

Interannual variability of carbon cycle implied by a 2-D atmospheric transport model

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Abstract: A 2-dimensional atmospheric transport model is deployed in a simplified CO₂ inverse study. Calculated carbon flux distribution for the interval from 1981 to 1997 confirms the existence of a terrestrial carbon sink in mid-high latitude area of North Hemisphere. Strong interannual variability exists in carbon flux patterns, implying a possible link with ENSO and other natural episodes such as Pinatubo volcano eruption in 1991. Mechanism of this possible link was investigated with statistic method. Correlation analysis indicated that in North Hemisphere, climatic factors such as temperature and precipitation, to some extent, could influence the carbon cycle process of land and ocean, thus cause considerable change in carbon flux distribution. In addition, correlation study also demonstrated the possible important role of Asian terrestrial ecosystems in carbon cycle.

Keywords: 2-D transport model; inverse study; carbon cycle; ENSO; interannual variability

Introduction

The continuous accumulation of atmospheric CO₂, mainly due to increase in emission from anthropogenic sources, is one of the major concerns in climate change issues. In 1980s and 1990s, fossil fuel combustion released CO₂ at a relatively steady rate of about 6 GtC/a, but only about half of the CO₂ emitted remained in the atmosphere (Houghton, 2000). Investigation (Tans, 1990) on CO₂ budget indicated clearly that, oceans, as a whole, could not account for all the loss of CO₂, so the effects of terrestrial ecosystems, especially in North Hemisphere, should not be neglected. Atmospheric oxygen concentration and $\delta^{13}\text{C}$ measurement could provide information regarding the partition of oceanic and terrestrial sinks (Battle, 2000), while *in-situ* observation of CO₂ flux at different kinds of ecosystems, have presented some evidence for the land biosphere CO₂ uptake (Goulden, 1996). However, limitations exist in these methods. Oxygen concentration and $\delta^{13}\text{C}$ measurement could separate global oceanic and biospheric sinks, but could not provide spatial distribution of these sinks. *In-situ* flux observation directly measures the land-atmosphere CO₂ exchange, but could only cover small-scale regions (about 1 km²; IPCC, 2001). So far, the location and extend of northern terrestrial sink, is still under hot debate in research on carbon cycle (Kaminski, 2001; Holland, 1999).

Inverse models, which utilize both atmospheric transport models and ambient concentration data from atmospheric monitoring, are currently undergoing fast development. The basic idea of such models is to get the best possible distribution of carbon fluxes through minimizing the discrepancy between simulated and observed atmospheric CO₂

concentrations. Because of the capacity of determining temporal and spatial distribution of CO₂ releases and uptakes, inverse models have greatly improved our knowledge in carbon cycle (Bousquet, 2000). But arguments still exist in the methodology of inverse research, partly due to the sparseness of CO₂ observation sites (IPCC, 2001), and partly due to distinction among different inverse models and calculation approaches (Kaminski, 2001). In this research, we developed a simplified 2-dimensional CO₂ inverse model based on a 2-D atmospheric chemical transport model. Using this model, we estimated the yearly global carbon flux pattern for the period from 1981 to 1997 and made some calculation on interannual variability of global carbon fluxes.

1 Inverse method

1.1 Model description

The original 2-D atmospheric chemistry and transport model was developed by Zhang (Zhang, 1997; 2001). Horizontally, the model domain covers the regions from 90°S to 90°N at resolution of 5° and is averaged at longitude. Vertically, the model includes 21 levels from the ground to 20 km, with a resolution of 1 km. Therefore the grids of the model is totally 36 × 21. The chemical mode of the model includes 34 species and 104 reactions (Zhang, 2001). In the model, atmospheric constituents (CO₂ and other species) are driven by residual circulation calculated from the diabatic rate (Zhang 1997). 2-dimensional tracer equations are solved with Peaceman-Rachford method (Su, 1989; Wang, 1992).

Through altering the diffuse coefficients of the original model, an atmospheric CO₂ transport model was developed. According to Tans *et al.* (Tans, 1989), when testing the model, the seasonal cycle of atmospheric CO₂ at different

altitude was used as the gauge for vertical transport, while the inter-hemispherical difference of surface ^{85}Kr was used as the criterion for horizontal transport. To test the steadiness of the model, we simulated the trend of global CO_2 during the interval from 1950 to 1998, and found good agreement between the modeled trend and the observation data in Mauna Loa and South Pole Station.

