

Southern hemisphere ocean CO₂ uptake: reconciling atmospheric and oceanic estimates

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ABSTRACT

Using an atmospheric inversion model we investigate the southern hemisphere ocean CO₂ uptake. From sensitivity studies that varied both the initial ocean flux distribution and the atmospheric data used in the inversion, our inversion predicted a total (ocean and land) uptake of 1.65–1.90 Gt C yr⁻¹. We assess the consistency between the mean southern hemisphere ocean uptake predicted by an atmospheric inversion model for the 1991–1997 period and the T99 ocean flux estimate based on observed $\Delta p\text{CO}_2$ in Takahashi et al. (2002; *Deep-Sea Res II*, **49**, 1601–1622). The inversion can not match the large 1.8 Gt C yr⁻¹ southern extratropical (20–90°S) uptake of the T99 ocean flux estimate without producing either unreasonable land fluxes in the southern mid-latitudes or by increasing the mismatches between observed and simulated atmospheric CO₂ data. The southern extratropical uptake is redistributed between the mid and high latitudes. Our results suggest that the T99 estimate of the Southern Ocean uptake south of 50°S is too large, and that the discrepancy reflects the inadequate representation of wintertime conditions in the T99 estimate.

1. Introduction

Carbon dioxide is increasing in the atmosphere primarily due to the burning of fossil fuels. However, less than half of the anthropogenic CO₂ emitted remains in the atmosphere. The ocean and the terrestrial biosphere take up the rest of the anthropogenic CO₂. To predict the future climate we need to know the future atmospheric CO₂ levels, which requires understanding the roles the ocean and the terrestrial biosphere play in controlling the concentration of CO₂ in the atmosphere. For the ocean, this includes determining the magnitude and spatial distribution of the oceanic CO₂ fluxes. For this study, the CO₂ fluxes refer to the sum of anthropogenic and natural CO₂ fluxes.

One method for determining CO₂ fluxes is to use the spatial and temporal patterns of atmospheric CO₂ con-

centrations and knowledge of atmospheric transport to infer the surface CO₂ flux. The process is known as an inversion since it reverses the natural direction of causality. The method has been widely used (Keeling et al., 1989; Tans et al., 1990; Enting et al., 1995; Bousquet et al., 2000) and provides an independent check on other integrated estimates of surface fluxes.

Although the sparse data coverage leaves regional flux estimates highly uncertain, atmospheric inversions have yielded some consistent results at hemispheric scales driven primarily by the large-scale interhemispheric gradient in atmospheric CO₂. The interhemispheric gradient is predominantly forced by the asymmetry in fossil fuel combustion (approximately 95% occurs in the northern hemisphere). Early studies noted that the simulated interhemispheric gradient from the spatial distribution of fossil fuel sources was substantially larger than the observed gradient (Tans et al., 1990; Law et al., 1996). Inverse models attempt to reproduce observed CO₂ gradients by inferring

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surface CO_2 flux distributions. Thus it is not surprising that most inverse studies of CO_2 fluxes have suggested large northern hemisphere sinks (usually over land). Less noted, but nearly as ubiquitous, has been the finding of a corresponding reduction in the southern hemisphere uptake (Keeling et al., 1989; Tans et al., 1990; Rayner et al., 1999) relative to ocean-derived uptake estimates (Metzl et al., 1999; Takahashi et al., 1997; Takahashi et al., 2002).

Historically, ocean CO_2 flux estimates based on the observed CO_2 partial pressure differences between the surface ocean and the atmosphere ($\Delta p\text{CO}_2$) (Takahashi et al., 1997; Metzl et al., 1999) and global ocean carbon models (Matear and Hirst, 1999) have generally produced larger Southern Ocean CO_2 uptakes than atmospheric inversions (Rayner et al., 1999; Bousquet et al., 1999) (Fig. 1).

