Atmospheric Tracer Transport Model Intercomparison Project (TransCom)

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Abstract:

A multi-phase program of model intercomparison is proposed to reduce uncertainties in the global carbon budget resulting from differences among atmospheric tracer transport simulations. The TransCom program is already well underway, having begun in 1993 and completed two major experiments. The results to date are summarized in a Technical Report and indicate that significant differences among the participating models need to be explored in much more detail if the intercomparison is to be useful in reducing uncertainties in the carbon budget of the atmosphere. A three-year program of further research is proposed. In the first year, a "calibration" experiment will be undertaken to allow quantitative evaluation of the realism of simulated tracer transport of SF_6 by comparing the model results to observations of this anthropogenic trace gas. New model diagnostics will be incorporated into these runs which will permit a mechanistic analysis of transport processes that determine the outcome of the experiment. In the second and third years, sensitivity experiments will be designed and performed based on the calibration results. These experiments will aid not only in reducing the uncertainties associated with differences among the models, but also contribute to the understanding of processes that will aid future model development. A progress report will be delivered at a major international meeting in 1997, and a final report will be presented at another meeting in 1998.

Motivation:

A great deal of information on the exchange of carbon between the atmosphere and the Earth's surface is contained in the observational record of spatial and temporal variations of atmospheric trace gases (*e.g.*, Conway *et al.*, 1994; Francey *et al.*, 1995; Keeling *et al.*, 1995). Because surface carbon fluxes are convolved with atmospheric transport processes to produce the distribution of CO_2 observed by monitoring networks, numerical models of scalar tracer transport by the atmosphere are necessary to estimate sources and sinks of CO_2 from atmospheric observations (Enting and Mansbridge, 1989, 1991; Tans *et al.*, 1989; Keeling *et al.*, 1989; Enting *et al.*, 1995). Such calculations may be driven by wind fields simulated by General Circulation Models (GCMs) (Fung *et al.*, 1983, 1987; Tans *et al.*, 1990; Enting *et al.*, 1995), by analyzed wind data derived from observations (Heimann and Keeling, 1989), or the transport may be computed on-line in a GCM (Denning *et al.*, 1995).

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. 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.

Overview:

The atmospheric tracer transport comparison project (TransCom) was conceived at the Fourth International CO_2 Conference in Carqueiranne in 1993. Up to now, the project has in-

volved simple cooperation among a diverse and geographically separated group of researchers involved in the tracer transport problem, contributing their time and resources without official recognition or support. TransCom has been coordinated since that time by Peter Rayner, formerly at Princeton University and since mid-1994 at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Division of Atmospheric Research in Australia.

An initial set of two experiments was performed using 12 models, and involved an aseasonal northern hemisphere source (fossil fuel emissions forced by fluxes derived by Inez Fung from emission the inventories of Marland, 1989) and a seasonal biotic source (annually balanced net ecosystem exchange with the terrestrial biosphere according to Fung *et al.*, 1987). The intent of these experiments was to use the "fossil fuel" simulation to compare the annual mean spatial structure among the models, and to use the "biosphere" experiment to document the behavior of the simulated seasonal cycles. The results of these initial experiments have been analyzed, were presented in a poster by Law, Rayner, and Enting at the IGBP/GAIM Science Conference, and will appear this month in a technical report (Rayner and Law, 1995).

Some key findings of the initial experiments are:

- There is qualitative agreement among the models with regard to the annual mean meridional distribution of the "fossil fuel" tracer at the surface, which is encouraging given the importance of this variable for inversion calculations. Nevertheless, the simulated hemispheric mean response at the surface varies among the models by nearly a factor of 2.
- Even the qualitative agreement among the models in the fossil fuel experiment breaks down when the three-dimensional structure of the tracer is considered.
- Variations in seasonal behavior of CO_2 in the "biosphere" experiment are even more pronounced, especially over continental regions which lack observational constraints.
- The annual mean meridional response of the models to seasonal biotic forcing defines two mutually exclusive scenarios. Models which represent turbulent mixing in the planetary boundary layer (PBL) simulate an Arctic-to-Antarctic 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.
- Both resolved transport and sub-grid scale "column physics" are important in determining the responses obtained by the models to the prospected forcing.

