Comparison results: time series

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GOME Evolution "Climate" Product v2.01 vs. ECMWF ERA-Interim
GOME Evolution "Climate" Product v2.01 vs. SSM/I HOAPS4

In order to assess the quality and stability of the GOME Evolution "Climate" product the monthly Total Column Water Vapour (TCWV) data set is compared with simulated data as well as independent satellite observations.

Reference data

The simulated H_2O total column data used here are based on the European Centre for Medium Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data set (Dee et al., 2011) and include monthly means of daily means results. ERA-Interim is the latest global atmospheric reanalysis produced by ECMWF and provides a coherent record of the global atmospheric evolution constrained by the observations during the period of the reanalysis (1979 to present). An advantage of using reanalysis data for the comparison is that they provide a global view that encompasses essential climate variables in a physically consistent framework. However, the accuracy of the data assimilation scheme will depend on the quality and availability of observations in the selected time frame. Large errors in reanalysis products can originate from the lack of observations, changes in the observing system and shortcomings in the assimilation model. Known key limitations of the ECMWF ERA-Interim data set are a very intense water cycling (precipitation, evaporation) over the oceans and positive biases in temperature and humidity (below 850 hPA) compared to radiosondes in the Artic.
Figure 1 shows the distribution of the monthly mean TCWV product in June and December 2010. In both hemispheres, the total column precipitable water vapour distribution follows the seasonal cycle of the near surface temperature and so the tropical total column precipitable water has a maximum during the northern hemisphere (NH) summer, and a minimum in winter. It is important to note that, since the SSM/I and SSMIS temperature radiance observations have been assimilated into ERA-Interim over ocean, the products are not completely independent from each other.

The GOME-Evolution Climate product is also compared with the CM SAF total column water vapour product derived from SSM/I and SSMIS observations on-board the Defence Meteorological Satellite Program (DMSP) platforms using the HOAPS (Hamburg Ocean-Atmosphere Fluxes and parameters from Satellite) algorithm for TCWV (Schlüssel and Emery, 1990; Andersson et al., 2010). The HOAPS algorithm and associated products are widely used in the scientific community and have been positively evaluated in independent retrieval assessment (Schröder et al., 2013).
The newly released HOAPS-4.0 climatology is available as monthly averages on a regular latitude/longitude grid with a spatial resolution of 0.5° x 0.5° from July 1987 to December 2014. It is based on data from SSM/I instruments on DMSP F-08, F-10, F11, F13, F14 and F15 platforms. In order to further extend the HOAPS product in time, data from the successor instrument SSMIS on DMSP F-16, F17 and F-18 were used from late 2005 onwards. All SSM/I and SSMIS instruments have been carefully recalibrated, corrected and intercalibrated. Among others, the intercalibration is carried out as function of scene temperature and accounts for diurnal cycle effects (Fennig et al., 2017).
In HOAPS-4.0 a 1D-Var retrieval was implemented to retrieve, among others, TCWV with uncertainty estimates. The OISST (Optimum Interpolation Sea Surface Temperature) data set from NCEI was used as auxiliary input. As an example, the mean TCWV distribution from HOAPS-4.0 is shown in Figure 2. The data set has global coverage, within +/- 180° longitude and +/- 80° latitude, but the product is only defined

for ice-free oceanic surface.

