Assimilating stratospheric temperature and ozone synthetic retrievals in a Chemistry-Climate Model with an Ensemble Kalman Filter

Thomas Milewski, Michel S. Bourqui, Department of Atmospheric and Oceanic Sciences, McGill University, Montreal, Canada

1. Abstract

The focus of this study is to test the applicability and look at the advantages of ensemble data assimilation in the under-observed stratosphere. This amounts to determining if a limited number of ensemble members can accurately produce spatial, temporal and cross-species background error-covariances to propagate information from the seldom observations to the full system state.

The study has been performed using an ensemble of simulations from a chemistry-climate model (IGCM-FASTOC), assimilating synthetic satellite ozone or temperature retrievals, mimicking ENVISAT-MIPAS observations. It is found that our ensemble Kalman filter can constrain well the stratospheric chemistry and dynamics, in the context of a perfect-model twin experiment, given proper localization of the background error covariances, even with a limited amount of observations.

The cross-species background error covariances are critical in this achievement, particularly the one representing the advection of the dynamical and chemical variables. However, significant but non-deleterious noise is observed in the analysis ensembles, a noticing opposite to other ensemble data assimilation systems which tend to exhibit an under-variability in their ensembles.

2. Data Assimilation Experimental Setup

Chemistry-climate model :
IGCM-FASTOC run on σ-levels at T21L26 resolution, lid at 0.1 hPa, with interactive ozone chemistry (Bourqui et al., 2005).
Model forecasts :
129 ensemble members initialized from the Jan 1st state vectors of a time-slice run of 129 years.
State vector:

$$\psi = \left(\mathbf{u},\ \mathbf{v},\ \mathbf{T},\ \mathbf{q},\ \mathbf{P_s},\ \mathbf{O_x},\ \mathbf{N_2O_5},\ \mathbf{NO_x},\ \mathbf{HNO_3}\right)^{\mathrm{T}}$$

Perfect-model twin experiment :
True state chosen initially among the 129 years so as to minimize the temperature RMS error over the stratosphere.
Observations are created from the true state by adding normally-distributed, unbiased random perturbations.
Data assimilation analyses are compared to the true state.

Double-EnKF assimilation :
Double Ensemble Kalman Filter (EnKF) with localization of forecast error-covariance matrix with prescribed horizontal and vertical decorrelation lengths (Ch and Cv).

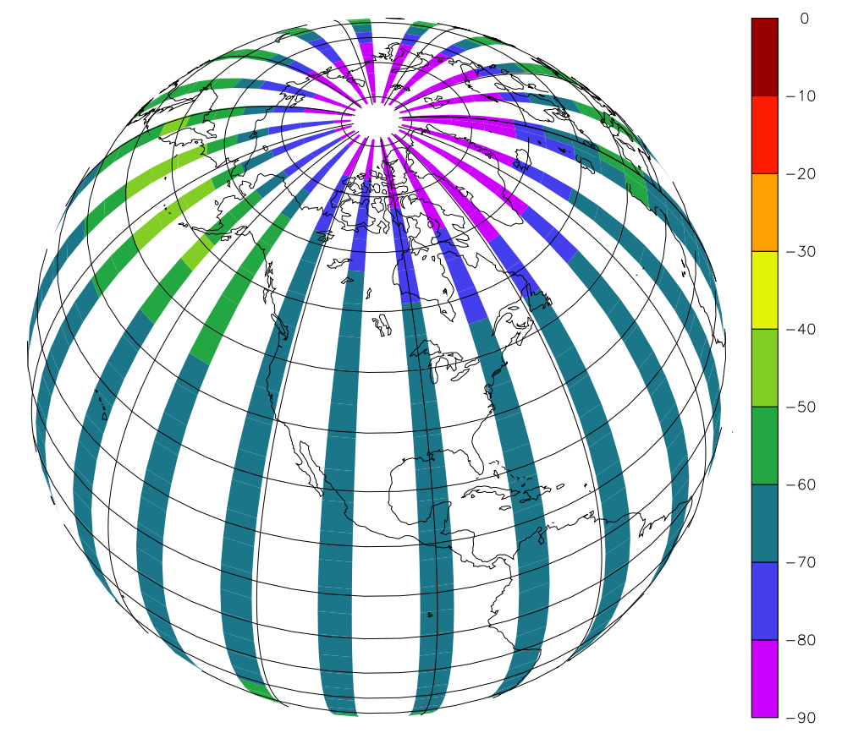

Figure 1: Example of a single-level coverage of daily MIPAS temperature observations to be assimilated.

