Title
Impact of Fraserdale CO
2
observations on annual flux inversion of the North American boreal region

Journal
Tellus B, 57(3)

ISSN
0280-6509 1600-0889

Authors
Yuen, C.-W.
Higuchi, K.
Baker, D.
et al.

Publication Date
2005-07-01

DOI
10.1111/j.1600-0889.2005.00150.x

Tellus (2005), 57B, 203–209

TELLUS

Impact of Fraserdale CO_2 observations on annual flux inversion of the North American boreal region

By CHIU-WAI YUEN[1], KAZ HIGUCHI[2*] and the TRANSCOM-3 MODELLERS[3], [1]*Earth System Research, 45 Duxbury Drive, Toronto, Ontario M1V 5H2, Canada;* [2]*Air Quality Research Branch, Meteorological Service of Canada, 4905 Dufferin Street, Toronto, Ontario M3H 5T4, Canada;* [3]*D. Baker, P. Bousquet, L. Bruhwiler, Y.-H. Chen, P. Ciais, A. S. Denning, S. Fan, I. Fung, M. Gloor, K. R. Gurney, M. Heimann, J. John, R. M. Law, T. Maki, S. Maksyutov, B. Pak, P. Peylin, M. Prather, P. Rayner, J. Sarmiento, S. Taguchi, T. Takahashi*

(Manuscript received 29 October 2004; in final form 18 February 2005)

ABSTRACT

In TransCom-3 (Level 1), atmospheric CO_2 measurements from 76 monitoring stations for the period 1992–1996 and 16 atmospheric transport models were used to constrain annual mean CO_2 fluxes over 11 land and 11 ocean regions. The tower measurements of atmospheric CO_2 from Fraserdale, a continental site in northern Ontario, Canada are now available and processed for use in the TransCom-3 inverse modelling framework. In this short study, we show that by including this set of continental CO_2 data, the estimated flux for the North American boreal region becomes nearly zero, a reduction of about 0.26 Pg C yr^{-1} from the previous estimate. The uncertainty of the estimated flux for this region is also reduced by ~30%. All transport models show negative changes for boreal North America, with the strongest responses (~ −0.5 Pg C yr^{-1}) shown by NIRE, NIES, CSU and SKYHI. Furthermore, models showing a strong response in boreal North America tend to show strong sensitivity in middle- and high-latitude Asian regions.

1. Introduction

Recent studies on the carbon budget of Canadian boreal forests using different approaches show inconclusive results on the net exchange of carbon between the terrestrial biosphere and the atmosphere. A forest inventory study by Kurz and Apps (1999) indicates Canada's forests to be a weak source (~0.08 Pg C yr^{-1}) during the 1980s. On the other hand, ecosystem modelling by Chen et al. (2000, 2003) identifies this region as a weak sink (~0.05 Pg C yr^{-1}) in the last two decades. Global annual carbon flux inversions with atmospheric tracer transport models also yield moderate flux sensitivity over Canada's forests. A source of 0.26 Pg C yr^{-1}during 1992–1996, was estimated in the TransCom-3 (Level 1) experiment (Gurney et al., 2002) while Fan et al. (1998) found it to be a sink of 0.2 Pg C yr^{-1} during 1988–1992.

In these inverse modelling studies, Canadian continental CO_2 observations were not available to constrain the estimated flux over the North American boreal region. Despite having high variability due to spatio-temporal biospheric fluxes, mixing and synoptic transports, however, atmospheric CO_2 data at continental sites exhibit strong (less diluted) signals of the regional terrestrial fluxes that can be used to constrain inverse continental flux estimates. Gloor et al. (2000) and Patra et al. (2003) have demonstrated the advantage of adding a Canadian continental station for reducing the uncertainty in the North America boreal forest flux estimate.

