Global carbon dioxide sinks: An investigation of the role of the biosphere in the tropics and middle to high latitudes in the northern hemisphere

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Abstract A key uncertainty in understanding and managing the global carbon cycle is the role played by the biosphere in taking up and releasing CO_2. The sources and sinks of atmospheric CO_2 were investigated using a global 3-dimensional Lagrangian tracer transport model. The transport model is based on observed global wind fields at 2.5 degrees resolution obtained from ECMWF. Model runs, based on studies performed as part of the international TRANSCOM model intercomparison, were undertaken using two source distributions representing key components of the global carbon cycle. One model run was performed simulating the release of CO_2 from fossil fuel combustion during the mid-1980's. The second run examined the uptake and release of CO_2 from the natural biosphere and assumed no annual averaged net uptake or release of CO_2. Model predictions of the latitudinal gradient in atmospheric CO_2 can be compared with observations to infer sources and sinks of atmospheric CO_2. Model results indicate that during the 1980's a sink for CO_2 in the biosphere at middle to high latitudes in the northern hemisphere is unlikely to be large whereas a substantial sink in the tropics is clearly a strong possibility.

1. INTRODUCTION

The global carbon cycle continues to be modified by the action of humankind, particularly as a consequence of western agricultural and industrial development and more recently as a result of the rapid pace of industrialisation in the newly industrialised countries. The negative consequences of the dramatic increase in atmospheric carbon dioxide and other radiatively active trace gases are considered to be of sufficient magnitude that action should be taken to stabilise the concentration of these trace gases in the atmosphere. At present it is not clear whether this is achievable on either political, scientific, economic or social grounds.

Our poor understanding of the processes governing the exchange of trace gases between the atmosphere and the ocean and biosphere limits our ability to develop policies which will lead, efficiently, to the stabilisation of the concentration of trace gases. The issue of major concern at present is the relative importance of the biosphere and the oceans in the uptake of atmospheric carbon dioxide. The magnitude of the uptake of carbon dioxide by the oceans, a long term sink, and the biosphere, a potentially short lived sink sensitive to land use decisions, has critical implications for the long term evolution of atmospheric carbon dioxide levels and the policies that we may develop in order to achieve stabilisation of atmospheric carbon dioxide levels.

The uncertainty in our understanding of the sources and sinks of atmospheric carbon dioxide remains despite the considerable effort in both the theoretical modelling of the carbon cycle and the rapid extension of global observational networks measuring the concentration of greenhouse gases in the atmosphere. This paper presents recent modelling results using the Australian National University - Chemical Transport Model (ANU-CTM) and examines these results in light of other recent research on the sources and sinks of atmospheric carbon dioxide.

2. DESCRIPTION OF THE ANU-CTM

The model used in this study is based upon the Lagrangian tracer modelling approach of Taylor (1989). The approach is described in full in Taylor (1989) and Taylor et al. (1991). While a large number of numerical and computational transport schemes have been developed, no one scheme has proven best for all applications. For our purposes, we require a computationally efficient approach which, as we are studying the magnitude of sources and sinks, should also conserve the mass of tracer by definition. The Lagrangian transport model described by Taylor (1989) and Taylor et al. (1991) satisfies these requirements.

Briefly, the modelling approach adopted here uses a stochastic Lagrangian advection scheme to move air parcels representing a known mass of a tracer gas in air according to a wind field on a 2.5 by 2.5 degree

