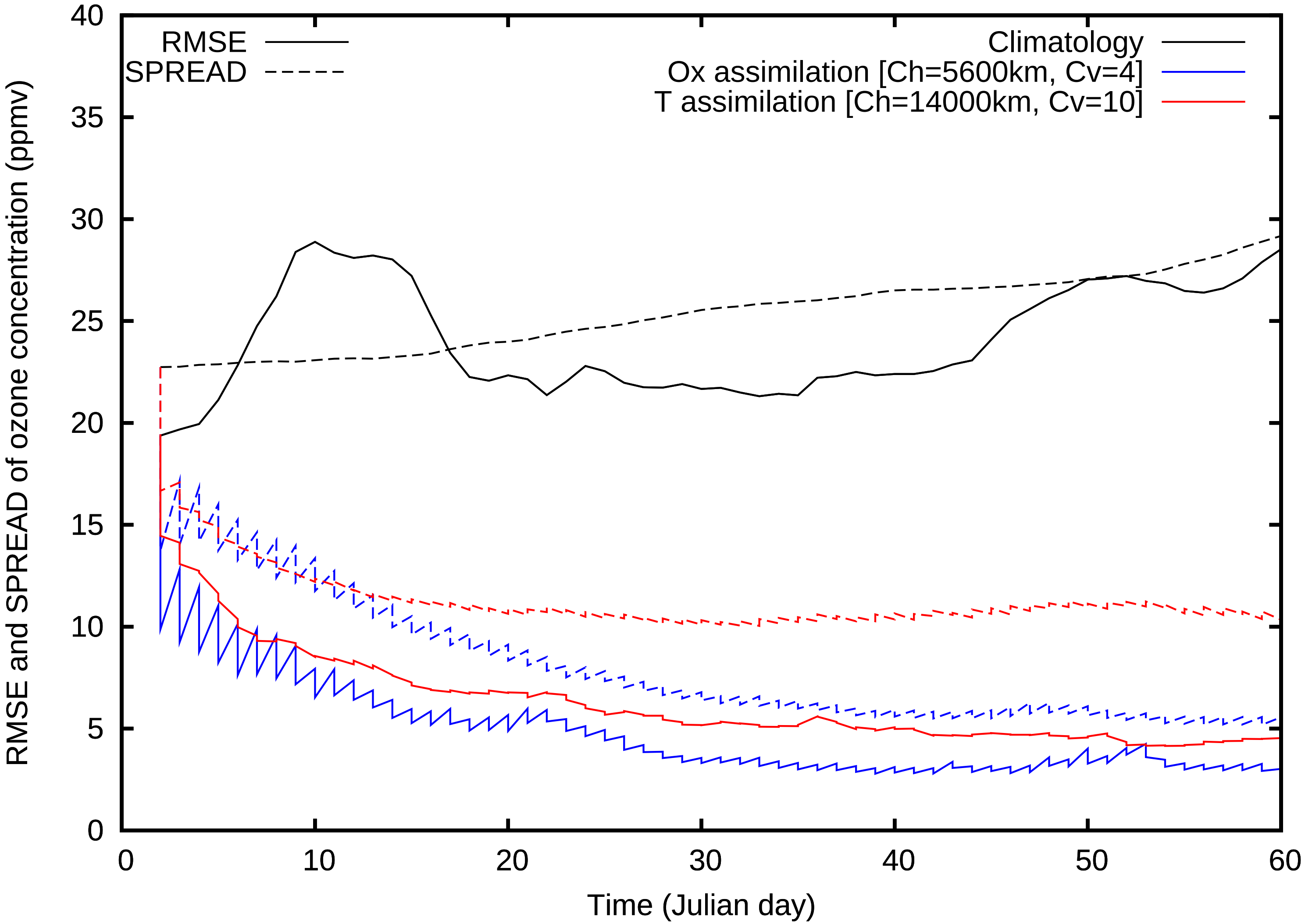
INTRODUCTION

EnKF-CCM
- EnKF Theory
- Chemistry-Climate Model
- Filter Configurations
- Observations
- **Optimal Simulations**

