Developments in Bias Correction for Reanalysis

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INTRODUCTION

A major problem with the use of observations for climate analysis is the presence of biases, and the effect on the estimation of climate signals of changes in these biases, their sampling frequencies, and details of the analysis techniques. This problem also exists in atmospheric reanalyses, which combine many different types of observations together with information from sophisticated models in order to produce accurate and dynamically consistent estimates of global atmospheric parameters.

In spite of best efforts to remove all systematic errors at the source, some residual biases inevitably remain. Their presence can be readily detected in a reanalysis system by monitoring the data against a common reference. The data assimilation then provides a final opportunity to correct the biases in the data, and possibly in the model as well, based on the consensus of all information presented to the analysis system. This idea, and the practical challenge of dealing with a heterogeneous and evolving observing system, has led to the development of automated bias correction schemes embedded in the analysis component of the data assimilation system.

In this paper we briefly review the use in ERA-Interim of a variational bias correction scheme for adaptively correcting biases in satellite radiance data, and discuss practical aspects such as the need for constraining the system where model biases are large and observations are sparse. We also discuss the extension of the variational approach for correcting other types of observations, including ozone profile data. Finally we present some thoughts on using the data assimilation to correct model biases, and show experimental results obtained with a weak-constraint formulation of the four-dimensional variational analysis method in use at ECMWF.

VARIATIONAL BIAS CORRECTION OF RADIANCE DATA

Bias correction of observations has always been a practical necessity both for NWP and reanalysis. Due to the growing complexity of the observing system and its evolution over long time periods, some kind of automated system for handling the bias corrections is now indispensable. Variational bias correction of radiance data was first implemented for at NCEP in their Statistical Spectral Interpolation analysis system (Derber and Wu 1998) and later at ECMWF (Dee 2004) by extending the ECMWF 4D-Var analysis system.

J_b: background constraint for x $\qquad$ J_β: background constraint for β

$$J(\mathbf{x}, \boldsymbol{\beta}) = \underbrace{(\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1} (\mathbf{x}_b - \mathbf{x})}_{J_b} + \underbrace{(\boldsymbol{\beta}_b - \boldsymbol{\beta})^T \mathbf{B}_\beta^{-1} (\boldsymbol{\beta}_b - \boldsymbol{\beta})}_{J_\beta} + \underbrace{[\mathbf{y} - \mathbf{b}_o(\mathbf{x}, \boldsymbol{\beta}) - \mathbf{h}(\mathbf{x})]^T \mathbf{R}^{-1} [\mathbf{y} - \mathbf{b}_o(\mathbf{x}, \boldsymbol{\beta}) - \mathbf{h}(\mathbf{x})]}_{J_o}$$

J_o: bias-corrected observation constraint

Variational bias correction provides an automatic inter-calibration of the observing system in the context of the forecast model, producing bias corrections that improve the consistency of the information entering the analysis. Figure 1 shows an example of bias corrections produced during the first 10 years of reanalysis in ERA-Interim, in this case for radiance data from MSU channel 2 on NOAA-10, 11, 12, and 14. The corrections account for systematic errors in the data (e.g. due to calibration issues) but also for errors in the fast radiative transfer model used to simulate the data (e.g. due to inaccurate spectroscopy). The corrections may also falsely correct the data for errors in the background which are due to forecast model bias, especially where observations are sparse (such as in the stratosphere).

