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Estimation of the total CO_2 content of the atmosphere from satellite observations

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Abstract: Stabilization of the total CO_2 content of the atmosphere is the target of the climate strategies that are proposed for climate change mitigation. The accuracy of our knowledge about the total CO_2 content of the atmosphere, its growth and seasonal variations depends on the size of geographic coverage of the CO_2 monitoring network. A good opportunity to enhance the monitoring network arose recently due to the launch of the Greenhouse gases Observing Satellite (GOSAT). The data coming from GOSAT provide unprecedented geographic coverage of column averaged CO_2 concentrations and, therefore, may have the potential to improve the estimates of the atmospheric CO_2 content. This paper presents the algorithm (and an example of its implementation) for calculating monthly values of the total CO_2 content in the atmosphere proceeding from the GOSAT data. The algorithm presented in this paper is to facilitate the integration of GOSAT data into the current activities on monitoring the total CO_2 content of the atmosphere.

***Keywords**:* climate change, carbon dioxide**,** atmosphere, satellite observations, environmental monitoring

1 INTRODUCTION

The total CO_2 content of the atmosphere, reported in GtC, Gt-CO_2, or in ppm is calculated from the global average CO_2 concentration [Conway and Tans, 2010]. Since the latter is calculated from the CO_2 concentrations measured at monitoring stations [Conway et al., 1994; Masarie and Tans, 1995], the accuracy of the result depends on the size and geographic coverage of the CO_2 monitoring network. A good opportunity to enhance the monitoring network arose recently due to the launch of the Greenhouse gases Observing Satellite (GOSAT) [JAXA, 2010; Kasuya et al., 2009; NIES, 2010].

GOSAT provides unprecedented geographic coverage of column averaged CO_2 concentrations (XCO_2). The data coming from GOSAT [Yokota et al., 2009] may have, therefore, a potential to improve the estimates of the atmospheric CO_2 content [Heimann, 2009]. This paper reports on our progress in developing an algorithm for calculating monthly values of the total CO_2 content of the atmosphere proceeding from the GOSAT data.

2 RESULTS AND DISCUSSION

The algorithm is written in Mathematica language [Wolfram, 1999; Wolfram, 2010], and is freely available on request as a Mathematica package file. The package file contains the source code of the functions that one may need to calculate atmospheric CO_2 content proceeding from the GOSAT data. Although Mathematica notation is quite understandable, the use of functions is explained in more simple language below (subsection 2.1). The subsection 2.2 is to discuss the validity of the developed algorithm, and the section 2.3 is to discuss the scientific significance of the algorithm as a tool for exploring the potential of the GOSAT data.

2.1 Algorithm

Calculation of the atmospheric CO_2 content for a given month consists of following major steps:

1. Read GOSAT data and compile the array of XCO_2 for the given month;
2. Interpolate GOSAT data along the geographic grid of half-degree resolution;
3. Calculate the average of interpolated values.

The GOSAT data on daily XCO_2 are provided as a set of HDF files. Each file contains information about the coordinates of the points of observations, observed values, and some additional information. The function GetDataForDay[yyyymmdd] selects the marine observations and forms a list of records {longitude of the cell where the observation point falls, latitude of the cell where the observation point falls, observed XCO_2 in ppm} for the day yyyymmdd (e.g., "20091109"). It should be noted here that we use GOSAT data over oceans only. This is essential for making the results of calculations compatible with the global average monthly [CO_2] reported by NOAA/ESRL.

The function GetDataForMonth[yyyymm] forms the list of similar records for the month yyyymm (e.g., "200911"), namely, {longitude of the cell where the observation point falls, latitude of the cell where the observation point falls, the average of XCO_2 observed within this cell during the given month}.

Thus compiled observations are first interpolated along latitudes. The function LatitudinalInterpolation constructs an approximate function that interpolates the data along the given latitude (that is, the list of records {longitude, XCO_2}) and gives the row of 720 interpolated XCO_2 values. Applying this function to all latitudes (precisely, latitudinal belts of half-degree width), we obtain the list of records {latitude, {the row of 720 interpolated XCO_2 values}}, which "columns" serve as the input for MeridionalInterpolationR function. This function interpolates observations from the points on the same longitude between the maximal and minimal latitudes of observations. That is, each of the "columns" mentioned above is the list of records {latitude, interpolated XCO_2 at the cell on the cross of this latitude and given longitude}. Applying MeridionalInterpolationR to each "column", we obtain 720xL array of pairs {latitude, XCO_2}, where L is the width of latitudinal belt covered by data. The function GlobalInterpolationR, that combines LatitudinalInterpolation and MeridionalInterpolationR, gives a similar, but smoothed result -- it returns 11-term moving averages of the pairs {latitude, XCO_2}.