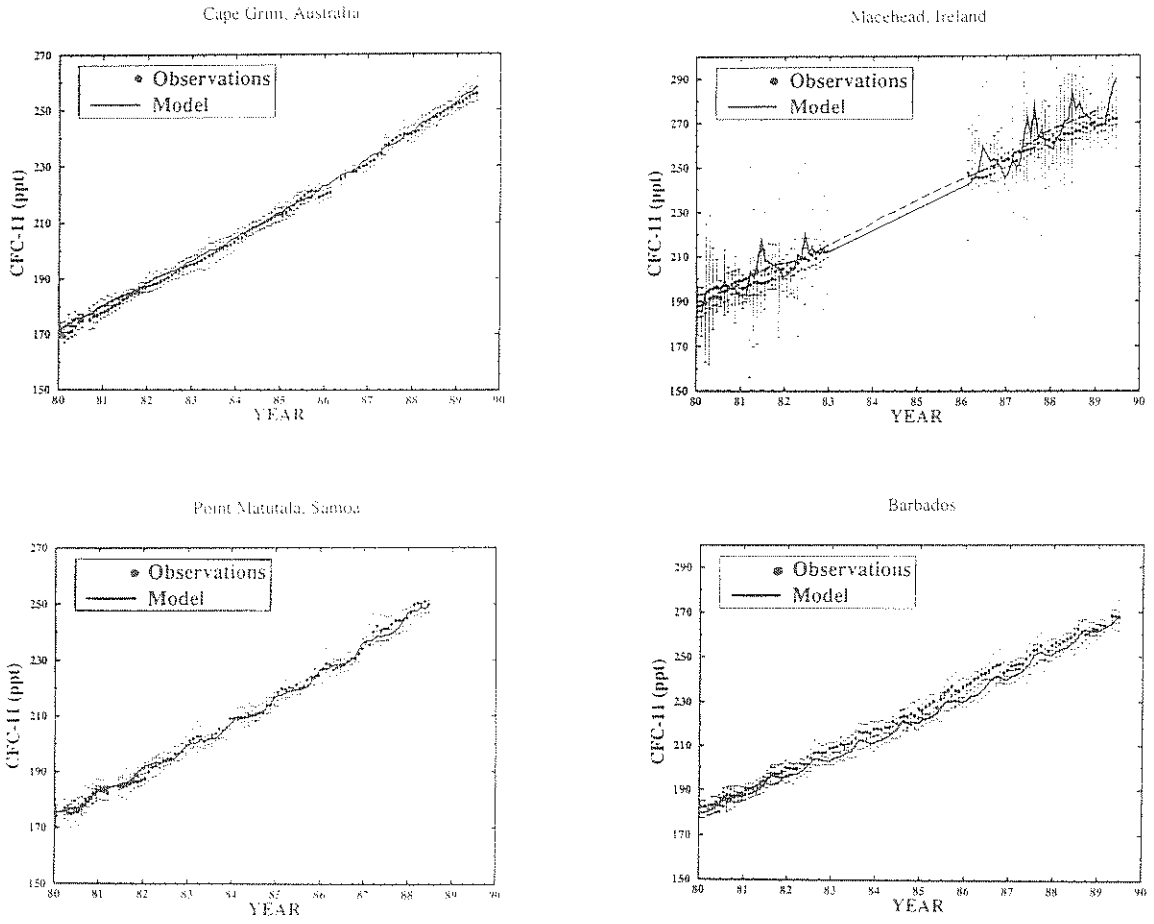

Figure 1: Observations of CFC-11 at four ALE/GAGE sites and corresponding model predictions obtained using ANU-CTM with prescribed, annually varying estimates, of the CFC-11 flux. Error bars on the observations reflect the uncertainty in the measurements after selection of data points which do not include the effects of 'pollution'. Model predictions include 'pollution' events so show greater variability, particularly at monitoring sites in the Northern hemisphere in close proximity to the major sources of CFC-11.