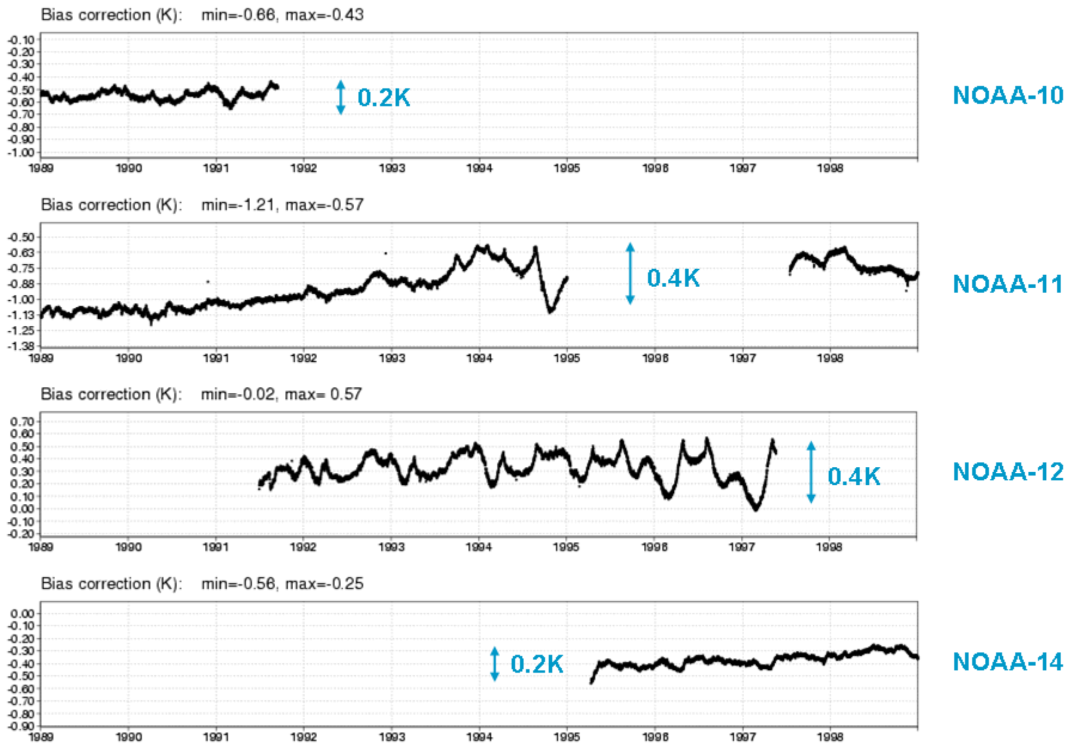

Figure 1: Global mean bias corrections for MSU channel 2 radiances in ERA-Interim

There are strong indications that variational bias correction of radiance data is beneficial to the quality of the ERA-Interim reanalysis. For example, the vertical consistency of the temperature analysis, as well as the fit to radiosonde data in the polar regions, is much improved compared to ERA-40; see Figures 2 and 3.

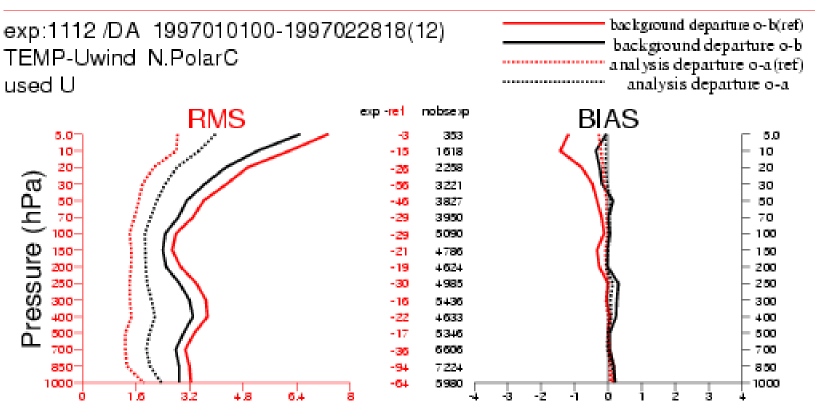

Figure 2: Fit to radiosonde u-wind observations in the Arctic regions for ERA-40 (red) and ERA-Interim (black).