Since the monthly GOSAT observations cover only limited range of latitudes, we use NOOA/ESRL observations at Barrow [Tans, 2011a], Mauna Loa [Tans, 2011b], American Samoa [Tans, 2011c] and South Pole [Tans, 2011d] to fill the gaps. The function RefDataFor[month] creates a 360x720 array of interpolated CO_2 concentrations, [CO_2], for a given month, using the same algorithm as above. Then, the function GlobalInterpolationF combines the GOSAT observations with the NOAA/ESRL observations to make a 720x360 array of combined CO_2 concentrations, where the rows represent [CO_2] in the half-degree cells along corresponding meridians. The important detail here is the way in which XCO_2 are adjusted to fit [CO_2]. The XCO_2 values are lower than [CO_2] values by 9 ppm in average. The function Xoffset determines the optimal offset for each meridian, which is defined as an offset that reduce the difference between XCO_2 and $[CO_2]$ at the edges of latitudinal belt covered by GOSAT observations.

In the end, the function AverageValueOfRaster calculates weighted average of the 720x360 values using cell areas as the weights.

2.2 Testing

The algorithm of data interpolation is similar to the Masarie-Tans algorithm [1995], which is used to produce global average monthly $[CO_2]$ from NOAA/ESRL observations. Hence, to test the validity of the algorithm we may simply apply it to the observations at Barrow, Mauna Loa, American Samoa and South Pole and compare the result with the global average monthly $[CO_2]$ reported by NOAA/ESRL [Conway and Tans, 2010]. The global average monthly $[CO_2]$ reported by NOAA/ESRL are produced from the larger number of marine observation points, and thus we cannot expect that our algorithm will give exactly the same result, but we may expect that the discrepancy will not be large. The results of such test presented at the Figure 1 conform to our expectations -- the discrepancy does not exceed 1 ppm

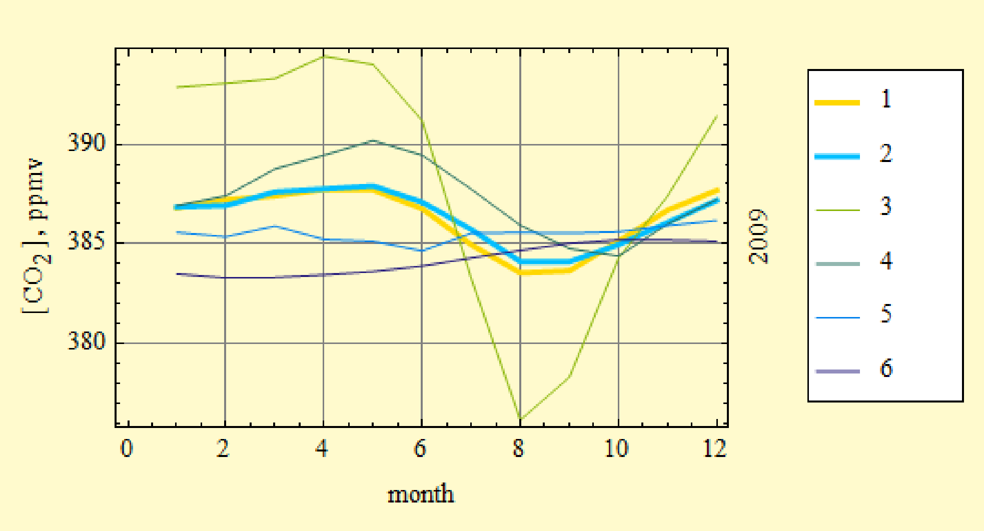

Figure 1. Testing the algorithm of data interpolation: 1 – global average $[CO_2]$ reported by NOAA/ESRL; 2 – results of algorithm application to the data from Barrow, Mauna Loa, American Samoa and South Pole stations; 3 – $[CO_2]$ at Barrow station; 4 – $[CO_2]$ at Mauna Loa station; 5 – $[CO_2]$ at American Samoa station; 6 – $[CO_2]$ at South Pole station. (NB. The amplitude of seasonal variations depends on the observation point. This shows that the size of the monitoring network is essential for improving the estimates of seasonal changes in total CO_2 content of the atmosphere.)

