Appendix

On the estimation of regional CO_2 fluxes from GOSAT data and the simulation of three-dimensional CO_2 concentration distributions based on the flux estimates

The GOSAT Project, a joint undertaking of the Ministry of the Environment Japan, the National Institute for Environmental Studies, and the Japan Aerospace Exploration Agency, has been providing the general public with the global distribution data of CO_2 concentrations (column-averaged dry air mole fractions of CO_2, hereafter referred to as X_{CO2}) retrieved from GOSAT data obtained over clear-sky regions. The X_{CO2} retrievals were updated in June 2012 and the data have been made available to the general public as version 2 of the GOSAT FTS SWIR Level 2 data product. Through comparison with reference data obtained with high-resolution Fourier transform spectrometers installed at ground-based observational sites, the mean and standard deviation of the differences (biases) were found to be -1.2 ppm and 2.0 ppm, respectively, which are much smaller than the corresponding values for version 1 data product. The number of the concentration data also increased by 30 to 50% (depending on the season) compared to the version 1 data product.

Researchers of the Project estimated regional CO_2 fluxes from the improved GOSAT X_{CO2} retrievals and from data collected by networks of surface CO_2 monitoring stations, via inverse modeling. Until recently, regional CO_2 fluxes were inferred from the ground-based network data obtained at about 200 monitoring stations around the globe. Since many of the monitoring stations are located in the developed nations, the uncertainties of fluxes estimated for regions located far from the monitoring networks were sizable. The researchers confirmed that these uncertainties were reduced by using the GOSAT X_{CO2} retrievals. The regional CO_2 flux estimates and their uncertainties calculated for twelve months from June 2009 to May 2010 will now be made available to the general public as the GOSAT Level 4A data product.

1. Method of CO_2 flux estimation

CO_2 fluxes for 64 regions of the globe (Figure 1, left) were estimated on a monthly basis from both the GOSAT X_{CO2} retrievals and ground-based CO_2 monitoring data (GLOBALVIEW-CO2; hereafter referred to as GV). The locations of the GV monitoring stations are shown on the right panel of Figure 1. Blanks in the ground-based monitoring network are found in South America, Africa, Middle and Near East, and Asia. Prior to their use in the inverse modeling process, the weekly GV values were converted into monthly means. The GOSAT X_{CO2} retrievals, after correcting their biases by adding 1.2 ppm to all X_{CO2} values, were gridded to 5°×5° latitude-longitude grids and averaged on a monthly basis.

As examples, the GV values and the bias-corrected GOSAT X_{CO2} retrievals for July 2009 and January 2010 (summer and winter in the Northern Hemisphere, respectively) are displayed in Figure 2. These two panels show that GOSAT X_{CO2} retrievals successfully fill out the blanks in the ground-based monitoring network, except for the high-latitude regions of the Northern Hemisphere where local solar zenith angles are low, and for regions that are frequently covered by clouds and aerosols.

Figure 3 shows the regional CO_2 flux estimates and their uncertainties for these selected months. It should be noted here that with the computation scheme used, the July and January fluxes were estimated not only from observations in the corresponding months but also from neighboring months. The results for

July, during which the photosynthetic activity of terrestrial plants in the Northern Hemisphere is high, show that many regions in the Northern Hemisphere are net sinks of CO_2 (indicated with green color). Most of these regions in January, during which the plant photosynthesis is generally weak in the Northern Hemisphere, are shown to be net sources of CO_2 (red color). Region #20 (Figure 1, left) is mostly desertic and its net CO_2 balance throughout the one-year period was estimated to be nearly zero.