Several recent air–sea CO_2 flux estimates for the Southern Ocean (N. Metzl, personal communication; Gloor et al., 2002) give lower oceanic uptakes consistent with atmospheric inversion estimates. Data col-

lected on French OISO cruises during summer and winter in the Indian sector of the austral ocean (January and August 2000) suggest that the Southern Ocean is a summer CO_2 sink as generally observed (Metzl et al., 1995; 1999; Takahashi et al., 2002) but could be a significant source of CO_2 to the atmosphere during winter. The regional CO_2 flux estimate based on this cruise data was obtained from a one-dimensional biogeochemical model of $\Delta p\text{CO}_2$ (N. Metzl, LBCM/IPSL, personal communication). We extrapolate the regional estimate to the full seasonal cycle for the entire Southern Ocean (1b, Fig. 1). Such an extrapolation may introduce large biases and errors into the estimate, which can only be improved with incorporation of more data. The Gloor et al. (2002) estimate (5, Fig. 1) is based on an ocean inversion method that uses ocean observations of dissolved inorganic carbon (DIC) to infer ocean CO_2 fluxes. The method is limited by the need to prescribe the ocean transport and by the ability to compute the anthropogenic CO_2 concentration (Gruber, 1998) and the atmospherically derived CO_2 concentration (Gruber et al., 1996) from the observed DIC and hydrographic data. The method may introduce biases into the estimate. For example, biases could be caused by errors in the prescribed ocean transport and errors in the computed anthropogenic CO_2 concentration. Although both these new estimates appear consistent with atmospheric inversion results, at present the potential errors in these estimates have not been quantified and it is premature to claim consistency with the atmospheric inversion results.

Early inverse studies were carried out when fewer oceanic CO_2 flux estimates were available. The advent of more comprehensive ocean $\Delta p\text{CO}_2$ compilations (Takahashi et al., 2002) enables one to combine the independent atmospheric concentration data and oceanic CO_2 flux estimates in an inversion and rigorously compare the oceanic and atmospheric methods for determining fluxes. The southern extratropics are a particularly good region for such a study since the almost complete ocean coverage reduces complications that might arise from terrestrial CO_2 exchange. We use the inversion technique to combine atmospheric data and ocean flux estimates to compare and assess their consistency in the extratropical southern ocean, and to obtain an improved estimate of the CO_2 uptake. Considering how critical the Southern Ocean is for CO_2 uptake and how relatively data-poor this region is, it is essential that all oceanic and atmospheric data are used to estimate the CO_2 fluxes.

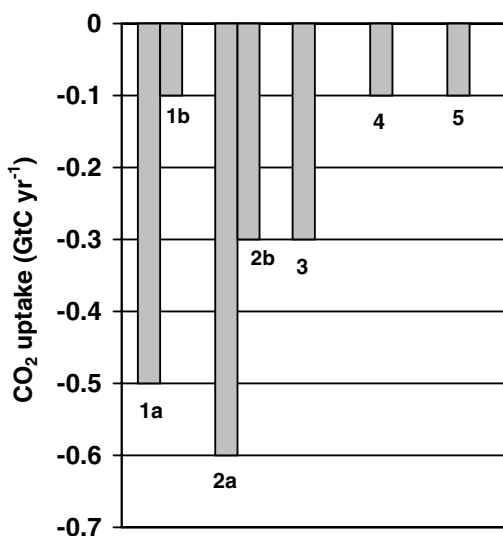


Fig. 1. Estimates of the Southern Ocean (south of 50°S) CO_2 uptake (Gt C yr^{-1}). 1. Regional ocean observations of $\Delta p\text{CO}_2$ from (a) Metzl et al. (1999) and (b) N. Metzl, LBCM/IPSL, (personal communication), which includes winter observations. (2) $\Delta p\text{CO}_2$ compilations (a) T99 in Takahashi et al. (2002), and (b) Takahashi et al. (1997). (3) Ocean carbon-cycle model of Matear and Hirst (1999). (4) Atmospheric inversion model of Rayner et al. (1999). (5) Ocean inversion model of Gloor et al. (2002).