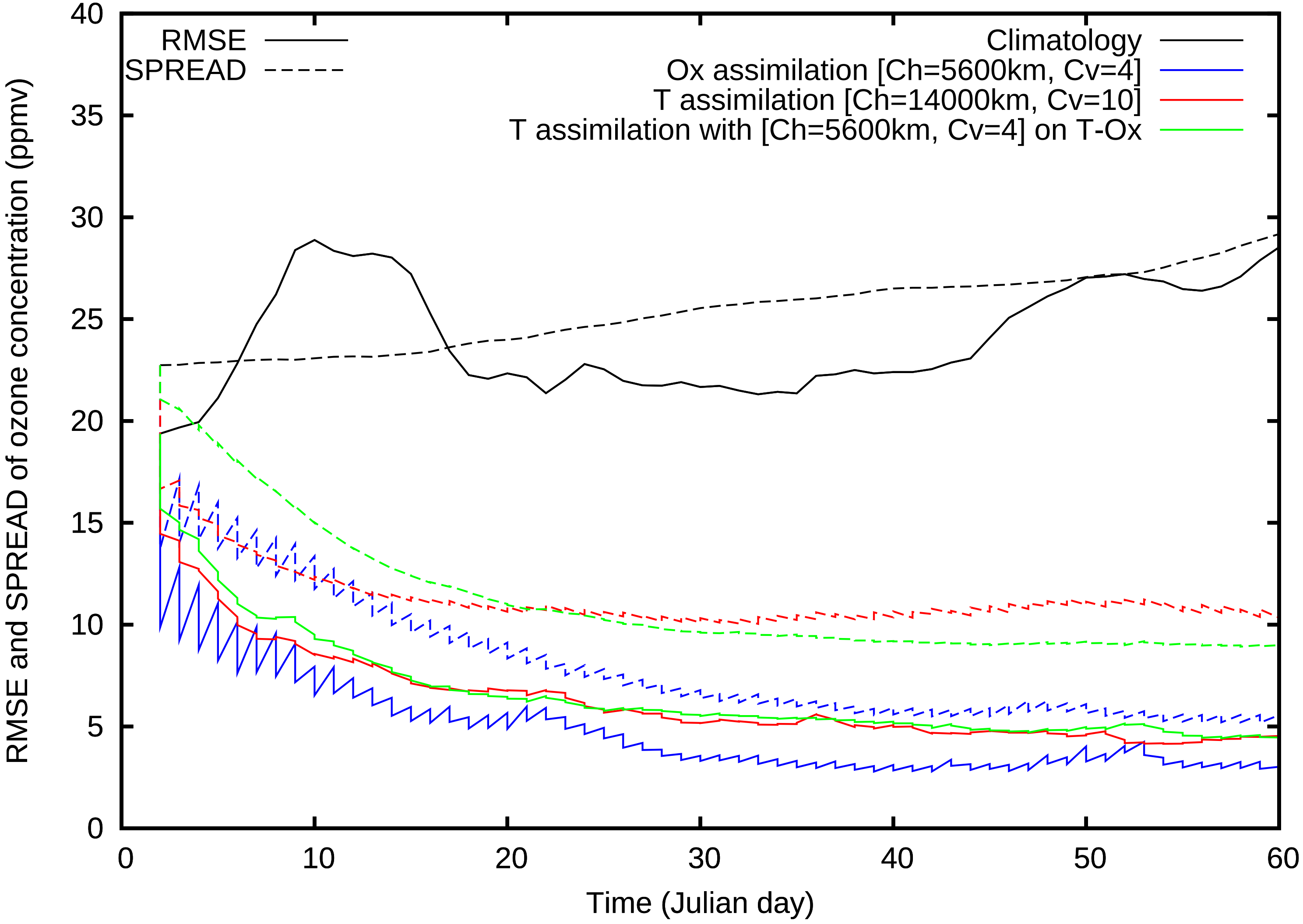
CHEMISTRY-DYNAMICS INTERACTION

ENSEMBLE KALMAN SMOOTHER

CONCLUSIONS AND FUTURE WORK



Evolution of Optimal Simulation: Ozone



CHEMISTRY-DYNAMICS INTERACTION

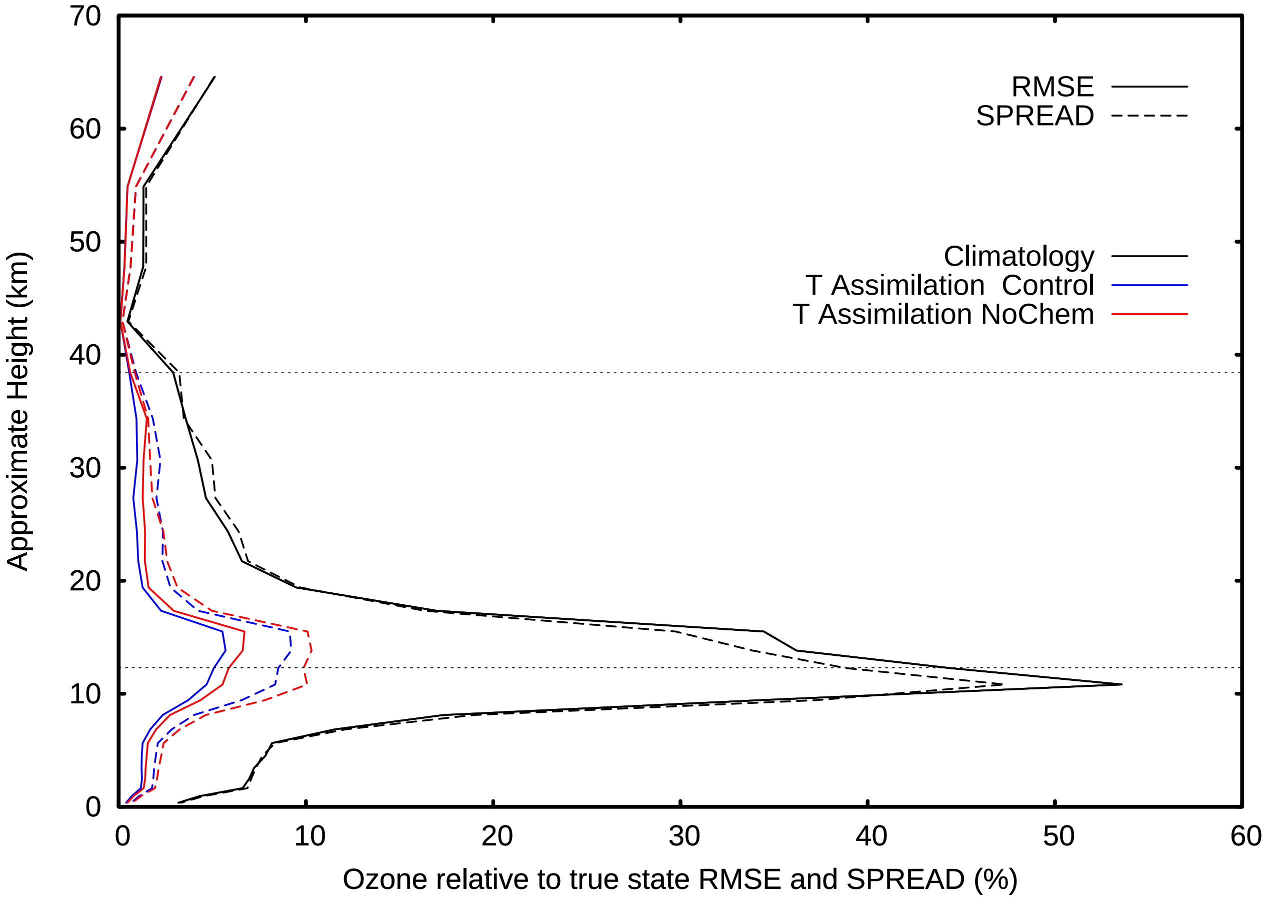
Chemistry-dynamics interaction

Experiments

- Temperature assimilation
  - “Control”
  - “NoChem”: no temperature-chemistry cross-covariances
- Ozone assimilation
  - “Control”
  - “NoDyn”: no ozone-dynamics cross-covariances
  - “NoWinds”: no ozone-winds cross-covariances
  - “NoTemp”: no ozone-temperature cross-covariances

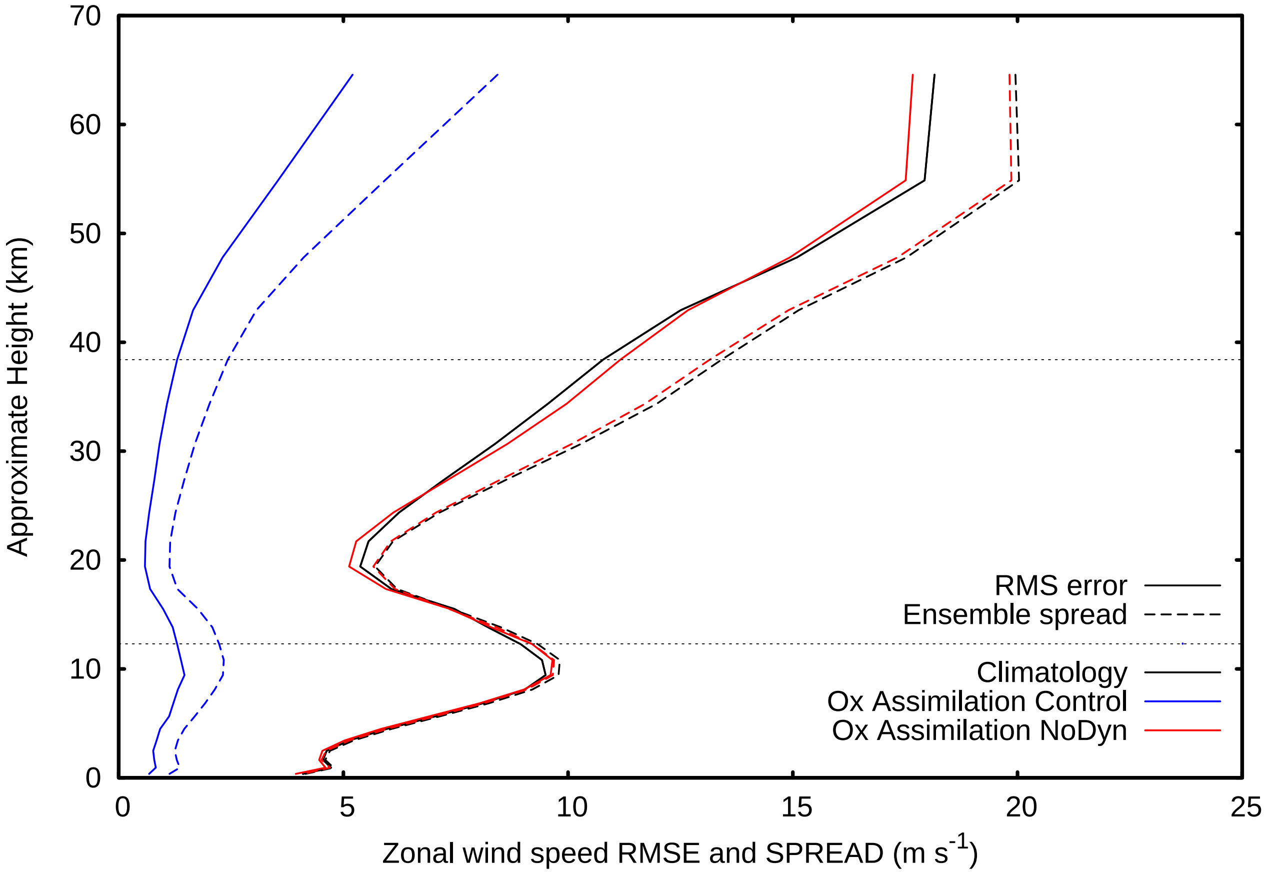
Simulation are run for 60 day. We take time averages over the last 45 days of RMSE and SPREAD and we analyze them for each variable and scenario.

