Atmospheric horizontal gradients for slant-path assimilation of radiances in Environment Canada's weather forecast system

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Abstract

We investigate the use of horizontal gradient information for the simulation and assimilation of slant radiances in Environment Canada's weather forecasting system. These gradients of atmospheric variables, at each altitude layer, are used to construct slant background profiles for radiative transfer simulation.

With respect to vertical background profiles, the following improvements are shown

- forward operator performance
- a reduction in the analysis increment
- a reduction in the statistics of a priori error
- both **short and long-range** forecast improvements

These are particularly relevant for observations at higher zenith angle, in mid to high latitudes, and for channels sensitive to temperature in the upper troposphere and low stratosphere.

Introduction

In a slant radiance observation, besides the direct effect of a longer path, there is an effect through the **background field**, which is **not spherically symmetric**. The impact of this slant background field information has been the subject of previous studies.

- In Joiner and Poli [2005], it was evaluated the impact over several channels and instruments. This was largest in the upper troposphere and stratosphere, and affected mostly temperature channels, but was considered small for most.
- Bormann et al. [2007] and Healy et al. [2007] showed benefits of keeping more extensive horizontal information in simulations of **limb observations**, respectively of MIPAS radiances and GPS radio occultation bending angles.
- In Bormann [2017], a **comprehensive 2-dimensional observation operator** (along azimuth x altitude) improves radiance simulation for high-peaking temperature channels at mid and high latitudes, and for high peaking humidity channels at mid-latitudes. Improvements lasted up to 3 days in the forecast.

In this study, the impact of horizontal variability of temperature T, pressure P and moisture q in the simulation and assimilation of satellite radiances, is explored in Environment Canada's weather forecast system. The description of the background state is more complete than a spherically symmetric vertical profile, but the additional state information is chosen to be very limited: **linear horizontal gradients**. These are calculated along east (x) and north (y) by local best fit to T, $\log P$, and $\log q$ model outputs, from the surface to the model lid (0.1 hPa), over a radius of 100 km around the observation's ground footprint. The low resolution (the model has a 25 km grid) is intended to capture the **larger scale structures**, mostly in the T field. It cannot capture smaller-scale variability that may develop in the moisture field. This **cutoff** was chosen as the background **gradients are expected to be accurate only above certain length scale**.

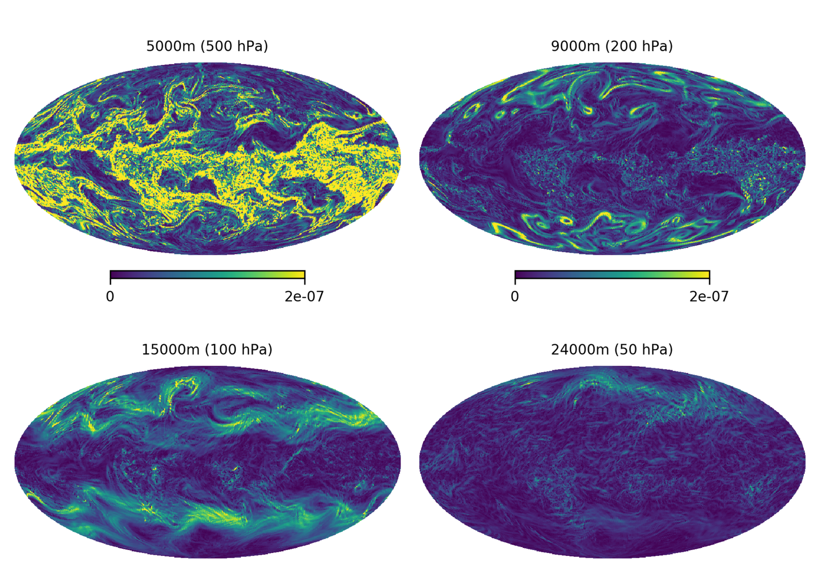

Figure 1: Global *horizontal* T gradient (absolute value $|\nabla_h T|$, in K/m) at several altitudes, with their approximate pressure levels), at 01 Jan 2017, 06 UTC. For comparison, vertical gradients are of the order of 10^{-3} K/m

With these gradients, slant background profiles are constructed. The RTTOV operator (v10) may then be applied to these profiles, instead of a standard vertical profile, to simulate radiances. This is only applied to AMSU-A (onboard NOAA15/18/19 and METOP-1/2) and ATMS (onboard JPSS) observations. The choice was done to focus on channels that are mostly sensitive to temperature in the upper troposphere and low stratosphere.