Continuous atmospheric CO_2concentration measurements at the top of a 40 m tower at Fraserdale (49.9°N, 81.6°W) in the remote northern Ontario boreal forest (see Fig. 1) from early 1990 to late 1996 (Higuchi et al., 2003) are now available to be used as an additional constraint in the annual inverse calculation. The Fraserdale data cover almost the same period (1992–1996) as GLOBALVIEW-CO_2 (2000) data used in the annual flux inversion intercomparison of the TransCom-3 (Level 1) experiment (hereafter, referred to as TransCom-3). In this study, the TransCom-3 work is supplemented by including the Fraserdale data to investigate the impact on the annual regional biogenic flux estimates, with emphasis on boreal North America. A number of papers (Gurney et al., 2002, 2003; Law et al., 2003; Maksyutov et al., 2003; Patra et al., 2003) have been published on the results of TransCom-3 and should be referred to for details.

In TransCom-3, annual surface CO_2 fluxes for 11 land and 11 ocean regions (Fig. 1) are deduced using the Bayesian synthesis inversion method (Enting, 2002). In this study we follow the calculation procedure described in Gurney et al. (2002), using results from 16 global atmospheric transport models:

*Corresponding author.
e-mail: kaz.higuchi@ec.gc.ca

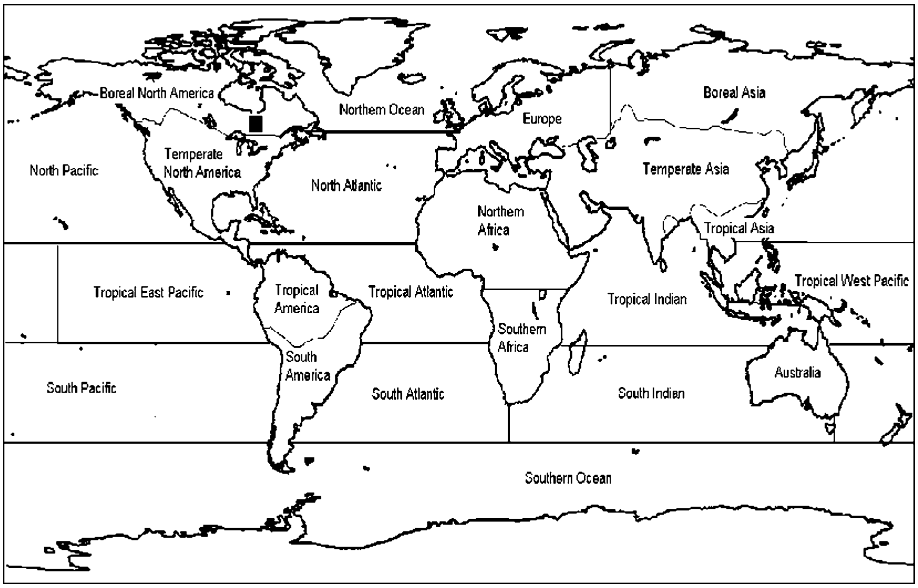

Fig 1. TransCom-3: 22 terrestrial and oceanic basis function regions. The location of Fraserdale is marked by the black solid square.

CSU, UCB, UCI, UCIs, UCIb, JMA, MATCH-CCM3, MATCH-NCEP, MATCH-MACCM2, NIES, NIRE, RPN, SKYHI, TM2, TM3 and GCTM.

2. Fraserdale 40 m tower data

The salient characteristics of the Fraserdale 40 m tower CO_2 data have been described by Higuchi et al. (2003). Here, only a brief summary is presented. Fraserdale is remotely located in the northern Ontario boreal forest, with prevailing winds from the western half. Hourly CO_2 values indicate strong summertime diurnal cycles, due to diurnally changing surface biogenic processes and boundary layer mixing, and are typical of other vegetated mid-latitude continental measurements (Bakwin et al., 1998). Seasonal variations, computed from afternoon data, show (1) a stronger seasonal amplitude of about 20 ppm (parts per million), (2) earlier spring draw-down; (3) a lower and earlier appearance of the summer minimum and (4) higher concentrations during winter and autumn, as compared with a remote site such as Alert (Higuchi et al., 2003). Despite being measured at a relatively low height compared with other continental tall towers (496 m at North Carolina and 396 m at Wisconsin), the Fraserdale afternoon data reflect the site's influence by regional biospheric activities, which should be resolvable by the relatively coarse resolution of global transport models used in TransCom-3. Therefore, annual mean and data variability at Fraserdale, required inputs from each site to the inversion, will be derived from afternoon values to maximize regional biotic influence and minimize bias towards diurnal signals.