Data needed in this study consist of two parts: the initial data set of carbon fluxes and the observed atmospheric CO_2 data. For the first part, we synthesized statistic data for fossil fuel emission (Marland, 1999) and land use change (Houghton, 2002), output data from an oceanic carbon cycle model (Jin, 1998) and output data from two terrestrial carbon cycle models (Sitch, 2000; Ito, 2001), and allocated the totaled data to each grid. For the second part, data products from GlobalView (Globalview- CO_2 , 2001) were employed.

1.2 Method sketch

After verifying the 2-D CO_2 transport model, a simplified CO_2 inverse method was built up. The process of this inverse research is as follows: Firstly, the pattern of atmospheric CO_2 was simulated with the initial carbon flux data set; then, according to the difference between modeled and measured CO_2 data, the carbon flux data set was adjusted (the flux adjustment here is based on a previous numerical experiment. P_i stands for the CO_2 concentration change in cell I, when a carbon flux of $\pm 0.2 \text{ GtC/a}$ is manually input into cell I during the experiment. ΔC_i stands for the difference between observed and modeled CO_2 concentration, in inverse study. And the flux adjustment for cell I is: $B_i = \frac{\Delta C_i}{n \cdot P_i} F_i$, where, F_i is the original input flux for cell I in this step, and n is set at 5 in this study). The modified flux data set was again applied to model simulation. Such procedure was repeated until the modeled CO_2 concentration met the preset request.

In this study, in order to avoid the relatively large simulation errors in polar areas, we selected the domain from 60°S to 60°N as the area of research. And in most cells (ground level) included, the difference between modeled and measured model should be below 0.25 ppmv, with few exceptions (no more than 0.5 ppmv in each grid). An additional requirement in the research is that there should be no substantial differences in the outputs from the last two steps of simulation. That is, if we define a function D to reflect the accuracy of the simulation, ΔD (the D difference for the last two steps) should be less than 0.1.

$$D = \sum (\Delta C_i)^2. \quad (1)$$

In the equation,

$$\Delta C_i = C_{oi} - C_{mi}. \quad (2)$$

Here C_{oi} and C_{mi} stand for observed and modeled CO_2 concentration at grid i , respectively. As an example,

simulated and observed CO_2 data from 1981 to 1985 are presented in Fig. 1.

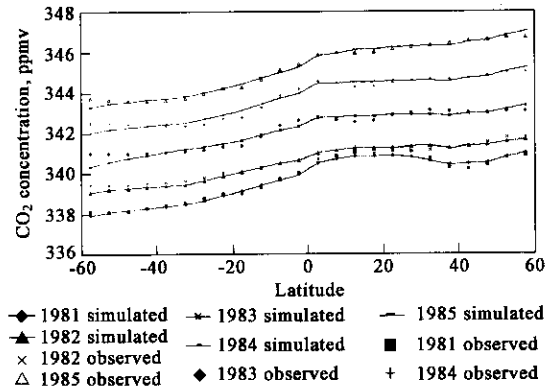


Fig. 1 Simulated and observed meridional distribution (60°S — 60°N) of CO_2 for the period of 1981—1985

It is clear in Fig. 1 that, in most grids, with the final adjusted carbon flux input, simulation shows reasonably good agreement with observation. But the slight model deviation in polar areas, as mentioned above, still influences a few grids in high latitude, especially the grids of 60°S . This could probably induce some errors in our inverse study. As the original carbon flux in high latitude area is relatively small, we conclude that errors originated here could be rather limited.

2 Results from inverse study

2.1 Carbon flux distribution

Employing the 2-D CO_2 inverse method, and input data from data processing, the average carbon flux pattern was computed from 1981 to 1997 (Fig. 2). During this period, mid-high latitude area of North Hemisphere was a major source region of atmospheric CO_2 . Fossil fuel emission dominates the CO_2 release in this region (30 — 60°N), with an average annual emission of about 4.5 GtC (Marland, 1999).