The construction of the slant profile was applied to the full nonlinear operators of these data. Impact through linear operators (tangent and adjoint) was found to be very small, and for numeric simplicity linear operators are still evaluated over vertical profiles.

NB: Linear operators act on a grid of lower resolution.

Simulation of observations

Observations of brightness temperature were simulated with the same radiative transfer operator, using **vertical background** fields, and **slant background** fields. The statistics (standard deviation, σ) of Observation minus Background (OMB) of both are compared:

$$\frac{\sigma_{OMB_{slant}}}{\sigma_{OMB_{vertical}}} \qquad (1)$$

All data have been dynamically bias-corrected within their respective cycles.

For channel 9 of ATMS and AMSUA, the most impacted in both instruments, there is respectively an average of 2% and 1.7% reduction in the standard deviation of OMB. See Figure 2.

This reduction of σ_{OMB} varies by **zenith angle**. There is no reduction at nadir, and becomes noticeable for side-looking scan positions. This dependence is shown in Figure 2 for channel 9 of ATMS **(b)** and AMSUA **(d)**. At high zenith angles, there is more than 6% and 4% reduction of σ_{OMB} in this channel 9, respectively.

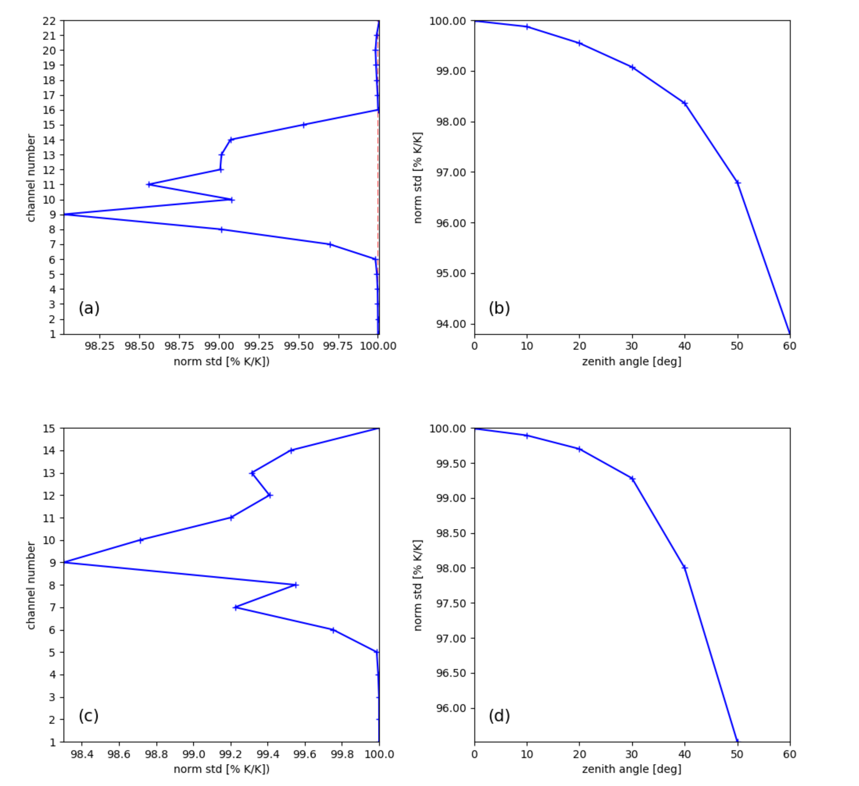

Figure 2: Left panels: std ratio (see Equation 1) of OMB brightness temperatures, using a slant vs vertical background, for all ATMS/JPSS (top) and AMSUA/NOAA18 (bottom) channels (global data over 20170101-20170111). Normalized to 100. Right panels: zenith angle dependence of this ratio, for channel 9 of each instrument.