2. Methods

We use a time-dependent Bayesian synthesis inversion method as described by Rayner et al. (1999). The set-up of our calculations follows their paper except for the differences described below. We use a different atmospheric transport model, in our case the CRC-MATCH model used by Law and Rayner (1999) and included in the study of Gurney et al. (2002). The influence of errors in atmospheric transport is not explicitly dealt with in this paper, but they have been assessed in a comparison of atmospheric transport models (Gurney et al., 2002). Considering the results from their study, we find our solutions are robust against atmospheric transport. The inversion of Rayner et al. (1999) used uniform source patterns within 26 regions. We have incorporated the geographical distribution of fluxes within the ocean regions (Fig. 2). This is achieved by fixing the initial source pattern and solving for the offsets from this distribution within each ocean region. Hence we can study the effect of different small-scale flux structure on the inversion. The atmospheric data used include the monthly-mean CO₂ concentrations from 65 stations marked in Fig. 2. The data are a preliminary version of the dataset used by Bousquet et al. (2000), and we use data from the period 1980–1997. We also use the O₂/N₂ record from Cape Grim, Tasmania (Langenfelds et al., 1999) to constrain the net global CO₂ uptake by the terrestrial biosphere and the

oceans. Unlike Rayner et al. (1999) we do not use the $\delta^{13}\text{C}$ record from Cape Grim. Given the formulation of the Rayner et al. (1999) study, $\delta^{13}\text{C}$ was not used to determine the long-term mean net fluxes, so this difference is not significant.

3. Results and discussion

Figure 3 shows the zonal mean atmospheric CO₂ gradients estimated from TransComIII atmospheric transport models using identical terrestrial (Randerson et al., 1997), ocean (Takahashi et al., 2002) and fossil fuel fluxes (Gurney et al., 2002). All the models overestimate the observed interhemispheric gradient in atmospheric CO₂. The overestimation could be attributed to errors in the fluxes or bias in modelled atmospheric transport and the atmospheric observations.

The effect of atmospheric transport on the southern hemisphere uptake has been tested by Gurney et al. (2002). They performed 16 inversions using 16 different transport models. The reduction in the southern hemispheric uptake is one of their most robust findings. Interhemispheric atmospheric transport in each of the 16 models was assessed using tracer SF₆ simulations (Denning et al., 1999). They find that even models that underestimate interhemispheric transport produce a reduced southern hemisphere uptake relative to the T99 ocean flux estimate in Takahashi et al. (2002),

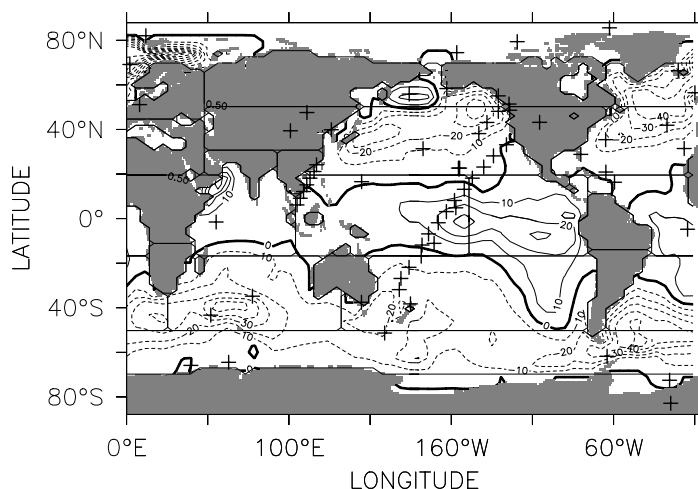


Fig. 2. Annual mean ocean flux estimate ($\text{g m}^{-2} \text{yr}^{-1}$) T99 in Takahashi et al. (2002), which is used as the initial ocean source distribution in the control inversion. The dashed contour lines denote negative values, which indicate a flux into the ocean (atmospheric sink). The inversion solves for the 26 regions (boxes) and uses atmospheric CO₂ concentrations from the 65 marked atmospheric stations (+).

