Atmospheric Tracer Transport Model Intercomparison Project (TransCom)

Introduction:

A key component in the projection of future global change is the ability to predict future concentrations of atmospheric greenhouse gases such as carbon dioxide (CO_2). Unfortunately, the current state of the science cannot completely account for the growth rate and interannual variations of atmospheric CO_2 with confidence, so accurate prediction of future concentrations is difficult.

Only about half of the anthropogenic CO_2 remains in the atmosphere, and the fate of the other half is not completely understood. Both the ocean and terrestrial biosphere currently act as significant sinks for anthropogenic CO_2, but their relative contributions are a matter of intense debate (Schimel *et al*, 1995). The terrestrial net sink is almost impossible to measure directly, even at a single location, because it results from a small imbalance between large natural uptake and efflux by photosynthesis and ecosystem respiration, neither of which can be accurately measured at large spatial scales. Until the mechanisms involved in the terrestrial uptake are more clearly elucidated, predicting the future behavior of such a sink (and therefore the atmospheric concentration) will be very difficult.

One important approach to understanding and predicting the terrestrial net carbon uptake involves inferring its magnitude and geographic distribution from the spatial and temporal variations in atmospheric CO_2 concentration as observed by global flask sampling programs (Conway et al., 1994; Francey et al., 1995; Keeling et al., 1995). The observed concentration field is determined by the surface fluxes of CO_2 (which we want to know) and the transport of CO_2 in the atmosphere. The atmospheric transport may be simulated by numerical models, and the unknown surface fluxes may then be determined from the observational data by inversion (Enting and Mansbridge, 1989, 1991; Tans *et al.*, 1989, 1990; Keeling *et al.*, 1989; Ciais *et al.*, 1995; Enting *et al.*, 1995; Fan *et al.*, 1998).

The current suite of carbon budget inversion studies produce results which are difficult to reconcile with one another. A recent calculation by Song-Miao Fan and colleagues at Princeton University (Fan *et al.*, 1998) found that the carbon sink in the Northern Hemisphere between 1988 and 1992 was dominated by terrestrial uptake in North America. Their results, if correct, imply that the terrestrial sink approximately compensates for the anthropogenic emissions in this region. Peter Rayner and colleagues at Monash University in Australia performed an inversion using most of the same data but a different CTM and a different mathematical method. They found that the northern terrestrial sink was distributed more evenly across the northern continents, with North America acting as only a weak sink (Rayner *et al*, 1997). A third study has concluded that the terrestrial sink is dominated by Eurasia (Bousquet *et al.*, 1998)

As high time-resolution global data on additional species become available ($\delta^{13}C$ and $\delta^{18}O$ of atmospheric CO_2 and atmospheric O_2/N_2 ratio), the use of synthesis inversion techniques with atmospheric tracer transport models will result in much more reliable estimates of the changing global carbon budget of the atmosphere. Improvements in the quality and quantity of the observational data and in the mathematical formalism associated with the inversion calculation have brought us to the point where one of the biggest sources of uncertainty now lies in the transport models themselves (Law *et al*, 1996; Denning *et al*, 1999).

The time has come for a thorough and systematic evaluation of the transport models, comparing model results against one another and against the real world. In addition, we hope to use the results of the experiments described herein to advance the mechanistic understanding of spatial and temporal variations of biogenic trace gas concentrations at the global scale.

TransCom:

The Atmospheric Tracer Transport Model Intercomparison Project (TransCom) was conceived at the Fourth International CO_2 Conference in Carqueiranne in 1993. TransCom is a special project of the International Geosphere-Biosphere Programme (IGBP), Global Analysis, Interpretation, and Modeling (GAIM) Project, the objective of which is to quantify and diagnose the uncertainty in inversion calculations of the global carbon budget that result from errors in simulated atmospheric transport. The project is part of a larger GAIM research program which aims to develop coupled ecosystem-atmosphere models that describe time evolution of trace gases with changing climate and changes in anthropogenic forcing.

Initially coordinated by Peter Rayner at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), TransCom is now being coordinated by Scott Denning at the Department of Atmospheric Sciences, Colorado State University. Two distinct phases of the TransCom have now been completed with a third phase about to begin.

TransCom phase 1:

The first phase of TransCom, which involved about a dozen modeling groups from around the world, examined the atmospheric concentration response to surface emissions of fossil fuel CO_2 and the activity of terrestrial ecosystems. These experiments were designed to address two salient features of atmospheric CO_2: (1) the annual mean north-south (meridional) gradient arising from fossil fuel emissions; and (2) the seasonal cycle arising from the seasonal exchange of CO_2 between the atmosphere and terrestrial ecosystems, with a net zero flux at each grid point but with strong uptake during the growing season balanced by release by decomposition.

Results of this initial intercomparison were reported by Rayner and Law (1995) and by Law *et al* (1996). With a few exceptions, there was good agreement among the models with regard to the annual mean meridional distribution of the "fossil fuel" tracer at the surface. A few models simulated extremely strong interhemispheric gradients of fossil-fuel at the surface, and these models also simulated very low concentrations aloft over the emissions region. This suggests that the high surface mixing ratios simulated by these models resulted from vertical trapping of tracer in the emissions region, rather than from weak interhemispheric transport.