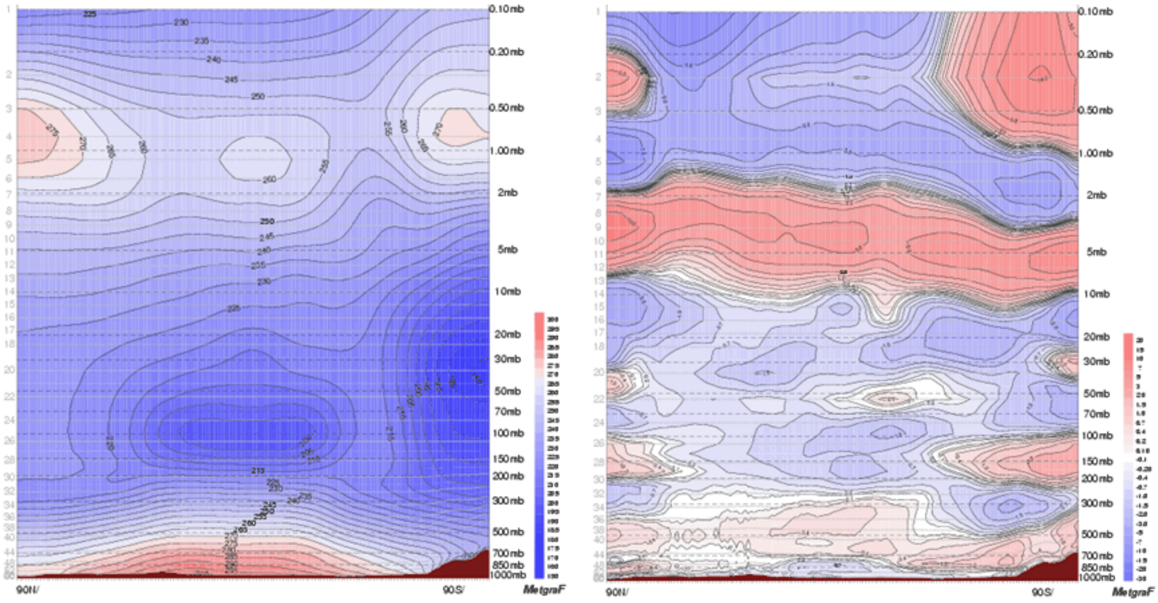

Figure 3: Aug 1993 zonal mean temperatures for ERA-Interim (left) and the difference relative to ERA-40 (right).

VARIATIONAL BIAS CORRECTION OF OZONE PROFILE DATA

The variational bias correction method is quite general and may be applied to data types other than radiances. For the next-generation analysis system in development at the ECMWF we are considering the use of this approach to provide bias corrections for ozone data. Figure 4 shows a timeline for ozone observations used in ERA-Interim during the period 1989-2002. The observing system is quite complex, consisting of retrieved total column ozone together with ozone profile data from sensors with different vertical resolutions, and many gaps in the data. Closer inspection reveals many systematic differences among the different sources of ozone information entering the analysis.

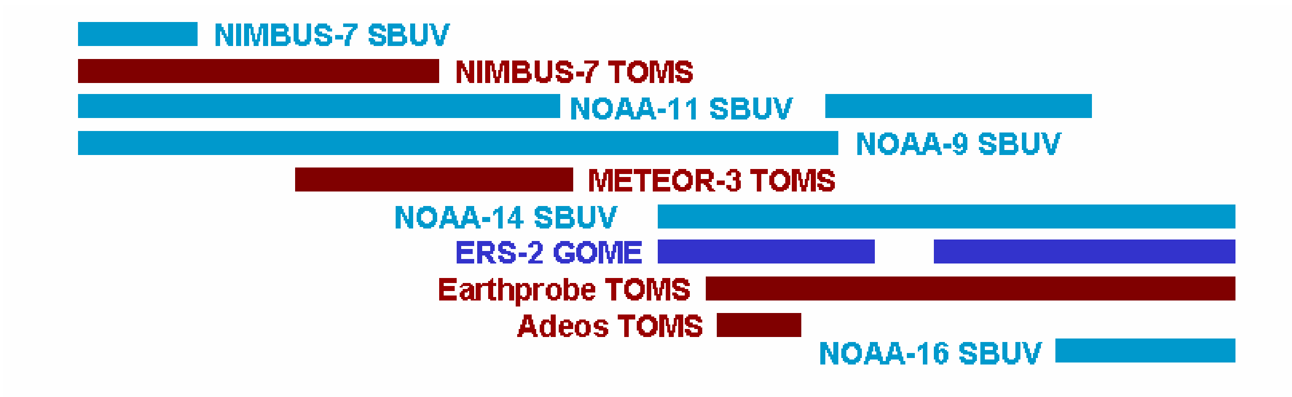

Figure 4: Timeline of ozone data sources used in ERA-Interim between 1989 and 2002.