T assimilation : effect on O_x analysis



$\longrightarrow$ Dynamical part of the system reduce most of the $\mathbf{O_x}$ error, but $\mathbf{T}$-Chemistry covariances are useful as well.

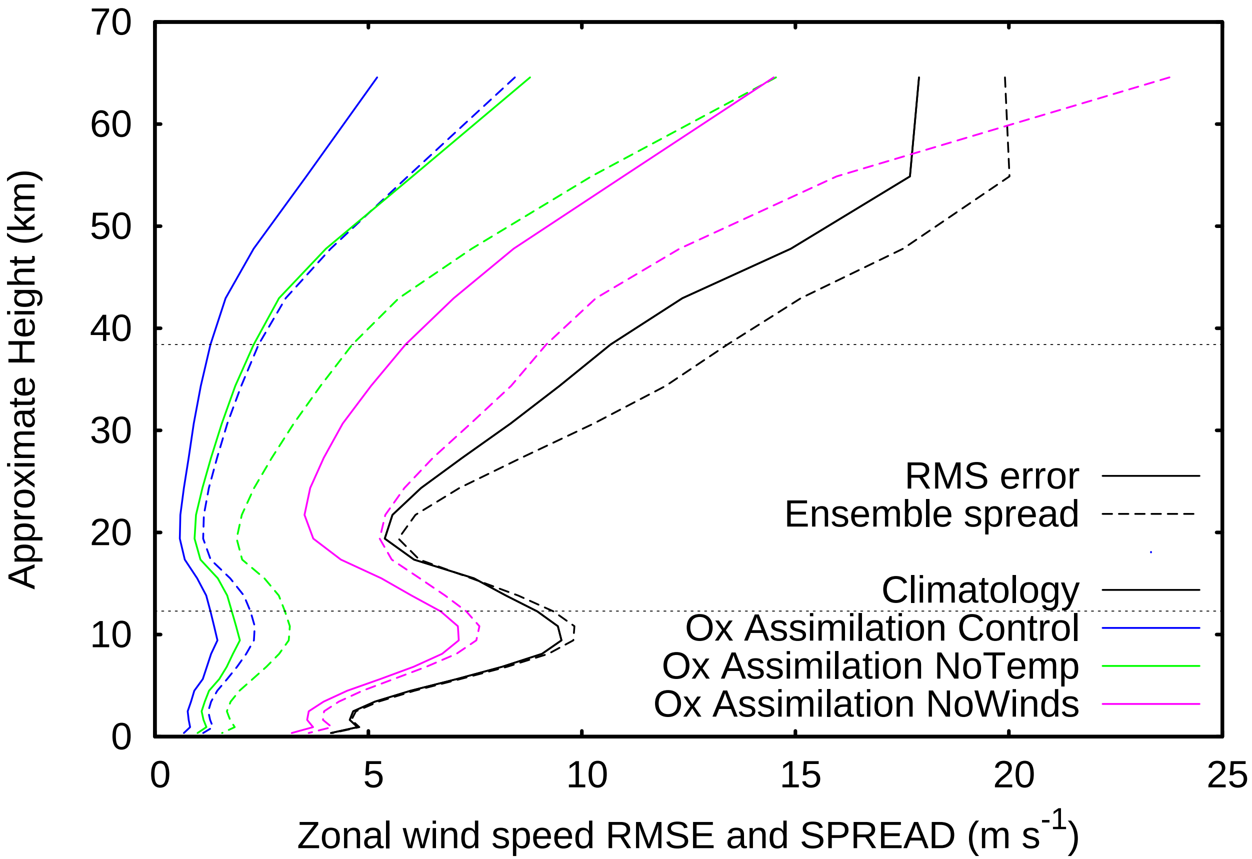
$\mathrm{O_x}$ assimilation : effect on $\mathbf{u}$ analysis



$\longrightarrow$ Analyzed chemical state can not constrain dynamics.

$\longrightarrow$ $\mathbf{O_x}$-Dynamics covariances constrain well the $\mathbf{u}$ RMSE.

O_x assimilation : effect on u analysis



$\rightarrow$ $\mathbf{O_x}$-wind covariances are the real vector of information from the chemical observations to the dynamical model state.

ENSEMBLE KALMAN SMOOTHER

Ensemble Kalman Smoother

Would assimilating future observations be more efficient than increasing the number of observations at analysis time ?

Experiments

- EnKF Mipas Ozone assimilation sequentially at DAYS 31, 32 and 33.
- EnKF 3X Mipas Ozone assimilation (3X more observations horizontally than Mipas coverage) at DAY 31.
- EnKS Mipas Ozone assimilation where DAY 31, 32 and 33 ozone observation are assimilated to constrain the analysis at DAY 31.

→ Ensemble forecasts launched from the resulting analyses.