Assimilation experiments

Assimilation experiments were conducted for two periods of two and half months, in boreal winter (20161215-20170228) and in boreal summer (20160615-20160831). Each experiment runs a 4DEnVar assimilation system (4D, driven by an EnVar-based background error estimation). The assimilation windows are of 6-hours, on 81 hybrid levels, with model resolution of 25 km and analysis increment horizontal resolution of 50 km. The experiments shown below are

- **G252H17V1**: the boreal winter vertical-background control
- **HIV2017FB**: its counterpart with slant-background
- $\mathbf{FB_{SA}}$: AMSUA and ATMS radiance a priori **statistics have been reevaluated**, from results of HIV2017FB.
- **S2**: for consistency, AMSUA and ATMS a priori statistics are **equally reevaluated**, from results of G252H17V1

In all cases 2-week spin-up periods are allowed before the evaluation of statistics.

Field of view dependence: Standard deviation of difference (see Figure 3) between observation and short-range forecast estimations (OMB), for the vertical background control (G252H17V1) and the slant background experiment (HIV2017FB), as a function of the scan positions, for channel 9 of ATMS instrument, averaged over the period 20170101-20170131. Observations have been bias corrected.

The reduction in the observation operator error means the **a priori observation error** may also be reduced, with respect to its initial value for the affected channels. The observation error is in general set as a large scale average of σ_{omp}, and had been set with previous data.

This estimation procedure is applied to experiment $HIV2017FB$, and reduced error statistics are found for the impacted channels. The updated error used to run a new slant-background: FB_{SA}. For consistency, the same is done with the control: the same reevaluation is performed over the control $G252H17V1$ results, and a new control is re-run: $S2$. All forecasts are compared against their own analysis.

Standard deviation of forecast error: $([std(S2) - std(FB_{SA})]/std(S2) * 100)$ is shown in Figure 4 averaged over the entire globe **(a)** and only over the Arctic **(b)**, for geopotential height at different forecast hours. Red indicates slant-background is better, blue that vertical background is better. Cross-check of the different runs indicates that the improvement in forecast at short range is due to the introduction of the gradient operator, whereas the reevaluation of the a priori error leads to a positive impact in the long-range forecast.

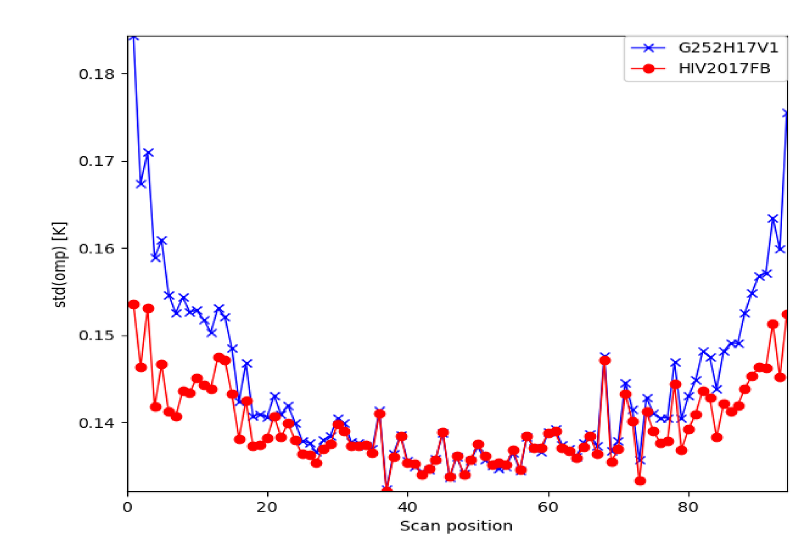

Figure 3: OMB Statistics vs scan position, for ATMS channel 9.