latitude/longitude grid with seven vertical levels at 1000, 850, 700, 500, 300, 200 and 100 hPa. Wind field data were obtained from the ECMWF in the form of a five year record of local 0h and 12h observational analysed fields reported on a 2.5 by 2.5 degree grid. These data, and the analysis procedures used to generate the data, are described in detail by Lorenc (1981). The wind field includes a mean and time varying component. The availability of observed global wind fields at a fine resolution (2.5 degrees) at a number of pressure levels was preferred to using General Circulation Model (GCM) wind fields. However, GCM wind fields could be substituted if desired. The mean vertical motion is included within the European Centre for Medium Range Weather Forecasting (ECMWF) data set. Rapid vertical transport associated with convective cloud transport is not explicitly included. However, the model does properly represent the vertical mixing process by including a time varying component as well as a mean vertical motion. For relatively long lived trace gases, such as CO_2, rapid vertical transport does not significantly affect the vertical concentration profile. Costen et al. (1988) estimate that the change in carbon monoxide concentration would be at most 30 per cent in the tropics if no account of vertical transport due to rapid convective mixing were included.

The location L, of parcel P, in a grid cell located at latitude i, longitude j, level l and at time t is evaluated as

$$L_{ijlt} = L_{ijlt-1} + D_{ijlt} \qquad (1)$$

where D_{ijlt} is the displacement of the parcel occurring over one time step and is calculated for each wind speed component, u, v and w independently according to

$$D_{ijlt} = \Delta t[r_{ijl} + s_{ijl}N(0,1)] \qquad (2)$$

where Δt is the time step in seconds, r_{ijl} is the appropriate bi-monthly time period mean wind velocity (ms^{-1} for displacements in latitude and longitude and hPa s^{-1} in the vertical) and s_{ijl} the standard deviation of wind velocity over a bi-monthly time period derived at each grid point, and $N(0,1)$ represents a random sample from the standard normal distribution.

The flux of a trace gas into the atmosphere is computed based on estimates of anthropogenic emissions and the exchanges between the atmosphere, the oceans and the terrestrial biosphere. The flux of a trace gas is added or removed from air parcels present within the corresponding lowest level grid square of the model.

Mixing ratios were derived by translating the Lagrangian air parcel coordinates to Eulerian grid coordinates. The Eulerian grid was based on the 2.5 by 2.5 degree wind field grid. The divisions in the vertical were centred about the pressure levels with the boundaries lying at the pressure mid-point between the pressure levels. The concentration of a trace gas within each air parcel was then computed. The concentration on the Eulerian grid was calculated as the average of the Lagrangian air parcel concentrations within each grid box.

One year model simulations with CFC-11, carbon dioxide, methyl chloroform, methane and other trace gases with 100 000 air parcels on the VP-2200 at the ANU Supercomputer facility require only 70 seconds of central processing time. The location of air parcels at each time step can be stored if so desired to avoid the recalculation of the transport component during subsequent model runs. This approach will be used in future studies involving more detailed atmospheric chemistry models. The performance of the model in simulating the distribution of CFC-11, in comparison with observations, is shown in