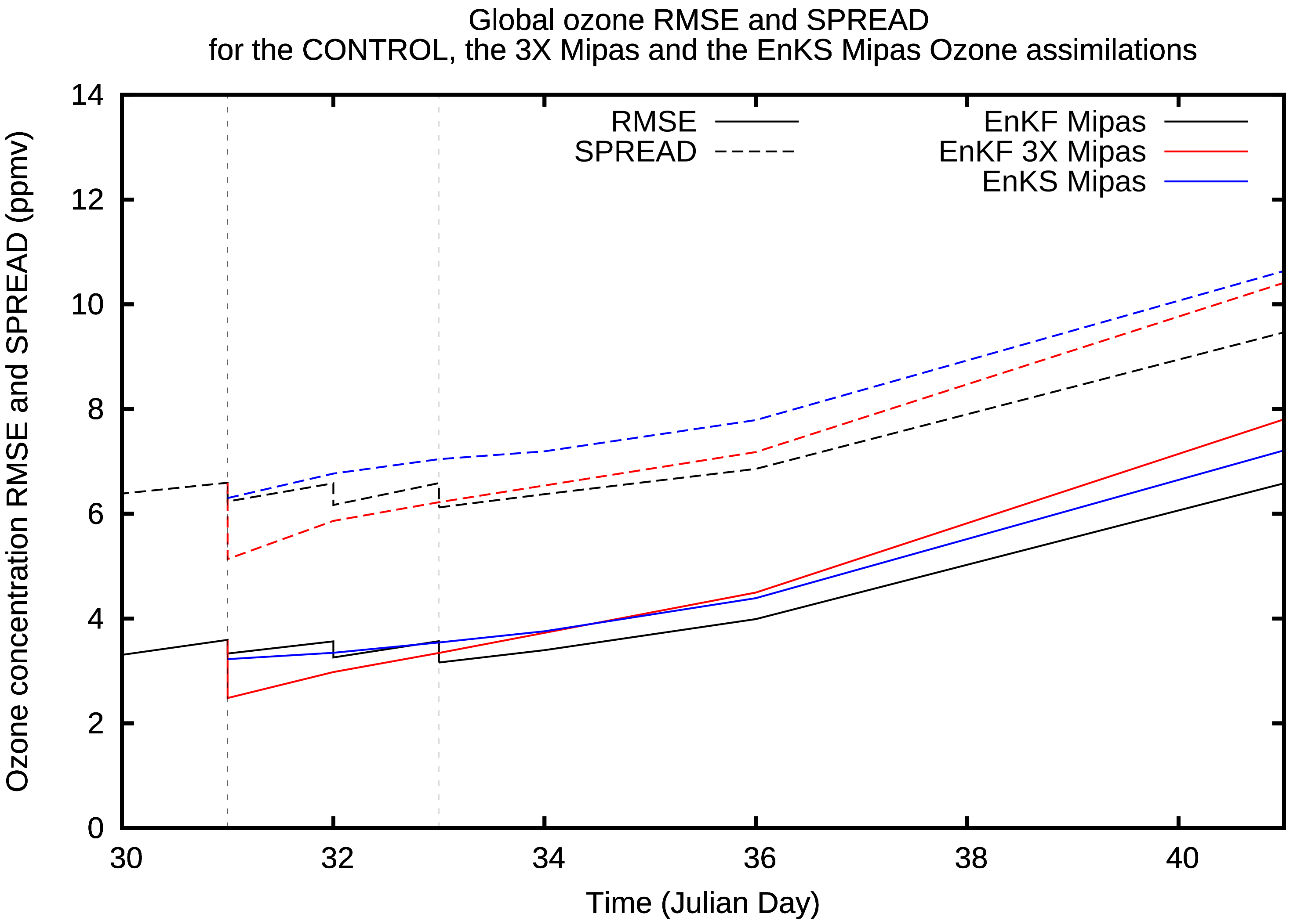
EnKS configurations

model state vector

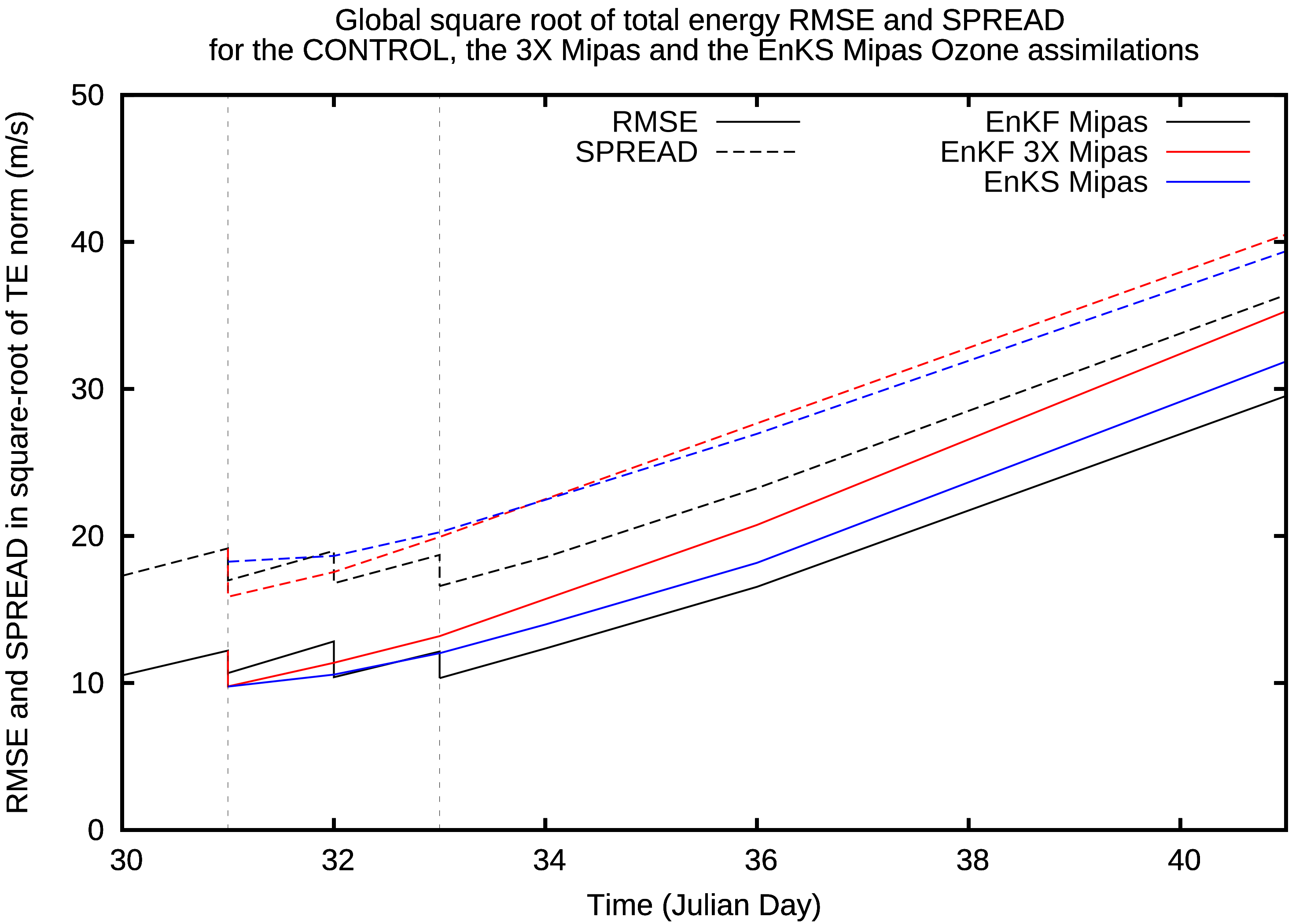
$$\begin{pmatrix} \mathrm{u} \\ \mathrm{v} \\ \mathrm{T} \\ \mathrm{P_s} \\ \mathrm{Q} \\ \mathrm{O_x} \\ \mathrm{N_2O_5} \\ \mathrm{NO_x} \\ \mathrm{HNO_3} \end{pmatrix}$$

- Initial ensemble is analyzed state on DAY 30 from the simulation assimilating Mipas ozone observations
- Perfect-model twin experiment
- Double-EnKS single assimilation of daily observations
- Added temporal ($C_t = 10$ days) covariance localization
- No covariance inflation
- Analysis performed on DAY 31

Ensemble Forecasts : Ozone



Ensemble Forecasts : Total Energy



CONCLUSIONS AND FUTURE WORK

Summary

EnKF-CCM :

- EnKF assimilation of MIPAS-like stratospheric observations in the IGCM-FASTOC can efficiently constrain the whole model state.
- Two-month ozone (10% error) or temperature (2K error) assimilation experiments yield approximately the same constraint on the dynamical state of the system.
- Temperature assimilation has however more problems constraining the chemical state.

CHEMISTRY-DYNAMICS INTERACTION:

- $\mathbf{T} - \mathbf{O_x}$ covariances permit to slightly improve the ozone analysis, compared to using only $\mathbf{T}$-dynamics covariances.
- $\mathbf{O_x} - \mathbf{u}$ and $\mathbf{O_x} - \mathbf{T}$ covariances permit to constrain wind motion during ozone assimilation, but particularly $\mathbf{O_x} - \mathbf{u}$ covariances.

