Abstract

Atmospheric chemical tracer transport models (CTMs) can be used to calculate surface fluxes of trace species from spatial distributions of concentration, by a set of methods collectively known as “inversion.” This technique has been applied to the study of sources and sinks of CO_2, and the results have important implications for policy responses. Different CTM groups have produced conflicting results using the same observational data. We will conduct a three-year series of experiments in which leading chemical tracer transport models from around the world are used to calculate the global carbon budget of the atmosphere. The objectives of the proposed research are (1) to quantify the uncertainty in the O_2 budget that arises from differences in simulated transport; (2) to diagnose the mechanisms that produce these differences; and (3) to recommend and prioritize improvements to the models and observing network to reduce this source of uncertainty in the future.

1 Introduction

The development of rational policy responses to global change requires the prediction of future levels of atmospheric CO_2 that will result from any particular scenario or policy option for anthropogenic emissions. Confident predictions of this kind require a quantitative understanding of the carbon sources and sinks in the Earth system, and how they respond to land use, nutrient deposition, climate change, and CO_2 itself. Although major progress has been made in the past 10 years toward such a characterization of CO_2 sources and sinks, a quantitative accounting is not yet possible (IPCC, 1996).

Most of what we know about the global carbon budget has been derived from the now 40-year-long record of atmospheric CO_2 sampled in clean "background" locations. These data are interpreted with a high degree of confidence at the global scale, leading to a detailed record of the time series of the rate of increase. The rate of combustion of fossil fuels is known from econometric tabulations (Marland, 1989; Andres *et al*, 1996), so the history of atmospheric CO_2 can be used to infer the integral of all other sources and sinks in the Earth system by subtracting this anthropogenic emission rate (Keeling *et al*, 1989a, 1995; Conway *et al*, 1994; Francey *et al*, 1995). Such analyses have led to the conclusion that about half of the CO_2 from the emission of fossil fuels is removed from the atmosphere by sinks that vary in strength by about a factor of two from year to year. The cause of these interannual fluctuations is difficult to determine, as are the underlying sink mechanisms.

The nature and variability of the sinks of anthropogenic carbon have also been investigated using the spatial distribution of atmospheric CO_2 as measured by flask samples collected in the remote marine boundary layer. Until recently, the distribution of these flask sampling sites was so sparse that the data were only sufficient to characterize the north-south gradient. The addition of new stations and recent efforts to combine sampling networks through intercalibration (Masarie and Tans, 1996, see Fig 1) has made it possible to analyze the longitudinal variations as well.

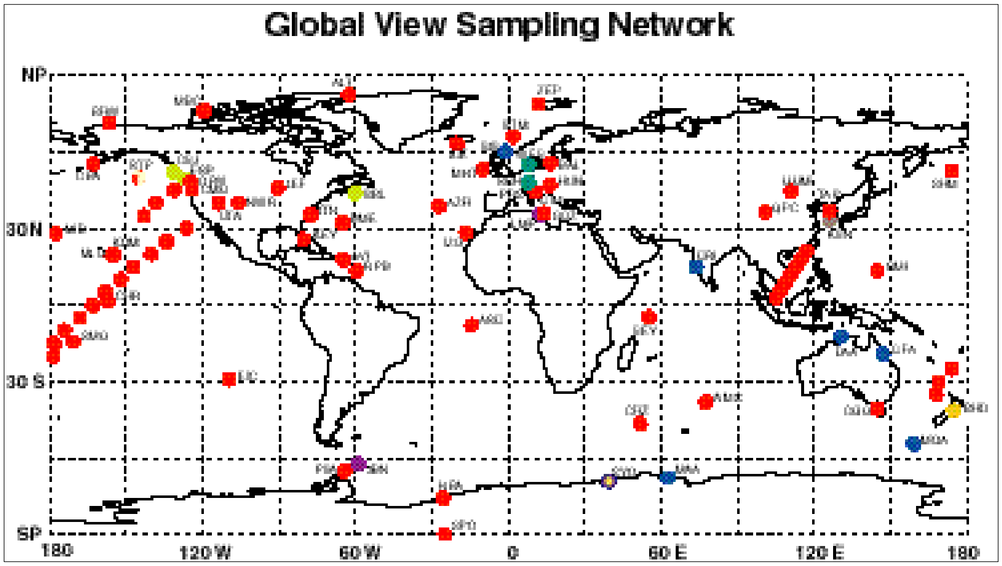

Figure 1: Flask sampling station locations (Masarie et al, 1996)