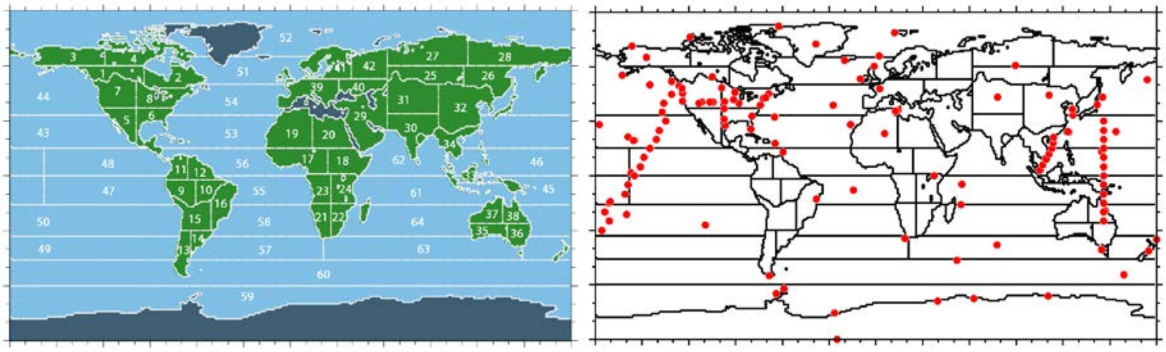

Figure 1. Left: Boundaries of the 64 regions used for inverse modeling. The numbers embedded in the figure are region IDs. Regions in dark blue are not considered in the flux estimation. Right: locations of the ground-based monitoring stations (red dots; including airborne and ship-based sites) whose data were used in this analysis.

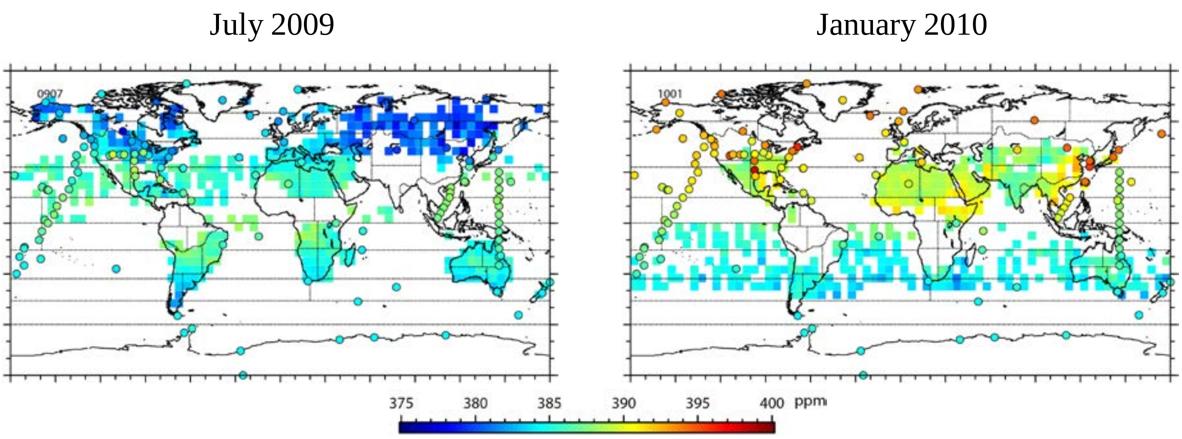

Figure 2. 5°×5° gridded GOSAT X_{CO2} retrievals (squares) and ground-based GV concentrations (circles) used as input for the inverse modeling (monthly means). Left: July 2009 (summer in the Northern Hemisphere). Right: January 2010 (winter in the Northern Hemisphere).

