Sensitivity of inverse estimation of annual mean CO_2 sources and sinks to ocean-only sites versus all-sites observational networks

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Sensitivity of inverse estimation of annual mean CO_2 sources and sinks to ocean-only sites versus all-sites observational networks

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Received 5 December 2005; accepted 12 January 2006; published 14 March 2006.

[1] Inverse estimation of carbon dioxide (CO_2) sources and sinks uses atmospheric CO_2 observations, mostly made near the Earth's surface. However, transport models used in such studies lack perfect representation of atmospheric dynamics and thus often fail to produce unbiased forward simulations. The error is generally larger for observations over the land than those over the remote/marine locations. The range of this error is estimated by using multiple transport models (16 are used here). We have estimated the remaining differences in CO_2 fluxes due to the use of ocean-only versus all-sites (i.e., over ocean and land) observations of CO_2 in a time-independent inverse modeling framework. The fluxes estimated using the ocean-only networks are more robust compared to those obtained using all-sites networks. This makes the global, hemispheric, and regional flux determination less dependent on the selection of transport model and observation network. **Citation:** Patra, P. K., et al. (2006), Sensitivity of inverse estimation of annual mean CO_2 sources and sinks to ocean-only sites versus all-sites observational networks, *Geophys. Res. Lett.*, *33*, L05814, doi:10.1029/2005GL025403.

1. Introduction

[2] Inverse estimation of CO_2 fluxes (+ve for sources, −ve for sinks) at the regional scale depend greatly on the simulation of atmospheric transport [*Gurney et al.*, 2002] and the chosen CO_2 observing network [*Law et al.*, 2003; *Rödenbeck et al.*, 2003; *Patra et al.*, 2005]. The transport models used in the TransCom-3 intercomparison study reflect large differences in terms of the parameterisation of atmospheric dynamics as well as the source of meteorology (e.g., winds, temperature) (see *Gurney et al.* [2003] for details on model configurations). One of the largest contributors to the spread of results in the TransCom study was due to varying levels of seasonal rectification simulated by the transport models [*Denning et al.*, 1995; *Gurney et al.*, 2003, 2004]. Models that simulate greater seasonal amplitude in surface CO_2 concentrations as a result of seasonally varying biospheric exchange tend to estimate larger CO_2 sinks in northern land [*Gurney et al.*, 2004].

[3] In this work we address the sensitivity of annual mean CO_2 sources and sinks to CO_2 observing networks by using networks of different numbers of stations and different mixes of marine and continental sites.

2. Methods

[4] The TransCom-3 (Level-1) experimental framework, which is designed to estimate annual-mean CO_2 fluxes and associated uncertainties from 22 partitions (11 land and 11 ocean) of the globe (see Figure 1), is employed here. TransCom-3 uses the time-independent inversion methodology [*Enting et al.*, 1995] with the participation of 16 different transport models [*Gurney et al.*, 2002]. The participation of multiple transport formulations allows us to obtain two types of *a posteriori* flux uncertainties; 1) 'within-model' uncertainty (the multi-model RMS of the flux uncertainties), and 2) 'between-model' uncertainty (1σ of the estimated fluxes using different transport models) [*Gurney et al.*, 2002]. The former is primarily governed by the amount of atmospheric observations and the latter is a measure of agreement between transport models.

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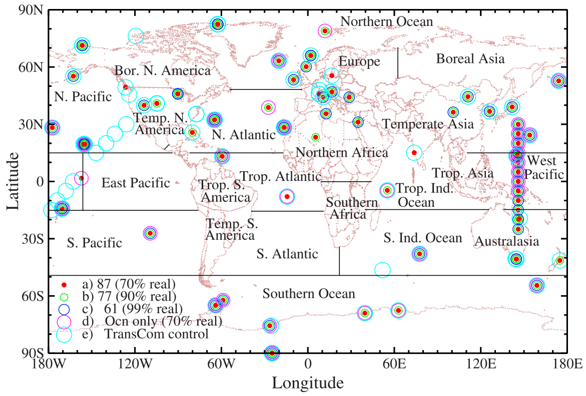

Figure 1. Observational networks constructed in this study based on fraction of real data in the GlobalView data set are shown. We have considered the stations with a, 70%; b, 90%; c, 99% real data; d, ocean only network corresponding to network a; and e, network used in TransCom control inversions (70% real data). These networks consist of 87, 77, 61, 42 and 75 stations, respectively. Three sets of additional ocean-only networks are constructed out of networks b, c, and e (not shown), consisting of 38, 30, and 37 stations, respectively. The inverse model regions are marked grossly.