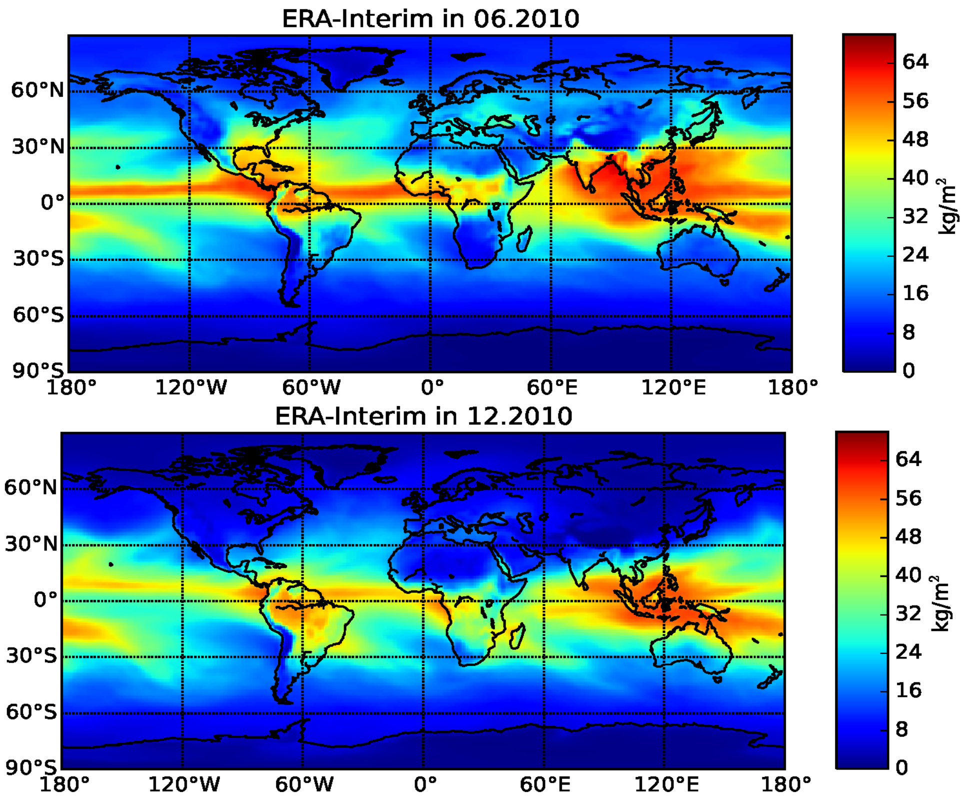

Figure 1: ECMWF ERA-Interim product: geographical distribution of the monthly mean H_2O vertical columns in June and December 2010.

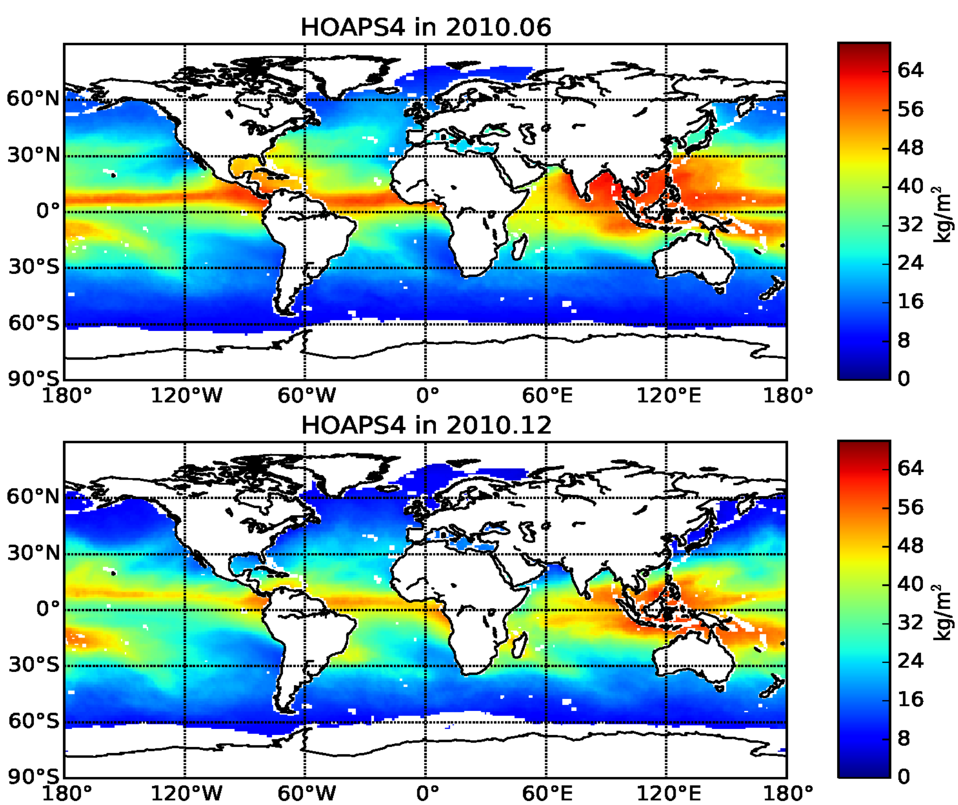

Figure 2: CM SAF HOAPS-4.0 product: geographical distribution of the monthly mean H_2O vertical columns derived from SSM/I and SSMIS measurements in June and December 2010.

Mean bias time series and stability

The GOME-Evolution Climate product has been compared with the ERA-Interim and the CM SAF monthly gridded means in the overlap period between June 1995 and December 2015 (for ERA-Interim) and June 1995 to December 2014 (for CM SAF), respectively. However, due to the sparse coverage of H_2O observations in June 1995, the results obtained in this month are skipped in the computation of the mean statistics. For the comparison all water vapour data are regridded on a regular 1.° x 1.° latitude/longitude grid. Regions north of +/-80° of latitude and land surfaces are not included in the CM SAF data set. Moreover, it should be noticed that in the GOME-Evolution Climate product observations are masked for cloudy conditions using a simple cloud masking based on the retrieved O_2 SCD (Wagner et al., 2006).