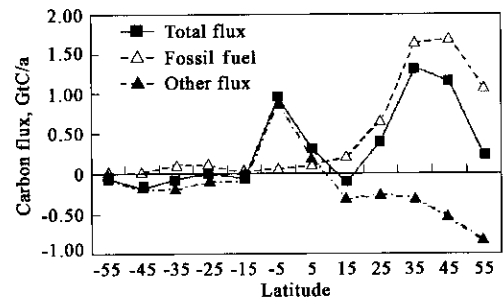


Fig. 2 Latitudinal distribution of carbon flux (average of 1981—1997)

The second biggest CO_2 source region was the equatorial area (20°S — 20°N), with oceanic emission of about 0.75 GtC in 1990 (Takahashi, 1997). Another important carbon source in this region is land-cover change; Houghton (Houghton, 2002) estimated that, in 1990 CO_2 emissions from land-use change in Tropical Africa, Central America, South and

Southeast Asia could amount to 2.0 GtC/a.

Data for mid-high latitude area of South Hemisphere indicated that this region is a weak sink of atmospheric CO₂. We attribute this sink to geographic distribution of oceans in this region.

Incorporated with results from other researches, carbon flux pattern we obtained could provide more in-depth information about different kinds of carbon sources and sinks. Subtracting the CO₂ emission from fossil fuel combustion (Marland, 1999) from the total flux, the rest of the data, mentioned as other flux in Fig. 2, reflects the integrated effects from earth-atmosphere exchange and ocean-atmosphere exchange. Distribution of this "other flux" reveals that oceans and land ecosystems in the equatorial region could be an important carbon source, possibly due to high surface sea temperature and strong human influences on land cover. Also shown in the flux distribution is that, despite the large fossil fuel release in the same area, terrestrial ecosystems in mid-high latitude of North Hemisphere (30°N—60°N) could be significant carbon sinks. Taking into account the CO₂ uptake of oceans from this region (about 0.6 GtC/a; Jin, 1998), we estimated that this possible terrestrial sink could be about 0.8 GtC/a, which is higher than the sink to ocean.

2.2 Interannual variability in carbon cycle

Considerable interannual variability in total carbon flux as well as meridional distribution has been detected in this inverse research. Research by Conway *et al.* (Conway, 1994) and Keeling *et al.* (Keeling, 2000) showed that El-Nino/Southern Oscillation (ENSO) events maybe had contributed to this variability.

Our study also confirmed this possible correlation (Fig. 3). Gong and Wang (Gong, 1999) studied SST (sea surface temperature) index during the past 100 years. Their results indicated that, during the period of our research, 1982/1983, 1986/1987, 1991—1993/1994 were years that ENSO occurred (Fig. 3). As shown in the figure, there are strong fluctuations in the rate of atmospheric CO₂ increase during ENSO episodes. Also worthy of mention is that, rather strong change in CO₂ increase rate also occurred in years with La-Nina events: 1988—1989, 1996 (Gong, 1999; Fig. 3).

Variation in carbon flux distribution was also found during ENSO episodes. Take the case of 1982 for an

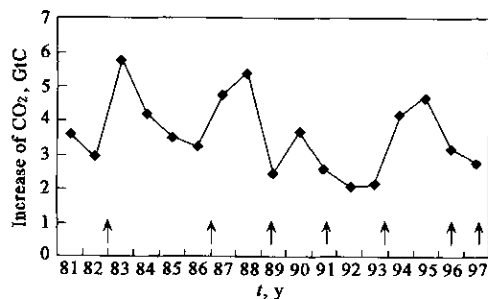


Fig. 3 Annual increase of atmospheric CO₂ (1981—1997)

example; the flux distribution of this year was quite different, compared with the average flux distribution of 1981, 1984 and 1985 (Fig. 4).

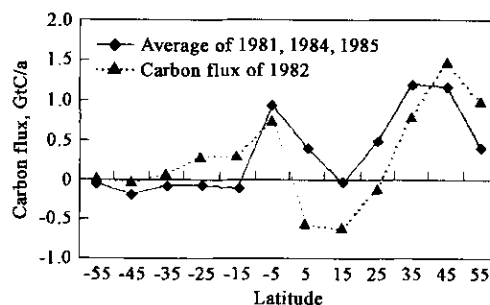


Fig. 4 Interannual variability in meridional distribution of carbon flux (1982 and average of 1981, 1984, and 1985)