[5] Atmospheric CO_2 data networks are constructed from the GlobalView-CO_2 analysis product [*Climate Monitoring and Diagnostics Laboratory*, 2004] using real weekly data cutoff levels of 70%, 90%, and 99% for the period of 1999–2001. This means that candidate monitoring locations must contain these percentages of non-interpolated data in order to be considered for one of the monitoring networks. Ocean-only data networks are created by deleting the land and coastal (off large continents) measurement sites (see Figure 1). The data uncertainties are calculated following TransCom-3 procedure (R. Law, personal communication, 2001), and minimum data uncertainty for annual mean concentrations is set to 0.30 ppm. The analysis period of 1999–2001 is chosen for using CO_2 observations from larger number of sites compared to the TransCom-3 experiments (1992–1996) [*Gurney et al.*, 2003], and to avoid extreme climate conditions, such as the 1997/98 El Niño and anomalous forest fires (e.g., the 2002 Siberian fires). The fossil fuel CO_2 emission distribution here is that due to *Brenket* [1998] and scaled to 6.6 Pg-C yr^{-1}.

3. Results and Discussion

3.1. Global and Hemispheric Scale Flux and Uncertainty

[6] Figure 2 shows CO_2 flux estimates for the global and aggregated (North, Tropics, and South) land/ocean regions corresponding to the period 1999–2001. Average uncertainties associated with the derived flux are shown as the vertical bars. The total CO_2 sink on the earth's land and ocean surface is estimated to be 3.42 Pg-C yr^{-1}. Partitioning of global land and ocean fluxes (Figures 2a and 2e) indicate that with an increasing numbers of land sites the ocean (land) tends to be a weaker (stronger) sink. However, the spread is still well within the range of between-model uncertainties ($\sim$0.51 Pg-C yr^{-1}). In contrast, total land and ocean fluxes for the ocean-only (all-sites) networks are 0.79(1.09) and 2.63(2.33) Pg-C yr^{-1} respectively. The ocean-only networks have both a smaller between-model uncertainty and a larger within-model uncertainty when compared to the all-sites cases. The smaller between-model uncertainty reflects greater agreement among the transport models when the networks are comprised of oceanic monitoring sites. In general, within-model uncertainties decrease with an increase in observational network size.

[7] From the flux distributions in the northern latitude belt (Figures 2b and 2f) we find that total CO_2 sinks in northern lands is intensified slightly (from 1.12 to 1.41 Pg-C yr^{-1}) with increasing numbers of stations in the all-sites networks. The northern land sink for the ocean-only case produced a net sink of 1.48–1.60 Pg-C yr^{-1}. The total northern region sink is estimated to be about 3.30 Pg-C yr^{-1} using all the data networks. The tropical oceanic source ($\sim$0.60 Pg-C yr^{-1}) appears to be network independent, and no systematic variation in tropical land fluxes for all-sites networks is observed. Low sensitivity of tropical land fluxes presumably reflects the small numbers of sites. The estimated fluxes for tropical and southern latitude belts appear robust with the variation in ocean-only networks. This stability in determination of tropical land and ocean sources probably indicates that net tropical flux is constrained by the measurements at marine sites, and the land-ocean partitioning is produced by the ocean flux. Between-model flux uncertainties (thick bars) due to the

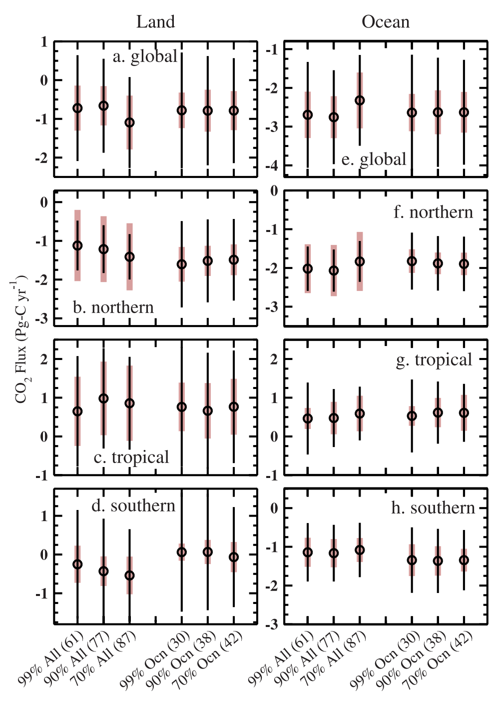

Figure 2. Global/hemispheric scale fluxes derived using TransCom-3 inverse model setup and 16 global transport models are shown. Average fluxes obtained using 16 transport models are marked by circles, and 'between-model' (thick line) and 'within-model' (thin line) flux uncertainties are shown as vertical bars. Results on left (right) side of each panel are due to using 'all-sites' (ocean-only) data networks. The % of 'real' data, network type, and number of stations in each data network are given as the x-axis tick-levels.

