PSEUDO-DATA INVERSION OF COLUMN-CO$_2$ OBSERVATIONS BY REMOTE SENSING USING A HIGH RESOLUTION INVERSE MODEL

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ABSTRACT:
A framework of inverse modeling is developed for surface source estimation of CO$_2$ at very high spatial resolution. The source functions are constructed for 432 regions of the global at 10 x 15 degrees latitude-longitude area. This inverse model is used to evaluate the utilities of columnar measurements of CO$_2$ from the satellites in surface source estimations at regional scale

1. INTRODUCTION
The in situ measurements of CO$_2$ are the main source of information that is typically used in the surface source inversion studies. Now there are emerging possibilities of obtaining CO$_2$ distributions and time series from the satellite borne measurements (Chedin et al., 2003 and references therein). In the past utility of satellite measurement in surface source estimations has been studied based on low resolution inverse modeling, i.e., about 20-50 regions inversion (e.g., Rayner et al., 2001; Pak and Prather, 2001; Rayner et al., 2002; Patra et al., 2003a). However, it is well known that the footprint of CO$_2$ source signals at any measurement location is smaller than such inverse model regions. Thus it is important to carry out the pseudo-data inversion studies for the future satellite sensors at a much higher spatial resolution of the inverse models.

In this work we have used a very high resolution inverse model that divides the globe in 432 regions to evaluate the benefits of satellite measurements in source estimations. These results have also been compared with the inversion results based on surface measurements.

2. MATERIALS AND METHODS
We have used a time-independent Bayesian inverse model to estimate the regional flux uncertainties of annual mean CO$_2$ source estimations. Since the estimation of fluxes depends on actual concentrations, no discussion on absolute fluxes can be given in such studies.

The earth’s surface is divided in 432 regions of 15 x 10 degrees longitude-latitude dimension and source functions (also referred as basis functions) have been constructed. Each of the regions is assigned 1 Pg C/year as net annual flux, which is distributed similarly as the net ecosystem production. These basis functions are simulated using the NIES/FRSGC global transport model (Maksyutov and Inoue, 2000), which has been tuned for running efficiently on the Earth Simulator. In total 3 nodes each having 8 processors are employed for the whole set of simulation using MPI (Message Passing Interface) based directives. Eighteen basis functions are simulated on one processor and the meteorological fields are broadcasted to each node at the preprocessing stage of each run. The ECMWF operational analysis of the meteorology parameters are used to drive the model transport.

The Bayesian inverse modeling procedure and its numerical realization is based on the one described in Enting et al. (1995). In this algorithm, a cost function is minimized to reduce the mismatches between the atmospheric observations and transport model predicted responses to surface fluxes, and a priori sources and predicted sources. The inverse model solution provides optimal estimates for regional fluxes, and a mathematical expectation for statistical error of the flux estimates, referred to here as flux uncertainty $C_S$

$$C_S = (G^T . C_D^{-1} . G + C_{S_0}^{-1} )^{-1}$$ (1)
where G is the transport model operator, $C_D$ and $C_{So}$ are the atmospheric data uncertainty and a priori flux uncertainty, respectively.

In Bayesian inversion, the data uncertainty and a priori regional source uncertainty are the integral part of the calculation. The data uncertainty generally constitute two parts; the random (can be reduced by increasing the measurement frequency) and systematic (possible to rid of by sufficient validation campaign) part. In this work we have used the residual standard deviations (RSDs), estimated from daily column simulations, as a measure of error due to data representativeness and transport modeling error (see Patra et al., 2003 for details). The value of RSD used in the calculation depends on cloud cover corrected measurement frequency as shown in Fig. 1. Further, an additional data uncertainty varying from 0.0 ppm to 4 ppm is added to the scaled RSD to account for the overall measurement error arising from the treatment of atmospheric and spectroscopic parameters during the data retrieval process. The data uncertainty for surface observations are calculated from the GLOBALVIEW (2000) dataset. A surface measurement network that has 115 stations is used in this work. For the regional flux uncertainties, we have started with 1.0 and 0.1 Pg C/year per region. While the former allows the estimated fluxes to vary freely and enabling uncertainty reduction possible by low quality data (i.e., unconstrained inversion), the latter inversion is fairly tightly constrained by the prior estimations and any further reduction in uncertainty needs high quality observations.