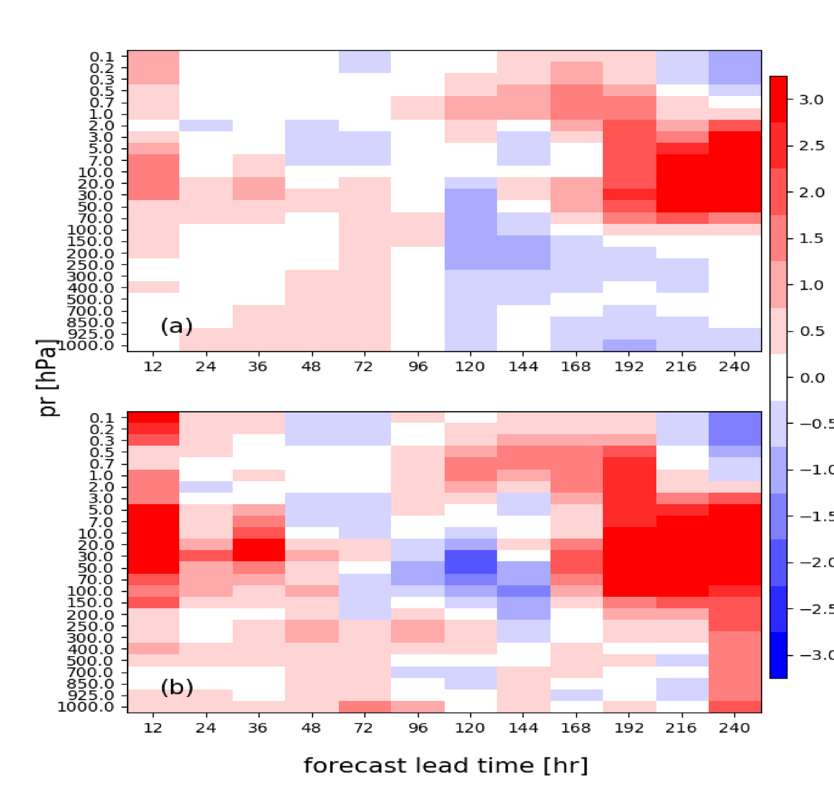

Figure 4: Forecast statistics: % change in σ of geopotential height, slant vs vertical. Red is improved. Global (above), and Arctic (below).