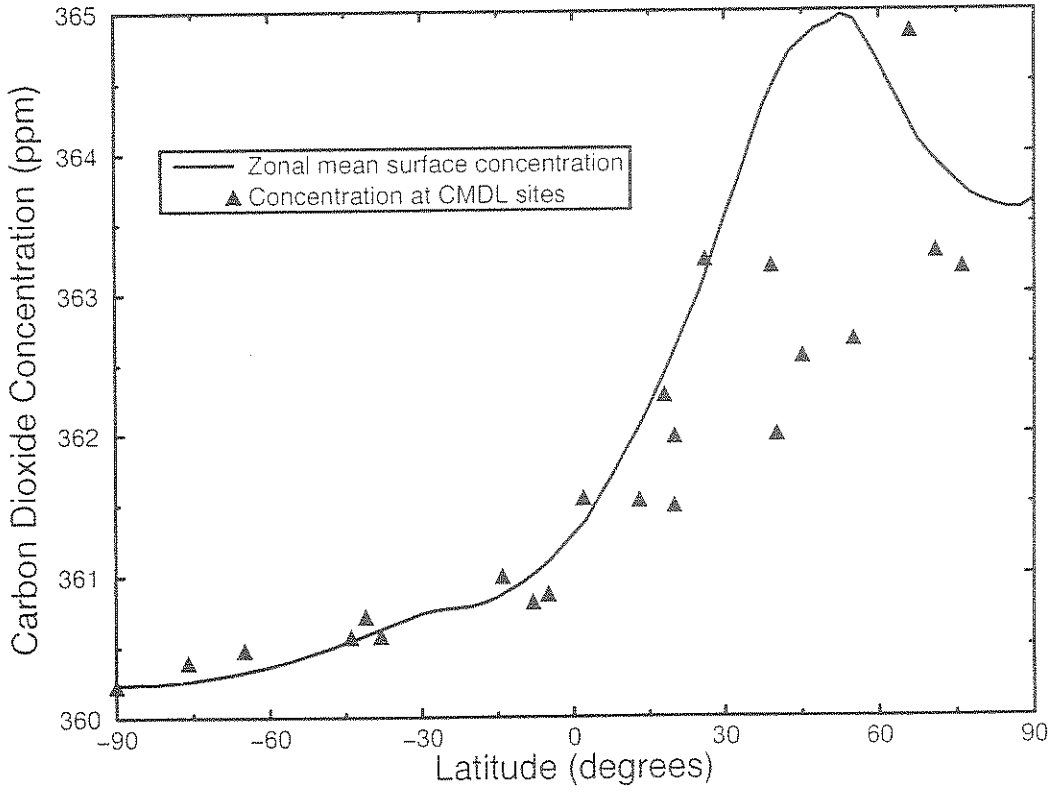

Figure 2: The annual averaged zonal mean surface concentration from the ANU-CTM model with the model predicted concentrations at CMDL monitoring sites. The surface CO_2 flux includes only a 5.3 GtC source representing the flux of CO_2 from fossil fuel combustion only. The difference between the zonal mean concentrations and the concentrations at CMDL sites indicates that CMDL sites may not generate estimates of CO_2 concentrations representative of zonal mean concentrations at mid-northern latitudes. This has critical implications for determining the sources and sinks of atmospheric CO_2.

Figure 1. While the model performance is very good for CFC-11 it should be noted that testing model performance against CFC-11 alone does not provide a complete test of a tracer transport model as CFC-11 fluxes vary over relatively long time scales in comparison with the substantial seasonal variation in CO_2 concentrations.

3. CARBON CYCLE MODELLING RESULTS

3.1 3-Dimensional modelling results

The ANU-CTM global 3-D model requires that only a small (~ 300 MtC) sink be invoked in addition to the expected North Atlantic ocean uptake in order to match CO_2 concentrations at the Climate Modelling and Diagnostics Laboratory (CMDL) monitoring sites. In the tropics a CO_2 sink is required to balance the release of CO_2 from tropical deforestation (Taylor, 1989). The 3-D modelling study described in Taylor (1989) employed nearly identical biospheric and fossil fuel CO2 fluxes as those used in the TRANSCOM experiment.

Figure 2 shows the response of ANU-CTM to the fossil fuel only experiment of TRANSCOM. Figure 3 illustrates the response of ANU-CTM to the biosphere only experiment of TRANSCOM. TRANSCOM modelling results indicated that the response of the 3-D models to the fluxes of CO2 between the biosphere and the atmosphere are critical in determining the presence or otherwise of a large Northern Hemisphere sink. Notably, ANU-CTM does not substantially overpredict the amplitude of the seasonal cycle in the Northern Hemisphere.

3.2 Box diffusion carbon cycle results

The ANU-BACE box diffusion carbon cycle model experiments (Taylor, 1995), which incorporate a deterministic biosphere model (Taylor and Lloyd, 1992), yield a maximum uptake for the biosphere from CO_2 fertilisation, consistent with atmospheric observations for the period 1750-1990. The fertilisation effect is estimated to have a magnitude of ~2 GtC for 1990 most of which occurs in the tropics. (Taylor and Lloyd, 1992; Enting *et al.* 1994).