In TransCom-3, annual mean CO_2 concentration data and variability at 76 selected sites during the period 1992–1996 are obtained from the GLOBALVIEW-2000 dataset. The hourly Fraserdale data are available from 8 February 1990 to 4 December 1996. The proxy daily averages are computed as the means of hourly afternoon data from 15:00 to 18:00 local sidereal time (LST). There are 2385 daily mean values and 105 missing data points in the time-series. The longest internal gap is a 34 d break in early 1995. Consistent with the GLOBALVIEW-2000 data, the Fraserdale time-series is smoothed, filled-in and extended to the end of 1996, using the curve fitting and data extension (latitude reference method) techniques described in Masarie and Tans (1995) and GLOBALVIEW-2000. The curve fitting software was downloaded from the Climate Monitoring and Diagnostics Laboratory NOAA World Wide Web site (http://www.cmdl.noaa.gov/ccg/sw/ccgvu/overview.html).

Table 1. Annual mean CO_2 concentration and data variability at Fraserdale and at the three Siberian sites

Site	Annual mean CO_2 conc. (ppm)	Data variability (ppm)
Fraserdale	359.63	1.05
Surgut (61°N, 73°E)	359.55	0.74
Yakutsk (62°N, 130°E)	360.09	0.78
Novosibirsk (55°N, 83°E)	359.34	0.92

The annual mean CO_2 concentration for the period 1992–1996 is calculated to be 359.63 ppm (Table 1). The data variability is estimated as the residual standard deviation (RSD) of the measurements about the smoothed curve fitted to the observation. Its magnitude is found to be 2.87 ppm and is within the range of RSD (1–6 ppm) at other continental sites (Gloor et al., 2000). To prevent over-fitting the station data, the RSD is then scaled by the square root of $8P$ where P is the fraction of the observed data in the 5 yr period (Gurney et al., 2002). The scaled variability at Fraserdale is found to be 1.046 ppm (Table 1), near the lower end of those for the four other continental stations (ITN, BAL, SCH and HUN) included in TransCom-3 (1.057–2.232 ppm).

3. Mean model sensitivity

We will focus the discussion on the inverse estimates of fluxes for the northern middle- and high-latitude regions where the strongest sensitivity is found. The TransCom-3 annual mean inversion results (Gurney et al., 2002) are referred to as the control case.

3.1. Posterior flux

With the inclusion of the Fraserdale data (case Frd in Fig. 2), it is not unexpected to find that the largest impact is over boreal North America where the weak source (0.26 Pg C yr^{-1}) in the control case becomes a very weak sink (-0.003 Pg C yr^{-1}). This change, however, is still within the flux variability of the control case. Meanwhile, the boreal Asian sink is affected in the opposite way, weakening from -0.52 Pg C yr^{-1} in the control case to -0.31 Pg C yr^{-1}. Thus, the northern boreal region as a whole remains as a sink, increasing slightly in strength. Thus the disappearance of the North American boreal source is essentially counterbalanced by the weakening of the sink in boreal Asia, resulting from the fact that these two regions, connected by the west-to-east atmospheric transport (Gloor et al., 1999; Patra et al., 2003), are weakly constrained due to a relative lack of observations. It is also interesting to note that the temperate Asian sink is enhanced slightly by about 0.12 Pg C $yr^{-1}$to -0.74 Pg C yr^{-1}. Since the global background fluxes are tightly constrained, there are counteracting responses between neighbouring regions to maintain the observed global concentration growth rate.