2.3 Implementation

Applying the algorithm to the GOSAT observations, we expected that the results would be close to the global average monthly $[CO_2]$ derived from the data that are used to fill the gaps in latitudinal coverage (reference $[CO_2]$). Since the gaps are wide, the data that are used to fill the gaps should have strong effect on the global average. Besides, we adjust XCO_2 to fit reference $[CO_2]$ at some points, and thus reduce the difference between average GOSAT-based [CO_2] and average reference [CO_2], although the method of adjustment is not intended for this purpose.

The results of the algorithm application are shown at the Figure 2. Not all of them conform to the expectations mentioned above. The difference between average GOSAT-based [CO_2] and average reference [CO_2] was small in November (2009), Decmber (2009), January (2010), and May (2010). However, it was large in February (2010), July (2010), and August (2010).

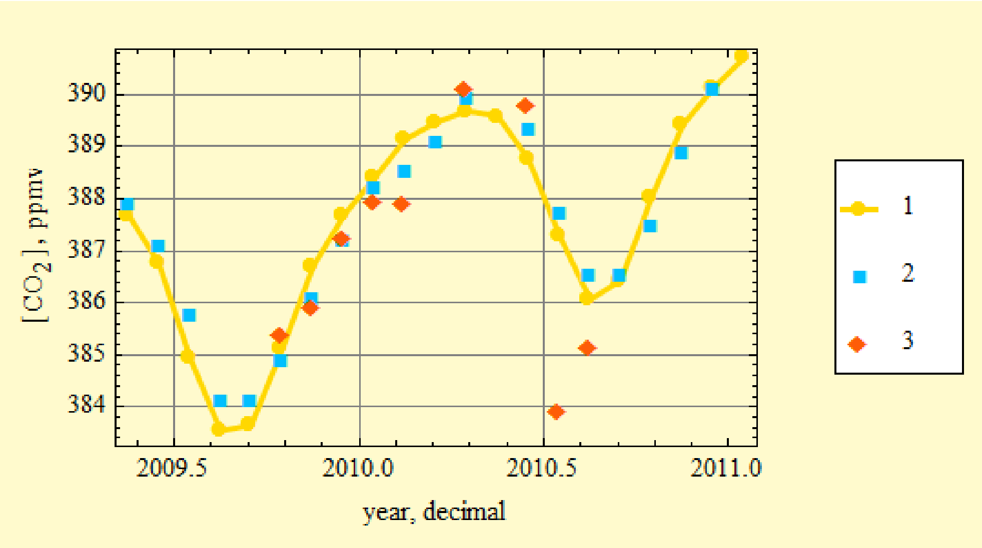

Figure 2. The results of the algorithm implementation: 1 – global average [CO_2] reported by NOAA/ESRL; 2 – results of algorithm application to the data from Barrow, Mauna Loa, American Samoa and South Pole stations; 3 - results of algorithm application to the GOSAT data.

The discrepancy between average GOSAT-based [CO_2] and average reference [CO_2] results from specific features of the GOSAT data for a given month. As it can be seen from the Figure 3, the GOSAT observations for July (2010) cover the latitudes between 30S and 50N - that is, about 40% of the Earth surface. The average GOSAT-based [CO_2] varies in a quite narrow range of values between 10S and 50N, but it grows sharply from 382 ppm at 10S to 395 ppm at 30S. Due to the large range of variations in [XCO_2], it was not possible to adjust XCO_2 values to fit well the reference [CO_2] values at the edges of latitudinal belt covered by GOSAT observations. The average GOSAT-based [CO_2] is higher than the average reference [CO_2] by 7.5 ppm at the south edge, and lower by 7.5 ppm at the north edge. Consequently, the average GOSAT-based [CO_2] is lower than the average reference [CO_2] by 6-8 ppm within the latitudinal belt from 0 to 50N.

The GOSAT observations for December (2009) cover the latitudes between 45S and 5S – that is, about 20% of the Earth surface. The average XCO_2 values vary between 376 and 379 ppm within this belt (that is lower than reference [CO_2] by 9 ppm in average), and the value at the south edge is very close to the value at the north edge. The average reference [CO_2] values vary between 385.8 and 386.6 ppm within this belt, and therefore the difference between average GOSAT-based [CO_2] and average reference [CO_2] at the edges of the belt is less than 1 ppm, and it does not exceed 1.5 ppm within the belt.