Figure 5 shows some results of an experiment using variational bias correction of ozone data. During the selected period high-resolution ozone profile data from GOME on ERS-2 were re-introduced into the system (on 4 January 1997). The plots show opposite bias corrections produced by the variational scheme for SBUV data (for the layer between the surface and 16 hPa) and GOME data (for the layer between 32 and 18 hPa). Plots in Figure 6 show the impact of the variational bias corrections (applied to all ozone data in the system) on the analysis increments.

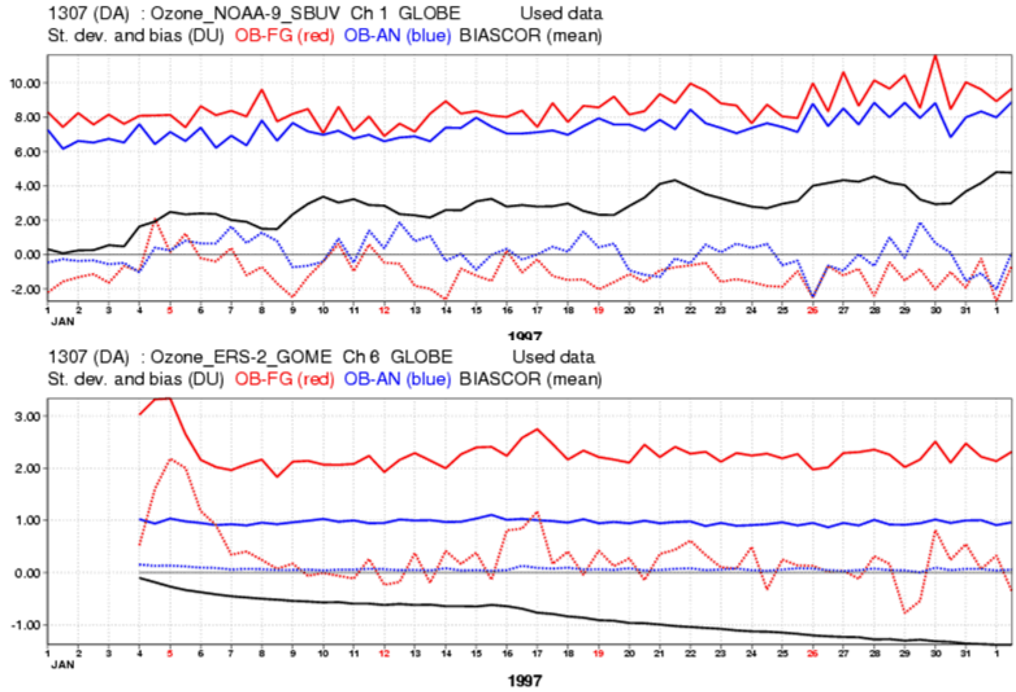

Figure 5: Departure statistics for SBUV (top, layer between the surface and 16 hPa) and GOME ozone layer data (bottom, layer between 32 and 18 hPa) during January 1997. Shown are: global means (dashed) and standard deviations (solid) of analysis (blue) and background (red) departures, and global mean bias corrections (black).