Table 1. Comparison of Estimated Average Fluxes (in Pg-C yr^{-1}) From This Study (Period: 1999–2001), TransCom-3 (Period: 1992–1996) [*Gurney et al.*, 2003], and Other Independent Studies[a]

Flux Region	Prior Fluxes and Uncertainty	TransCom Control Estimates (92–96)		This Study (Network With 70% Real Data)				Other Estimates (Min./Max.)[b]	Land Use Change Flux (1990–99)[c]
				Estimated Flux		Flux Uncertainty			
		All-Sites	Ocn Only	All-Sites	Ocn Only	'Within-'	'Between-'		
Boreal N America	0.00 ± 0.73	0.28	0.16	0.28	0.12	0.63	0.15	∼+0.08	0.03 ± 0.2
Temp. N America	−0.20 ± 1.49	−0.82	−0.59	−0.56	−0.69	0.93	0.50	−0.37/−0.7	−0.11 ± 0.2
Trop. S. America	0.55 ± 1.41	0.67	0.58	0.50	0.55	1.17	0.42	–	0.75 ± 0.3
Temp. S. America	0.00 ± 1.23	−0.13	0.09	−0.16	0.01	1.06	0.18	–	–
Northern Africa	0.15 ± 1.33	0.01	−0.15	0.19	−0.24	1.06	0.46	–	0.35 ± 0.2
Southern Africa	0.15 ± 1.41	−0.29	−0.27	−0.22	−0.03	0.96	0.39	–	–
Boreal Asia	−0.40 ± 1.51	−0.60	−0.56	−0.33	−0.29	0.78	0.45	–	–
Temperate Asia	0.30 ± 1.73	−0.42	−0.41	−0.34	−0.66	1.12	0.77	–	–
Tropical Asia	0.80 ± 0.87	0.42	0.44	0.16	0.46	0.66	0.23	–	1.09 ± 0.2
Australasia	0.00 ± 0.59	−0.16	−0.16	−0.16	−0.06	0.56	0.09	–	–
Europe	−0.10 ± 1.42	−0.61	−0.34	−0.46	0.03	1.06	0.38	−0.14/−0.2	−0.02 ± 0.2
North Pacific	−0.50 ± 0.27	−0.25	−0.39	−0.89	−1.14	0.50	0.25	−0.48/−0.5	
West Pacific	0.15 ± 0.39	−0.16	−0.10	−0.26	−0.18	0.33	0.30	0.10/0.0	
East Pacific	0.47 ± 0.37	0.63	0.66	0.62	0.66	0.34	0.23	0.59/0.50	
South Pacific	−0.23 ± 0.63	0.51	0.33	−0.24	−0.50	0.63	0.35	−0.26/−0.2	
Northern Ocean	−0.44 ± 0.35	−0.30	−0.34	−0.53	−0.35	0.21	0.07	−0.30/−0.3	
North Atlantic	−0.29 ± 0.27	−0.45	−0.56	−0.41	−0.40	0.34	0.06	−0.28/−0.3	
Tropical Atlantic	0.13 ± 0.41	−0.05	−0.03	−0.10	−0.08	0.33	0.09	0.17/0.15	
South Atlantic	−0.13 ± 0.55	−0.04	−0.04	−0.13	−0.16	0.43	0.08	−0.13/−0.1	
Southern Ocean	−0.88 ± 0.72	−0.46	−0.50	−0.17	−0.18	0.35	0.23	−0.55/−0.7	
Tropical Indian	0.12 ± 0.48	−0.34	−0.54	0.34	0.21	0.37	0.33	0.17/0.1	
South Indian	−0.56 ± 0.41	−0.24	−0.09	−0.54	−0.50	0.39	0.13	−0.48/−0.5	
Northern Land	−0.40 ± 3.17	−2.16	−1.73	−1.41	−1.49	1.05	0.40	–	−0.02 ± 0.5
Tropical Land	1.50 ± 2.12	1.10	0.87	0.85	0.77	1.45	0.72	–	2.20 ± 0.6
Southern Land	0.15 ± 1.96	−0.59	−0.34	−0.54	−0.07	1.28	0.42	–	–
Northern Ocean	−1.23 ± 0.52	−1.00	−1.29	−1.84	−1.89	0.70	0.29	–	
Tropical Ocean	0.87 ± 1.02	0.08	−0.01	0.60	0.61	0.75	0.46	–	
Southern Ocean	−1.80 ± 1.61	−0.24	−0.30	−1.09	−1.35	0.78	0.29	–	
Total Land[d]	1.25 ± 4.29	−1.65	−1.20	−1.09	−0.79	1.36	0.50	–	2.18 ± 0.8
Total Ocean[d]	−2.16 ± 1.53	−1.16	−1.60	−2.33	−2.63	1.36	0.52	−1.46/−2.12	

