Assimilation of IASI observations in the context of the GEMS and MACC projects

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1 Introduction

The European Global and regional Earth-system (Atmosphere) Monitoring using Satellite and in-situ data (GEMS) project (Hollingsworth *et al.*, 2008) has built a system that is capable of assimilating various sources of satellite and in-situ observations to monitor the atmospheric concentrations of greenhouse gases, reactive gases, and aerosol. The new system is an extension of current data assimilation and forecast capabilities for numerical weather prediction (NWP) that are in place at ECMWF coupled to a full chemistry transport model (CTM). It can be used to monitor the composition of the atmosphere, infer estimates of surface fluxes, and produce global, short-range and medium-range air-chemistry forecasts, combining remotely sensed and in-situ data with state-of-the-art modelling. Deliverables include synoptic analyses and forecasts of three-dimensional global distributions of key atmospheric trace constituents including greenhouse gases (CO_2 and CH_4), reactive gases (O_3, NO_x, SO_2, CO, and HCHO), and aerosols (dust, sea salt, organic matter, black carbon, sulphate and stratospheric aerosol). The global assimilation/forecast system also provides initial and boundary conditions for the regional air-quality ('chemical weather') forecast systems, which are run in ensemble mode on a common European domain to provide an uncertainty range together with the most likely forecast. The global system has been used to run a reanalysis for the period 2003 - 2007 and is currently also running in near-real-time (NRT) mode. On 1 June 2009 the GEMS project will be continued in the Monitoring of Atmospheric Composition and Climate (MACC) project, funded by the European Commission's Framework 7 program.

In this paper, we describe the first efforts to assimilate IASI radiances and retrieval products in the GEMS system. This is very much work-in-progress, but first results are already encouraging.

2 IASI CO retrievals

A near-real-time analysis suite for aerosol and global reactive gases has been running daily at ECMWF since July 2008 as part of GEMS pre-operational near-real-time (NRT) production stream. Retrieval products of atmospheric composition received within a 24-h time window can be assimilated in the NRT analysis. MODIS aerosol optical depth retrievals and total column ozone products from OMI and SBUV have been assimilated since the start of the NRT-analysis, and their assimilation provides satisfactory results. IASI CO retrievals became available in NRT in February 2009 from LATMOS/CNRS-ULB (Clerbaux *et al.*, 2009). Because CO retrievals from the MOPITT instrument were already succesfully assimilated in the GEMS reanalysis, we compared the CO retrievals from the two instruments as a first check. Figure 1 shows mean column CO concentrations in 10^{18} molecules/cm^2 for the period 27 August to 31 August 2008 retrieved from IASI and MOPITT. Although there are some differences between the instruments, the CO fields show very similar

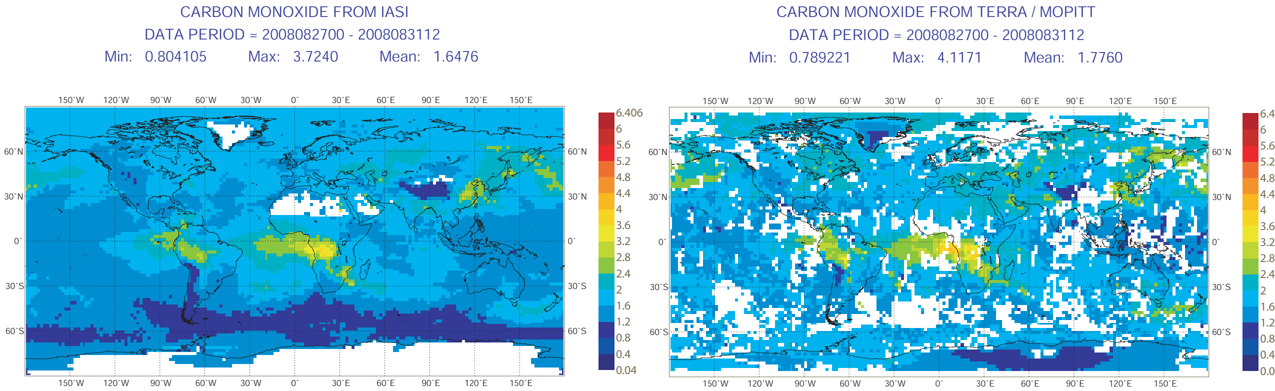


Figure 1: Four-day mean CO column concentrations for IASI and MOPITT.