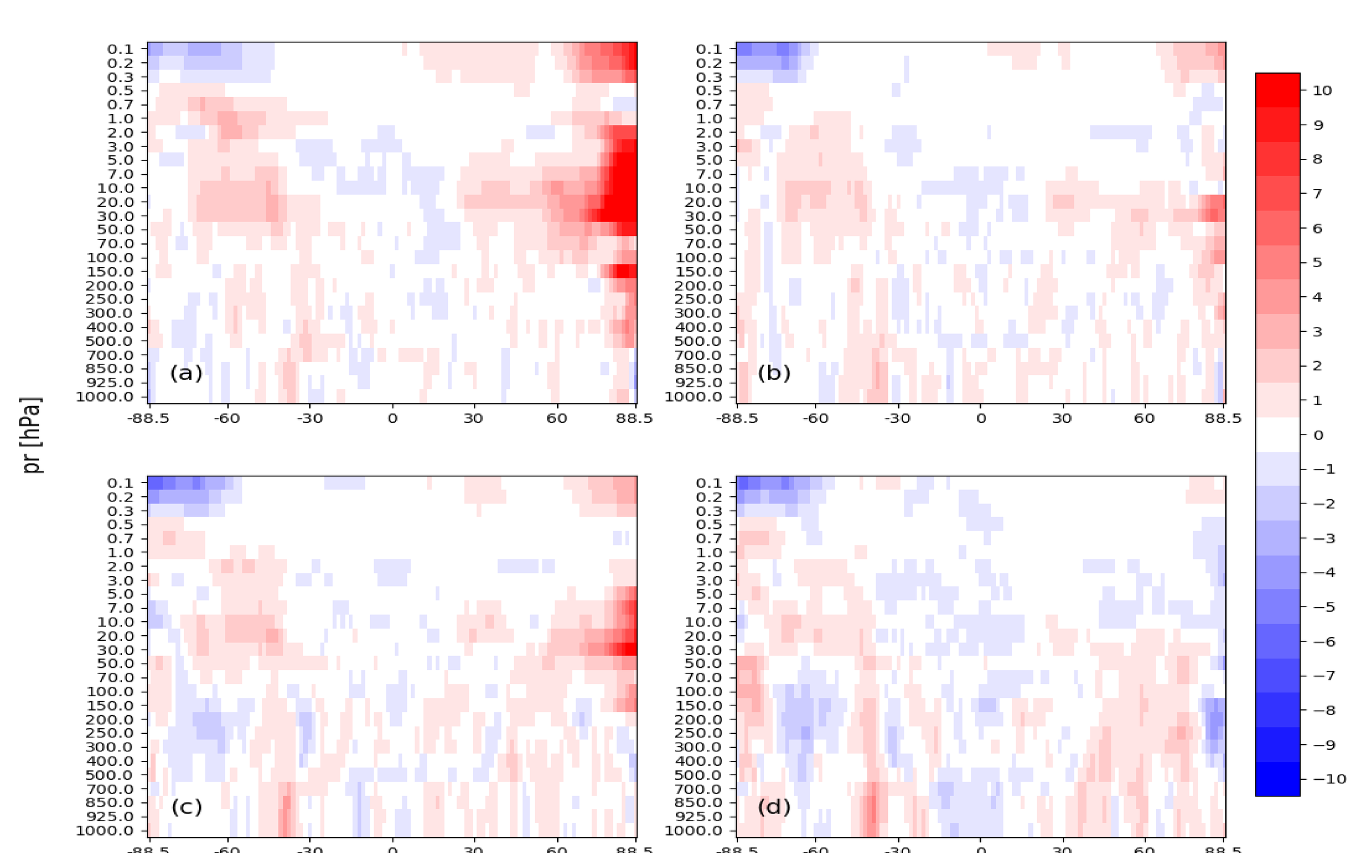

Figure 5: Normalized (%) zonal/altitude forecast error reduction of the geopotential (slant background vs vertical), respectively at 12 (a), 24 (b), 36 (c), and 48 (d) hour. Red is improved. There is up to 10% reduction at 12-hour forecast in the Arctic.

Conclusion and remarks

- We used linear horizontal gradients to estimate of the model fields' variability and to build slant profiles for radiance observation simulation and analysis. The background profile is an object that contains the vertical information of any variable required (P, T, q), and their respective horizontal local average gradients ($\nabla_h P$, $\nabla_h T$, $\nabla_h q$).
- The produced horizontal structure is effectively high-pass filtered, with a cutoff scale of 100 km. The intent is to capture the gradients with larger scales.
- The impact is shown to be significant (e.g. 6% reduction in ATMS simulations) for the simulation of radiances at high zenith angles, upper troposphere/lower stratosphere regions, and mid and higher latitudes, particularly in temperature channels. With respect to more sophisticated descriptions of the background state, it captures most of the potential improvement with respect to a purely vertical background.
- Since the OMB statistics are lower (atmospheric gradients were a component of background error) we have explored the assimilation with lower a priori error.
- A set of four assimilation experiments (vertical/slant background and original/updated a priori error) were performed to examine the impact of (1) slant-path radiative transfer in the assimilation cycle and (2) the effect of reduced background error. The short-range forecast improvement can be attributed to the impact of the gradient-aware forward operator, whereas the long-range improvement is a result of the modification of the observation error estimate.
- The small scale features have been filtered out using only the large-scale horizontal gradients. This can be desirable as: 1-if the model misrepresents or incorrectly locates features, this does not affect the quality of the results, as long as this misrepresentation is smaller than the filter cutoff scale. In other words, overfitting to possible incorrect fields are avoided; 2-the analysis is performed on a lower-resolution grid, where the information from smaller-scale features is lost. The unnecessary additional computing time and observation operator complexity is avoided, while obtaining similar improvements as with an operator that would handle these higher-resolution features.
- Also related to this cutoff of small scales, since the linear observation operators (tangent, adjoint) act on a grid of lower resolution, the background for these is still evaluated in a vertical profile.
- These results are ready for implementation. Future development will be dedicated to the study of other efficient descriptions of high-pass filtered descriptions of the background state, and the analysis of the optimal cutoff scale length.

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