Synthetic observations:
The EnKF assimilates a daily MIPAS coverage (Fig. 1) instantaneously, every 24 hours at 00Z. The synthetic temperature or ozone retrievals span a vertical region ranging between 12 and 38 km (grey horizontal dotted lines in Fig. 3), with global coverage achieved in three days. Random perturbations from true-state $\mathbf{T}$ or $\mathbf{O_x}$ interpolated on pressure levels. Perturbations are with a standard deviation of 2 K for $\mathbf{T}$ and equal to 10% of the true $\mathbf{O_x}$ mixing ratio.

3. Experiments

In order to compare the relative importance of the different background error covariances for constraining the different state variables, we run data assimilation experiments where some specific covariances are switched off, as described in Table 1, and look at time averages of the analysis variables over the last 45 days of the simulation.

T assimilation	$\mathbf{O_x}$ **assimilation**
Control $\mathbf{T}$ obs transmit their information to all variables	**Control** $\mathbf{O_x}$ obs transmit their information to all variables
NoChem $\mathbf{T}$ obs transmit their information only to $\mathbf{u}$, $\mathbf{v}$, $\mathbf{T}$, $\mathbf{q}$ and $\mathbf{P_s}$	**NoDyn** $\mathbf{O_x}$ obs transmit their information only to $\mathbf{O_x}$, $\mathbf{N_2O_5}$, $\mathbf{NO_x}$, $\mathbf{HNO_3}$ and $\mathbf{P_s}$
	NoTemp $\mathbf{O_x}$ obs transmit their information to all variables except $\mathbf{T}$
	NoWinds $\mathbf{O_x}$ obs transmit their information to all variables except $\mathbf{u}$ and $\mathbf{v}$

Table 1: Description of the different data assimilation experiments.

Diagnostics :
RMS difference between ensemble members ψ_m and ensemble mean $\overline{\psi}$ over the N variables:

$$\mathbf{SPREAD} = \sqrt{\tfrac{1}{N(M-1)} \sum_{i=1}^{N} \sum_{m=1}^{M} \left[\psi_m(i) - \overline{\psi}(i)\right]^2}$$

RMS difference between ensemble mean $\overline{\psi}$ and true state ψ^t over the N variables:

$$\mathbf{RMSE} = \sqrt{\tfrac{1}{N} \sum_{i=1}^{N} \left[\psi^t(i) - \overline{\psi}(i)\right]^2}$$

Total energy norm: $$\mathbf{TE} = \mathbf{u}^2 + \mathbf{v}^2 + \frac{\mathrm{C_p}}{\mathrm{T_{ref}}}\,\mathbf{T}^2 + \frac{\mathrm{R_\alpha\, T_{ref}}}{\mathrm{P^2_{ref}}}\,\mathbf{P_s}^2$$