Quantitative interpretation of the spatial structure of atmospheric CO_2 in terms of sources and sinks at the surface requires accounting for atmospheric transport upstream of the observing stations. This is done using numerical models in which CO_2 is transported by winds derived either from analyzed observations or from general circulation models (GCMs). The process of inferring surface sources and sinks from observed concentration patterns using a transport model is referred to as “inversion” of the data (Enting and Mansbridge, 1989, 1991; Hartley and Prinn, 1993; Enting *et al*, 1995). Inversion of the interhemispheric gradient of CO_2 concentration can be accomplished using a two-box model of atmospheric mixing; the more dense network of observing stations can only be interpreted in terms of continental fluxes with a full three-dimensional chemical tracer model (CTM).

Several groups are now using three-dimensional CTMs to perform time-dependent inverse calculations of the atmospheric carbon budget with continental or regional resolution (Rayner *et al*, 1998; Fan *et al* , 1998; Gloor *et al*, 1998; Peylin *et al*, 1998?). These inversions, made possible by the expansion of the global flask network, innovative mathematical techniques, and the use of multiple geochemical tracers, may yield valuable insights into the processes responsible for removing CO_2 from the atmosphere. In addition, there is the possibility that such calculations may eventually prove useful for monitoring the rate of anthropogenic CO_2 emissions from continents or even countries.

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*, 1997) 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 almost evenly across the northern continents, with North America acting as only a weak sink (Rayner *et al*, 1997).

Much of the difference among the various inversions can be explained in terms of differences in the simulated tracer transport among the CTMs used by the various groups (Law *et al,* 1996; Denning *et al,* 1998, 1999). Inversion calculations of the CO_2 budget are an important source of information about the carbon budget which will become even more important as efforts are made to reduce or mitigate fossil fuel emissions. Given this central role, it is imperative to characterize the present uncertainty in carbon sinks that arises from the uncertainty in CTM transport and to prioritize improvements in both the models and the observing system that might reduce this uncertainty. We propose here a model intercomparison study to do this, building on a set of recently completed experiments with many of the CTMs in use by the CO_2 inversion community.

2 Previous Results

2.1 TransCom

The Atmospheric Tracer Transport Model Intercomparison Project (TransCom) is a project of the IGBP Global Analysis, Interpretation, and Modeling (GAIM) Task Force, initiated at the 4th International CO_2 Conference at Carquerianne, France, in 1993. The initial aim of TransCom was to provide an understanding of the importance of differences in atmospheric tracer transport models used in CO_2 budgets studies. TransCom participants include about a dozen modeling groups around the world (Table 1). Although the experiments have not included reactive chemistry, many of the participating models form the basic “dynamical cores” used in simulations of reactive species. Therefore, our results are highly relevant to understanding the errors in simulations of tropospheric pollutants and should be of interest to the atmospheric chemistry community.

The initial TransCom study 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.

Table 1: Participating Models

Model	Horizontal Grid	# Levels	Advection	Wind
ANU	2.5°	7 pressure	Lagrangian	ECMWF
CCC	3.75°	10 sigma/pres.	Spectral	On-line
CSIRO9	3° x 5.6°	9 sigma	Semi-Lagrangian	On-line
CSU	4° x 5°	17 sigma	2nd order	On-line
GFDL-GCTM	256 km	11 sigma	2nd order	GFDL ZODIAC
GFDL-SKYHI	3° x 3.6°	40 sigma	2nd order (horiz), 4th (vertical)	On-line
GISS	4° x 5°	9 sigma	Slopes	GISS GCM II
GISS-UVIC	4° x 5°	9 sigma	Slopes	GISS GCM II'
MUTM	3.33° x 5.63°	9 sigma	Spectral	MU GCM 7
NCAR CCM2	2.8 x 2.8	18 sigma	Semi-Lagrangian	On-line
NIRE	2.5°	15 sigma/pres.	Semi-Lagrangian	ECMWF
TM2	7.5° x 7.5°	9 sigma	Slopes	ECMWF
TM3	3.75° x 5°	19 sigma	Slopes	ECHAM3 GCM
Scripps TM1	8° x 10°	9 sigma	Slopes	ECMWF

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 (Fig 2a), which is encouraging given the importance of this variable for inversion calculations. A few models simulated extremely strong interhemispheric gradients of fossil-fuel at the surface (not shown in the figure), 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.