Figure 3 shows a time series of globally averaged absolute mean bias and mean RMS of the TCWV distribution between the GOME-Evolution Climate products and the reference data sets. The agreement is good for both comparisons: through the whole period the monthly bias ranges between -1.3 and 0.4 kg/m^2 in the two time series (excluding the results for June 1995). Further analysis points out a seasonal dependence in the results: the bias has systematically higher (negative) values in the northern hemisphere summer and lower values in the northern hemisphere winter months. The monthly averaged bias between the Climate product and ERA-Interim data ranges from a minimum of -1.31 kg/m^2 in June 2003 to a maximum of -0.06 kg/m^2 in February 1997 (blue line and points in the left panel of Figure 3). Even larger seasonal variations (up 1.7 kg/m^2) in the distribution of the mean bias are visible when plotting the bias between the Climate product and HOAPS-4.0 data (magenta line and points in the right panel of Figure 3). Interpreting these results, we should have in mind the limitations of GOME-type instrument retrieval. Although a specific advantage of the visible spectral region is that it is sensitive to the water vapour concentration close to the surface and that it has a comparable sensitivity over land and ocean, the accuracy of individual observations is, in general, reduced for cloudy sky conditions. Since the microwave instruments can measure the water vapour also below clouds, a seasonal cycle of the geographic distribution of the bias could be caused, among other reasons, by the seasonality of cloud properties, as well as the variability of the geographic distribution of major cloud structures as the Intertropical Convergence Zone (ITCZ).

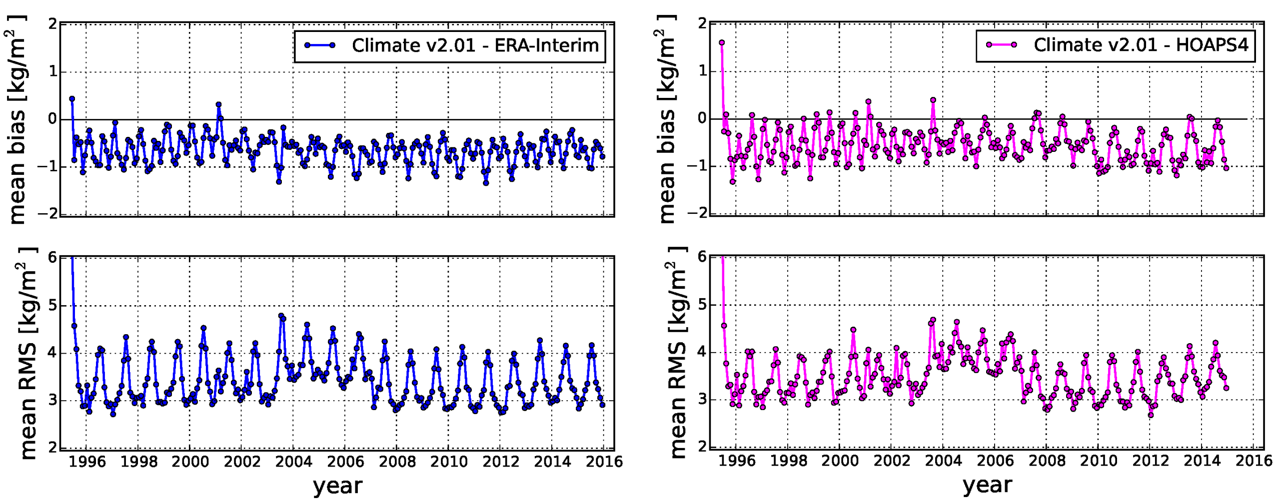

Figure 3: Left panel: Global monthly mean bias (top panel) and mean RMS (bottom panel) between the GOME-Evolution Climate product and the ECMWF ERA-Interim simulated data. Right panel: Global monthly mean bias (top panel) and mean RMS (bottom panel) between the GOME-Evolution Climate product and the CM SAF HOAPS-4.0 data set.

When averaged over the full time series the mean bias is -0.65 kg/m^2 for the comparison with ERA-Interim reanalysis and -0.60 kg/m^2 for the comparison with the HOAPS-4.0 data set, implying on average slightly drier results for the GOME-Evolution Climate product. These biases translate in percent differences of about 3%, below the optimal threshold of accuracy for water vapour products. On the other hand, the Root Mean Square Error (RMS) is larger, about 3.4-3.5 kg/m^2 on average. The RMS for the water vapour measurements is evaluated from the mean squared difference between the Climate product and the reference data in each grid point and it has a relatively high value due to the high water vapour natural variations. The bottom panels of Figure 3 also show the presence of heteroscedasticity in the time series, since the RMS is systematically higher for the period 2003-2007, although there are not inconsistencies in the bias estimate. The overall statistics are summarized in Table 1. The uncertainty margins provided for the bias and the RMSE statistics result from the spread of the bias and RMSE values in the time series.