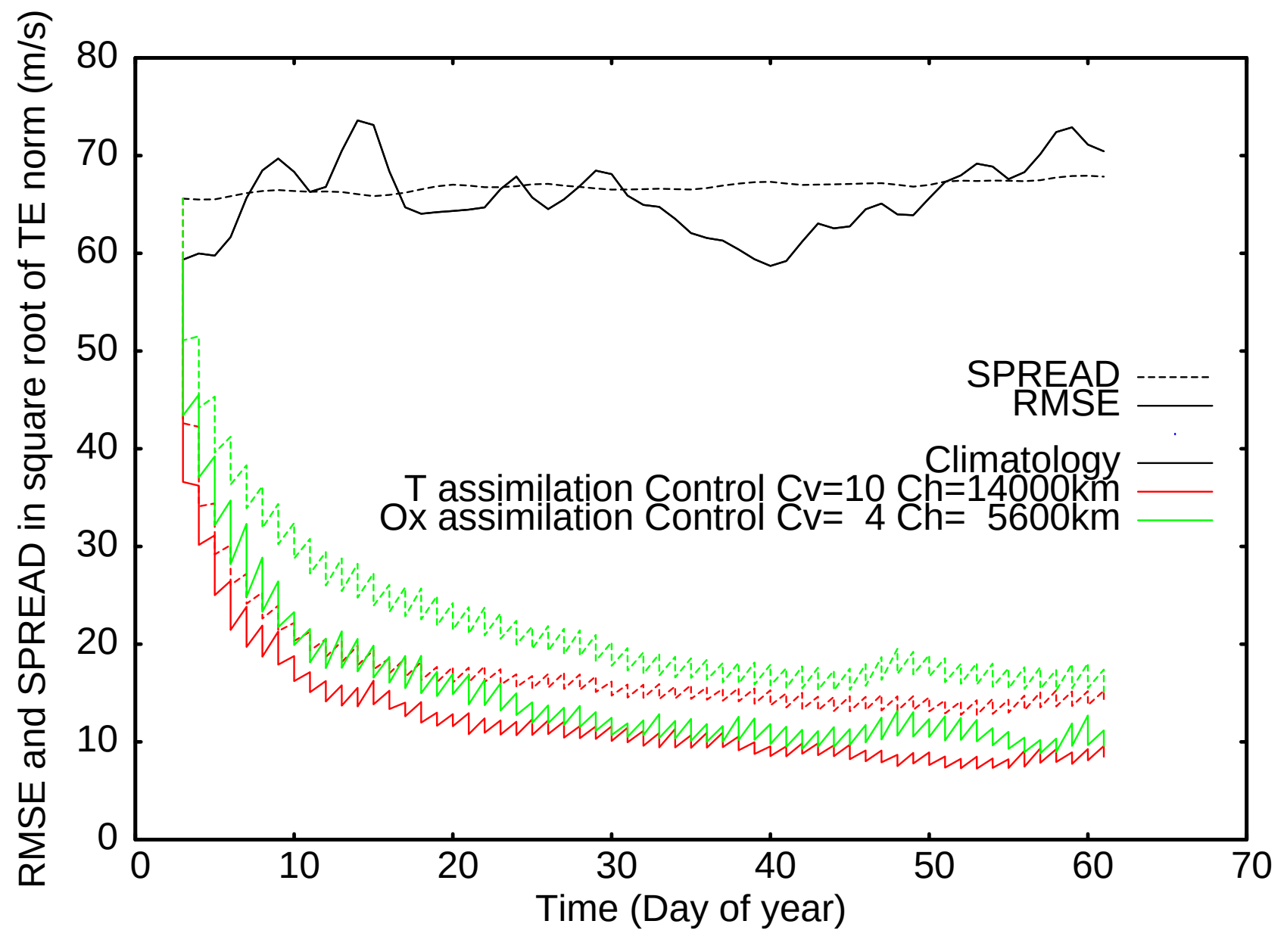

Figure 2: Evolution of global forecast and analysis RMSE and SPREAD in square-root of TE norm for climatological ensemble and the Control $\mathbf{T}$ and $\mathbf{O_x}$ assimilation experiments with optimal localization parameters.