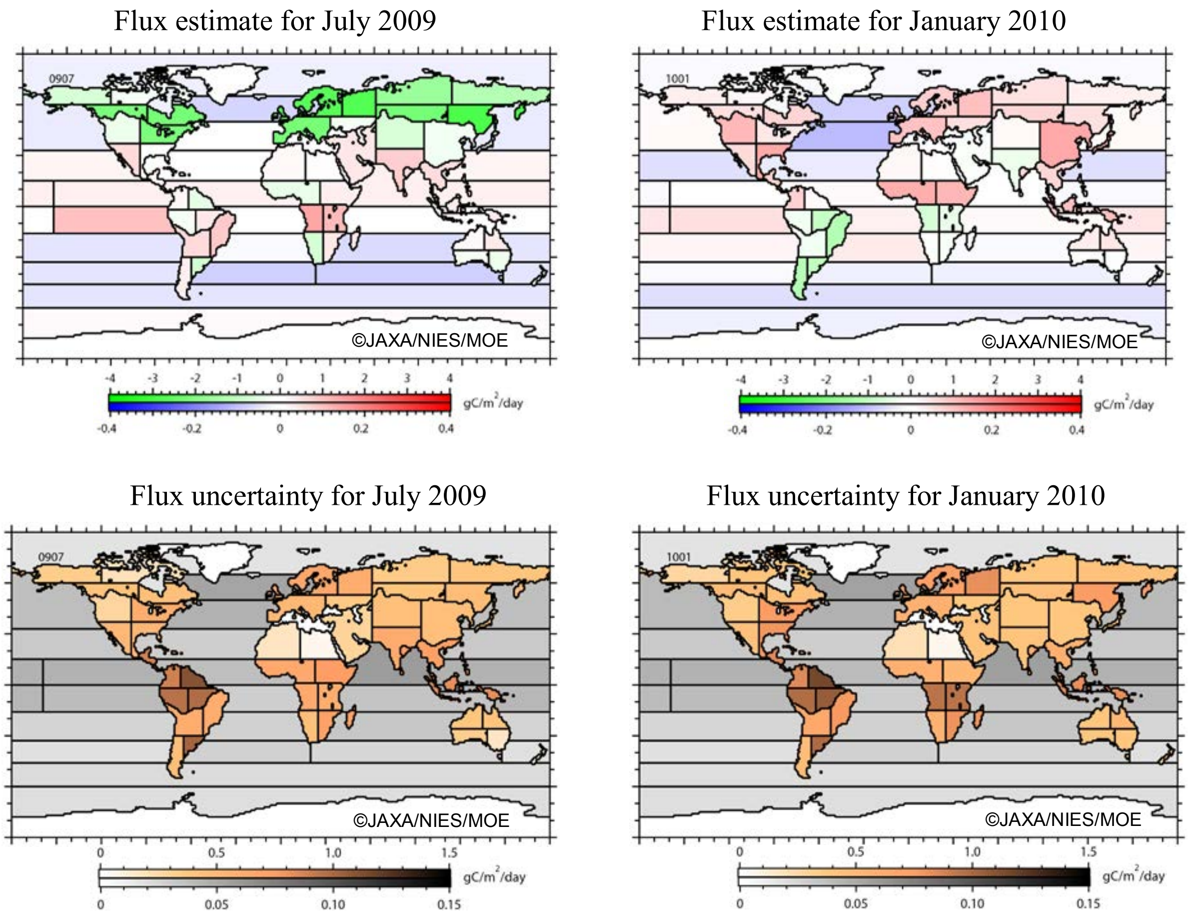

Figure 3. Fluxes (upper panels) and uncertainties (lower panels) estimated for 64 regions. Left: July 2009 (summer in the Northern Hemisphere). Right: January 2010 (winter in the Northern Hemisphere).

2. Evaluating the utility of GOSAT data

(1) Uncertainty of flux estimates

To evaluate the utility of GOSAT X_{CO2} retrievals for regional flux estimation, CO_2 fluxes and their uncertainties for the 64 regions over the one-year period were inferred from

1) GV data only and

2) both GV data and GOSAT X_{CO2} retrievals.

Here, the utility was evaluated based on the rate of reduction in flux uncertainty (UR) in percent. It is expressed as

$$\mathrm{UR} = \left(1 - \frac{\sigma_{GV+GOSAT}}{\sigma_{GV}}\right) \times 100$$

,

where σ_{GV} and $\sigma_{GV+GOSAT}$ denote the uncertainty of a monthly flux value estimated from GV data only and from both GV data and GOSAT X_{CO2} retrievals, respectively. Flux estimates associated with larger UR values are considered to be better characterized if the GOSAT X_{CO2} retrievals are used in the analysis.

(2) Uncertainty reduction

It was confirmed that through the addition of GOSAT X_{CO2} retrievals to the GV data, the uncertainties of monthly flux estimates for the blank regions of the ground-based monitoring network (e.g. South America, Africa, Middle and Near East, and Asia) were reduced by as much as about 60%. Figure 4 shows annual mean UR values for the 64 regions. The maximum annual-mean reduction rate was approximately 40%.