patterns with similar amplitudes. The IASI CO retrievals were then assimilated in NRT with favourable results after some spin-up in which the model is slightly drawn to the observations. Figure 2 shows histograms of the observation-model differences of the IASI CO assimilation before (left) and after (right) assimilation for the northern hemisphere (top), tropics (middle), and southern hemisphere (bottom). It can be clearly seen that the bias between the observations and the model is very small and that by assimilating the data we reduce the standard deviatiuon of the observation-model differences indicating a correction of the model towards the observations. In the near future, we expect to receive the MOPITT CO retrievals in NRT allowing us to assimilate the data from both instruments. However, this will require some bias corection to resolve the small systematic difference between the CO retrievals from both instruments.

3 IASI radiance assimilation

3.1 Radiance assimilation vs. retrieval assimilation

In operational NWP radiance assimilation has been the preferred method for satellite data assimilation for more than a decade now. This was feasible, because most meteorological instruments observe in the thermal infrared and microwave parts of the spectrum for which we have accurate fast radiative transfer models. Within the GEMS and MACC projects we currently rely more on retrievals, mostly because these retrievals are based on satellite observations in the ultraviolet, visible, and near-infared parts of the spectrum. In these spectral parts, (multiple) scattering forms an important part of the radiative transfer modeling, which is only recently being dealt with in fast radiative transfer models. Theoretically, there is no difference between the two approaches as long as all the relevant information is being fed to the data assimilation system. For instance, if we denote the retrieved constituent profile by $\hat{\mathbf{x}}$ and assuming the retrieved solution was in the linear regiem around the prior profiel $\mathbf{x}_a$, we can use the following observation operator in the assimilation:

$$H(\mathbf{x}) = \mathbf{x}_a + \mathbf{A}(\mathbf{x} - \mathbf{x}_a) \tag{1}$$

with the averaging kernel $\mathbf{A}$ described by

$$\mathbf{A} = \hat{\mathbf{S}}\mathbf{K}^T\mathbf{S}_y^{-1}\mathbf{K} \tag{2}$$

amd the full retrieval error covariance matrix $\hat{\mathbf{S}}$ described by

$$\hat{\mathbf{S}} = (\mathbf{K}^T\mathbf{S}_y^{-1}\mathbf{K} + \mathbf{S}_a^{-1})^{-1} \tag{3}$$

The retrieved profile, and therefore also its error covariance matrix and the averaging kernel, should be on the same (or more) levels as the data assimilation model. Because this is a lot of data to be transferred, simplifications are often made. However, these simplifications are not without loss of information. For instance, a