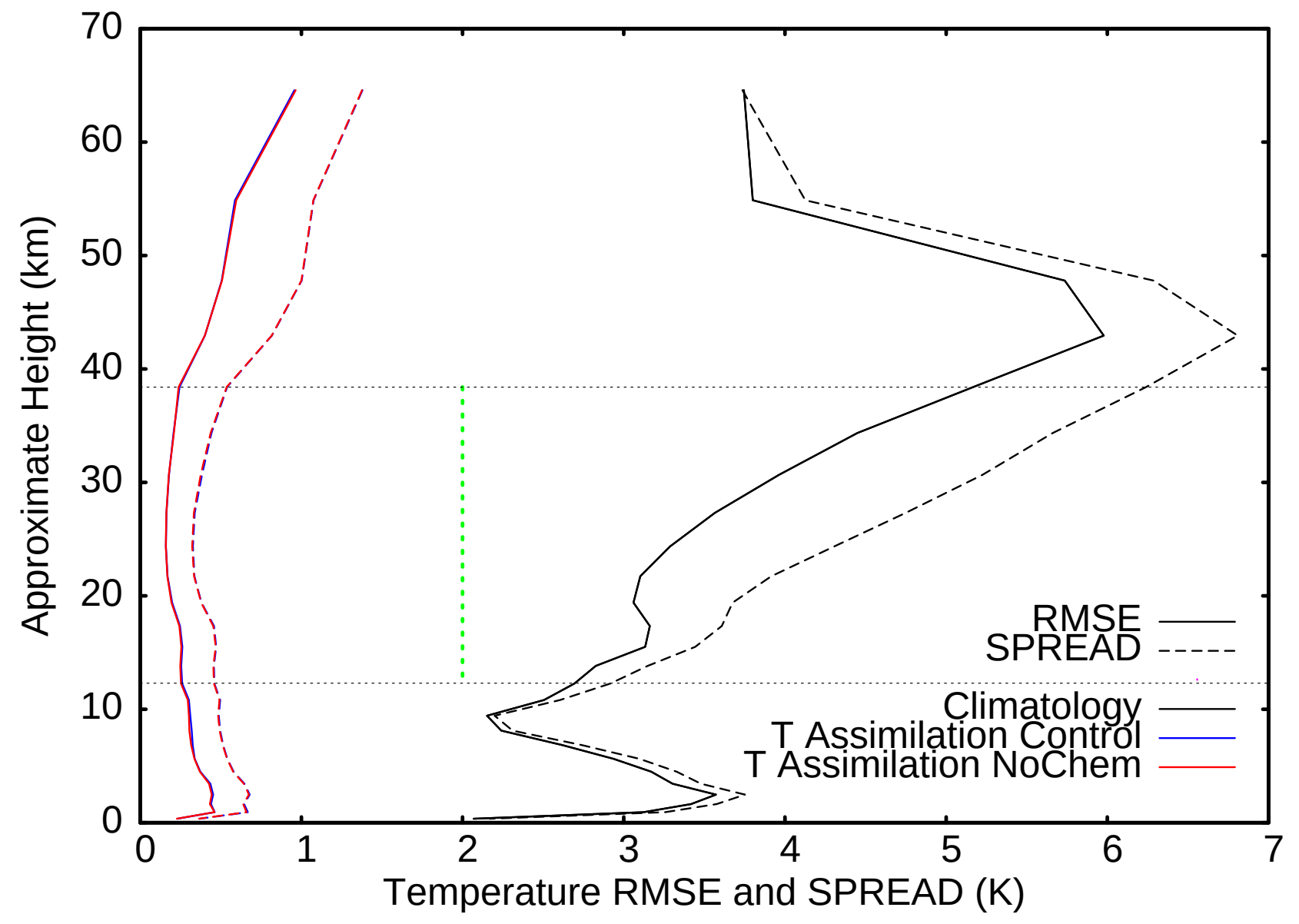

Figure 3: Time-averaged RMSE and SPREAD for the global analysis temperature by vertical levels, for the Control and NoChem $\mathbf{T}$ assimilation experiments.