Neither of the tracers simulated in the initial experiments is directly observable (both are *components* of the total CO_2), so it is impossible to decide with confidence which of the simulations is most realistic. Elimination of "outliers" among the models would reduce the uncertainty in the simulated responses by about half, but the group is uncomfortable with the rather arbitrary definition of "outliers" that would be necessary to interpret the results in this way. It would be very desirable to perform additional calibration experiments among these same models, using trace gases with known distributions of both sources and concentrations in order to reduce the current level of uncertainty.

Unfortunately, organizational changes at CSIRO now preclude continuing coordination of the project by Peter Rayner and his colleagues. Most of the group met during the recent IGBP/GAIM Science Conference and agreed to perform ongoing research to reduce the degree of scatter

among the model results. It was suggested that organizational support, recognition, and a modicum of funding could be provided by the IGBP/GAIM Task Force. A. Scott Denning at Colorado State University agreed to serve as the TransCom Coordinator if such an arrangement could be put into place.

The work performed by the project up to the present is designated herein as TransCom Phase 1. The following sections outline a proposed plan for organized research to build on the previous results and maximize their usefulness to the larger research community. Phase 2 will concentrate on model calibration using a trace gas that is well constrained by observational data. Phase 3 will build on the earlier work by carrying out sensitivity experiments to better understand the mechanisms which lead to differences among the models, and will lead to recommendations of specific actions that will reduce the level of uncertainty in such studies.

Objectives:

The primary objective of the TransCom Project is to reduce uncertainties in the global carbon budget of the atmosphere that result from differences among models of chemical tracer transport. In support of this objective, the following tasks will be undertaken:

- Evaluation of the realism of the various simulations of annual mean tracer distributions resulting from the aseasonal anthropogenic source used in the initial “fossil fuel” experiment. This will involve a model *calibration* using a different trace gas.
- Investigation of the mechanisms responsible for producing the large discrepancies among the model responses obtained in the initial experiments. This will involve both a careful analysis of the initial results and new *sensitivity experiments* designed to quantify the influence of various aspects of the model transport.
- Identification of key *measurements* which would result in the greatest reduction in the uncertainty associated with atmospheric inversion calculations.
- Recommendations for *process-oriented research* to improve the representation of global scale chemical tracer transport, and to further reduce uncertainties in global carbon budget calculations.

Research Plan:

Phase 2: Calibration

One of the greatest sources of uncertainty in the interpretation of the results of Phase 1 is the large range of responses of the models to the simple aseasonal emissions map represented in the fossil fuel experiment. Significantly, two of the models that produce the strongest spatial gradients in the annual mean concentration of the fossil fuel tracer also produce the greatest seasonal amplitude in the biosphere experiment. If these results could be compared against observations, the uncertainty in the surface concentration fields simulated in Phase 1 would be reduced by about half.

Calibration involves the simulation of a nearly unreactive atmospheric trace gas with relatively well-known emission distributions that are similar to fossil fuel CO_2, and for which sufficient observational data exist to evaluate the realism of the simulated concentration fields. Previous studies of this kind have been performed with Chlorofluorocarbons (CFCs) and with

^{85}Kr. Both of these gases have the advantages of long tropospheric lifetimes, relatively well-documented emissions concentrated in the middle latitudes of the northern hemisphere, no natural sources, and available concentration data across a range of latitudes. To be useful in constraining the inversion calculations described above, the annual mean meridional structure of the calibration tracer should be in pseudo-steady state, which is no longer the case for CFCs. Reductions in emission rates since the adoption of the Montreal Protocols have resulted in a slow relaxation of the meridional gradient, so that it is now problematic to choose a "steady state" period to simulate which is well sampled by the observational data. Calibration with ^{85}Kr is also problematic because of uncertainty in its emission rates in the former Soviet Union. Also, because this gas is emitted from a handful of discrete nuclear fuel reprocessing plants, differences among model simulations may overemphasize numerical problems in handling of point sources that are less of an issue with fossil fuel CO_2.

A better choice for model calibration is sulfur hexafluoride (SF_6).This anthropogenic gas is produced during electrical equipment manufacture, has an atmospheric lifetime of over 3000 years, and its concentration has increased more than 100-fold since 1970 (Maiss and Levin, 1994). Archival air samples collected for other purposes have been used to establish temporal trends, the meridional gradient, and the interhemispheric exchange time. Maiss and Levin (1994) showed that a linear growth rate model of emissions fit the data well. For TransCom, an aseasonal emissions map will be prescribed according to their model, with the geographic distribution based on electrical power usage statistics, as has previously been done for CFCs. Ingeborg Levin has agreed to provide these data as well as continuing data support for TransCom.