This case study shows that the discrepancy between average GOSAT-based [CO_2] and average reference [CO_2] appears when the meridional gradient in XCO_2 differs significantly from that in reference [CO_2].

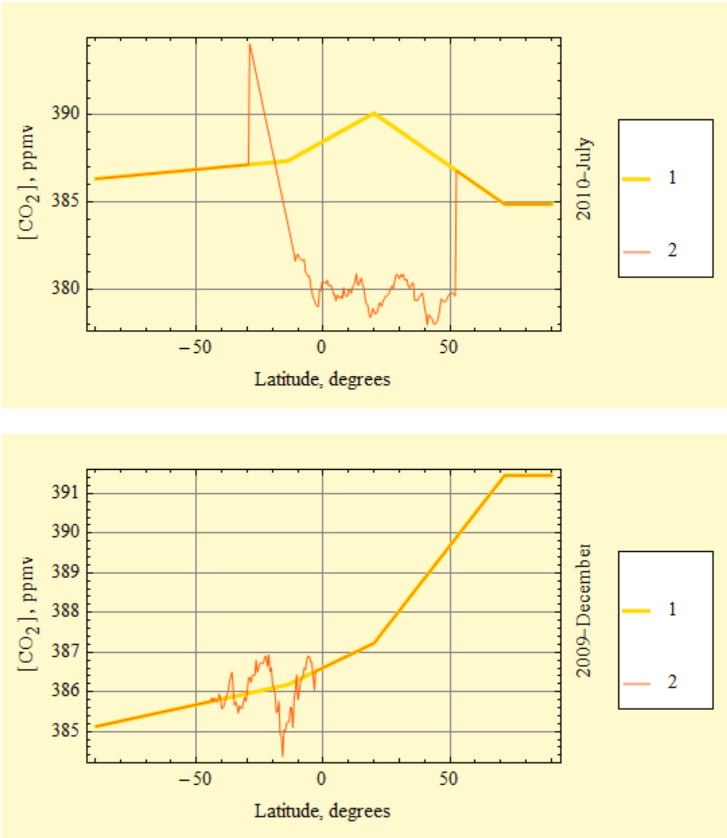

Figure 3. The average meridional gradient in [CO_2]: 1 – results of algorithm application to the data from Barrow, Mauna Loa, American Samoa and South Pole stations; 2 -- results of algorithm application to the GOSAT data (GOSAT-based [CO_2]).

3 CONCLUSIONS

The immediate implementation of the algorithm reveals some features of the GOSAT observations that are important for quantifying the magnitude of seasonal variations in the total atmospheric CO_2 content. However, it is too early to discuss the potential implications of the GOSAT observation. This paper is only to present the algorithm and to explain the method for calculating GOSAT-based estimates of the total atmospheric CO_2 content.

The method is generally similar to the method developed by Masarie and Tans [1995] for calculating global average monthly [CO_2] from NOAA/ESRL observations. The novel element is XCO_2 adjustment. Since XCO_2 is lower than reference [CO_2] by 9 ppm in average, we propose a technique for converting XCO_2 into GOSAT-based [CO_2].

The choice of the method stems from the idea that our efforts should be complementary to the NOAA/ESRL efforts on developing the best estimator for the global CO_2. The estimate of global CO_2 provided by NOAA/ESRL [Conway and Tans, 2010] is based on remote marine boundary layer (MBL) data only: this reduces the "noise" resulted from local peaks produced by anthropogenic sources and allows us to make the estimates directly from the observations, without having to use an atmospheric transport model.

Developing this method, we assumed that GOSAT may serve as an extension of the NOAA/ESRL CO_2 monitoring network which is used to assess the global average [CO_2] on monthly basis. And due to this reason we concentrated on the problem of data fusion – that is, on how to mix the data coming from new and old sources.

Combining old and new research methods is an ideal approach for gradual improvement of knowledge, especially, of the policy relevant knowledge, which must be relatively stable. The Keeling's curve, originally based on Mauna Loa observations, is an essential component of the policy relevant knowledge on the nature and scale of changes in the Earth System. We believe that it could be improved through satellite observations, and that our effort would facilitate the integration of GOSAT data into the current activities on monitoring the total CO_2 content in the atmosphere.

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