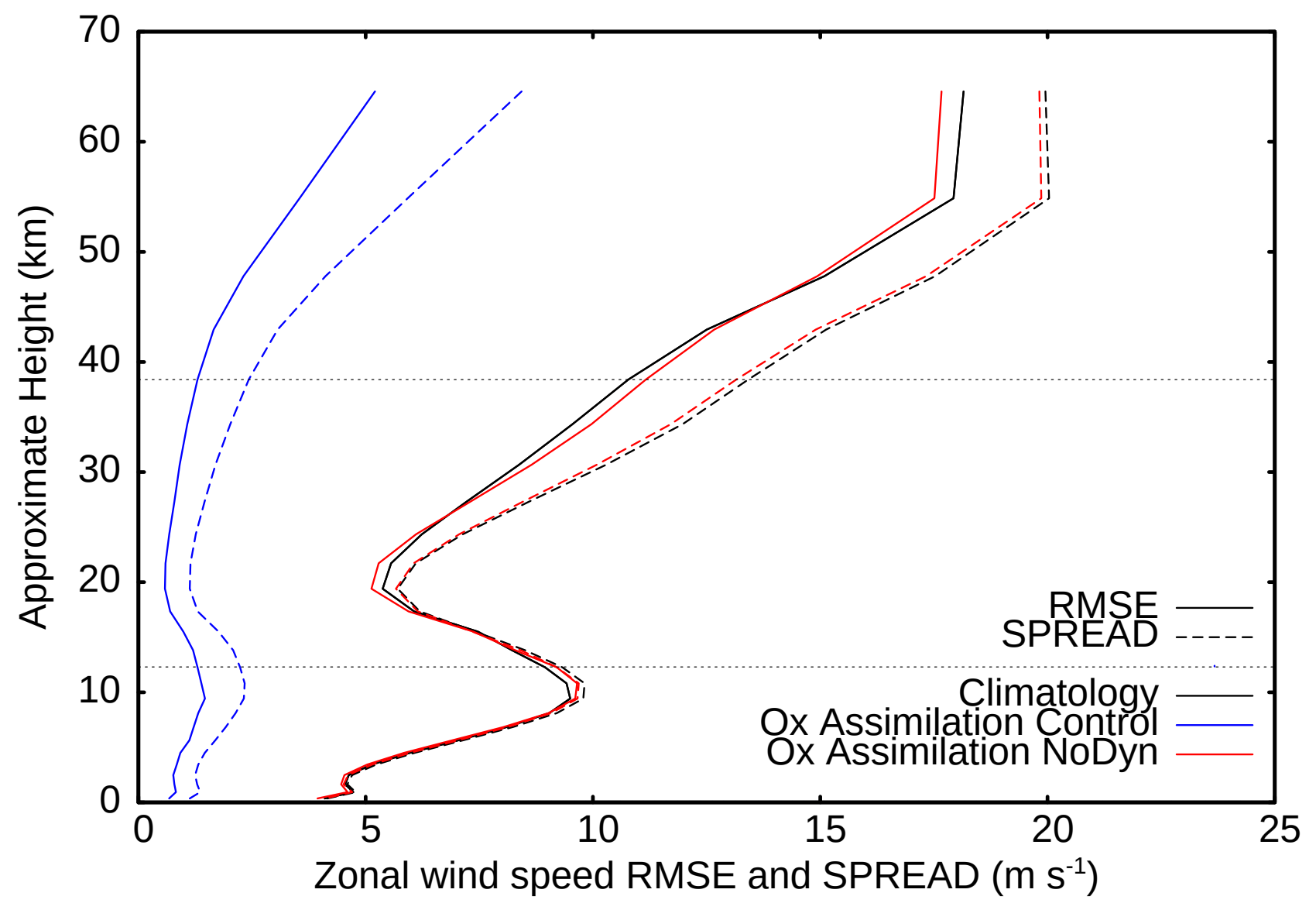

Figure 4: Time-averaged RMSE and SPREAD of global analysis zonal wind by vertical levels, for the Control and NoDyn $\mathbf{O_x}$ assimilation experiments.