Maksyutov et al. (2003) included aircraft data over eastern Siberia in the control inversion and found opposite responses in each boreal region, relative to the Fraserdale case. With different measurement levels of the three aircraft profiles regarded as individual sites, a total of 18 more stations were used. However, collocated measurements are coupled, and using them without adjustment violates the assumption of uncorrelated data. Indeed, by just adding the 1 km height Siberian data (Table 1) to the control inversion, similar results to those shown by Maksyutov et al. (2003) are obtained (case Sib in Fig. 2). Correlated data add no real additional constraint to an inverse estimate, and our results give a clear demonstration of this fact. With both Fraserdale and Siberian data (case Frd+Sib), either site's influence on its immediate region still dominates over the opposing effect of the other boreal sites. As a result, the North American boreal region remains a much weaker source (0.08 Pg C yr^{-1}) than the control while the Asian boreal sink is barely changed. Because of the see-saw compensatory effect of carbon flux allocation between boreal Asia and boreal North America, it is important that both regions are equally constrained. Inclusion of the tower measurements of CO_2 at Berezorechka in western Siberia obtained by

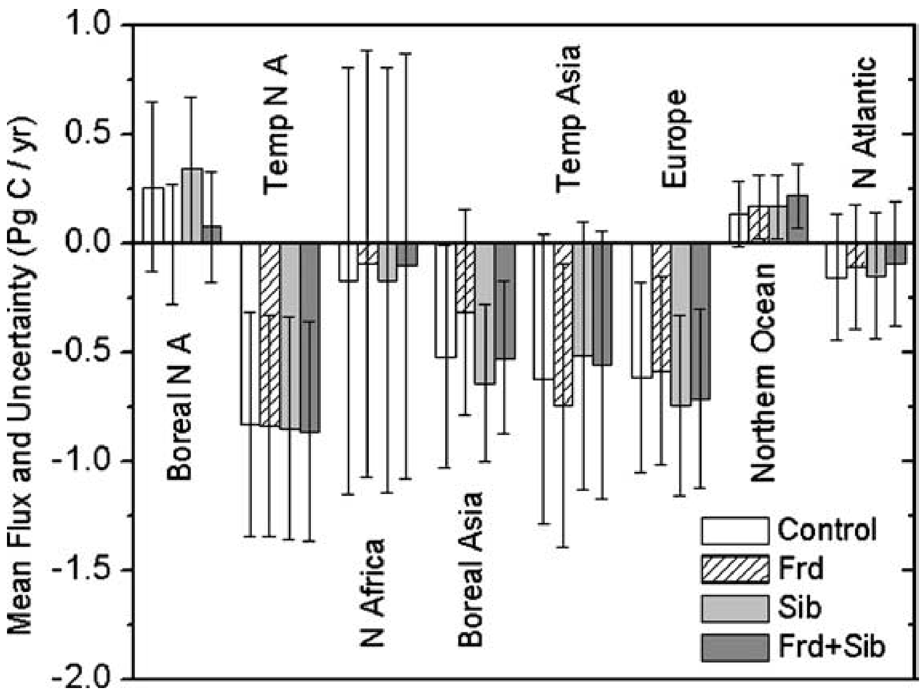

Fig 2. Mean estimated annual average flux (bars) and within-model uncertainty (error bars) over eight selected land and ocean regions for the following four inversion cases: (1) TransCom-3 control case, (2) inclusion of Fraserdale data, (3) inclusion of Siberian data and (4) inclusion of Fraserdale and Siberian data.

the National Institute of Environmental Studies (Machida, personal communication) should improve boreal flux estimates in the future.

3.2. Flux uncertainty

Adding Fraserdale to the control network of observational sites also produces the largest reduction in flux uncertainty (∼0.11 Pg C yr^{-1}) over boreal North America, a 28% decrease from the control value of 0.39 Pg C yr^{-1} (Fig. 2). This implies a moderate constraint by the additional measurements on the flux estimate. The Asian boreal region also experiences a secondary (8%) decrease of 0.04 Pg C yr^{-1}. We also find that the Siberian aircraft data alone (case Sib) lead to a significant reduction (15%) in the posterior flux uncertainty in boreal North America, in addition to its strongest impact on the Asian boreal flux. Under the combined constraints of both boreal data sets (case Frd+Sib), uncertainty in the boreal flux estimate is further reduced. Nevertheless, individual sites still exert the strongest impact on their immediate region. The present results ascertain the correlation in the responses of the two boreal regions when new observations in either region are included in the inversion.