In 1982, carbon flux from the equatorial area was much lower than that of other years, while CO₂ release from high-latitude North Hemisphere (40—50°N) showed opposite trend, with flux higher than other years. It is plausible to attribute the change in equatorial area to the oceans, as Feely *et al.* (Feely, 1987) reported that CO₂ emission from equatorial Pacific Ocean largely stopped in 1982. And the increase in CO₂ emission from 40—50°N could probably be related to the fluctuation in land biosphere activity, as flooding and droughts in different areas could restrain the CO₂ uptake of the terrestrial ecosystems. Correlations between droughts around the world and ENSO events have been identified by some investigators, for example, Gong and Wang (Gong, 1999). Derived from NCEP (National Centers for Environmental Prediction) data, average winter surface temperature of 1982 was 0.64°C, which was higher than the average winter temperature of 1981, 1984, and 1985 (-0.17°C). In addition, average summer surface temperature of 1982 (16.82°C) was lower than the average data of the three years (17.14°C). Results from dynamic vegetation model (Lucht, 2002) showed that, higher temperature in winter would stimulate the respiration of biosphere, thus increase the CO₂ emission from land; while lower temperature in summer may depress the photosynthesis activity, thus decrease the CO₂ uptake from land. So it could be concluded that ENSO and other episodes could influence some climatic factors such as temperature, precipitation and radiance, and therefore change both oceanic and terrestrial carbon cycle process. However, mechanism of these changes in carbon cycle process is not very clear yet, and more detailed investigations are necessary.

2.3 Effect of Pinatubo Volcano Eruption

Dramatic decrease in atmospheric CO₂ accumulation rate emerged after the occurrence of Mount Pinatubo Volcano Eruption in 1991 (Fig. 3). Generally, decline in surface temperature due to aerosols emitted by the eruption, is believed to be a major reason for this drop of carbon flux. Lucht *et al.* (Lucht, 2002) simulated the cooling effect of

the Pinatubo Eruption. Their results demonstrated a NPP (net primary production) reduction of 21.5 gC/m^2 as well as a higher R_h (heterotrophic respiration) reduction of 32.2 gC/m^2 . As a consequence, CO_2 emission from land strongly decreased during 1992—1993. Recently, another possible explanation for the CO_2 increase rate change was brought about by Gu *et al.* (Gu, 2003). They pointed out that aerosols from Pinatubo event greatly increased diffuse radiation worldwide in 1992 and 1993, hence enhanced the photosynthesis in the ecosystem they observed. Our analysis confirmed the temperature decrease during this period, but could not estimate the influence of other factors.

3 Correlation analysis

Relationship between carbon flux and climatic factors such as temperature and precipitation was further studied with statistic approach. As expected, no much obvious correlation was found, due to the limitation of 2-dimensional data and the complexity of carbon cycle. But carbon flux in the area between 40°N and 50°N , showed negative correlation with temperature (Fig. 5). Note that oceanic area in this region is relatively small and human activities (CO_2 release from fossil fuel and land use change) in this industrialized area are relatively constant. This anti-correlation may imply that, the activity of terrestrial ecosystems in this area, responses to climatic factors and contributes to oscillation in carbon flux. High temperature may cause enlarged NPP (Lucht, 2002), thus possibly induce the increase in land biosphere CO_2 uptake and the decrease in total carbon flux. But comparatively low carbon flux in 1992 and 1993 also indicated that, in many cases, other factors may also account. So the hypothesis that increased diffuse radiation after Pinatubo Eruption may cause more CO_2 uptake from land (Gu, 2003) should not be ignored.

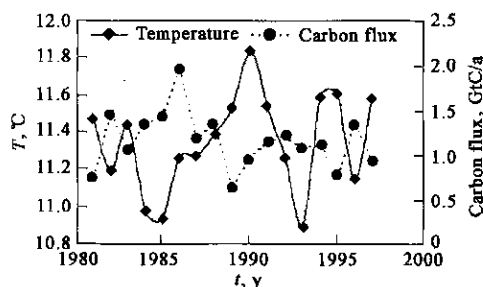


Fig. 5 Correlation between annually average surface temperature and carbon flux of 40°N — 50°N

Fig. 6 reveals the correlation between the carbon flux of 30°N — 60°N and the average surface temperature of Asia. Covering the area of 40°E — 120°E and 25°N — 60°N , region of Asia in this study, corresponds to territory with high NPP data in Asian continent (Matthews, 1983).