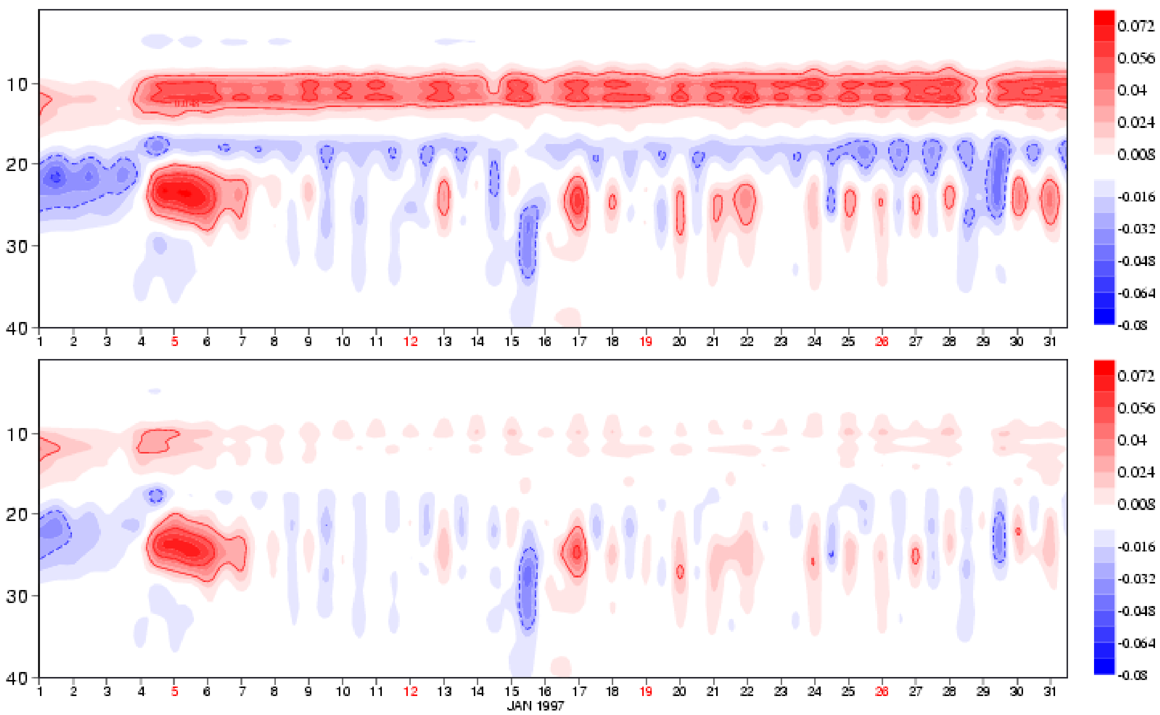

Figure 6: Globally averaged analysis increments for stratospheric ozone concentrations [mg/kg] for January 1997, for an experiment with (bottom) and without (bottom) variational bias correction of ozone data. Model levels 10, 20, 30, 40 indicated along the vertical axes approximately correspond to pressure levels 1, 10, 50, and 100 hPa, respectively.

USE OF WEAK-CONSTRAINT 4D-VAR TO CONTROL STRATOSPHERIC MODEL BIAS

Systematic model errors in the upper stratosphere can be quite large, as can be seen for example by looking at the average drift in the five-day forecast. Figure 7 shows the evolution of this drift in ERA-Interim upper-stratospheric temperature forecasts for a one-year period over the Antarctic region. It is typically on the order of 10K or more at model level 4, which corresponds to about 1 hPa in the ERA-Interim system. Although reasonably accurate observations for the upper stratosphere are provided by SSU and AMSU-A (but see Kobayashi et al., 2008) the standard 4D-Var analysis method is not designed to handle systematic model errors.

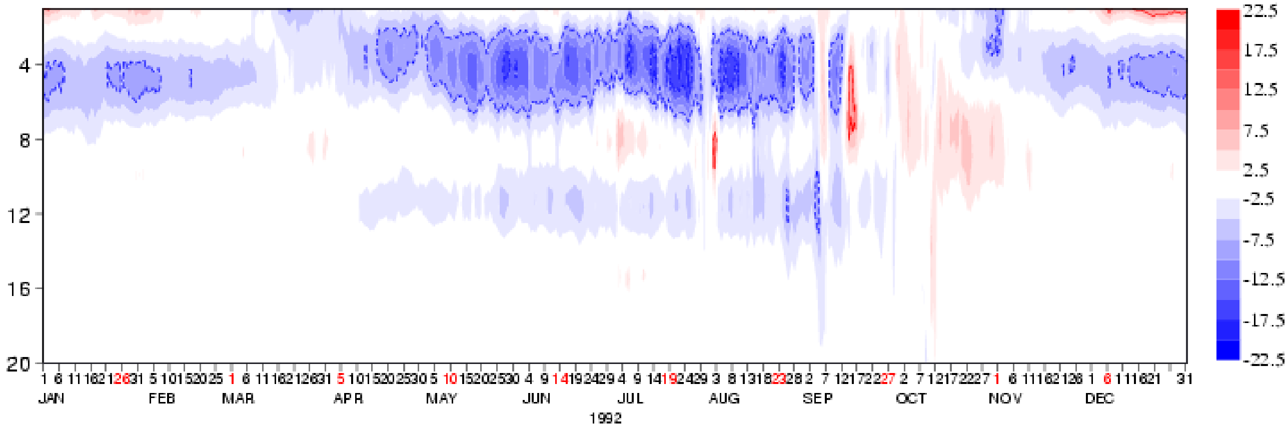

Figure 7: Evolution of the mean upper-stratospheric temperature [K] error (5-day forecast errors verified against analyses) over the Antarctic (south of 70S) during 1992. The vertical axis extends from about 40h to 0.1 hPa.

