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KEYNOTE PERSPECTIVE

The interannual variability of the global carbon cycle

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It has become clear from measurements of CO_2 concentration that there is substantial interannual variability of the carbon cycle. A number of factors have come together in recent years to make study of this variability a major focus of carbon cycle research. Among these factors are: a requirement to quantify uncertainty in budget estimates, the emergence of long and spatially resolved concentration time series (Conway et al., 1994), more sophisticated three-dimensional atmospheric transport models and the advent of models of carbon source processes (Dai and Fung, 1993). The scientific objective is to elucidate the processes which control the observed interannual variability.

The inverse techniques which infer changes in sources from changes in concentrations generally do not explain the causes for source variations. Hence it is usual to notice such variations before we can explain them. For example, it is likely that the reduction of global growth rate in CO_2 concentrations in the early 1990s is largely due to an increase in biotic uptake in the northern extratropics (Conway et al., 1994; Ciais et al., 1995a,b). The biogeochemical mechanisms underlying such increases in uptake are less certain. Circumstantial evidence suggests a role for the eruption of Mt. Pinatubo in June 1991.

The signals from concentration histories are ambiguous in some respects. In three similar studies, Francey et al. (1995), Keeling et al. (1995) and Nakazawa et al. (1997) deduced different histories of global ocean and land fluxes from CO_2 and $\delta^{13}C$ time series. The differences arise mainly from different experimental determinations of $\delta^{13}C$ through the 1980s and are not yet resolved. Experimental problems aside, there are also interpretative difficulties with the extra species used in such calculations. For $\delta^{13}C$, there is a poorly-known flux caused by the disequilibrium between the atmosphere and other reservoirs. This flux is proportional to the total or gross exchange not the net carbon fluxes we wish to determine. In the language of inverse problems this flux is a nuisance variable since it must appear in the $\delta^{13}C$ budget (it is probably the second largest term) but is of little intrinsic interest. Studies using $\delta^{13}C$ often implicitly assume some properties of this flux. For example, Francey et al. (1995) deduce it from simple models representing terrestrial and ocean carbon storage. Rayner et al. (1999) assume it is poorly-known but slowly varying.

Work presented at the 5th International Carbon Dioxide Conference has refined the zonal or global scales of previous studies to deduce regional variations of fluxes. An important tool in this work has been the application of three-dimensional transport models to the determination of fluxes over several years. Previously, computational expense limited the use of such models to constructed climatologies representing several years, e.g., Tans et al. (1990) and Keeling et al. (1989). The new studies combine the spatial information available from three-dimensional models with the multi-tracer information from previous global studies. Several such studies were presented at the 5th International CO_2 conference, e.g., by S. Piper

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combining records of CO_2 and $\delta^{13}C$ and by M. Bender using the shorter record of O_2/N_2. The O_2/N_2 record, while initially proposed as simpler to interpret than $\delta^{13}C$ is not without difficulty. For example, changes in marine biomass will couple oceanic carbon and oxygen fluxes, contrary to the usual assumption. Unfortunately the CO_2 observing network does not yet detect continental sources well. Thus inferences about interannual variability of the terrestrial flux are obtained from global multi-tracer relationships combined with large-scale CO_2 variations.

An unresolved problem for studies using transport models is the potential for interannual variability of transport. All studies so far have neglected this variability. Bousquet et al. (1996) and Law and Simmonds (1996) went some way to showing that this omission was unlikely to be critical but a definitive test has not yet been performed. The emerging availability of long consistent sets of meteorological analyses does point to a solution in the near future.

The direct study of the interannual variability of source processes has proceeded through observational studies and modelling. One observational study, Braswell et al. (1997) relates global temperature changes to changes in CO_2 global growth rate. They propose a mechanism based on changes in microbial competition for nutrients to explain high correlations for temperature leading CO_2 by 1.5–2 years. The second approach involves modelling the processes and applying interannually varying forcing (temperature, precipitation, wind stress, etc). This approach has seen more use in the terrestrial biosphere following the study of Dai and Fung (1993). The conference presentation by M. Heimann compared the interannual variability of several terrestrial models. While there is a spread of results, the general conclusion of such work is that the interannual variability in CO_2 concentrations can be largely explained by variability of the terrestrial source alone. In particular there is large variability on ENSO frequencies. This finding was supported by ocean model results presented by C. Le Quéré. They used a semi-diagnostic global ocean model with resolution concentrated in the tropics and so suited for ENSO simulations. They found less ocean variability than suggested by the observations of Feely et al. (1987) and much less than predicted by the studies of Francey et al. (1995) or Keeling et al. (1995). Note that Rayner et al. (1999), using essentially the same input data as Francey et al. (1995) but including three-dimensional global transport, inferred ocean variability closer to the Feely et al. (1987) observations.

The long-noted relationship between the El Niño southern oscillation and CO_2 sources is an obvious focus for studies of interannual variability either via inverse techniques or direct modelling of processes. Recent three-dimensional inverse studies, e.g., Law (1999), Rayner et al. (1999) suggest somewhat differing amplitudes for interannual variability of tropical fluxes. A common element, however, is a robust relationship between tropical fluxes and ENSO. While the sparse tropical observing network does not allow clear separation of land from ocean signals, there is the suggestion of a role for the ocean, particularly early in an ENSO event.

The CO_2 records capable of spatially resolving sources, and the NDVI measurements often used by terrestrial modellers, only span a few ENSO events. These ENSO events have different lifecycles, in particular the extended event of the early 1990s is quite unusual. The inverse studies suggest the relationship with fluxes holds even in the case of such unusual events, giving us some confidence in the robustness of the relationship. However the different history of each event makes it difficult to select among the various proposed linking mechanisms.

There is, as yet, no published attempt to combine the predictions of process studies of interannual variations in oceanic and terrestrial sources and check for consistency with concentration observations. The Bayesian techniques used by, for example, Enting et al. (1995) can include prior information on interannual variability from process models and assess the consistency of such flux estimates with observed concentrations. The technique also provides an optimal correction to source estimates. Such a consistency check and an improvement in continental concentration observations are the two most likely advancements in this area in the next few years.

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