The group will come to consensus on driver data and exact methodology for the calibration experiment by January 1, 1996. The experimental specification will include new model diagnostics quantifying tracer transport by the mean flow and by resolved eddies, and by sub-grid scale processes such as boundary layer turbulence and cumulus convection. The driver data will be distributed by the Coordinator, who will also be responsible for producing written documentation of the experiments to be performed. Simulations will be run by the various modeling groups during the first half of 1996, and results will be submitted electronically to the Coordinator, who will perform preliminary analyses and make them available to the entire group via the World Wide Web.

A TransCom Phase 2 workshop will be organized to coincide with the American Geophysical Union meeting San Francisco in December of 1996. This will be a forum for discussion, analysis, and interpretation of the results of the calibration experiment, and a planning meeting for Phase 3. At this point, comparison of the simulated tracer fields with the SF_6 data will have defined a target range of responses which may be considered realistic in terms of spatial gradients in the annual mean. These results in turn will be used to draw more robust conclusions from the Phase 1 results presented by Rayner and Law (1995), and to identify at least some of the mechanisms in the models which cause the disagreement in the Phase 1 results.

Phase 3: Sensitivity Experiments

Based on the results of the Phase 2 calibration experiments, a limited set of sensitivity experiments will be agreed upon to quantify the effects of various physical (and possibly numerical) mechanisms on the uncertainty in the simulated concentration fields. Possible experiments include: using finer resolution in space, time, or both; changing model parameters such as diffusivity; and disabling sub-grid scale vertical transport by moist and dry convection. The

methodology will be determined by the results of Phase 2, and designed to allow quantitative estimation of the effects of problematic aspects of the model transport. These experiments, in conjunction with the results of Phases 1 and 2, will guide the participants in future model development and allow the identification of key voids in the observational data which could be addressed to provide the most efficient use of limited resources in reducing carbon cycle uncertainties.

As in Phase 2, a period of discussion and consensus building will culminate in agreement on experimental protocols by January, 1997. The simulations will be performed over the following months, with results archived and analyzed by the Coordinator and circulated via the World Wide Web. A TransCom report would be presented at the Fifth International CO_2 Conference, to be held September, 1997 in Australia. This report is not envisioned as a final report, but rather as fitting in the program along with presentations on the OCMIP and VEMAP projects, to bring the rest of the community up to date on our progress and invite comment. Most of those interested in the details of the simulations will already be participating in the experiments.

Phase 4: Analysis, Interpretation, and Recommendations

The final phase of organized TransCom activity will involve careful review and interpretation of the results with special emphasis on addressing crucial needs for new observational data and process-oriented research to reduce uncertainties in the carbon budget of the atmosphere associated with transport simulations. This activity may or may not involve new simulations, but will certainly build on emerging research being pursued by the participants and others (e.g., simulations and model validation using other trace gases such as, CH_4 and N_2O, stable isotopes of C and O, or the atmospheric O_2/N_2 ratio).

During this period, the Coordinator will maintain a comprehensive data archive of experimental results and documentation, provide additional analytical support, facilitate the interpretation of the results, and write a final report. The results of the TransCom project will then be presented at the Quadrennial International Symposium on Atmospheric Chemistry Seattle (August, 1998), sponsored by the CACGP (Commission on Atmospheric Chemistry and Global Pollution) of IAMAP. A session has already been proposed on Transport and Circulation Models for Interpreting Changes in Atmospheric Chemistry, which the TransCom Coordinator could chair. This would be the best forum for bringing the results of the project to the wider atmospheric chemistry community.

Summary:

We propose the continuation of a model intercomparison project begun in 1993, with the objectives of quantifying differences among simulated transport of CO_2 among models, evaluating the mechanisms responsible, and reducing uncertainties in the global carbon budget resulting from these differences. A three-year research program is proposed. In the first year, a calibration of the models will be performed with a tracer of whose emissions and concentrations are relatively well-known, and new model diagnostics will be used to evaluate the mechanisms responsible for differences among the models. In the second and third years, sensitivity experiments will be designed and performed to aid in model development and further reduce the uncertainties in estimates of the global carbon budget based on the use of these models.

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