Data	**Mean bias (kg/m^2)**	**RMSE (kg/m^2)**	**Median (kg/m^2)**	**25th PCTL (kg/m^2)**	**75th PCTL (kg/m^2)**
Climate – ERA-Interim (07.1995 - 12.2015)	-0.65 +/- 0.27 -3.18%	3.42 +/- 0.47	-0.51 +/- 0.38	-2.37 +/- 0.57	1.08 +/-0.32
Climate – ERA-Interim (07.1995 – 12.2012)	-0.65 +/- 0.28 -3.19%	3.43 +/- 0.48	-0.51 +/- 0.39	-2.38 +/- 0.58	1.09 +/- 0.33
Climate – HOAPS4 (07.1995 – 12.2014)	-0.55 +/- 0.34 -2.71%	3.49 +/- 0.43	-0.56 +/- 0.23	-2.76 +/- 0.36	1.54 +/- 0.50
Climate – HOAPS4 (07.1995 - 12.2012)	-0.54 +/- 0.33 -2.67%	3.49 +/- 0.44	-0.55 +/- 0.24	-2.74 +/- 0.37	1.55 +/- 0.49

Table 1: Bias and RMS statistics. The computations refer to the average difference between the GOME-Evolution Climate product and the reference data sets. The time periods considered are July 1995 - December 2015 for the comparison Climate – ERA-Interim, and July 1995 - December 2014 for the comparison Climate - HOAPS-4.0. Also the results for the period July 1995 to December 2012 are shown to demostrate that the issue with the stability of the time series which was present in the GOME-Evolution Climate product version 1.0 is now solved.

A negative but very small stability was found based on a simple linear least-square regression analysis applied to the mean bias time series: -0.07+/-0.03 kg/m^2 per decade for the differences with the ERA-Interim data and -0.09 +0.04 kg/m^2 per decade for the HOAPS-4.0 data. The small p-values (<0.05) indicate that these results are statistically significant. However, in order to take into account the serial correlation, an augmented Dickey-Fuller (ADF) test is applied to test the null hypothesis of whether a unit root is present in the time series. The trend-stationarity is used as alternative hypothesis. The p-value associated to the ADF statistic indicates that we cannot reject the null hypothesis: the test statistic is lower that the 10% critical value for both bias time series.

In the left panel of Figure 4 the global mean bias between the GOME-Evolution Climate product and the ECMWF ERA-Interim data set is computed separately for land (green line) and ocean surfaces (blue line). Over land a larger variability in the mean bias and RMS with seasons is observed, consistently with the results observed in the validation against radiosonde (see Table 1). Especially in the summer months, we notice a really negative bias over land areas, a problem which has been already observed in the validation of the GOME-2 Level 2 data (see Grossi et al., 2015) and probably depending on larger saturation effects in the GOME-type measurements. The results over ocean, on the other hand, agree very closely with the bias computed between the Climate product and the CM SAF HOAPS-4.0 data set, as can be seen in the right panel of Figure 4.

Data	Mean bias (kg/m^2)	RMSE (kg/m^2)	Median (kg/m^2)	25th PCTL (kg/m^2)	75th PCTL (kg/m^2)
Climate – ERA-Interim Land (07.1995 - 12.2015)	-1.71 +/- 0.71	3.45 +/- 0.64	-1.19 +/- 0.95	-3.06 +/- 1.14	0.16 +/-0.39
Climate – ERA-Interim Ocean (07.1995 – 12.2015)	-0.25 +/- 0.31	3.29 +/- 0.38	-0.28 +/- 0.26	-2.08 +/- 0.44	1.53 +/- 0.44

Table 2: Bias and RMS statistics. The results refer to the average difference between the GOME-Evolution Climate product and the ERA-Interim data set between July 1995 and December 2015, computed separately for land and ocean surfaces.