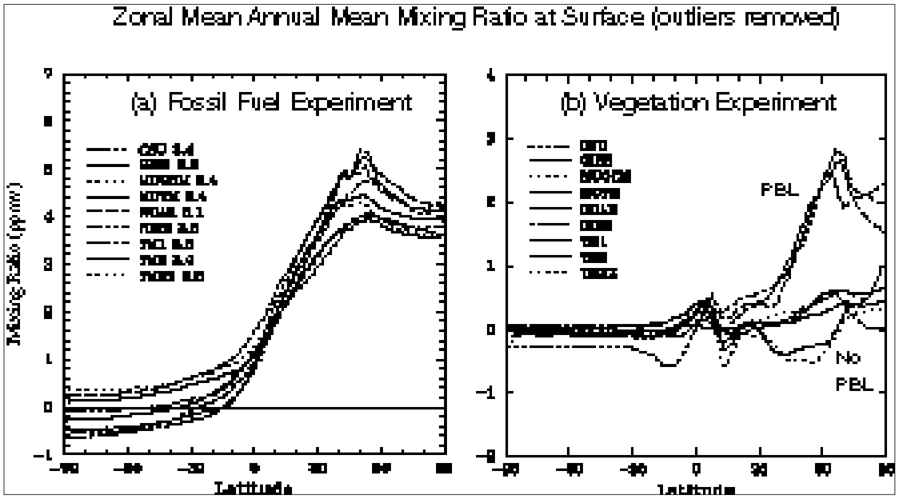

Figure 2: Simulated annual mean surface mixing ratios

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 (Fig 2b). 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.

2.2 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 are impossible. 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, we sought to understand the mechanisms by which the models diverged so strongly in their results. 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.

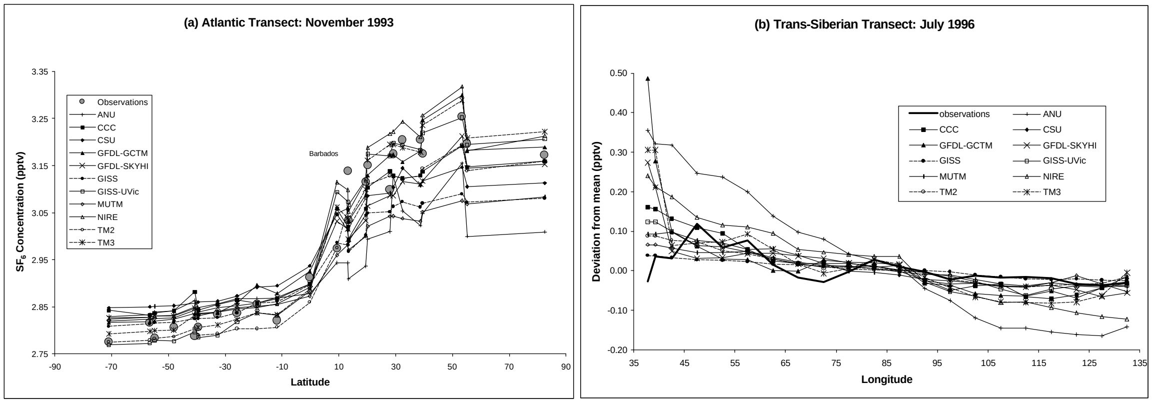

Figure 3: Simulated and observed surface SF_6 mixing ratio for marine (a) and continental (b) locations

While most of the models are reasonably successful in reproducing the "background" observations of SF_6, some underestimate marine boundary layer values due to excessive vertical convective transport (Fig 3a). Many of the models are less successful at continental locations near sources, where most models significantly overestimate SF_6. The “more convective” models match the observations better at these continental sites than do the “less convective” ones (Fig 3b). 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 are distinct differences in the intensity of interhemispheric exchange among the models, these differences cannot 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 suggest 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.

3 Proposed Research

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 now propose to conduct an inversion intercomparison experiment. This will allow us to directly quantify the contribution of simulated tracer transport to the overall uncertainty associated with regional carbon source/sink estimates produced by inversion calculations.

The primary objective of the proposed experiment is to determine the effect of differences in simulated tracer transport among participating atmospheric models on the results of carbon cycle inversions. Secondary objectives are to diagnose the mechanisms that produce these differences and to suggest improvements to models and the global observing system to produce more robust inversions. 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. We request support for this coordination activity only. Experimental calculations performed by individual CTM groups will be supported separately by the participants.