3. RESULTS AND DISCUSSIONS

Figure 2 shows the flux uncertainty reductions obtained by using the surface and pseudo-satellite measurements in the inverse model and a priori uncertainty of 1.0 Pg C/year per region. It is apparent that the high precision satellite measurements are as effective as the surface observations in reducing the estimated flux uncertainty for the inverse model regions. Note here that the surface measurement footprints are smaller or similar in size of the inverse model regions. Thus it is often seen that one surface measurement can sometime produce reduction in flux estimate uncertainties for two or more regions. As expected, the flux uncertainty reductions are concentrated in and around the place where there are surface measurements (Fig. 2b), and the flux uncertainty reduction is a function of data uncertainty and signal strengths. Apparently the strongest point for satellite measurements is that it can provide global coverage of CO$_2$ concentrations and as a result flux uncertainty can be reduced for almost all the partitions of the globe (Fig. 2c). However, Fig. 2d indicates that the uncertainty reductions weaken rapidly with the error in satellite observations. The uncertainty reduction in this case is $\sim$0.5 Pg C/year per region, which were about 0.9 Pg C/year per region in the case of higher accuracy observations (ref. Fig. 2C).

Figure 2: Station locations in the surface measurement network used in this study (A, seen as numbers) and corresponding flux uncertainty reductions ($= a$ priori flux uncertainty – estimated flux uncertainty) for each inverse model regions (B). Panels C & D depict the flux uncertainty reductions by using satellite column measurements with 0 & 2 ppm error in addition to the intrinsic data variability (RSDs).

The unusually high values of flux uncertainty reduction over the Antarctic land region are arising due to very low satellite data error as estimated by the RSD model. Several case studies have been carried out to test the...
utilities of satellite measurements of column CO₂ measurements. Figures 3, 4, 5 & 6 show the differences between the column measurements for the whole globe (total atmospheric column and 700-100 mb column) and that due to the data available only over the ocean regions (total atmospheric column and 700-100 mb column), respectively. The results from tightly constrained inverse model set up have been shown below.

As seen from Fig. 3, the satellite data are useful in the well-constrained inversion cases when the data errors are low (panel a). It is also clear that the surface measurements are more efficient in reducing the flux estimate uncertainties compared to the columnar satellite data. This is because the source signals are sharper near the ground and relatively less variable when column amount is measured. Such difference between the effect of surface and satellite observations on flux uncertainty reduction is even greater if the satellite columns are considered in middle-upper tropospheric layer, i.e. 700-100 mb (see Fig. 4). Only the diluted signal of sources and sinks near the ground reach up to this part of the troposphere. The largest variability can be captured within the planetary boundary layer (PBL) where the surface measurements are typically made.

Figure 3: Reductions in estimated flux uncertainties; left panels are obtained using the total column satellite data only and right panels are the results of using surface and pseudo-satellite data in combination. The a priori flux uncertainty is set to 0.1 Pg C/year for each of the regions.

Figure 4: Same as Figure 3, but the satellite measurements are considered from 700 to 100 mb height range (above the PBL).

Figure 5 shows the effect of ocean only measurements on the flux uncertainty reduction. Since the total ocean area is larger in the Southern Hemisphere (SH), the derived fluxes in inversion are better constrained in SH regions than those in the Northern Hemisphere (NH). The importance of data accuracy become further important for ocean only measurements compared to the global coverage. This is because the source strengths over the ocean regions are relatively weaker than that over the land regions. Also the vertical transport is faster in the NH due to higher planetary scale wave activity and the SH is relatively stable in terms of wave activity due to lesser contrast in the surface topography.

Figure 5: Reductions in estimated flux uncertainties; left panels are obtained using the total column over the ocean only data and right panels are the results of using surface and the ocean only pseudo-data in combination.

From Fig. 6, it can be said that the ocean only measurements in the middle-upper troposphere height regions are less or not useful in the surface source
inversion studies. Even at a very high precision, the effect of satellite data on flux uncertainty reduction is negligible (less than 0.01 Pg C/year per region) in all parts of the globe. The regions of small uncertainty reduction are concentrated in the equatorial latitudes only, where the surface signals are transferred very effectively by the large scale convective processes.

![Figure 6](image)

**Figure 6**: Same as Figure 5, but the satellite measurements are available in the 700 to 100 mb layer only.

### 4. CONCLUSIONS

From this study it can be concluded that the inverse models should be run at higher spatial resolution, approximately of the size of source footprints at surface measurement station, for a fair comparison of the satellite data utility against the ground-based observations. The colurmn satellite measurements are most effective in flux estimate uncertainty reductions if global coverage and total columns can be derived for CO2 concentrations. The partial column measurements (without the PBL) only over the ocean regions have almost zero influence on the constraining the inverse model estimates of CO2 fluxes.

### 5. REFERENCES