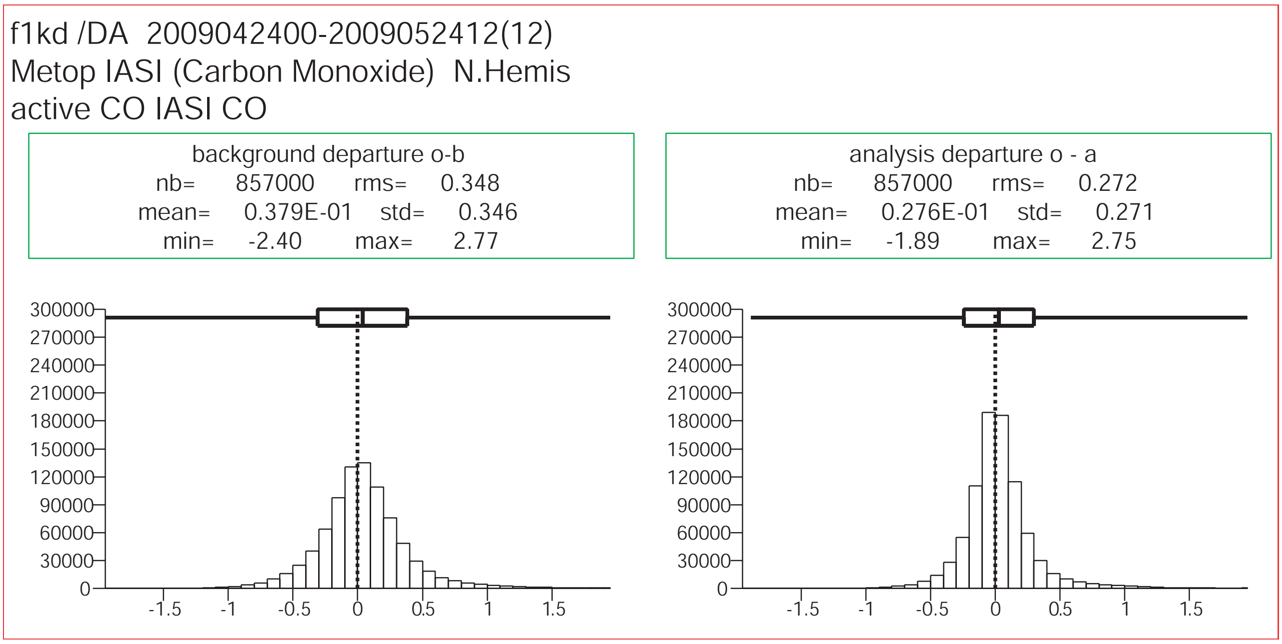


Figure 2: Histograms of the observation-model differences of the IASI CO assimilation before (left) and after (right) assimilation.

retrieved column amount can be provided using a simple integration operator $\mathbf{g}^T$:

$$\hat{z} = \mathbf{g}^T \hat{\mathbf{x}} \tag{4}$$

$$\sigma_{\hat{z}}^2 = \mathbf{g}^T \hat{\mathbf{S}} \mathbf{g} \tag{5}$$

$$\mathbf{a}^T = \mathbf{g}^T \mathbf{A} \tag{6}$$

However, the crucial information contained in $\mathbf{S}_y$, $\mathbf{K}$, and $\mathbf{S}_a$ is partly lost. Therefore, in the end one has to chose the most pragmatic solution for the problem at hand. Is it possible to process the complete retrieval information or in the other extreme the full line-by-line radiative transfer or does one have to make approximations by using simpler retrieval products (with loss of relevant information) or approximate radiative transfer models (with loss of accuracy). In the case of IASI we anticipate to use radianace assimilation for all products, although we started with the assimilation of simpel retrieval products as shown in the previous section. In the next two sections, we will therefore look at the assimilation of IASI radiances.

3.2 Bias correction

An important part of radiance assimilation is the bias correction. The assimilation system assumes un-biased gaussian distributed first-guess departures (difference between observation and model simulation) and therefore observations need to be corrected for these systematic differences. Biases can be caused by the observations themselves, the radiative transfer model, and the assimilation model itself. The general idea is to identify the cause of the bias as much as possible and then use a suitable bias correction model to correct for the bias. In its simplest form this can be a global mean fixed offset applied directly to the observed brightness temperatures. A more advanced bias model is used in the operational NWP assimialtion system, which describes the bias as a function of air-mass dependent variables. For the IASI methane sensitive channels we also observe a strong air-mass dependent bias, as shown in Figure 3. However, instead of fitting this bias with an air-mass

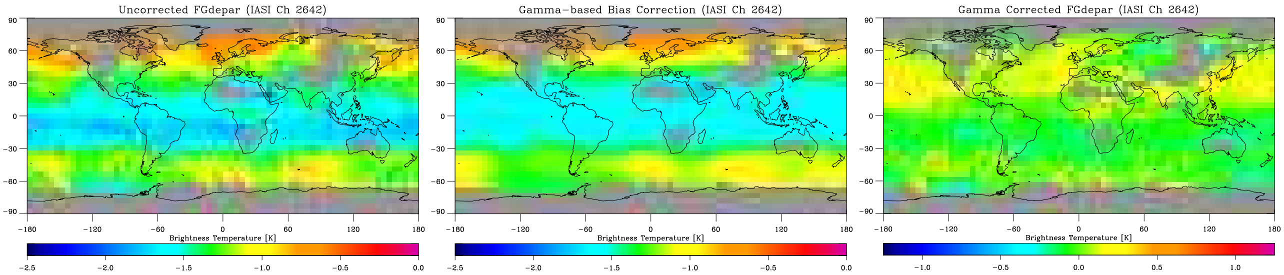


Figure 3: Uncorrected mean first-guess departures, bias correction, and corrected mean first-guess departures.