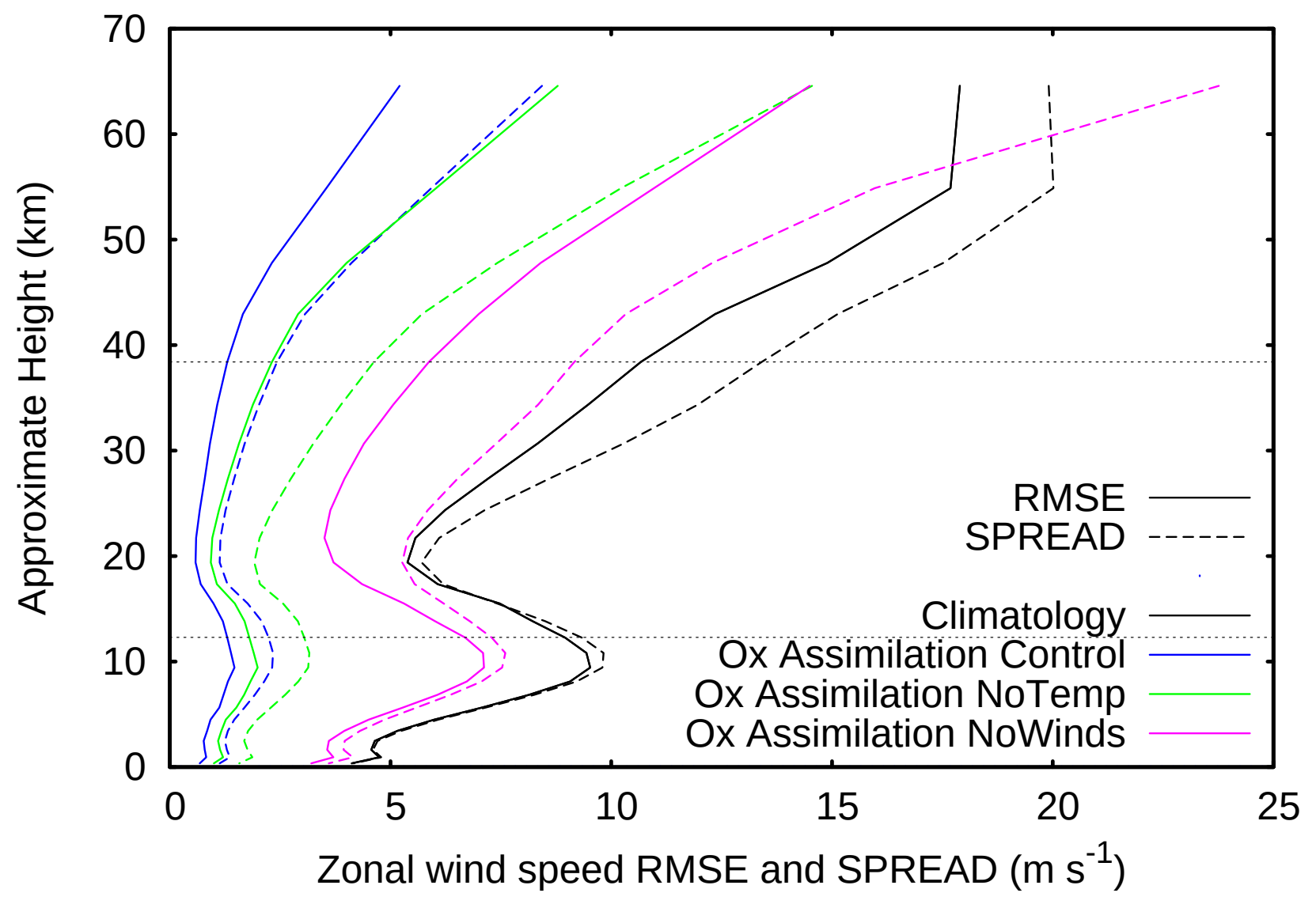

Figure 5: Time-averaged RMSE and SPREAD of global analysis zonal wind by vertical levels, for the Control, NoTemp and NoWinds $\mathbf{O_x}$ assimilation experiments.

4. Results

- Assimilation of temperature or ozone retrievals yield very similar global RMS errors, when localization parameters are chosen correctly (Fig. 2).
- Optimal localization parameters minimizing the global RMSE for temperature assimilation are 14000 km horizontally, and 70 km (10 units of log-pressure) vertically. For the ozone assimilation, shorter decorrelation lengths of 5600 km and 14 km (4 units of log-pressure) proved more optimal.
- The double-EnKF setup with proper localization allows for a strong constraint on all variables, but the ensemble is over-dispersive compared to the skill of the assimilation (SPREAD $>$ RMSE).
- When assimilating temperature, the inclusion of the covariances with the chemical variables does not yield superior results on the time-averaged wind and temperature analyses (Fig 3). It does improve the ozone analysis however, as expected (not shown). This indicates that ozone increments do not feedback to the dynamical variables (through radiation) during the 24-hour forecast phase.
- When assimilating ozone, the covariances with the dynamical variables are essential to constrain the wind and temperature analyses (Fig. 4). Specifically, it is the ozone-wind covariances that play a critical role in this transfer of information (Fig. 5).
- These results are schematically represented in Fig. 6 :