The box diffusion carbon cycle model also predicts a steady increase in the magnitude of the sink associated with CO_2 fertilisation, of the order of tens of MtC per annum, with the most rapid increases occurring recently. This result is consistent with the observed rate of increase in the amplitude of the seasonal cycle of atmospheric CO_2 in the Northern Hemisphere, as discussed below.

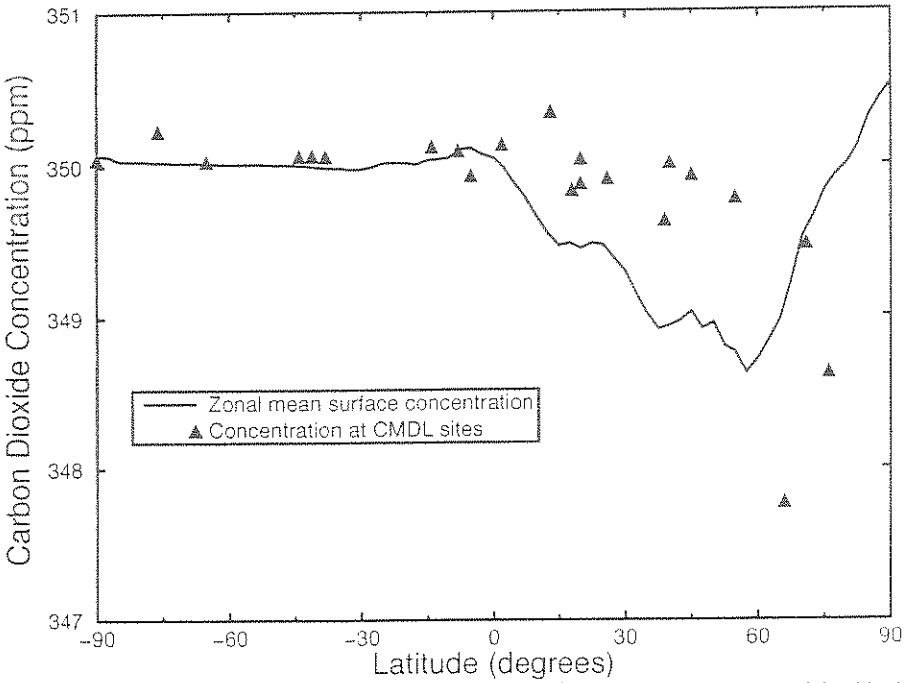

Figure 3: The annual averaged zonal mean surface concentration from the ANU-CTM model with the model predicted concentrations at CMDL monitoring sites. The surface CO_2 flux includes only a source representing the flux of CO_2 from the exchange of CO_2 between the atmosphere and the biosphere. The biosphere fluxes are assumed to be in steady state ie as an annual average no net flux of CO_2 occurs between the biosphere and the atmosphere. The resulting gradient reflects differences in the dispersion and intensity of CO_2 fluxes during summer and winter. Again, the difference between the zonal mean concentrations and the concentrations at CMDL sites indicates that CMDL sites may not generate estimates of CO_2 concentrations representative of zonal mean concentrations at mid-northern latitudes.