Trémolet (2007) shows how 4D-Var can be extended to account for model errors. This requires the use of the model as a weak constraint in the variational analysis, in contrast to the usual requirement in 4D-Var that the model equations be satisfied exactly during the analysis window:

$$\begin{aligned} J(x_0,\eta) &= \frac{1}{2}\sum_{i=0}^{n}[\mathcal{H}(x_i)-y_i]^T R_i^{-1}[\mathcal{H}(x_i)-y_i] \\ &+ \frac{1}{2}(x_0-x_b)^T B^{-1}(x_0-x_b)+\eta^T Q^{-1}\eta \\ &\text{with } x_i=\mathcal{M}_i(x_{i-1})+\eta_i . \end{aligned}$$

Results of a preliminary experiment involving the addition to the ERA-Interim system of a weak constraint applied in the stratosphere only are presented in Figure 8. We rely on the mean background departures with respect to radiance data from SSU channel 3 as a good measure of systematic model error in a deep layer of the upper stratosphere, roughly extending from 5 hPa to the stratopause. The figure shows that the average departures for August 1993, which clearly show the poor representation of the winter polar vortex, are in fact significantly reduced by allowing for model error in the analysis.

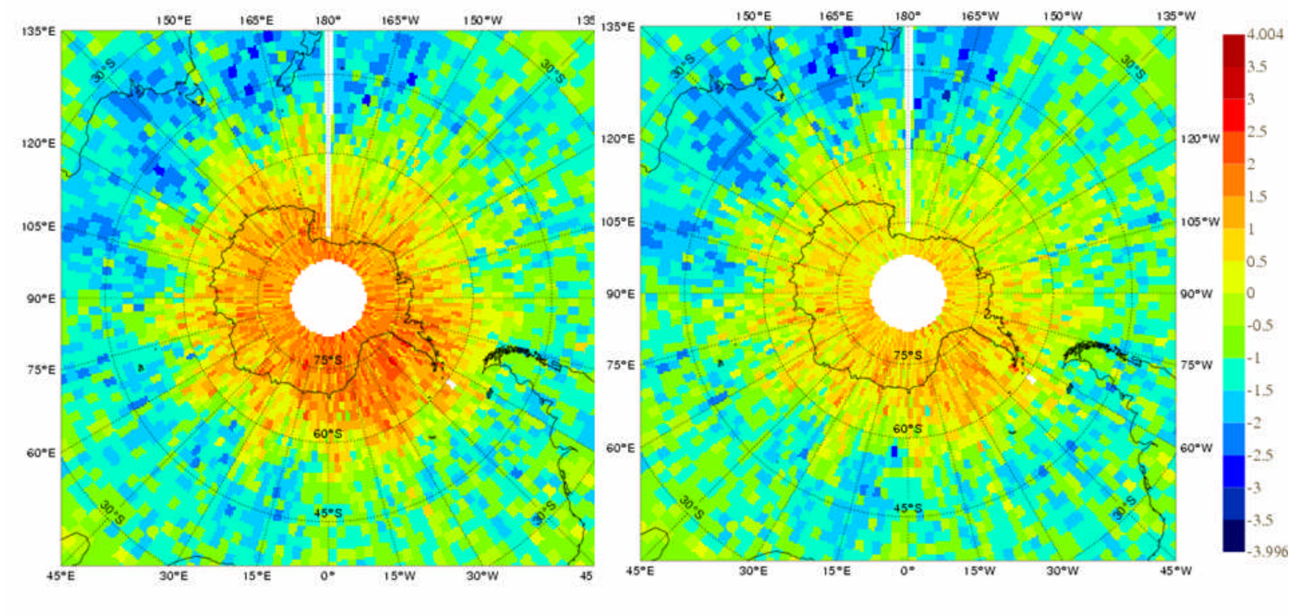

Figure 8: Mean background departures for SSU channel 3 radiances for August 1993, from ERA-Interim (left panel) and from an experimental assimilation using weak-constraint 4D-Var (right panel).

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