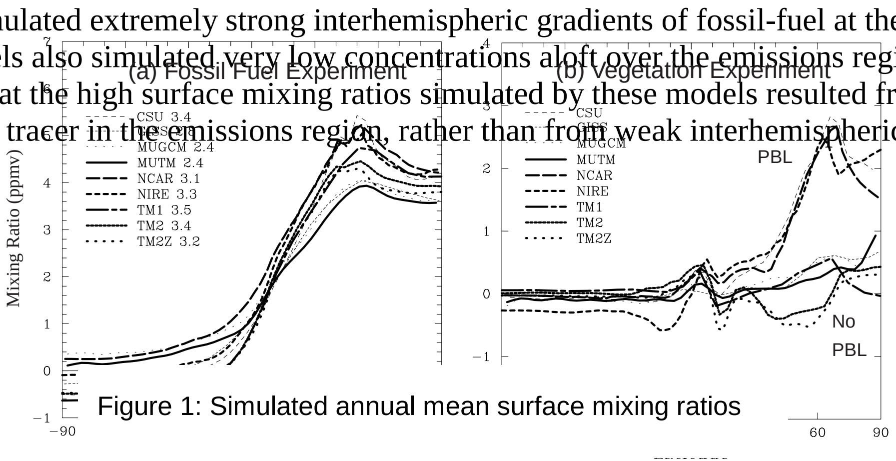

Figure 1: Simulated annual mean surface mixing ratios

There was qualitative agreement for the seasonal variations of CO_2 in the biosphere experiment, though this agreement diminishes over continental regions which lack observational constraints. The annual mean meridional response of the models to seasonal biotic forcing can be classified into two groups. Models which represent turbulent mixing in the planetary boundary layer simulate a pole-to-pole gradient in surface CO_2 that is roughly half as strong as that obtained in the fossil fuel experiment. The other models simulate a very weak meridional structure in these runs.

TransCom phase 2:

The results of the Phase 1 experiments showed a surprising degree of difference among the participating models, but observations of CO_2 arising purely from fossil fuel emissions or seasonal vegetation do not exist. Evaluation of the realism of the various model simulations is therefore impossible. In 1996, the participants agreed to perform additional experiments to "calibrate" the results of TransCom 1, and in addition, seek to understand the mechanisms by which the models diverged so strongly in their results (Denning *et al* 1999). With an extremely long atmospheric lifetime, a relatively well-known source, and a twenty year legacy of observations around the planet, SF_6 is an ideal trace gas for transport calibration purposes.

While most of the models were reasonably successful at reproducing the "background" observations of SF_6, some underestimated marine boundary layer values due to excessive vertical convective transport. Many of the models were less successful at continental locations near sources, where most models significantly overestimated SF_6. The "more convective" models matched the observations better at these continental sites than did the "less convective" ones. These results further emphasize the TransCom 1 findings that strong meridional gradients in simulated fossil fuel CO_2 at the surface were systematically associated with weak meridional gradients in the upper troposphere, and vice versa.

Although there were distinct differences in the intensity of interhemispheric exchange among the models, these differences could not be adequately understood in terms of spatial distributions of tracer at the surface. Interhemispheric mixing has long been associated with north-south concentration gradients determined from observations, but our results suggested that the meridional gradient measured at the surface is a poor predictor of the true interhemispheric mixing time of a given model.

Both resolved transport and sub-grid scale "column physics" were important in determining the responses obtained by the models. Surprisingly, differences in the subgrid-scale parameterized transport appear to be at least as important in determining model performance as the differences between analyzed winds vs. calculated winds.

TransCom phase 3:

The progress made in these first phases of the TransCom project can now be directly applied to resolving some of the discrepancies in estimates of the global carbon budget. To that end, we are in the early stages of constructing a CO_2 inversion calculation intercomparison. Participating transport models will be used to simulate the atmospheric response to an agreed-upon set of surface emission "basis functions" representing regional emissions and uptake of

CO_2 due to various processes (industrial emissions, ecosystem metabolism, air-sea gas exchange, biomass burning, etc). The focus of this inversion intercomparison activity will be to produce a formal estimate of the degree of uncertainty in such an inversion calculation that arises directly from the uncertainty in the model transport, the inversion methodology, and the observational dataset used. It is hoped that this ambitious activity can begin in late 1998, and that it can be completed in 2000-2001. A final phase of the project will use a set of sensitivity experiments to isolate the components of the models and methods that are most responsible for the different behavior they exhibit, using the results to recommend priorities for future model development and observational network improvements to reduce uncertainty.

The proposed experimental design reflects the tension between greater participation and greater diagnostic detail. We have chosen to specify a minimum experimental protocol that is straightforward to implement (to maximize participation by keeping the entry barrier low), and allow for more detailed experiments by those groups with sufficient resources and interest. This strategy is best pursued by centralizing many of the tasks to be performed, so that participation in the experiment requires a minimum of effort by a CTM group.

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