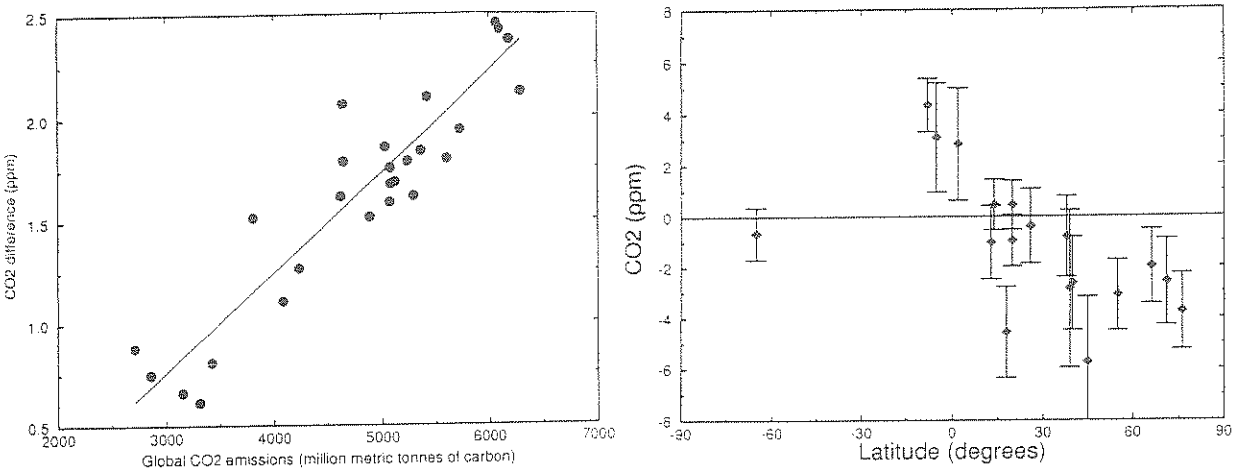

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Figure 4: (a) A plot of the magnitude of the CO_2 gradient between the CMDL monitoring sites at South Pole and Mauna Loa as a function of the global fossil fuel emissions; and (b)the estimated pre-industrial gradient in atmospheric CO_2 based on the linear extrapolation of the magnitude of the gradient between the South Pole and other CMDL monitoring sites with at least 10 years monitoring atmospheric CO_2. The error bars represent the standard error of the intercept in the linear regression.

3.3 The pre-industrial gradient

The pre-industrial gradient in atmospheric CO_2 features higher concentrations in the southern hemisphere. Figure 4 presents an estimate of the pre-industrial gradient derived from present day observations of the latitudinal gradient of CO_2 and its response to the increase in global fossil fuel emissions of CO_2. TRANSCOM model runs illustrate that this is not properly accounted for by most models including the GISS model and so in the Tans et al (1990) study. It is apparent that models incorporating a parameterisation of the seasonally varying boundary layer in combination with the biospheric releases lead to a substantial overprediction of the gradient in atmospheric CO_2 when compared with the pre-industrial gradient estimated in Figure 4.

4. LIMITATIONS OF THE 2-D INVERSION APPROACH

The 2-D inversion approach of Tans et al. (1989), as employed by Ciais et al (1995), is not an inverse approach - it is an iterative forward least squares fitting technique - which does not properly take into account the complex spatial and temporal relationship between fluxes of CO_2 and the transport of CO_2 to monitoring sites. This makes the 2-D model results difficult to interpret. Of particular concern is the need to obtain separate eddy diffusion parameters for each tracer used in a 2-D model. Validation of model transport in 2-D Eulerian models employing eddy diffusion coefficients is only possible using the tracer in question. Validation of tracer transport using CFC's or Kr-85, commonly used tracers, is not appropriate in these circumstances.

Of particular concern in the inverse estimation of sources and sinks of atmospheric CO_2 using 2-D dimensional models is the requirement that observations of atmospheric CO_2 which represent the true zonal mean concentrations be available. The CO_2 measurements at CMDL sites are probably not representative of the zonal mean concentrations at mid-northern latitudes. The bias is significant and leads, by definition, to the estimation of a substantial sink to compensate for the bias. CMDL measurements need to be corrected, using a 3-D model as a first approximation, to give unbiased estimates of the zonal mean concentrations for possible application in 2-D inversion studies.