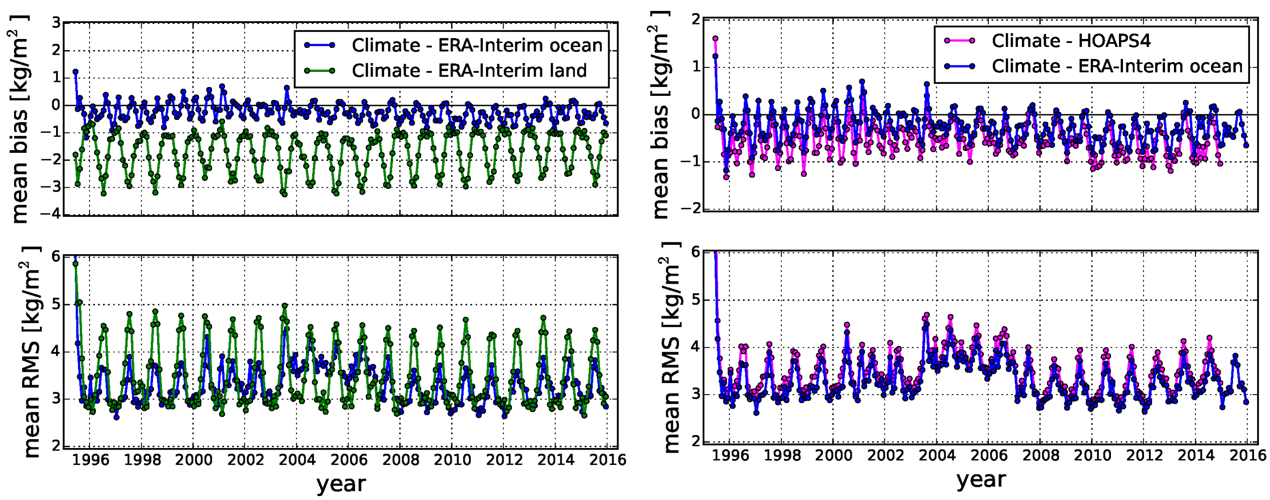

Figure 4: Left panel: Global monthly mean bias (top panel) and mean RMS (bottom panel) between the GOME-Evolution Climate product and the ECMWF ERA-Interim simulated data. The results are computed separately for land (green lines) and for ocean surfaces (blue line) Right panel: Global monthly mean bias (top panel) and mean RMS (bottom panel) between the GOME-Evolution Climate product and the CM SAF HOAPS-4.0 data set (magenta lines). Also shown for comparison is the bias and RMS with respect to the ERA-Interim data over ocean (blue lines).

In Figure 5 the mean and median bias and the associated standard deviations are aggregated by month over all years of our investigation: July 1995 to December 2015 for the bias with respect ERA-Interim simulated data (left panel) and July 1995 to December 2014 for the HOAPS-4.0 data set (right panel). In this way we further analyzed the seasonal component of the bias between the GOME-Evolution Climate product and the reference data. Looking at the blue and green histograms we can notice a systematic variance in the retrieved values, especially for the comparison against ERA-Interim data. A larger negative mean and median bias is observed in the northern hemisphere summer month and smaller bias in the winter month. The mean aggregated bias ranges between -1.04 kg/m^2 in June and -0.25 in February. High bias values retrieved in summer are associated prevalently to land areas. In particular, the humidity in Central Africa in June is much lower in the GOME-Evolution Climate product than in the ERA-Interim data set and absolute and relative differences can be larger than 10 kg/m^2 and 20% in this region. Even stronger differences are located in the region from India to the east coast of China and can be correlated to increasing humidity and stronger saturation effects in the GOME-type measurements (already observed in the Level 2 data). For the comparison against HOAPS-4.0 data, on the other hand, the months with highest and lowest mean bias are November and August, -0.82 kg/m^2 and 0.04 kg/m^2, respectively. A large positive bias is visible in the summer months in regions at high latitude, in particular the northern areas of the Atlantic and Pacific oceans. These areas are the dominating cause of the seasonal variations in the time series of the differences between the Climate product and the HOAPS-4.0 data set and were already observed in the comparison with Level 2 SSM/I and SSMIS measurements. Finally, in both comparisons the standard deviation associated to the bias (red histograms) is larger in the summer months, since there is a larger spread in the data distribution.