We have divided the experimental protocol into three levels. The first level focuses on annual mean carbon sources and sinks and will require a limited number of forward model runs by the participants using supplied input fields of regional carbon exchange. The second level expands on the first by including an inverse calculation of the strength of the seasonal cycle in regional fluxes, but will require a much larger number of CTM simulations by each participating group. The central Coordinator will perform inverse calculations from the CTM output submitted by participants in levels 1 and 2 to characterize the different model carbon source/sink distributions. The third level allows participants to perform their own inversions allowing for a first comparison of different inversion methods. This multi-level approach maximizes participation by making the entry level component (level 1) relatively simple to accomplish. The inclusion of level 2 and especially level 3 should be particularly interesting to those modeling groups that have extensive experience with inversion research.

3.1 Experimental Design

3.1.1 Level 1

The purpose of level 1 is to retrieve an annual mean carbon source/sink distribution for each participating model. This source/sink map will represent annual mean carbon exchange other than that arising from fossil-fuel emissions (which has a well-known source distribution). All participants will be required to submit results for the Level 1 experiment.

Participants will be supplied a gridded data set of the designated carbon exchange regions ("basis functions") comprised of 10 terrestrial and 10 ocean regions (Figure 4). These regions have been chosen to represent the major terrestrial biomes, and major ocean circulation features. Spatial structure of carbon exchange *within* terrestrial regions will be supplied from a satellite-based estimate of NPP in the land regions. Gridded input data sets of fossil-fuel emissions (Andres *et al*, 1996) and a global map of the annually-averaged neutral terrestrial biosphere exchange will also be supplied.

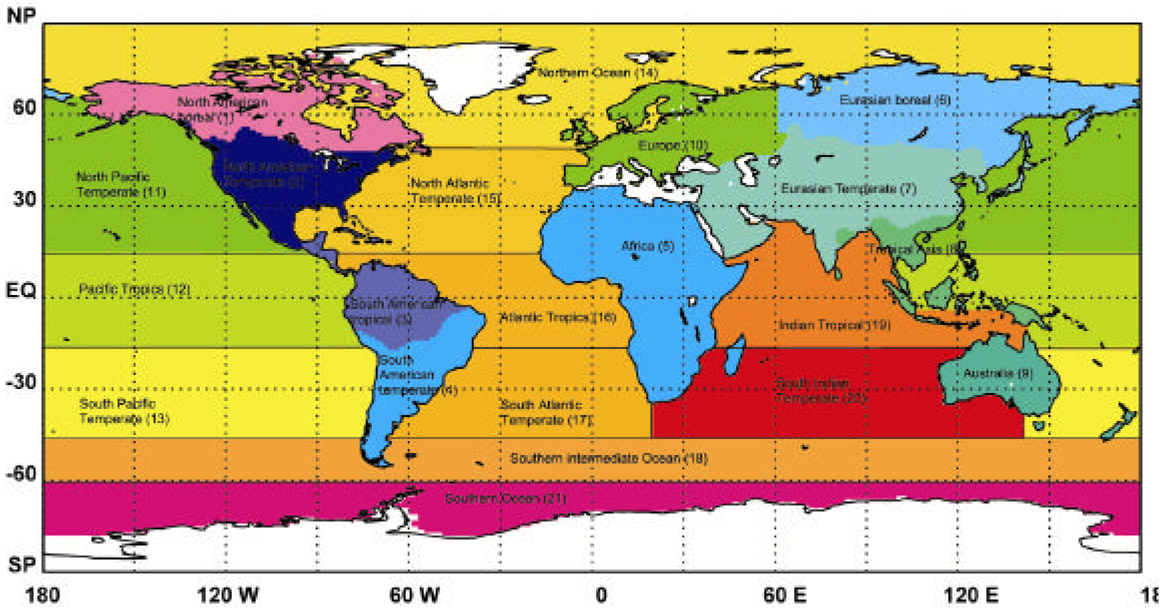

Figure 4: Basis function regions proposed for inversion intercomparison.