5. AMPLITUDE OF THE SEASONAL CYCLE

Invoking a large sink ~2-5 GtC in the latitude range 30-60N would be expected to induce a substantial increase in the amplitude of the seasonal cycle as the Net Ecosystem

Production (responsible for producing the seasonality in atmospheric CO_2 concentrations) in this latitudinal band is of order ~5GtC. Manning (1993), in a review of the available measurements of the seasonal cycle of atmospheric CO_2, found only small increases in the amplitude of the seasonal cycle. At Mauna Loa a 0.41ppmv increase in the amplitude has occurred over 10 years (Manning 1993). The average amplitude of the atmospheric CO_2 concentration at Mauna Loa is 7.2 ppmv which implies a small biospheric sink for CO_2 in the northern hemisphere biosphere with a magnitude around 0.35 GtC for the 10 year period. A large increase in the amplitude has not been seen in the CO_2 measurements even for the period 1991-1993.

6. CONCLUSIONS

Recent 3-D modelling results indicate that a large sink for atmospheric CO_2 in the mid-latitude biosphere is unrealistic. This conclusion is supported by box-diffusion carbon cycle modelling studies which incorporated mechanistic models of the uptake of CO_2 by the biosphere associated with CO_2 fertilisation. It has also been demonstrated that the pre-industrial latitudinal gradient in atmospheric CO_2, as presented in this paper, with a negative gradient between the Northern Hemisphere and the Southern Hemisphere, and the amplitude of the seasonal cycle are critical constraints for estimating the exchange of CO_2 between the atmosphere and the biosphere.

7. REFERENCES

Ciais, P. P.P. Tans, P.P., White, J.W.C., Trolier, M., Francey, R.J. , Berry, J.A., Randall, D.R., Sellers, P.J., Collatz, J.G. and Schimel, D.S. (1995) Partitioning of ocean and land uptake of CO2 as inferred by $\delta^{13}C$ measurements from the NOAA Climate Monitoring and Diagnostics Laboratory global air sampling network. *J Geophys. Res.*, **100**, 5051-5070.

Costen, R.C., Tennille, G.M. and Levine, J.S. (1988) Cloud pumping in a one dimensional photochemical model. *J. Geophys. Res.* **93**, 15,941-15,954.

Enting, I.G., Wigley, T.M.L. and Heimann, M. (1994) *Future emissions and concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses.* CSIRO Division of Atmospheric Research Technical Paper No. 31

Lorenc, A.C. (1981) A global 3-dimensional multivariate statistical interpolation scheme. *Mon. Wea. Rev.*, **109**, 701-721.

Manning, M.R. (1993) Seasonal cycle in atmospheric CO_2 concentrations. in *The Global Carbon Cycle*, M. Heimann (Ed.), Springer-Verlag, Berlin, 65-94.

Tans, P.P., Conway, T.J. and Nakazawa, T.(1989) latitudinal distribution of the sources and sinks of atmospheric carbon dioxide derived from surface observations and an atmospheric transport model. *J. Geophys. Res.*, **91**, 5151-5172.

Tans, P.P., Fung, I.Y. and Takahashi, T. (1990) Observational constraints on the global atmospheric CO2 budget. *Science*, **247**, 1431-1438.

Taylor, J.A. (1989) A stochastic Lagrangian atmospheric transport model to determine global CO_2 sources and sinks - a preliminary discussion. *Tellus*, **41B**, 272-285.

Taylor, J.A. (1995) Fossil fuel emissions required to achieve atmospheric CO_2 stabilisation using AU-BACE: a box diffusion carbon cycle model. *Ecological Modelling*, in press.

Taylor, J.A., Brasseur, G., Zimmerman, P.and Cicerone, R. (1991) A study of the sources and sinks of methane and methyl-chloroform using a global 3-d Lagrangian tropospheric tracer transport model. *J Geophys. Res.*, **96**, 3013-3044.

Taylor, J.A. and Lloyd, J.L. (1992) Sources and sinks of atmospheric CO_2. *Aust. J. Botany*, **40**, 407-418.