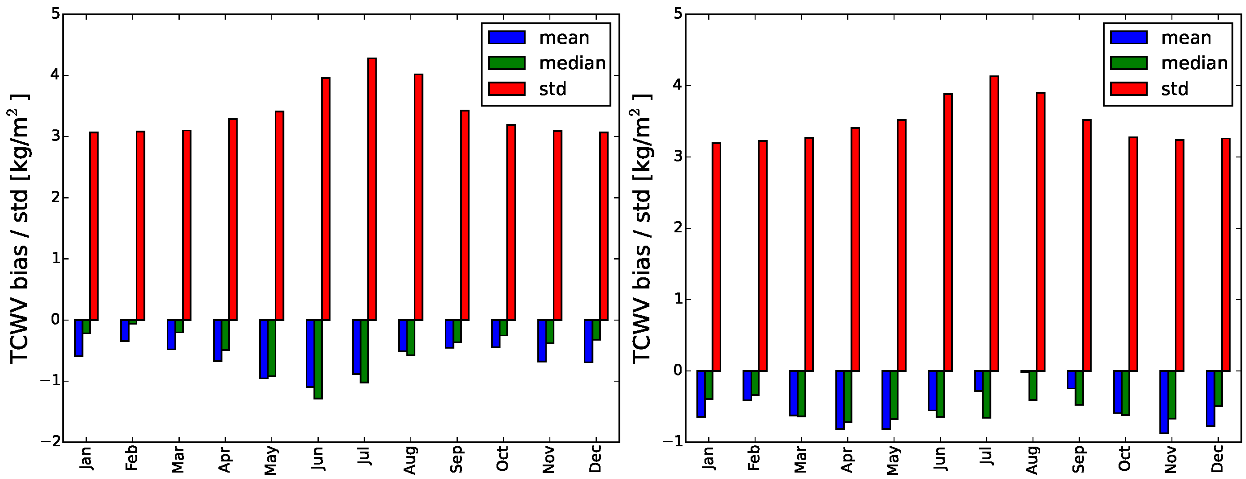

Figure 5: Mean bias (blue histograms), median bias (green histograms) and standard deviations (red histograms) derived from the comparison between the GOME-Evolution Climate product and the ERA-Interim data set (left panel) and the HOAPS-4.0 data set (right panel) and aggregated by months over the time period July 1995 to December 2015 and July 1995 to December 2014, respectively.

Some references :

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Schröder, M., Jonas, M., Lindau, R., Schulz, J., and Fennig, K. (2013): The CM SAF SSM/I-based total column water vapour climate data record: methods and evaluation against re-analyses and satellite. Atmos. Meas. Tech., 6, 765–775, doi:10.5194/amt-6-765-2013

Some more Figures:

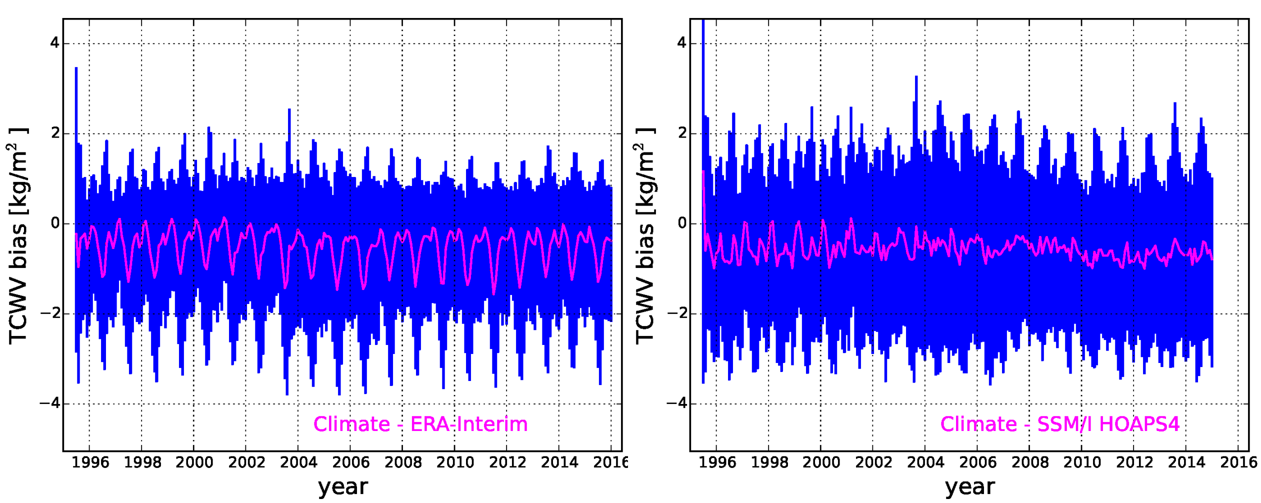

Figure 6: Global monthly median bias between the GOME-Evolution Climate product and the ERA-Interim simulated data (left panel) and between the GOME-Evolution Climate product the HOAPS-4.0 data set (right panel).