Correlation between carbon flux and climatic factors, as demonstrated above, implies that terrestrial carbon cycle

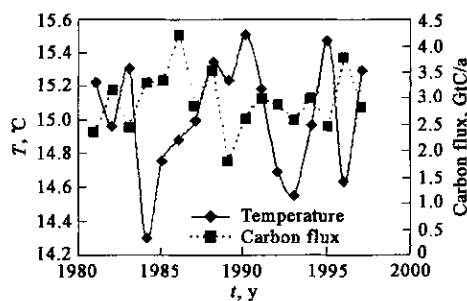


Fig. 6 Correlation between the surface temperature of Asia and the carbon flux of 30°N — 60°N

process in mid-high latitude area of north hemisphere, could probably dominate the carbon flux fluctuation in this area. Specially, the data for Asia could provide some clues about the longitudinal location of so-called “missing carbon sink”, which is now still under investigation. Some 3-dimensional inverse research (Bousquet, 2000; Fan, 1998) indicated that forest in North America could be the principal compartment of this carbon sink. But other investigations, including both inverse model study (Kaminski, 2001) and statistic research (Holland, 1999), have cast doubt on such assertions. In our study, the correlation analysis on Asia continent demonstrates the possible link between Asian ecosystems and carbon cycle in mid-high latitude of North Hemisphere. It is likely that carbon cycle change in Asian continent, triggered by ENSO and other episodes, could contribute to carbon flux change in the area of 30°N — 60°N . So the conclusion by Fan *et al.* (Fan, 1998) that a sink of about 2 GtC/a could be located in North America is at least debatable. Maybe a more proper opinion is that ecosystems of Europe, Asia and North America, jointly comprise the terrestrial carbon sink in North Hemisphere. Furthermore, there is evidence from remote sensing (Myneni, 1997) that supports this idea. Analysis of data from AVHRR (Advanced very high resolution radiometer) showed a progressive greening trend in the boreal zone, including North China, Central Europe, South Russia and Northwest Canada.

4 Conclusions

The validation of the model has been done by comparing computed results with observed data. Uncertainties still exist in model transport and so do uncertainties in inverse results. Numeric simulation with different sets of horizontal and vertical transport coefficients demonstrates that calculated carbon flux patterns are sensitive to model transport (Fig. 7).

Carbon flux distribution between 60°S and 60°N for the period of 1981—1998 was studied with our inverse method. The pattern of carbon flux distribution, coupled with known fluxes from fossil fuel combustion and ocean, strongly indicated the possible terrestrial carbon sink located in Northern Hemisphere (north of 30°N). There is considerable

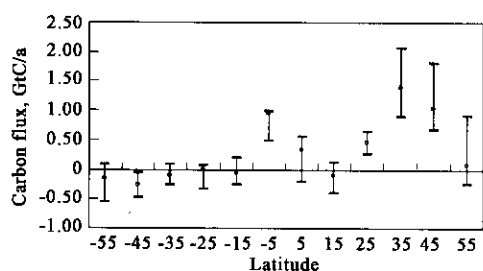


Fig. 7 Sensitivity of calculated carbon flux distribution to changes in model transport (average range for 1990—1995)

interannual variability in both the total amount and the spatial distribution of carbon fluxes, especially in years with ENSO events. Possible explanation for such variation is that fluctuations in temperature, precipitation and other factors, caused by ENSO and other episodes, have influenced the terrestrial and oceanic carbon cycle processes.

The relationship between carbon flux and climatic factors such as temperature and precipitation was investigated with statistic method. As expected, no much obvious correlation was found, due to the limitation of 2-dimensional data and the complexity of carbon cycle. But carbon flux in the area of 40°N—60°N, which included relatively large land area, showed negative correlation with temperature. This implied that, the activity of terrestrial ecosystems in this area, responses to climatic factors and contributes to oscillation in carbon flux. The data analysis also indicated that ecosystems in Asia continent could probably be important carbon sinks.

The inverse research could provide some information about carbon sources and sink. But due to the limitation of current model, further research work is needed for better understanding of carbon cycle, such as improvement of transportation simulation, 3-D model development and more monitoring data to validate model. And applying this inverse study to $\delta^{13}\text{C}$ cycle could be very informative if adequate monitoring data become available.

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