3.3. Standard deviations of flux estimates

Standard deviations of the flux estimates obtained with different transport models (or between-model flux uncertainties) are shown in Fig. 3 for the selected northern regions. Including the Fraserdale data in the inversion seems only to have a weak impact on the model spread of estimated fluxes. Temperate North America has the largest change, which still only amounts to a 16% decrease to 0.36 Pg C yr^{-1}. The between-model flux uncertainty over boreal North America remains at about 0.28 Pg C yr^{-1}. When the case Frd inversion is conducted without the background seasonal terrestrial flux there is only a weak decrease in model spread (∼ 7%) over boreal North America. This test indicates that the differences in rectifier effects among models may only be moderate over the boreal North American region. In comparison, there is a relatively strong sensitivity on model spread over temperate Asia, partially due to rectifier effects, when Mount Waliguan data are included in the control case (Law et al., 2003). In contrast to the control case, the posterior flux uncertainty over boreal North America (case Frd) has decreased to about the same value as the standard deviation. This indicates that additional observations are beneficial and the model-to-model differences are not critical in estimating flux in this region. As was found in Maksyutov et al. (2003), adding the Siberian data reduces the model spread significantly over the Asian boreal and temperate regions while moderately increasing it in boreal North America. However, this adverse effect in the North American region is neutralized if both boreal data are included in the inversion.

4. Individual model sensitivity

4.1. Data mismatch

All models show positive data mismatches (modelled−observed) at Fraserdale. The mean value is 0.98 ppm and is about the same magnitude as the data uncertainty at Fraserdale (1.046 ppm), indicating that the Fraserdale data constrain the estimated flux reasonably well. As stated by Law et al. (2003), if the data mismatch is noticeably larger than the data uncertainty at a site (in this case Fraserdale), then a "potential problem is implied". A positive bias implies that a larger sink would be needed

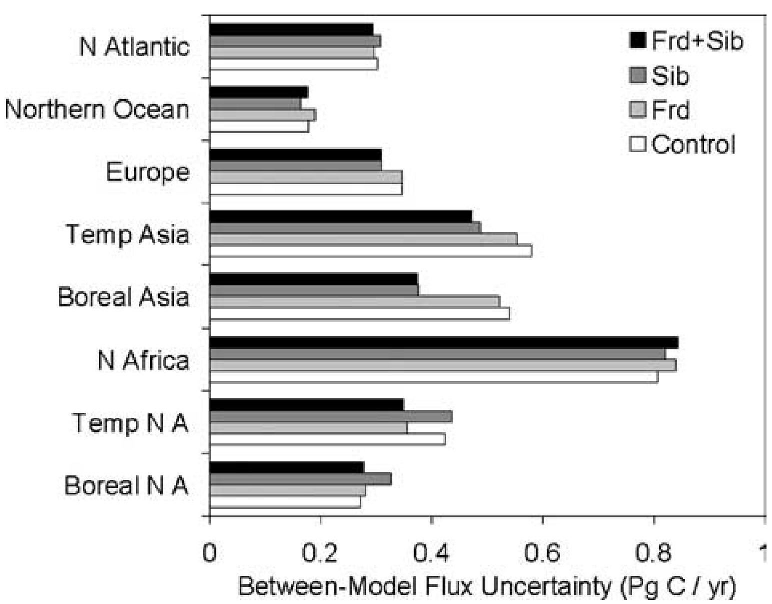

Fig 3. Between-model uncertainty over eight selected land and ocean regions for the following four inversion cases: (1) TransCom-3 control case, (2) inclusion of Fraserdale data, (3) inclusion of Siberian data and (4) inclusion of Fraserdale and Siberian data.