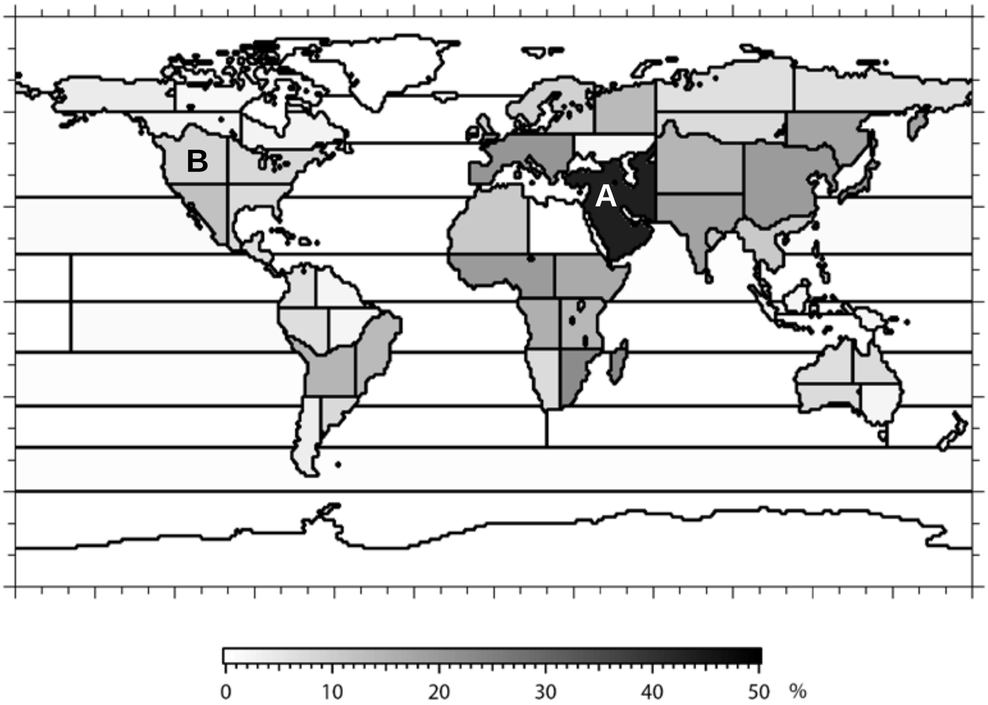

Figure 4. The rate of reduction in the uncertainty of monthly CO_2 flux estimates, achieved by adding GOSAT X_{CO2} retrievals to GV data. The values shown are annual means over the June 2009-May 2010 analysis period.

As an example, flux estimates and flux uncertainty reduction for two regions, Middle and Near East (Region A in Fig. 4) and north-western temperate North America (Region B in Fig. 4), are contrasted here. Regions A and B represent locations where the ground-based monitoring stations are sparse and dense, respectively. In Figure 5, the time series of monthly fluxes and their uncertainties estimated from GV data only and from both GV data and GOSAT X_{CO2} retrievals are presented. The solid lines in the figure show fluxes estimated from GV data (red) and from both GV data and GOSAT X_{CO2} retrievals (blue). The vertical bars (gray) indicate monthly uncertainty reduction rates (values are shown on the right axis). The green line and the green shaded area show the value of the a priori flux and uncertainty used in the inverse modeling. The a priori flux estimates are based on the inventories of anthropogenic emissions and wildfire emissions, and on model-simulated estimates of CO_2 exchange by terrestrial vegetation and oceans.

The GV-based monthly fluxes inferred for Region A (Middle and Near East) are associated with large uncertainty (red error bar) since the estimation of the fluxes is based on measurements taken far from this region. By adding the GOSAT X_{CO2} retrievals to the GV data, the uncertainty of the fluxes was reduced significantly (blue error bar). In contrast, a relatively large number of ground-based monitoring stations are located within and nearby Region B (north-western temperate North America). In addition, the data obtained at the ground-based monitoring stations have higher precision than the GOSAT X_{CO2} retrievals. Therefore, they have a larger influence on the determination of the region's flux values. Because of this, the fluxes and their uncertainties estimated from GV data only and from both GV data and GOSAT X_{CO2} retrievals are nearly identical over the analysis period.

In this inverse modeling analysis, the anthropogenic and wildfire emissions were both treated as known, and the CO_2 exchanges by terrestrial vegetation and oceans were optimized. Therefore, the changes in the flux estimates from red to blue seen in Figure 5, which are associated with larger uncertainty reduction rates, are considered as the result of the flux optimization by the additional information brought by GOSAT observations. For instance, the flux estimates for region A suggests that uptake in June 2009 and release in March and April 2010 by the terrestrial vegetation of this region were both smaller than what were estimated from the ground-based data only, even when the range of uncertainty was taken into account.

The above instance demonstrates that flux estimates for remote regions, located far from the ground-based monitoring stations and thereby associated with large uncertainties (e.g. the western seaboard regions of central Africa, south eastern Africa, Middle and Near East, and India) can be improved if the GOSAT X_{CO2} retrievals are used in the analysis.