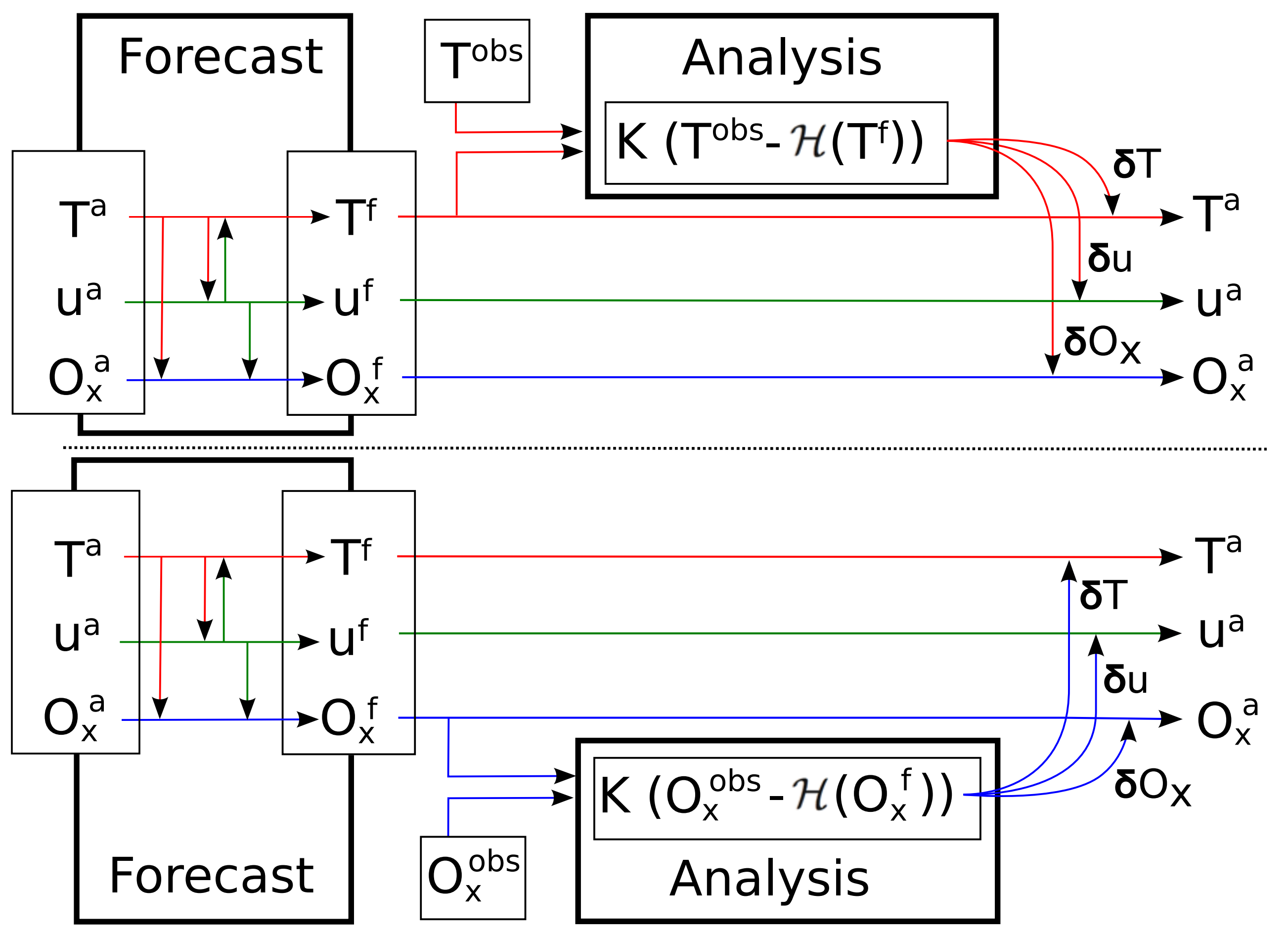

Figure 6: Schematics of information transfer between variables during the forecast (through model balancing) and analysis (through covariances) phases.

5. Conclusions and Future Work

With proper localization, our perfect-model twin experiment with EnKF assimilation of instantaneous synthetic retrievals of $\mathbf{O_x}$ or $\mathbf{T}$ retrievals (having MIPAS coverage and error characteristics) into a chemistry-climate model successfully and strongly reduces the analysis errors of all variables. This includes the ability of our EnKF system to constrain the dynamical part of the system state when assimilating only $\mathbf{O_x}$ observations, mostly through the ozone-wind sample covariances. Future work includes :

- Changing from instantaneous 00Z observations to asynchronous observations.
- Lifting the perfect-model hypothesis.
- Study the assimilation of a true state involving a stratospheric sudden warming (SSW).

References

Bourqui, M. S., C. P. Taylor, and K. P. Shine, 2005: A new fast stratospheric ozone chemistry scheme in an intermediate general-circulation model. ii: Applications to effects of future increases in greenhouse gases. *The Quarterly Journal of the Royal Meteorological Society*, **131**, 2243–2261.

Contact email: thomas.milewski@mail.mcgill.ca