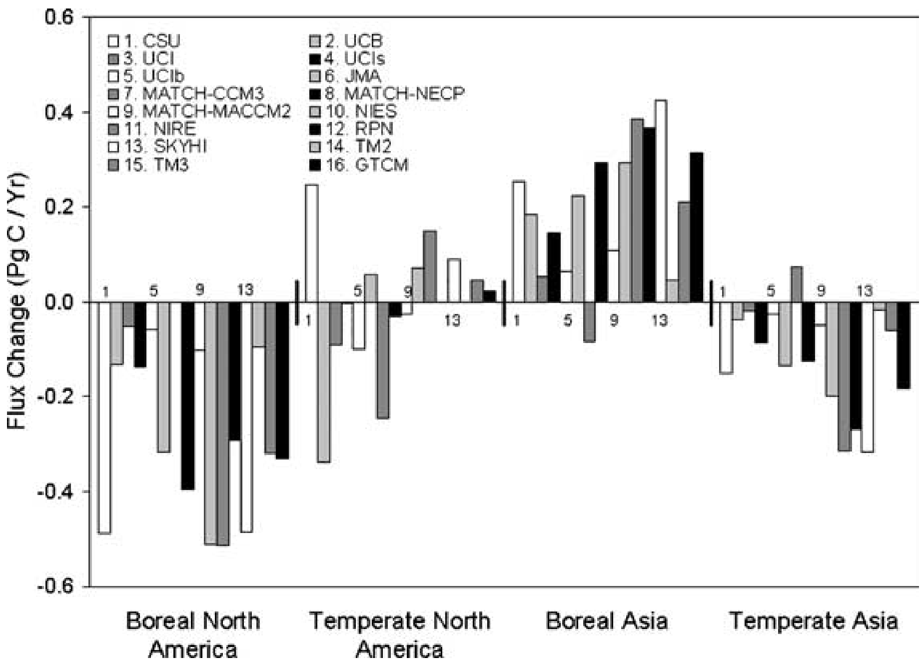

Fig 4. Change in posterior flux from the control case over the northern boreal and temperate regions for individual models in the Fraserdale case.

to fit the observations. As pointed out by Law (personal communication), all models give positive data mismatches at Fraserdale, indicating that other sites need to become smaller sinks or larger sources. Indeed, the positive mismatch at Fraserdale could indicate that the Fraserdale region is a stronger sink than other parts of the boreal North American region. The standard deviation of data mismatch across the models is 0.59 ppm with the largest two values (~2.2 ppm) simulated by UCB and GCTM and the smallest two (~0.35 ppm) by TM3 and TM2, and all others giving values around 0.9 ppm.

4.2. *Posterior flux change*

The individual flux changes (Frd−Control) for the four northern boreal and temperate regions that yield the largest sensitivities to the inclusion of the Fraserdale data are displayed in Fig. 4. All models have negative changes in the boreal North American region. The strongest effects (~ -0.5 Pg C yr^{-1}) are associated with NIRE, NIES, CSU and SKYHI, while MATCH-CCM3, UCI and UCIb show the weakest effects. Six models (NIRE, NIES, SKYHI, MATCH-NCEP, GTCM, RPN) have flux changes larger than the uncertainty. In the control case, only four models (UCIs and three MATCH models) simulate a very weak sink in boreal North America while six more models (CSU, UCB, JMA, NIRE, SKYHI, TM3) fall into this category when the Fraserdale data are included.

In temperate North America, the standard deviation of the changes among different models (0.14 Pg C yr^{-1}) is about the same as in the neighbouring boreal region (0.18 Pg C yr^{-1}). However, here, the changes scatter around zero, resulting in a weak mean sensitivity. In general, models with strong (weak) sensitivity in the boreal region have positive (negative) flux change in the temperate region, which remains as a sink for all models.

With the exception of MATCH-CCM3, all other models show positive flux changes over the Asian boreal region, while showing negative flux changes over the neighbouring temperate Asia. MATCH-CCM3 shows an opposite change in flux from other models, giving a negative value for boreal Asia and a positive value for temperate Asia. It is also interesting to note that this opposite behaviour by MATCH-CCM3 is also displayed in both North American and Asian boreal regions. In general, models showing strong responses in boreal North America also show strong sensitivity in middle- and high-latitude Asian regions.

4.3. *Flux uncertainty reduction*

Reduction in flux uncertainty (Frd−Control) simulated by different models is shown in Fig. 5 for the same four most responsive regions as in Fig. 4. In general, most models show the strongest decrease over boreal North America. The maximum is about -0.3 Pg C yr^{-1}. The interrelationships between the two boreal regions are also evident. The four highest sensitivities are displayed by CSU, TM3, NIRE and SKYHI, in broad agreement with their stronger simulated responses to the boreal North American source at Fraserdale (not shown). These models also produce strong flux decreases over boreal North America. The three least sensitive models are MATCH-CCM3, UCI and UCIb. The behaviour of UCI and UCIb can be explained by their weak simulated response. However, MATCH-CCM3 has a relatively moderate response but still yields little reduction.