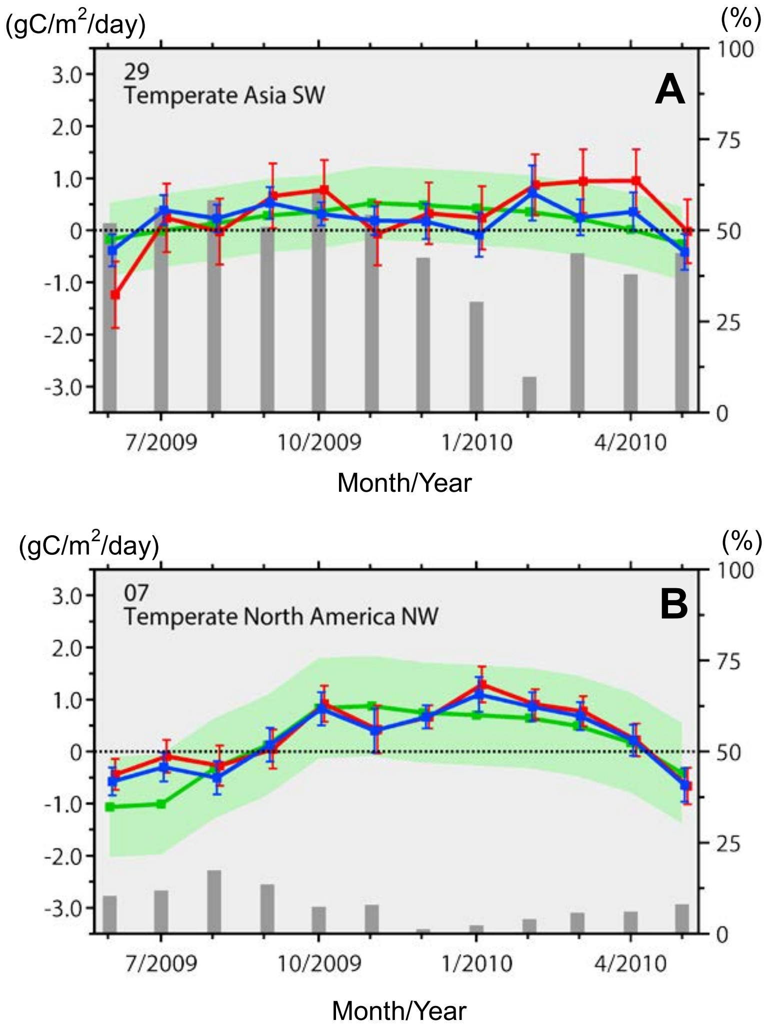

Figure 5. Time series of monthly fluxes and their uncertainties estimated from GV data only (red) and from both GV data and GOSAT X_{CO2} retrievals (blue). The vertical bars (gray) indicate monthly uncertainty reduction rates (values are shown on the right axis). The green line and the green shaded area show the values of the a priori flux and its uncertainty used in the inverse modeling. Upper panel: Middle and Near East (Region A in Figure 4; south western temperate Asia). Lower panel: north western temperate North America (Region B in Figure 4).

It should be noted, however, that these results are dependent on the quality of GOSAT X_{CO2} retrievals. Currently, GOSAT-based X_{CO2} values are also retrieved at several research institutes other than the National Institute for Environmental Studies. Figure 6 shows the mean and spread (one standard deviation) of the flux estimates for regions A and B based on five independently-retrieved X_{CO2} datasets. The green line and the shaded area show the mean and spread. The blue solid line shows the flux estimates based on the GOSAT Level 2 X_{CO2} retrievals. The spread suggests that flux values can vary depending on which X_{CO2} dataset is used for the flux estimation, and that there is still room for further improvement of the X_{CO2} retrieval algorithms.