dependent model we assumed that most of the bias is coming from errors in the spectroscopy. In the thermal infrared, these sepctroscopic errors translate into brightness temperatures as a function of temperature, which explains the air-mass dependent signal in Figure 3. Therefore, the bias correction model we use is a simple global mean correction factor (γ) for the total optical depth of each channel as was proposed by Watts and McNally (2008) :

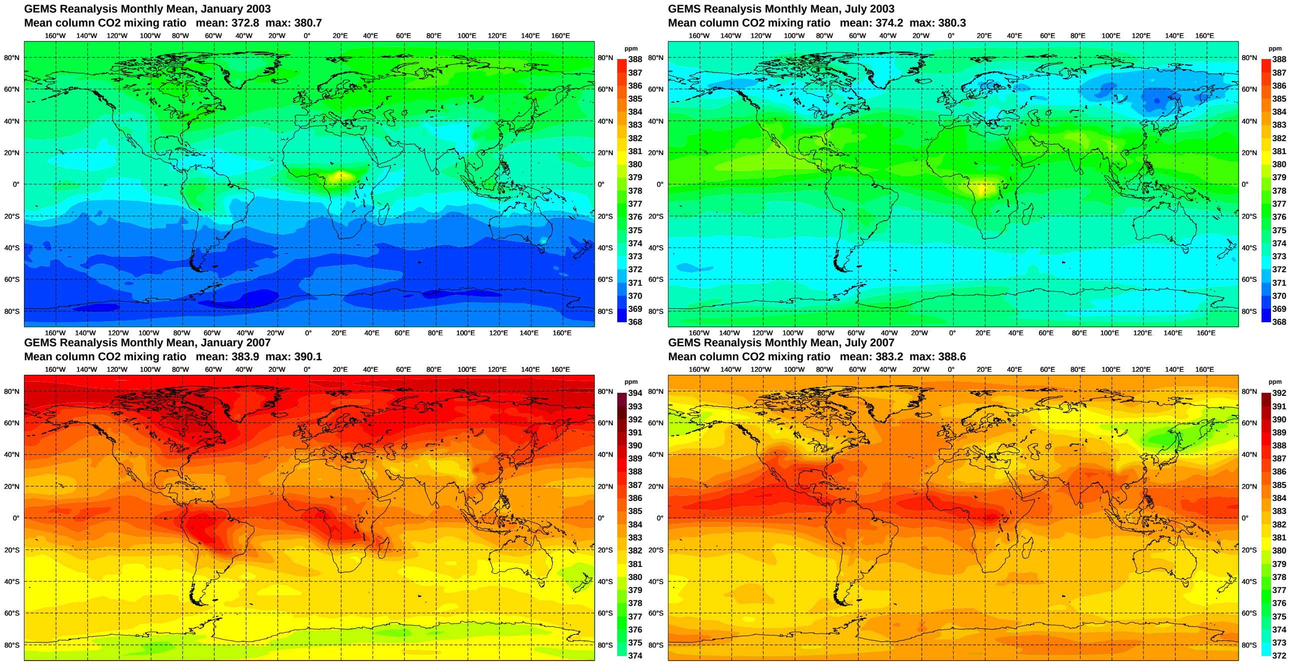
$$\mathscr{T}(p) = \exp[-\gamma \int_p^0 \kappa(p)\rho(p)\,dp] \tag{7}$$

Figure shows the brightness temperature pattern that was generated to fit the mean first-guess departures. The resulting value of γ was 1.06, which implies a 6% error in the absorption coefficient. The resulting first-guess departures are shown in Figure 3.