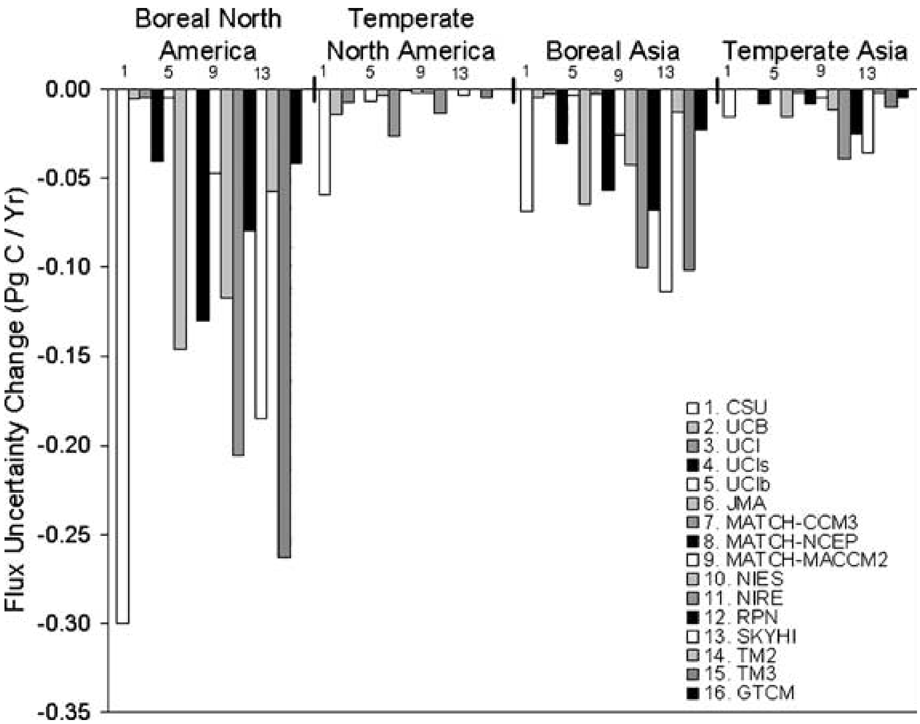

Fig 5. Change in flux uncertainty from the control case over the northern boreal and temperate regions for individual models in the Fraserdale case.

Patra et al. (2003) also noticed that MATCH-CCM3, UCI and UCIb did not pick a Canadian continental site among the first 14 stations selected in an optimal extension of the CO_2 observation network.

5. Conclusions

In this study, we have investigated the constraint of atmospheric CO_2 concentration measurements at Fraserdale, Canada, on the inverse estimate of average annual biotic flux over the North American boreal region for the period 1992 to 1996. This work provides additional results to those of the annual flux inversion intercomparison project (TransCom-3, Gurney et al., 2002) by including continental afternoon atmospheric CO_2 data from Fraserdale.

We have demonstrated that the largest flux sensitivity is over boreal North America, with a secondary offsetting impact over boreal Asia. The weak mean boreal North American source across the models (0.26 ± 0.39 Pg C yr^{-1}) in the control case turns into a very weak sink of -0.003 ± 0.28 Pg C yr^{-1}. This flux difference still lies within the flux uncertainty for that region estimated in the control case. There is a 28% reduction in posterior flux uncertainty, and little effect on the model spread of the estimated fluxes (0.28 Pg C yr^{-1}). The implication is that new observations are important in this region. Further observational constraints are demonstrated with the inclusion of Siberian aircraft data, but the effects of the Fraserdale data still dominate over boreal North America.

In addition to the Fraserdale site, high-precision atmospheric CO_2 concentration measurements were initiated recently on a 30 m tower at a black spruce site in the BERMS (Boreal Ecosystem Research and Monitoring Sites) network of CO_2 flux sites in northern Saskatchewan, Canada. The possible addition of two more continental atmospheric CO_2 measurement sites is being planned under the auspices of Fluxnet Canada. The results of the present study indicate that inclusion of these continental CO_2 concentration data, as well as the tower measurements of CO_2 at Berezorechka in western Siberia, in future inverse calculations should provide an additional constraint to the calculations and reduce uncertainties in the flux estimate over boreal North America and Asia.