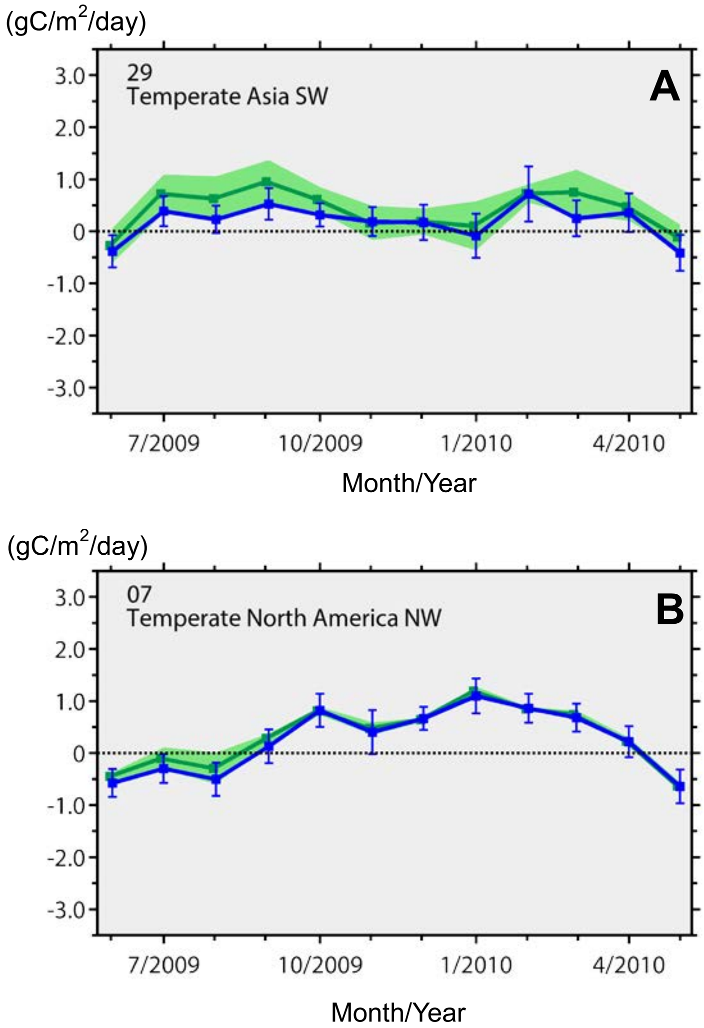

Figure 6. Mean (green solid line) and spread (green shade) of flux estimates for Middle and Near East (Region A in Figure 4) and north-western temperate North America (Region B in Figure 4) based on five independently-retrieved X_{CO2} datasets. The blue solid line shows the flux estimates based on the GOSAT Level 2 X_{CO2} retrievals. The same inverse modeling scheme and a priori data were used for processing each of the five X_{CO2} datasets.

The flux estimates obtained at this time are based on the assumption that the bias in the GOSAT Level 2 X_{CO2} retrievals is uniform throughout the globe and over the one-year analysis period. The flux estimates may change with further research.

3. Three-dimensional simulation of CO_2 concentrations based on the monthly flux estimates

The global distribution of CO_2 concentrations in the three-dimensional space can be modeled by using the calculated CO_2 flux estimates. The outcome of such simulation, the six-hourly CO_2 concentration on 2.5

degree latitude-longitude grid at 17 vertical levels, will be distributed to the general public as the GOSAT Level 4B data product.

Figure 7 presents the distribution of simulated CO_2 concentrations (monthly average) at an altitude of approximately 5000 m. Results for July 2009 and January 2010 are shown. The influence of anthropogenic and wildfire emissions are considered in the simulation. These simulation results are expected to be used for carbon cycle studies in regions where neither ground-based CO_2 observations nor GOSAT X_{CO2} retrievals are available. The simulated CO_2 concentration is affected by some uncertainty, and should be verified through comparison with ground-based reference values.

The simulation results can be viewed at the NIES GOSAT Project website, after the statement by the Japanese Minister of the Environment at UNFCCC COP18. (URL: https://data.gosat.nies.go.jp/ – Click on "Gallery" in the left column to access the plots).

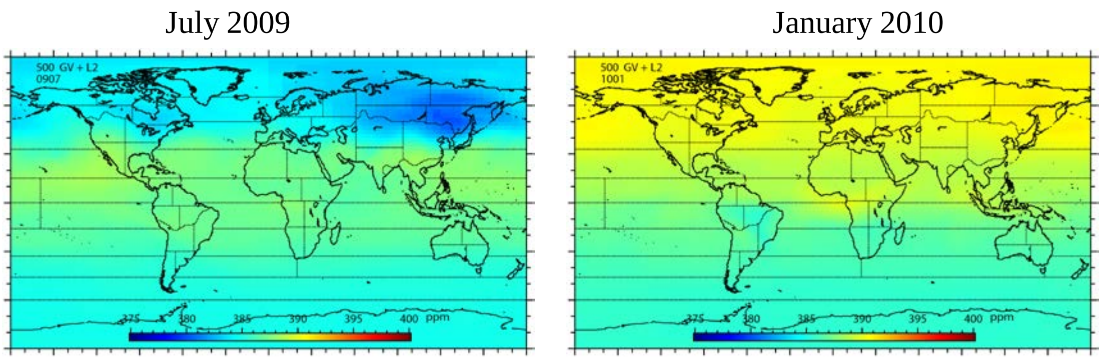

Figure 7. Distribution of simulated CO_2 concentrations (monthly average) at an altitude of approximately 5000 meters. Left: July 2009 (summer in the Northern Hemisphere). Right: January 2010 (winter in the Northern Hemisphere). These are simulation results based on the CO_2 flux estimates obtained and are affected by some uncertainty.