Assimilation experiments using non-diagonal radiance observation error covariances at Environment Canada

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19th International TOVS Study Conference. Jeju Island, South Korea, 26th March-1st April 2014

Introduction
Model background and observation error statistics are key inputs of modern data assimilation systems used in Numerical Weather Prediction. For a long time, it was often assumed in operational context that the observation covariance error matrix is diagonal. The neglected error correlations were, in principle, accounted for indirectly via for example data thinning or error inflation. In the case of radiances from vertical sounders, the advent of hyperspectral infrared sounders such as AIRS (Atmospheric Infrared Sounder), IASI (Infrared Atmospheric Sounding Interferometer) and the recently launched CrIS (Cross-track Infrared Sounder) with their thousands of channels represented an important challenge for the data assimilation community. Recently, inter-channel observation error covariances were estimated for these instruments by various authors (e.g. Garand et al. 2006, Bormann et al. 2010) using different methods which gave consistent results. The purpose of this study is first to estimate radiances observations error statistics including inter-channel correlations for all currently assimilated instruments (microwave and infrared) and then to evaluate the impact of their use in a near operational context in Environment Canada's upcoming Ensemble-variational (EnVar) global assimilation system.

Covariance estimation
In this study, the observation error covariance matrix is based on Derosiers diagnostic (Derosiers 2005) obtained posteriori from (O-F) and (O-A) statistics in a cycle:

\[
\mathbf{R} = (\mathbf{y} - \mathbf{H} \mathbf{x}_{\text{true}})(\mathbf{y} - \mathbf{H} \mathbf{x}_{\text{true}})^T
\]

where \( \mathbf{y} \) is the observation vector, \( \mathbf{x}_{\text{true}} \) is the assimilation background model state, \( \mathbf{H} \) is the observation operator (here RTTOV-10 fast radiative transfer model), and \( \cdot \cdot \cdot \) stands for averaging. Simplifying assumptions include: unbiased observations, no correlation between background and observation error and a realistic background error covariance matrix \( \mathbf{B} \). This approach was chosen because it is simple to implement. Also the work of Bormann et al. 2010 demonstrated that it gives qualitatively similar results to more complicated methods. We estimated the covariances using 21 days of quality controlled and bias corrected brightness temperatures from a reference cycle. The diagonal elements were symmetric and split in variance and correlation matrices:

\[
\mathbf{R}_{\text{diag}} = \frac{1}{\sqrt{\mathbf{R}}} \mathbf{R} = \frac{1}{\sqrt{\mathbf{R}}} \mathbf{R} = \text{diag}(\mathbf{R})/\text{diag}(\mathbf{R})
\]

The diagonal elements of the diagnosed Derosiers variances are by construction lower than the O-F values. Since in practice it is found that inflated errors are required, it decided to start with operational diagonal variances and to use the Derosiers correlation to define off-diagonal terms.

Assimilation system description
- It is a prototype of the experimental assimilation system to be implemented in Fall 2014
- 4D-EnVar system (4D assimilation system without tangent linear and forecast model adjoint)
- The \( \mathbf{B} \) matrix used results from the blending of an homogeneous isotropic matrix obtained using the NMC method with the covariance matrix of the Ensemble Kalman Filter assimilation system (192 members on a 60x300 vertical grid with 72 staggered vertical levels and a model top at 2 HPa)
- 60x300 Gaussian analysis horizontal grid.
- The assimilation system and the Global Environmental Multiscale (GEM) version 4 forecast model share the same vertical coordinate: 80 levels with a top at 0.1 hPa
- 15 km Yin-Yang forecast model horizontal grid
- To save time, all the experiments presented here were performed offline without two-way coupling between the EnVar and the EnKF system

Assimilated Observations
- Surface (SYNOP/SHIP/BUOYS/DREFTER)
- Radiosondes
- Aircrafts
- Satellite winds (geostationary imagers +MODIS)
- GPS radio occultations (COSMIC/GRACE)
- Scatterometers: Quikscat
- Microwave radiances:
  - AMSU-A from NOAA (15, 16, 18 and 19), AQUA and METOP-2 (11 channels)
  - AMSU-B and MHS from NOAA (16, 18 and 19) and METOP-2 platforms (4 chan.)
  - SSMI-5 from DMSP-16 (7 chan.)
- Infrared radiances:
  - AIRS from AQUA (142 channels)
  - IASI from METOP-1 (42 channels)
  - Geostationary imagers (1 H2O channel):
    - GOES-13, MTSAT-7 and MSG-2

Verification scores
- Use of the non-diagonal \( \mathbf{R} \) matrix leads to a better fit to dew point depression observations from radiosondes as it could be anticipated from the decrease of the weight of water vapor sensitive channels (from AMSU, IASI, AMSU-B and SSMI-5) which exhibit significant inter-channel observation error correlations.
- Verifications of 72 hours forecasts of winds, geopotential height and temperature against ERA interim reanalysis demonstrated that the impact of using a non diagonal \( \mathbf{R} \) matrix in our experiment is positive except in the Arctic. Again, similar results were obtained with verification again own analysis (not shown).
- In north America, significantly positive impact of using a non diagonal \( \mathbf{R} \) matrix on 72 hours forecasts was demonstrated both against radiosonde observations (left graphs), own analysis (not shown) and ERA interim reanalysis (right graphs).

Conclusion and final remarks
The assimilation code that will be used in Environment Canada future operational 4D-EnVar was modified to be able to use non diagonal observation error covariances metrics to account for radiances inter-channel error correlations. The computing cost relative increase associated to this enhancement is of the order of only 3%. Correlations matrices were estimated for all assimilated radiances from statistics of a reference assimilation cycle using the Derosiers diagnostic. As diagnosed variances are small compared to those to be used operationally with a diagonal matrix, it was decided to perform a first assimilation experiment with a non diagonal observation error using the diagnosed correlations and operational variances. To obtain a good cost function minimization convergence it was necessary to re-compute an estimate of the Hessian matrix used by the HUGO quasi-Newton minimization algorithm for preconditioning. With a proper preconditioning no convergence problem was observed during the cost function minimization. The comparison between the control and the experiment using a non diagonal \( \mathbf{R} \) matrix for radiances made during one month of assimilation was mostly favorable to the experiment both against radiosonde observations and analysis. Some difficulties were nevertheless observed in the Arctic and will be investigated. Additional tuning of the variances is planned, keeping Derosiers's correlations, and modifying the level of error inflation.