6. Acknowledgments

The TransCom-3 work was made possible through support from the National Science Foundation (OCE-9900310), the National Oceanic and Atmospheric Administration (NA67RJ0152, Amend 30) and the International Geosphere Biosphere Program/Global Analysis, Interpretation and Modeling Project. CWY acknowledges support during the preparation of the manuscript from Professor Jing Chen of the University of Toronto through funding by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). We would also like to thank several TransCom-3 participants who commented and made thoughtful suggestions on the first draft of the paper. Also the critical and constructive comments and suggestions made by two anonymous reviewers did much to improve the paper.

References

Bakwin, P. S., Tans, P. P., Hurst, D. F. and Zhao, C. 1998. Measurements of carbon dioxide on very tall towers: results of the NOAA/CMDL program. *Tellus* **50B**, 401–415.

Chen, J. M., Chen, W., Liu, J. and Cihlar, J. 2000. Annual carbon balance of Canada's forests during 1985–1996. *Global Biogeochem. Cycles* **14**, 839–850.

Chen, J. M., Ju, W., Cihlar, J., Price, D., Liu, J. and co-authors 2003. Spatial distribution of carbon sources and sinks in Canada's forests. *Tellus* **55B**, 622–641.

Enting, I. 2002. *Inverse Problems in Atmospheric Constituent Transport*. Cambridge University Press, Cambridge.

Fan, S., Gloor, M., Mahlman, J., Pacala, S., Sarmiento, J. and co-authors. 1998. A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. *Science*, **282**, 442–446.

GLOBALVIEW-CO_2 2000. Cooperative Atmospheric Data Integration Projection—Carbon Dioxide, CD-ROM. NOAA CMDL, Boulder, CO.

Gloor, M., Fan, S., Pascala, S., Sarmiento, J. and Ramonet, M. 1999. A model-based evaluation of inversions of atmospheric transport, using annual mean mixing ratios, as a tool to monitor fluxes of nonreactive trace substances like CO_2 on a continental scale. *J. Geophys. Res.* **104**, 14 245–14 260.

Gloor, M., Fan, S., Pascala, S. and Sarmiento, J. 2000. Optimal sampling of the atmosphere for purpose of inverse modeling: A model study. *Global Biogeochem. Cycles* **14**, 407–428.

Gurney, K., Law, R., Denning, S., Rayner, P. and co-authors. 2002. Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models. *Nature* **415**, 626–630.

Gurney, K., Law, R., Denning, S., Rayner, P. and co-authors. 2003. TransCom 3 CO_2 inversion intercomparison: 1. Annual mean control results and sensitivity to transport and prior flux information. *Tellus* **55B**, 555–579.

Higuchi, K., Worthy, D., Chan, D. and Shashkov, A. 2003. Regional source/sink impact on the diurnal, seasonal and inter-annual variations in atmospheric CO_2 at a boreal forest site in Canada. *Tellus* **55B**, 115–125.

Kurz, W. A. and Apps, M. J. 1999. A 70-yr retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecol. Model.* **9**, 526–547.

Law, R., Chen, Y.-H., Gurney, K. and TransCom 3 Modellers. 2003. TransCom CO_2 inversion intercomparison: 2. Sensitivity of annual mean results to data choices. *Tellus* **55B**, 580–595.

Maksyutov, S., Machida, T., Mukai, H., Patra, P., Nakazawa, T. and co-authors. 2003. Effect of recent observations on Asian CO_2 flux estimates by transport model inversions. *Tellus* **55B**, 552–529.

Masarie, K. A. and Tans, P. P. 1995. Extension and integration of atmospheric carbon dioxide data into a globally consistent measurement record. *J. Geophys. Res.* **100**, 11 593–11 610.

Patra, P., Maksyutov, S. and Transcom-3 Modelers. 2003. Sensitivity of optimal extension of CO_2 observation networks to the model transport. *Tellus* **55B**, 498–511.