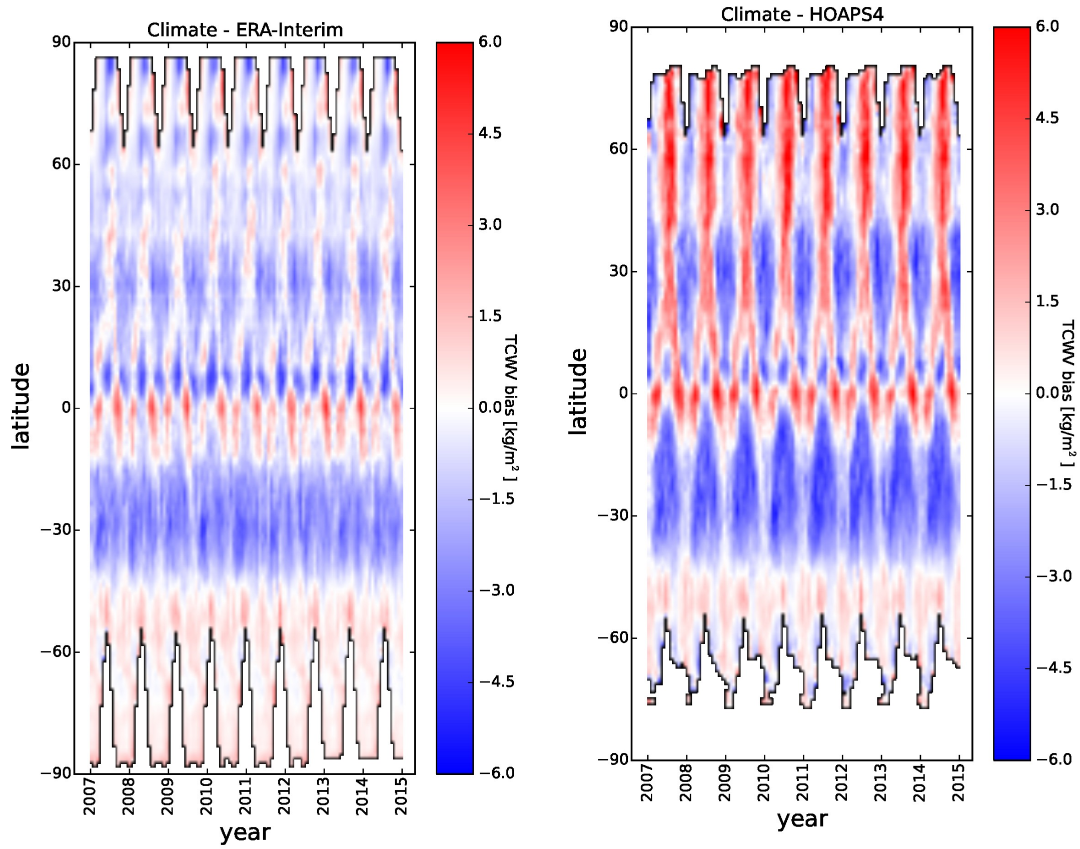

Figure 7: Contributions to the monthly bias between the Climate product and ERA-Interim (left panel) and the Climate product and the HOAPS-4.0 (right panel) as a function of the latitude bin.

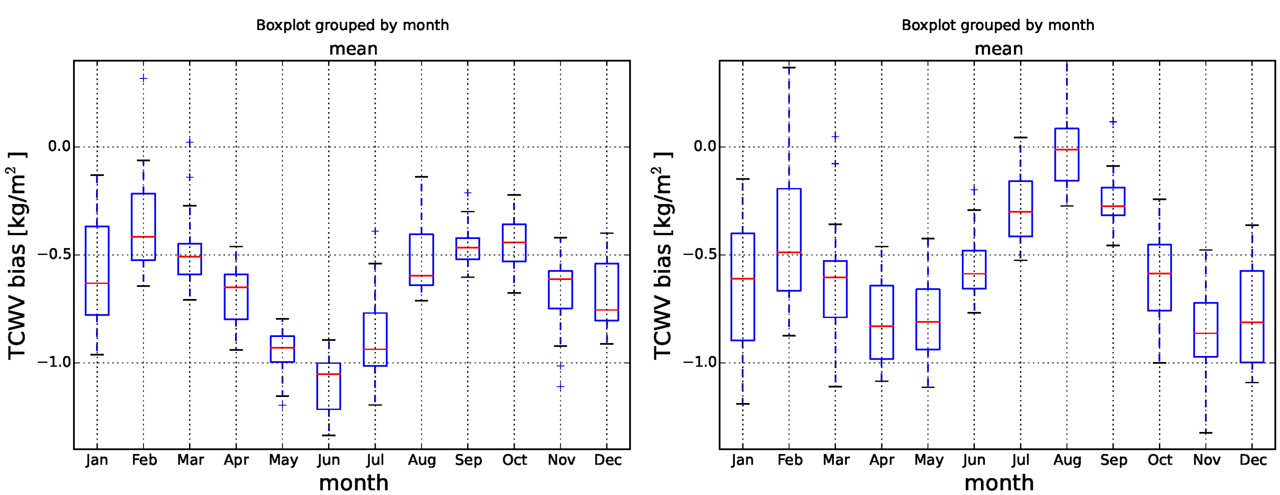

Figure 8: Box plot of the bias between the Climate product and the ERA-Interim data aggregated by month over the time period July 1995 to December 2015 (left panel) and between the Climate product and the HOAPS-4.0 data set over the time period July 1995 to December 2014 (right panel).