3.3 CO_2 results

Radiance observations from the Atmospheric Infrared Sounder (AIRS) (Aumann *et al.*, 2003) have been used in a CO2 reanalysis covering the period 2003 - 2007 (Engelen *et al.*, 2009). Monthly mean results for four different months are presented in Figure 4 showing both the seasonal variability and the annual trend. Clearly visible are biomass-burning signals over Africa as well as the strong uptake of CO_2 over Siberia in the summer. Assessing the quality of a complex system like a 4DVar is critical. As a first check on the performance of the AIRS CO_2 data assimilation, we made a comparison against aircraft observations from the NOAA/ESRL network (Tans, 1996) [see also http://www.esrl.noaa.gov/gmd/ccgg/aircraft.html]. The profiles usually observe the atmosphere between the surface and about 8 km altitude, which is more appropriate to assess the impact of AIRS on the CO_2 fields than the surface flasks. For every measured flight profile in the period January 2003 till December 2004 we have extracted profiles from an unconstrained CO_2 model run and the AIRS reanalysis. Time series were then created at 1000 m intervals for each station. For each time series the mean difference (bias) between the unconstrained model simulation and the observations and between the reanalysis and the observations was calculated as well as the standard deviation of the differences. Figure 5 shows for three altitudes (1000 m, 4000 m, and 7000 m) these bias and standard deviation values for all stations with sufficient data. The figure shows there is no significant change at 1000 m (bottom) between the unconstrained model and the AIRS reanalysis, both in bias and standard deviation. This is not surprising, because the AIRS sensitivity to CO_2 is very low at this level. Therefore, any information from the observations can only change CO_2 concentrations at this level through the transport or through the information spreading of the background covariance matrix. The latter is most likely not optimal and will therefore spread the information incorrectly. At 4000 m there is already a significant improvement in bias visible using the AIRS data and at 7000 m this improvement is very clear.

We expect to obtain very similar results from assimilating IASI radiances in the CO_2 absorption band. At least, the AIRS and IASI observations are very consistent as is illustrated in Figure 6. The figure shows the time monitoring of first-guess statistics for two (almost) identical CO_2 sensitive channels of AIRS and IASI. The



GEMS Reanalysis Monthly Mean, January 2003
Mean column CO2 mixing ratio mean: 372.8 max: 380.7

GEMS Reanalysis Monthly Mean, July 2003
Mean column CO2 mixing ratio mean: 374.2 max: 380.3

GEMS Reanalysis Monthly Mean, January 2007
Mean column CO2 mixing ratio mean: 383.9 max: 390.1

GEMS Reanalysis Monthly Mean, July 2007
Mean column CO2 mixing ratio mean: 383.2 max: 388.6

Figure 4: Monthly mean column-averaged CO_2 mixing ratios for January 2003, July 2003, January 2007, and July 2007.

systematic errors for this particular wavelength are almost identical and the standard deviation is smaller for IASI, which reflects the superior noise characteristics of IASI in the long-wave CO_2 absorption band.

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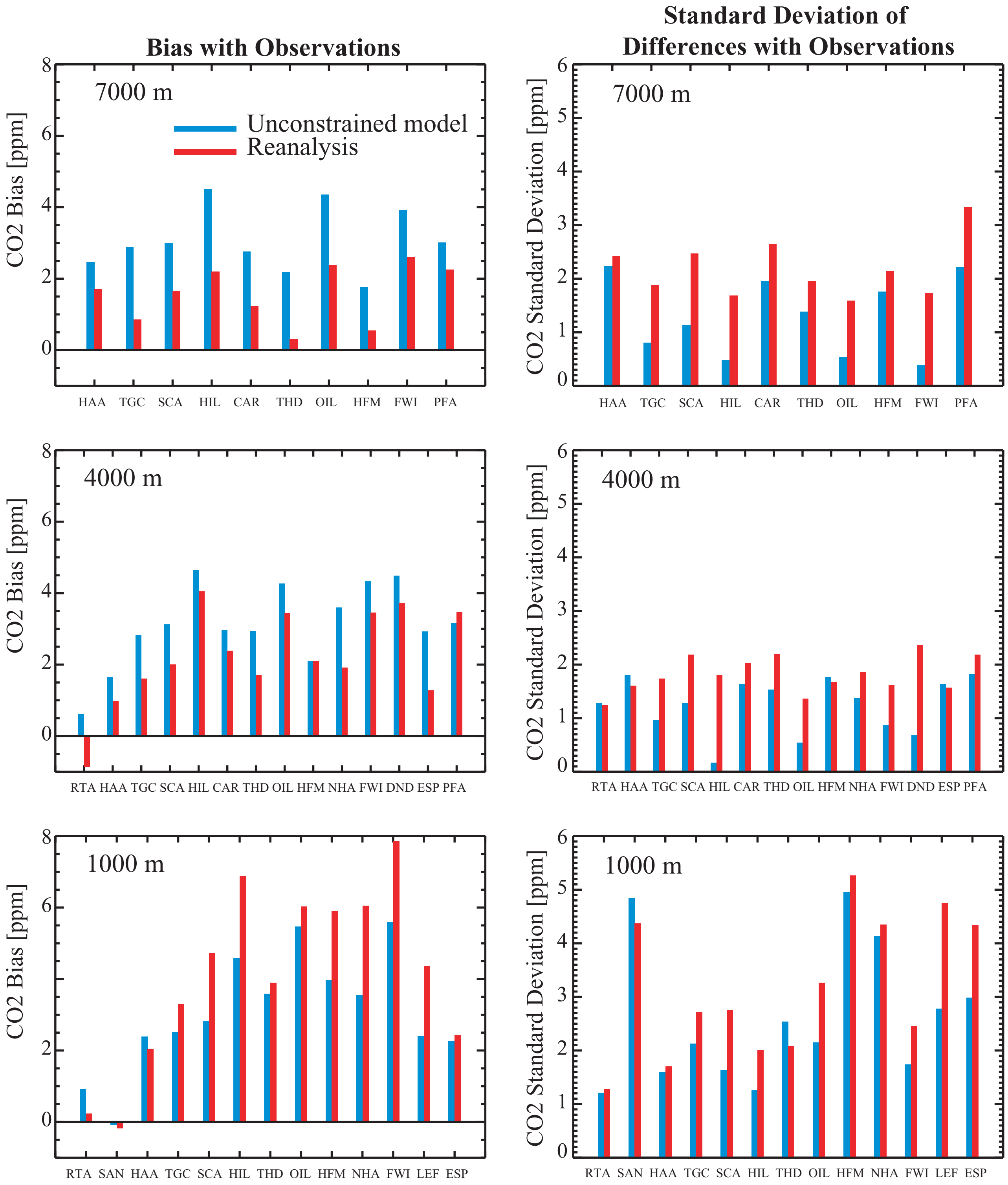