Participants will then run four-year CTM simulations with a unit carbon flux from each of these basis regions in addition to forward simulations of both the supplied fossil-fuel source and the neutral terrestrial biosphere exchange. Each group will also run the trace gas simulated in TransCom phase 2, sulfur hexafluoride (SF_6), in the 10 terrestrial regions (with a supplied emissions distribution). The SF_6 simulations will be used to evaluate the inversion methodology by calculating the “known” emission field using the same techniques as are used to determine the “unknown” CO_2 budget. The required Level 1 experiment will require 32 forward simulations, one for each of the basis regions, one each for fossil fuel emissions and the neutral terrestrial biosphere, and 10 for SF_6. Participants will submit monthly mean, three-dimensional arrays of tracer mixing ratio plus the three wind components (u, v, and ω). In addition, high-frequency output at a collection of chosen stations may also be required in order to perform time-series analysis.

The inversion calculation will be performed on the residual concentration field simulated by each model after “presubtracting” the effects of fossil fuel emissions and the neutral (annually balanced) terrestrial biota. The fossil fuel emission field is reasonably well determined form econometric data (eg, Andres *et al* , 1996), and presubtracting this will allow the inversion results to focus on the less-well-understood terrestrial and marine sources and sinks. Presubtraction of the neutral vegetation signal is necessary because of covariance (“rectifier”) effects that arise because of interactions of the atmospheric transport with the vegetation fluxes (Denning *et al* , 1995, 1996). The observational data used in the inversion calculation will be a subset of the NOAA GlobalView data (Masarie and Tans, 1996).

3.1.2 Level 2

The Level 2 experiment will incorporate the seasonal cycle of the terrestrial biosphere in the inversion, rather than presubtracting the seasonal “rectifier” effect. For each of the 20 basis regions previously specified, carbon exchange will be characterized by an annual mean plus two Fourier harmonics to capture seasonality.

Participants who wish to submit Level 2 results will perform 5 four-year simulations (annual mean plus four harmonics) for each of the 20 basis regions, for a total of 100 simulations. A modeling group that participates in the optional Level 2 experiment will have effectively completed all the requirements of Level 1.

3.1.3 Level 3

Many potential participants in TransCom phase 3 have had considerable experience performing carbon inversion studies. To ensure the participation of these groups and to satisfy their more specialized interests, a third level is included allowing participants to perform their own carbon inversion. Though the central TransCom phase 3 inversion will utilize only one inversion method, a number of different methods exist. Participants in level 3 must utilize the input databases supplied submitting only carbon source/sink maps resulting from their inversion effort. This will allow a first effort at comparing the differences due to inversion methods in addition to the underlying transport.

3.2 Central Coordination Activities

Support is requested for the following specific tasks, which will be performed at Colorado State University. The participants are expected to support their own modeling activities through their home institutions or through other research support.

3.2.1 Finalize development of the experimental protocol

The experimental design described in section 3.1 above was developed by participants at a workshop held in February, 1998 and through subsequent meetings and email discussions. In December, 1998, we will hold a “kick-off” workshop (supported by the IGBP/GAIM Office) to present this plan to invited participants from around the world. The purpose of the kick-off workshop is to solicit input on refinement of the protocol, and to provide guidance to potential participants on the resources available from the Coordinator. Following this workshop, a formal protocol will be produced describing the precise details of the experimental methods will be constructed and distributed to all participating modeling groups.

3.2.2 Produce and distribute input data for the model simulations

The proposed experiments will require gridded emissions data to be prescribed as a boundary condition for each CTM simulation. The central Coordinator will develop these emissions data for each basis region, and will supply them on a high-resolution grid to be interpolated by each CTM group, as appropriate. These input data will be made available on an ftp site maintained by the Coordinator, along with detailed instructions concerning how the data are to be used.

3.2.3 Maintain a web and ftp site to facilitate participation

The existing TransCom web site (http://transcom.colostate.edu) will be expanded to facilitate participation in the inversion intercomparison. The expanded site will include the full experimental protocol, links to the input data sets, and detailed “cookbook-style” instructions on the procedures required. The Coordinator will also maintain email lists to facilitate communication among participants, and will use the Web site to disseminate early results and analysis.

3.2.4 Collect and archive CTM results in a central database

Participants will submit CTM results to the centrally-maintained ftp site, where data quality-assurance checks will be performed before including them in an archival database. The database will be open for analysis by all participants, but must be both secure (password-protected) and flexible enough to allow easy access. This will give modeling groups the opportunity to investigate different comparative analyses. Each group can both contribute to, and benefit from, this process by collective identification of the key model assumptions, weaknesses, and differences.