[a]The fluxes are shown for both types of networks with 70% real data (network a in Figure 1); within-model and between-model flux uncertainties are given for the Ocean only network. Symbol '–' indicates data not available.

[b]Other estimates refer to those published results which are not primarily based on Bayesian inverse modelling of atmospheric CO_2. Boreal North American, Temperate North American, and European fluxes are based on *Kurz and Apps* [1999], *Pacala et al.* [2001], and *Janssens et al.* [2003], respectively. The oceanic fluxes are estimated from an updated data base of *Takahashi et al.* [2002].

[c]The regions of carbon fluxes due to changes in land use [*Houghton*, 2003] approximately matches with the inverse model regions.

[d]A correction for riverine input of carbon to the ocean (∼0.3 Pg-C yr^{-1} globally) should be made for comparison with source/sink inventories [*Sarmiento and Sundquist*, 1992].

all-sites networks are greater for northern land and ocean, and tropical land - a reflection of the greater challenge with simulating transport in these regions and the greater number of observations showing up the transport differences. For the tropical and southern oceans between-model uncertainties are smaller compared to the within-model uncertainties (thin bars).

3.2. Sub-Continental Scale Fluxes and Uncertainties

[8] Multi-model averaged fluxes from most of the land and ocean regions are more stable against any selection in the data network compared to those obtained using one particular transport model (see Figures S2 and S3[1]). At first glance this result itself is surprising, but this is clearly the advantage of multi-model transport when it is known that representation of transport in any single model is not perfect. The errors in regional flux estimations corresponding to individual models cancel out on averaging over a large number of models (Figures S2 and S3). This error in absolute flux estimation primarily arises from differences in vertical mixing of source signals near the ground and subsequent transport to the observing stations. For instance the models which transport regional source signals faster (slower) to the nearest observing stations needed smaller (larger) flux corrections to the prior fluxes for an identical change in the region's flux.

[9] The retrieved CO_2 fluxes and associated uncertainties using all-sites and ocean-only networks corresponding to 70% real data are given in Table 1. For most of the land and ocean regions the fluxes agree within 0.2 Pg-C yr^{-1} with exceptions for Europe, Temperate Asia, Tropical Asia and Northern Africa for which the absolute differences of 0.49, 0.32, 0.30 and 0.43 Pg-C yr^{-1} are observed. An oscillatory behaviour is found between the fluxes of these regions; their detailed features are discussed below. Greater European sink is estimated when CO_2 data at the land sites are included (network a; Figure 1). Europe has the largest number of land sites (7 in total) and experiences highest seasonal rectification because of the stable boundary layer in the winter, which probably lead to excess sink estimation. All the ocean region fluxes are retrieved

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL025403.

consistently using both types of networks (difference below 0.2 Pg-C yr^{-1}), except for the North and South Pacific regions.

3.3. Comparison Multi-Model Fluxes With Other Results

[10] Table 1 shows the multi-model mean fluxes estimated in the TransCom-3 control inversion, this work and a variety of other estimates. The 'all-sites' column under the 'TransCom Control Estimates (92–96)' heading is identical to *Gurney et al.* [2003], and the results in 'ocean-only' column are obtained using the marine sites only, selected following the same criteria as for the 1999–2001 period. The period of this study includes one La Niña event (in 1999) while the time period chosen in the *Gurney et al.* study includes prolonged El Niño conditions and the influence of volcanic aerosols following the Mount Pinatubo eruption in 1991. Therefore, differences between the two flux estimations can be attributed mainly to climate conditions and the choices of monitoring network. The other factors influencing our flux estimations could be the changes associated with the ecosystem management and fire activity etc. The carbon fluxes from land use change are shown in Table 1 [after *Houghton*, 2003]. The CO_2 flux estimates by inversion are effectively the sum of all flux components; mainly the land use change and net ecosystem uptake for land regions. Role of chemical formation of CO_2 by oxidation of reduced carbon compounds (e.g., CO, CH_4, NMHCs) [*Enting and Mansbridge*, 1991] is not accounted for in this inverse model. Thus only an overall comparison between the flux estimates will be done here.