Figure 5: Bias (left) and standard deviation of the difference (right) of the unconstrained model run (blue) and the AIRS reanalysis (red) relative to independent flight observations from the NOAA/ESRL network.

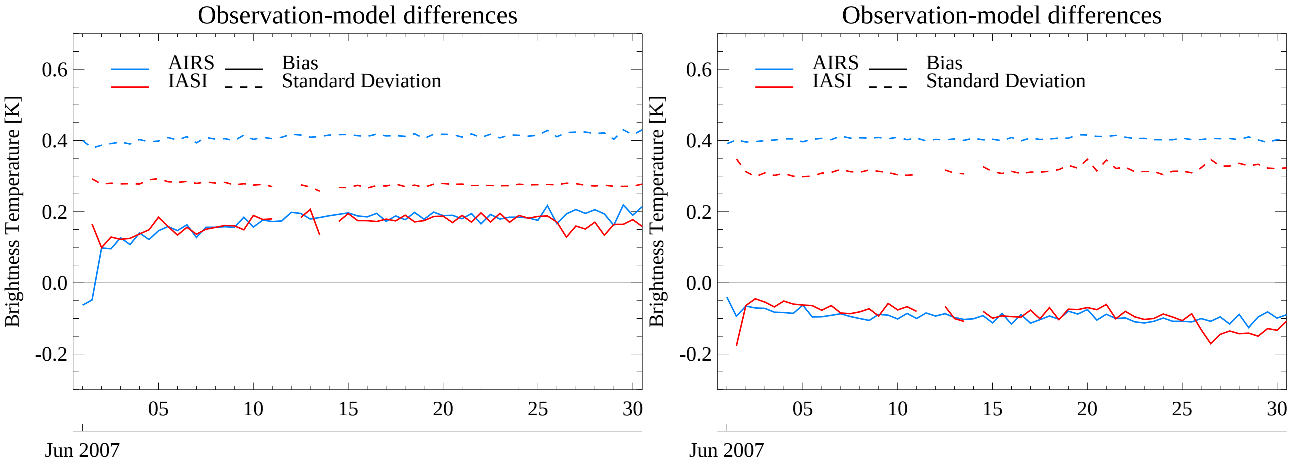

Figure 6: Time evolution of the first-guess statistics for (left) AIRS channel 210 and IASI channel 258 (14.1 μm) and (right) AIRS channel 173 and IASI channel 217 (14.3 μm).

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