3.2.5 Coordinate centralized analysis, distribute and archive results

Inversion calculations will be performed using the archived CTM results, using a variety of mathematical techniques. The Coordinator will be responsible for the exchange of data among the researchers performing these calculations. A Bayesian synthesis inversion method will be developed and performed by Peter Rayner and colleagues at the Cooperative Research Center for Southern Hemisphere Meteorology at Monash University in Australia through a subcontract from Colorado State University (see attached documentation). A different technique using simple Singular Value Decomposition without prior constraints will be applied by the Carbon Modeling Consortium at Princeton University (see attached letter of support). Other methods will also be explored, and may be used by the Coordinator or by other participants.

The Coordinator will prepare the submitted CTM data, transfer them to the collaborating institutions, and archive the results of these inversion calculations for each model. In addition to centralized inversion calculations, other analyses will be performed by interested participants such as time-series analysis, sensitivity analysis, optimal network design, etc. This system of distributed analyses will make use of specialized skills of some participants, spreading “intellectual ownership” in the TransCom process, but will require significant central coordination. Results of these specialized analyses will become part of the central archive. The Coordinator will collect the results of the distributed analyses and prepare easily accessible comparisons of these results for distribution to the participants through the TransCom Web site.

3.2.6 Conduct annual participants’ workshops

In addition to coordination of the experiment itself, the central coordinator will also organize an annual workshop for participants to review progress, deal with problems that occur, and determine the agenda for the following year. The first workshop will be held in December 1998 in San Francisco. Future workshops should be held in other countries to facilitate participation by an international modeling community. Travel and logistical support for these workshops *is not requested* in this proposal, but will rather be provided by the IGBP/GAIM Office (see attached letter of support).

3.2.7 Coordinate dissemination of results

The results from each modeling group will be compared and analyzed, and early results will be disseminated on the TransCom Web site as outlined above. In addition, the Coordinator will present the ongoing research to the wider research community at scientific meetings, and will coordinate the publication of core research by participants. This will include submission of manuscripts comparing the inversions, diagnosing the mechanisms, analyzing the uncertainty in the carbon budget, and recommending improvements to models and observing networks.

4 Management Plan

TransCom 3 will be coordinated by Dr. Scott Denning, Assistant Professor of Atmospheric Science at Colorado State University. He is a recognized leader in the field of numerical simulation of chemical tracer transport and carbon cycle inversion. He has published more than 20 articles in the peer-reviewed literature. He has coordinated TransCom 2 since 1996, and is already versed in the intricacies of coordinating research activities across four continents through email and Web sites. He will serve as the intellectual leader of the project, recruit participants, and supervise the other project personnel.

Kevin Gurney is a Research Associate who will be responsible for most of the day-to-day scientific work of the Coordination office. He has two Masters' Degrees (Atmospheric Science from MIT and Public Policy from UC Berkeley), and has worked in the areas of atmospheric chemistry and tracer transport for more than five years. He has published several articles in the peer-reviewed literature, and a respected book on stratospheric ozone. He will prepare the protocol documents and input data sets, maintain the TransCom data archive, perform quality assurance and analysis of submitted CTM results and inversion fluxes, and conduct scientific communication with participants.

Dr. Peter Rayner at the Cooperative Research Center for Southern Hemisphere Meteorology (CRC-SHM) at Monash University has been a leader in carbon cycle inversion research for several years, in collaboration with Prof. Ian Enting who developed much of the mathematical formalism. They and their colleagues will develop inversion methods for use in TransCom 3, under a subcontract from Colorado State University (see attached documentation). Rayner led TransCom from 1993-96.

Programming and data support will be provided by John Kleist, who has over 15 years experience in scientific programming, systems administration, and data management. Production of scientific graphics and Web development will be performed by Connie Uliasz, who will also handle logistical duties associated with international communication and collaboration.

5 Facilities and Equipment

The Principal Investigator has at his disposal research computing equipment to support most of the considerable needs of the proposed project. This consists of a Silicon Graphics (SGI) Origin 200 compute server with 4 processors, 768 MB of RAM, and 58 GB of disks, an SGI Octane workstation, and a network of PC workstations.

The SGI server runs scientific analysis and graphics software and Apache Web server software. An additional PC workstation is requested to support the creation of scientific graphics, and maintenance of the TransCom Web site. In addition, support is requested to purchase a large disk for the TransCom data archive, and backup tapes to support both routine and archival (off-site) backup of project data.

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