[11] We find a Temperate North American sink in the range of 0.56–0.69 Pg-C yr^{-1} depending on the network used. This value compares well with a recent land-based U.S. carbon sink estimate of 0.37–0.71 Pg-C yr^{-1} for the period 1980–1990 [*Pacala et al.*, 2001]. The Boreal North American flux (+0.12 Pg-C yr^{-1} for the ocean-only case) is also in fairly good agreement with that (~0.08 Pg-C yr^{-1}) estimated based on forest inventory for the 1980s [*Kurz and Apps*, 1999]. However, it should be mentioned here that though the top-down estimates in this study and the bottom-up estimates for the 1980s are similar in magnitude, a mechanistic relationship to reconcile each other cannot be established. Instead we assume that the changes in land-use and land/fire management in North America are not large between the 1980s and 1990s [*Houghton*, 2003]. Thus we believe these comparisons are valid under certain approximations. For several land regions with no measurement site the flux estimate is robust across all network selections for the period 1999–2001, such as Tropical South America (+0.50 to +0.55 Pg-C yr^{-1}), Temperate South America (−0.16 to −0.01 Pg-C yr^{-1}), South Africa (−0.22 to −0.03 Pg-C yr^{-1}), Boreal Asia (−0.29 to −0.33 Pg-C yr^{-1}). Generally, since the tropical land sources are smaller than their corresponding carbon fluxes due to land use change (see Table 1), these ecosystems are acting as net sinks of CO_2. In contrast, large differences between European flux with or without land stations are found during both the periods (1992–1996 and 1999–2001) of flux estimations; apparently the sink reduces by 0.27–0.49 Pg-C yr^{-1} when ocean-only networks are used. This sink is transferred mainly to Northern Africa and Temperate Asia regions for the ocean-only cases. The European flux estimates using ocean-only sites (−0.34 to +0.03 Pg-C yr^{-1}) compare better with other independent estimates of −0.37 to −0.07 Pg-C yr^{-1} [*Janssens et al.*, 2003].

[12] The North Pacific sink is estimated to be 0.89–1.14 Pg-C yr^{-1} in this study with very low between-model uncertainty. This uptake is larger than either the TransCom-3 or the *Takahashi et al.* [2002], 2003 updated values (referred here to as *TT*03), estimates of sink (0.25–0.39 or 0.48–0.57 Pg-C yr^{-1}, respectively). The North Ocean, North Atlantic, Tropical Atlantic, and South Atlantic fluxes are consistent across the ocean-only and all-sites networks and are in fairly good agreement with the *TT*03 average estimates as well as TransCom-3. The South Pacific sink estimate (0.24–0.50 Pg-C yr^{-1}) is in closer agreement with the *TT*03 estimates, due to the use of EIC station (27°S, 109°W) data. The source and sink attribution to Tropical Indian Ocean (TIO) and South Indian Ocean (SIO) is represented realistically in terms of the north-south gradient, and are in good agreement with *TT*03 (see Table 1). It is well known that the TIO has several upwelling zones and is generally accepted to be a source of CO_2 [*Takahashi et al.*, 2002].

4. Conclusions

[13] Estimated global and regional CO_2 fluxes and associated uncertainties are studied using a time-independent inverse model and atmospheric CO_2 observations from up to 87 locations around the world. In this analysis, we find that CO_2 observations from the land sites sometimes produce large differences in flux estimates, for example, for Europe. We suggest that the difficulty associated with using land-based observations should be addressed by improving the components in model transport. If the models can simulate the land observations, then adding these data to the flux inversions should reduce flux estimation errors as the land regions become better sampled. Using ocean-only monitoring networks, the estimated regional CO_2 fluxes for two North America regions and Europe are found to be in good agreement with other independent estimations. The independent flux estimates from other parts of the world are highly desirable, such as the Asia, Africa, and South America. The latitudinal distribution of regional ocean fluxes from this work is in fairly good agreement with those derived from ship-board based measurements. The use of multiple forward models has helped significantly to establish better comparison of flux determined by inverse modeling and bottom-up estimates.

[14] **Acknowledgments.** We thank Sander Houweling and the reviewers (Ian Enting and anonymous) for their thoughtful comments which have helped us to improve the quality of the manuscript. We appreciate the support of Hajime Akimoto for this study. TransCom-3 was made possible through support from the NSF (OCE-9900310), the NOAA (NA67RJ0152, Amend 30) and the IGBP/GAIM Project. The final 21 authors are TransCom-3 modelers.

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