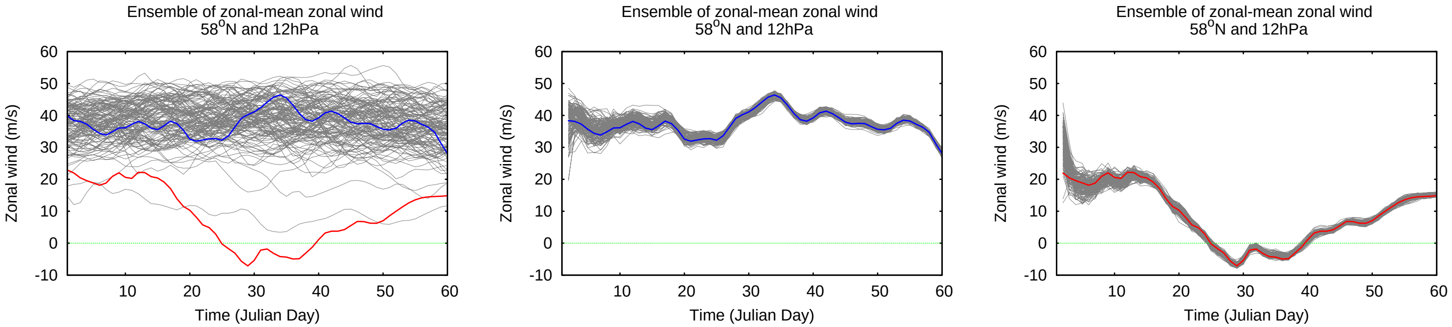
Milewski, T. and M.S. Bourqui, 2011: Assimilation of stratospheric temperature and ozone with an Ensemble Kalman Filter in a Chemistry-Climate Model. Monthly Weather Review, doi: 10.1175/2011MWR3540.1

ENSEMBLE KALMAN SMOOTHING :

- Assimilating future ozone observations rather than increasing the number of observations at analysis time seems to improve the dynamical forecast.
- However, the EnKS-initialized medium-range forecasts do not beat the EnKF-initialized forecasts in the present configurations.
- EnKS-initialized short range forecasts nearly as good as EnKF analyses.

Future work

- Ozone analysis divergence in UTLS in SINGLE vs MULTI-batch assimilation of observations.
- Playing with the Truth : stratospheric sudden warmings



- Playing with the Truth : model errors

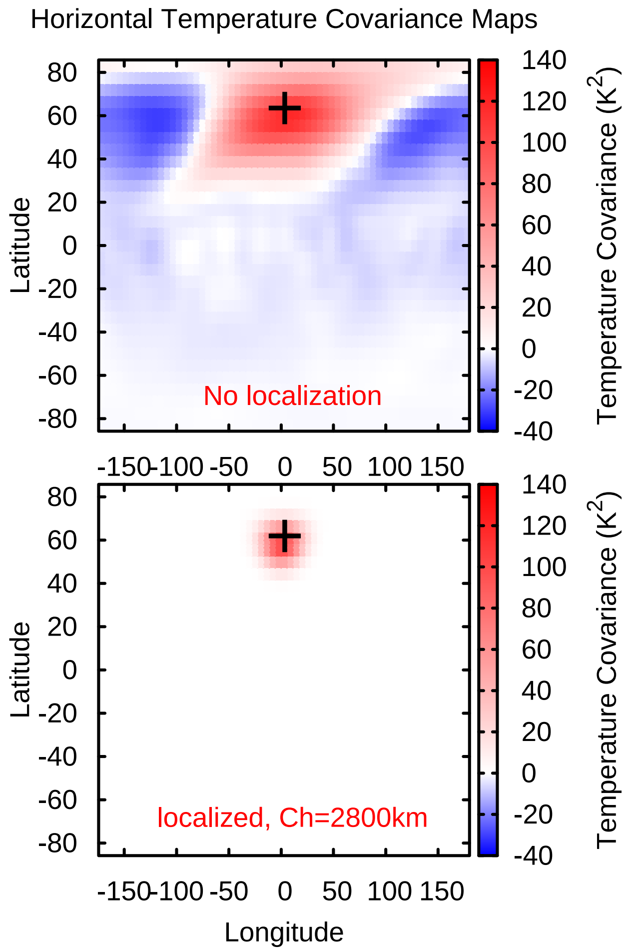
THANKS !
ANY FEEDBACK IS HIGHLY APPRECIATED

Localization

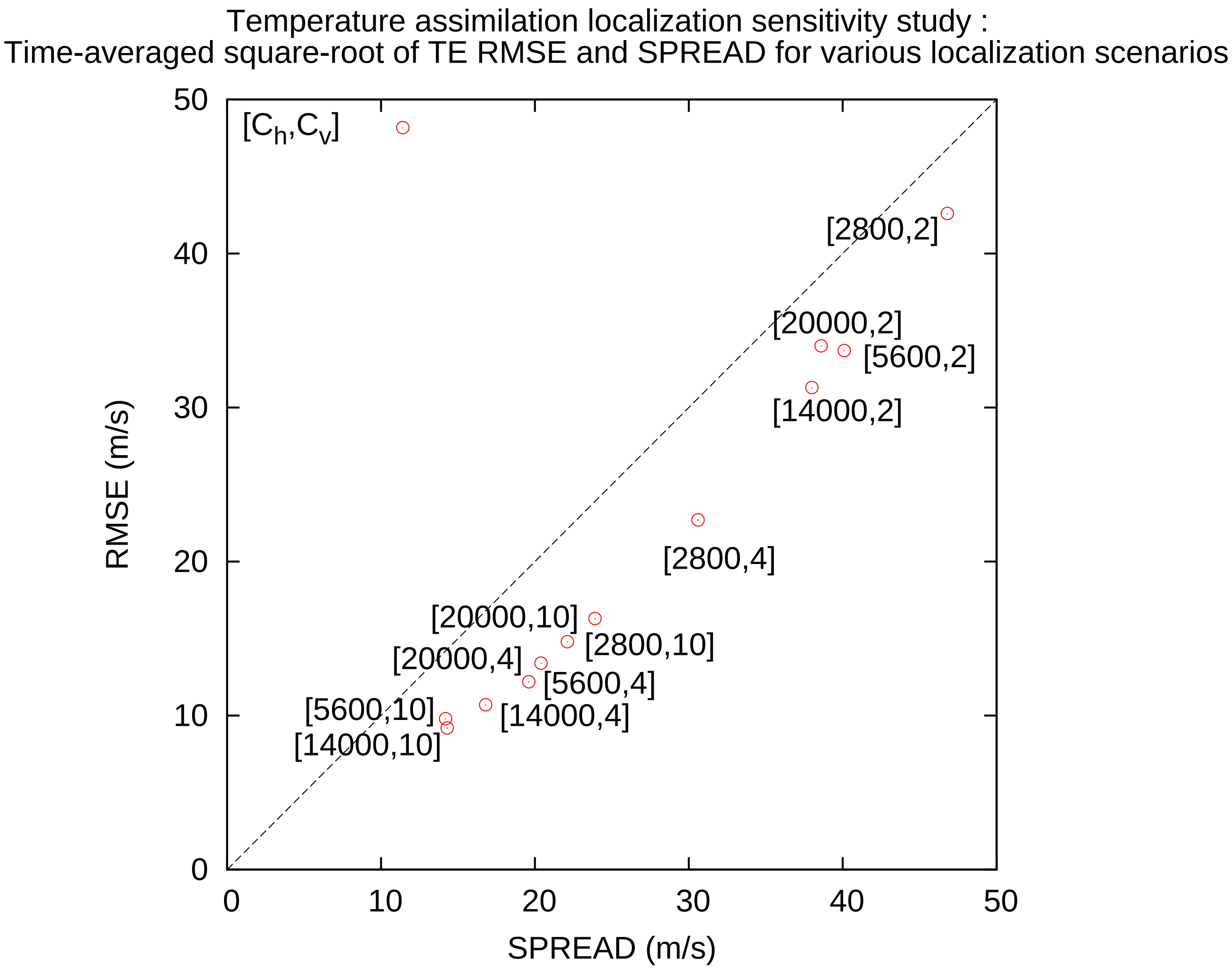
Localization: $\rho_v \circ \rho_h \circ \mathbf{P^f}$

+ remove far-away sampling noise.