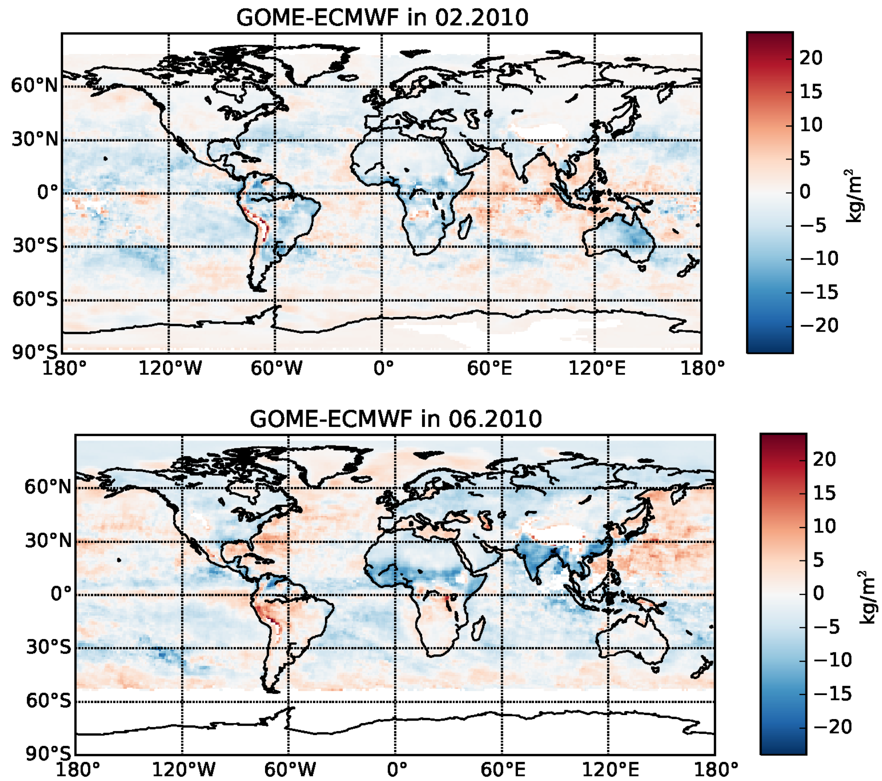

Figure 9: Geographical distribution of the differences observed comparing the GOME-Evolution Climate product and the ECMWF ERA-Interim simulated data in February 2010 (top panel) and June 2010 (bottom panel).

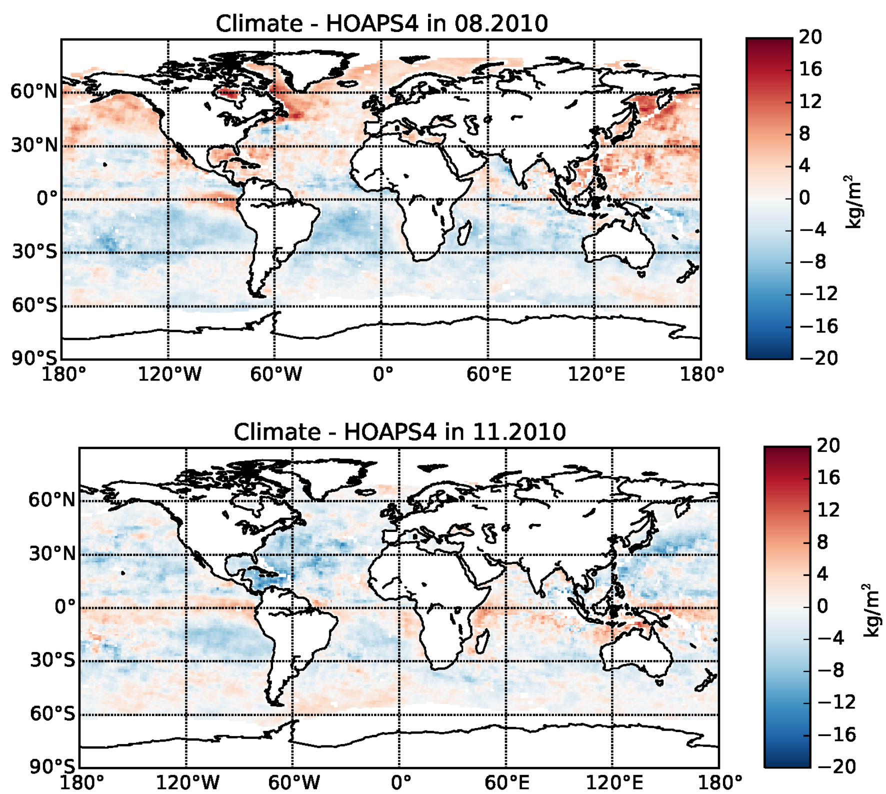

Figure 10: Geographical distribution of the differences observed comparing the GOME-Evolution Climate product and the CM SAF HOAPS-4.0 data set in August 2010 (top panel) and November 2010 (bottom panel).