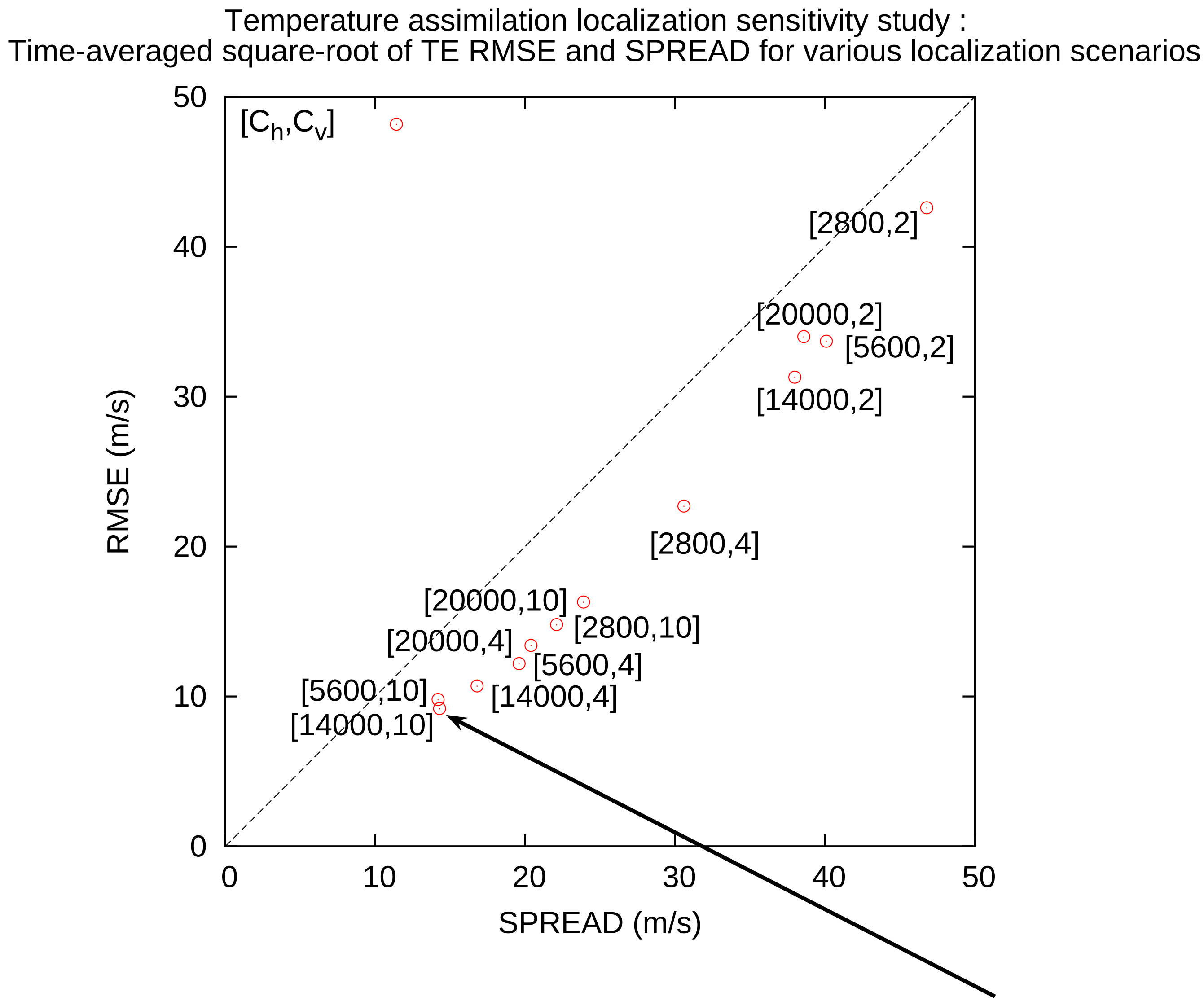
- lose the natural anisotropy : risk of introducing imbalance.



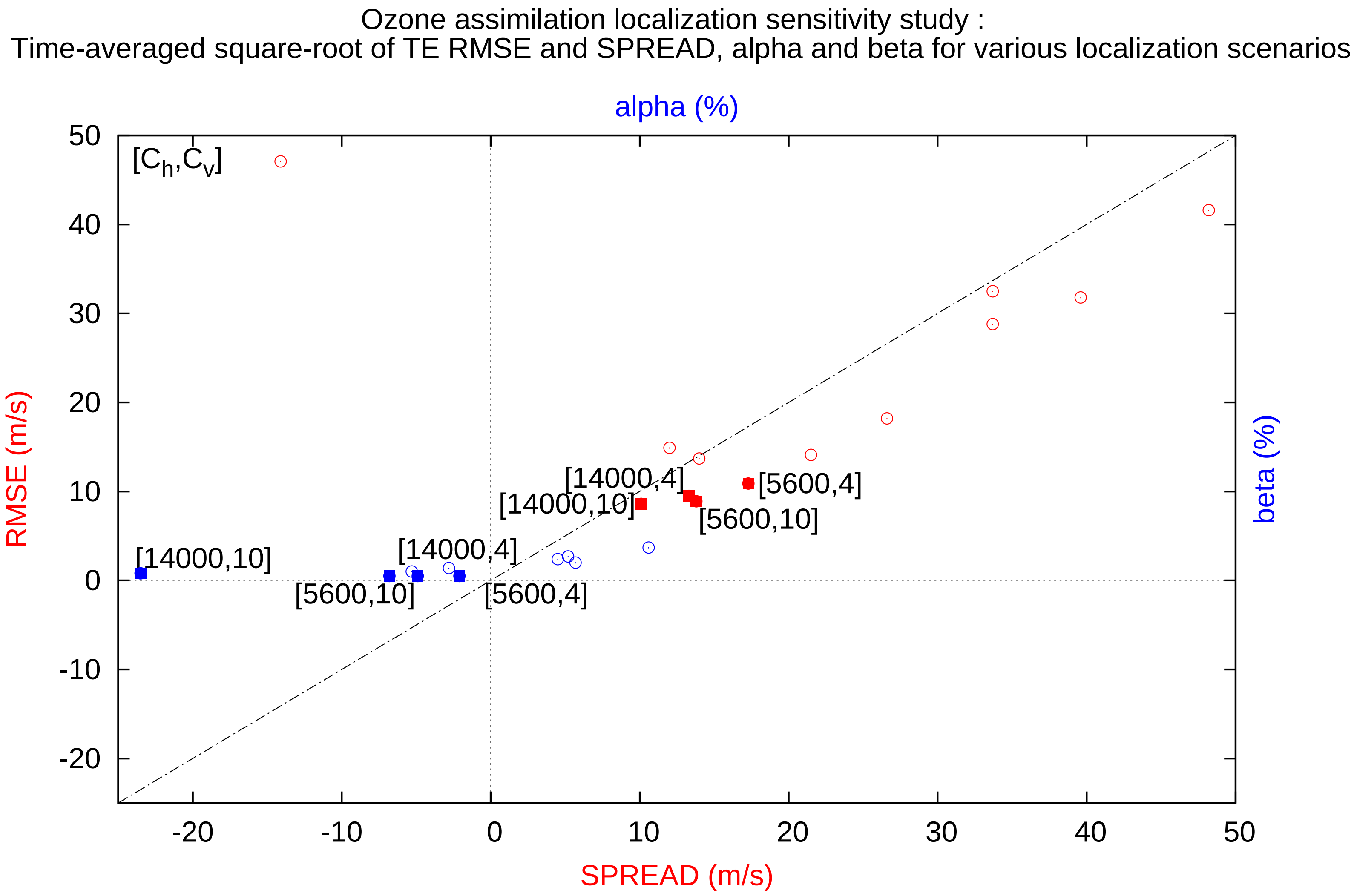
Optimal parameters: T assimilation



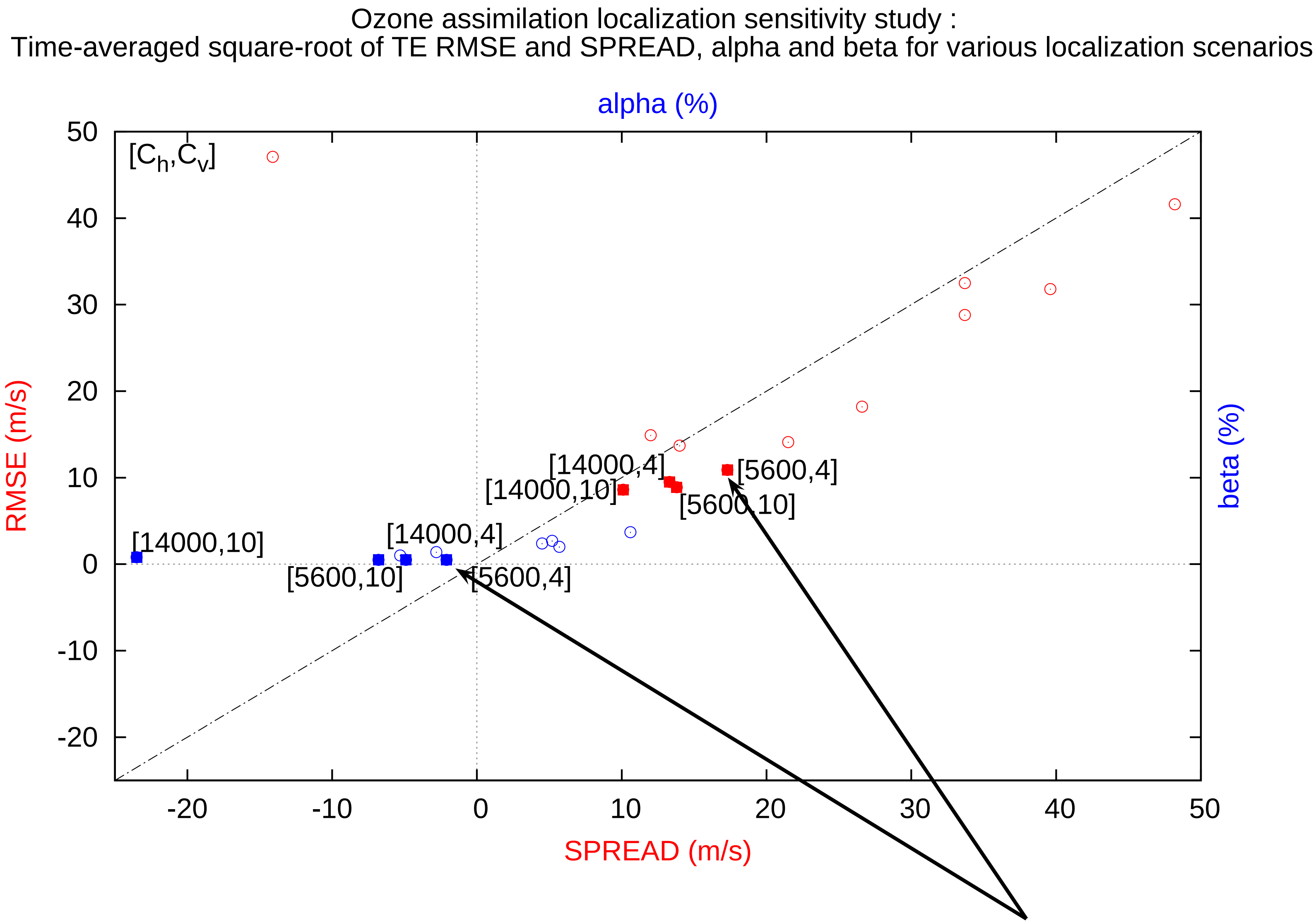
Optimal parameters: T assimilation



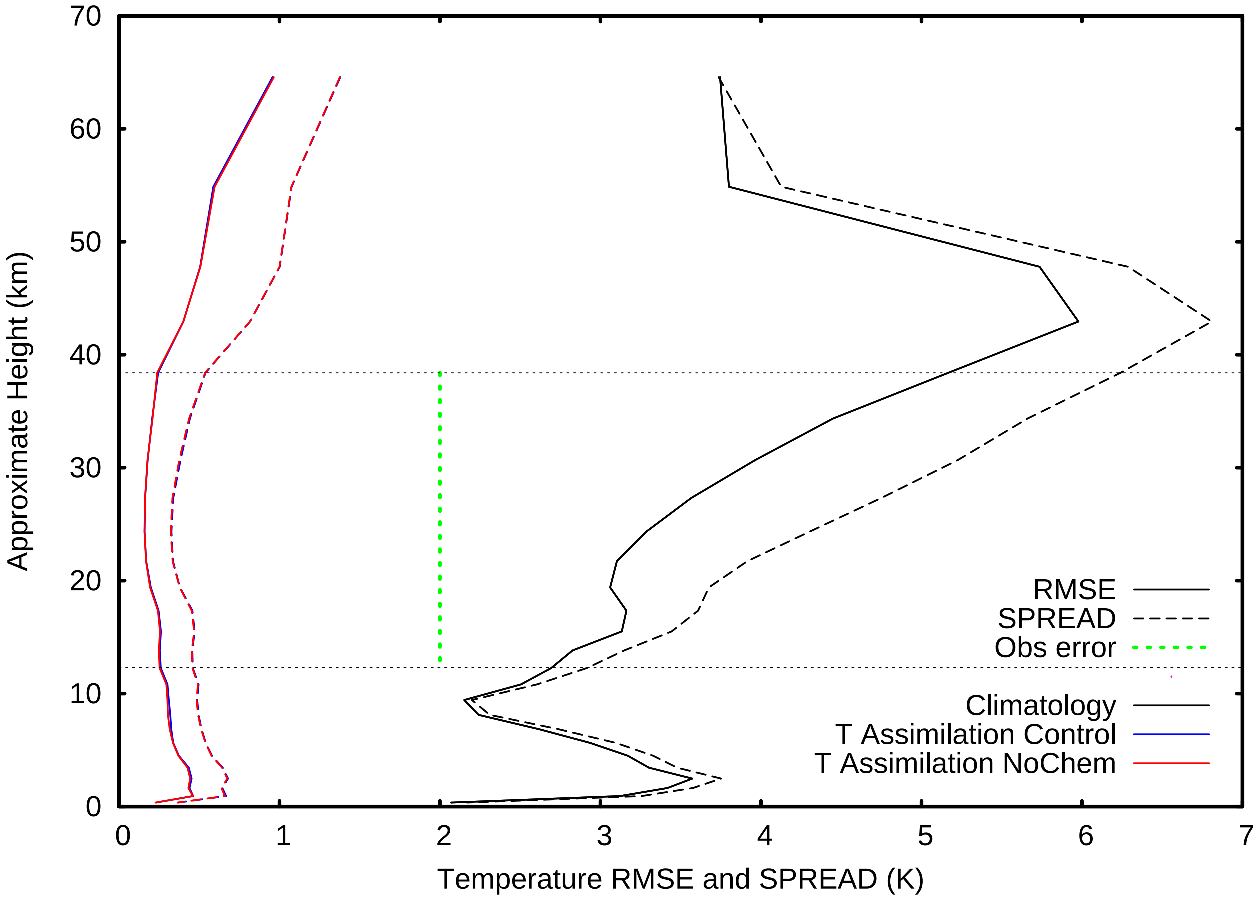
Optimal parameters: O_x assimilation



Optimal parameters: O_x assimilation

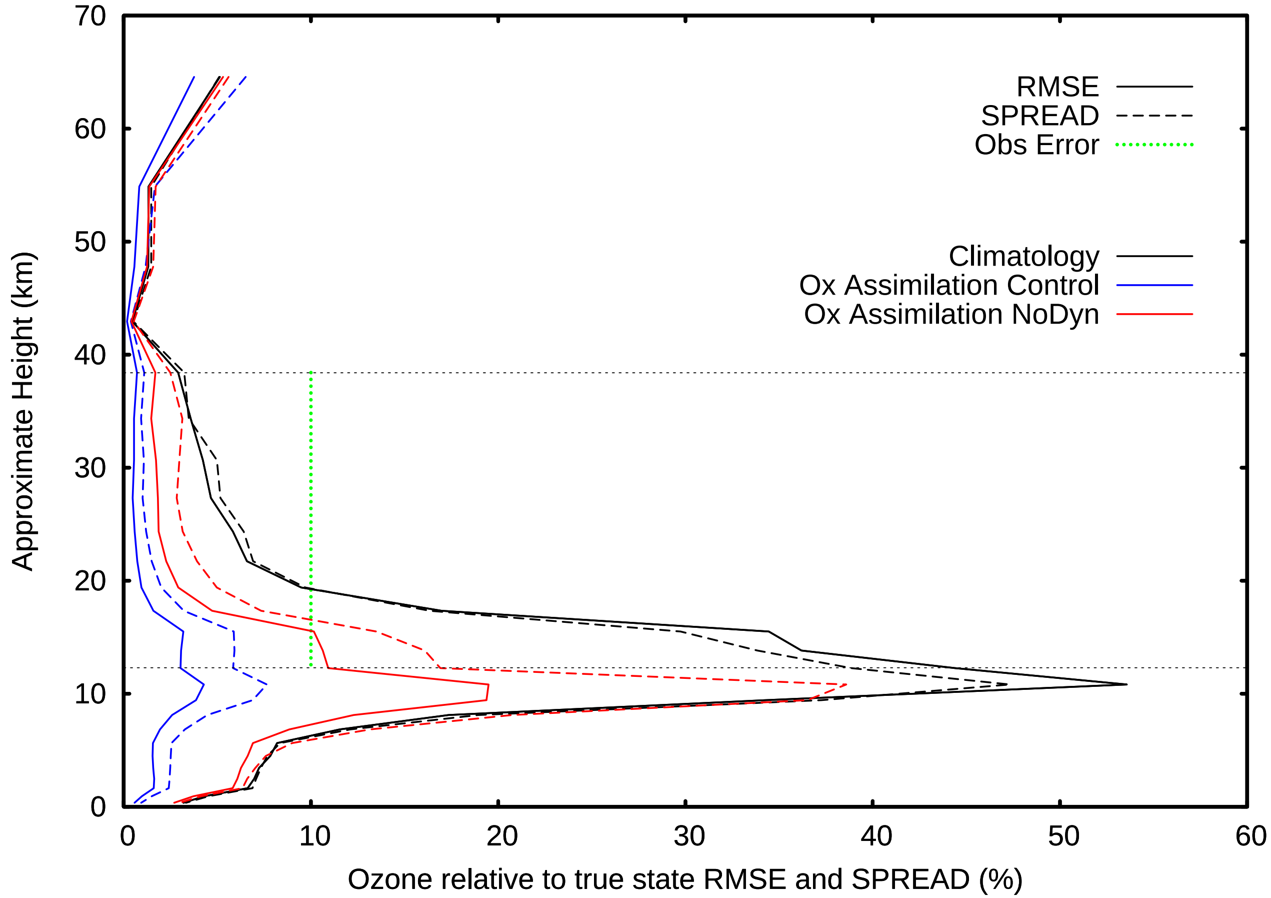


T assimilation : effect on T analysis



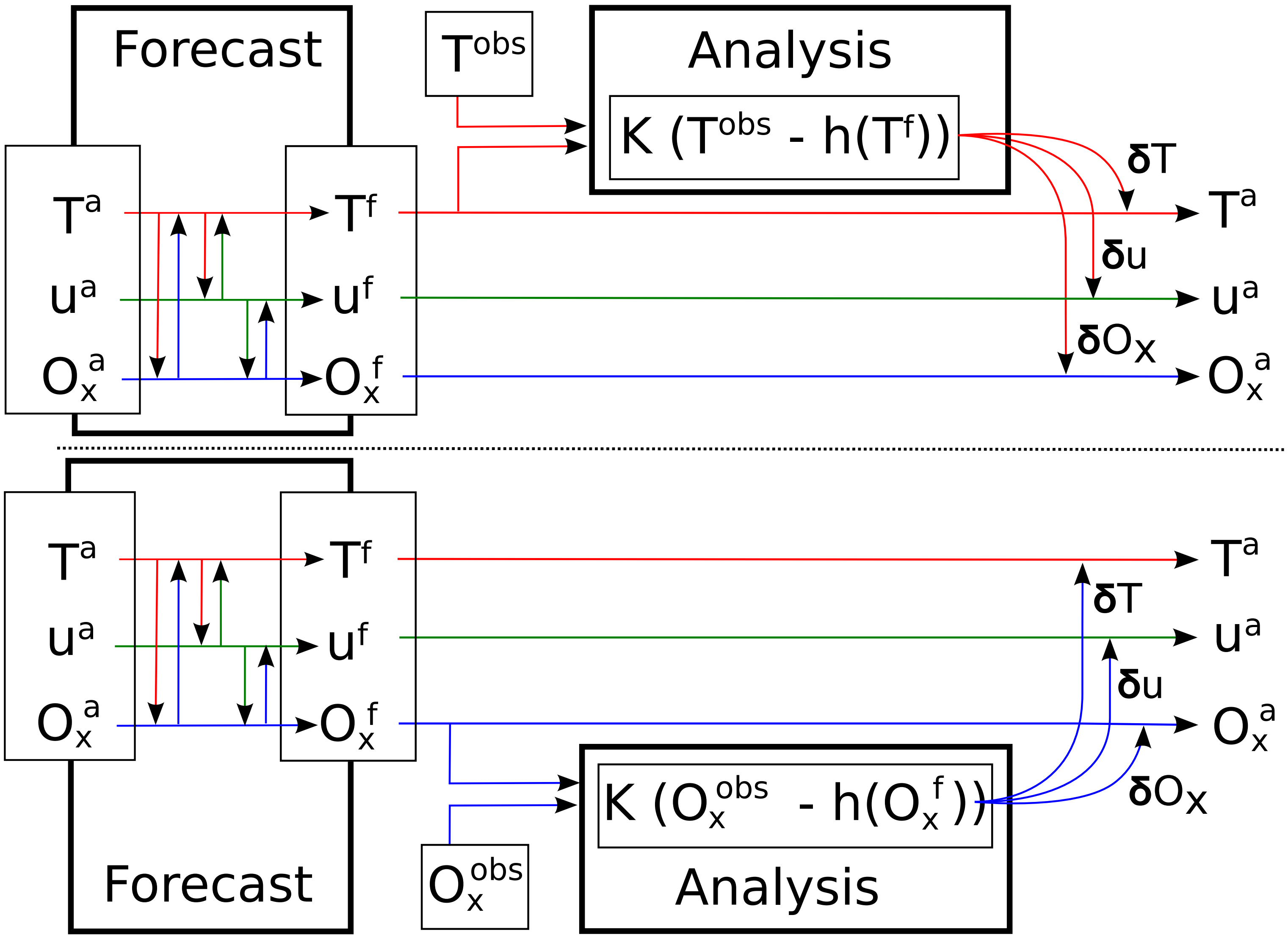
$\longrightarrow$ useless T-Chem covariances or ineffective radiation ?

O_x assimilation : effect on O_x analysis



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

Schematics:



Forecast
T^obs
Analysis
K (T^obs - h(T^f))
T^a
u^a
O_x^a
T^f
u^f
O_x^f
δT
δu
δOx
T^a
u^a
O_x^a
T^a
u^a
O_x^a
T^f
u^f
O_x^f
T^a
u^a
O_x^a
δT
δu
δOx
K (O_x^obs - h(O_x^f))
O_x^obs
Forecast
Analysis

Ensemble Forecasts