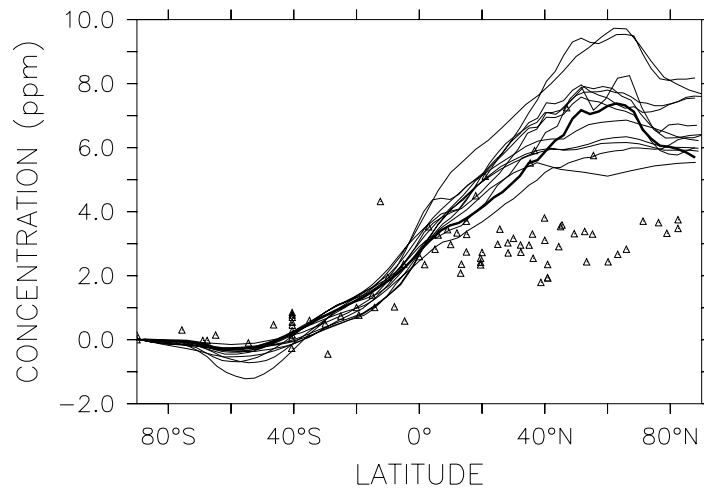


Fig. 3. The observed (Δ) annual mean atmospheric CO_2 concentrations (ppm) and the simulated (lines) interhemispheric gradients from a range of transport models (Gurney et al., 2002). The simulated gradients were produced from the best estimates of fossil fuel, terrestrial (Randerson et al., 1997) and oceanic (T99 in Takahashi et al., 2002) source fields. The bold line represents the atmospheric transport model, CRC-MATCH, used in our study. All data are normalised to the South Pole.

indicating that the gradient mismatch is not due to errors in the modeled interhemispheric exchange rates.

It is important to note that the transport model used in our study, CRC-MATCH, produces a good match to the SF_6 interhemispheric gradient, although the measurements do not allow precise calibration. Our transport model also produces a simulated interhemispheric CO_2 gradient that is within the range of the other transport models and overestimates the gradient by almost 5 ppm (Fig. 3). It is also worth noting that the simulated gradients in Fig. 3 are zonal mean concentrations, while the atmospheric observing stations are generally located to avoid the large fossil fuel and terrestrial sources. For a better comparison of interhemispheric gradients, we compared the north–south transect of the surface CO_2 concentration averaged between 170°E and 170°W to a transect through the Pacific marine sites. The mismatch was reduced by at most 30%, suggesting that sampling bias was not the major contributor to the gradient mismatch. This comparison also reduces the possibility of overestimating the impact of the (predominantly terrestrial) rectifier effect (Denning et al., 1995).

3.1. Control case

Using the inversion model we calculate monthly flux distributions from 1980 to 1997, which minimise the mismatch between simulated and observed con-

centrations throughout this period. The T99 ocean flux estimate in Takahashi et al. (2002) is used as an initial ocean CO_2 uptake estimate (Fig. 2). Our predicted flux distribution for the control case where the data constraints are weighted as in Table 1, follows the general uptake pattern obtained by previous studies (Enting et al., 1995; Ciais et al., 1995; Bousquet et al., 1999; Rayner et al., 1999). For the 1980 to 1997 period, the inversion matches the interhemispheric CO_2

Table 1. For the control case, uncertainties given to the initial estimates of sources and to the data constraints

Sources	
Flux	Standard deviation (Gt C yr^{-1})
Fossil fuel	0.3
Northern North Atlantic & Northern North Pacific	0.5
South Pacific	1.5
Other ocean regions	1.0
Land regions	1.2
Data	
Data type	Standard deviation
CO_2 data	Range. 0.3–5.2 ^a
O_2/N_2 trend	0.2

^aStation-dependent: see Bousquet et al. (1999) for details.

Table 2. Estimates of ocean CO₂ fluxes and the estimated annual mean southern hemisphere (ocean plus land) CO₂ fluxes (Gt C yr⁻¹) from the inversions^a

	Ocean CO ₂ flux (Gt C yr ⁻¹) 18–50°S	Ocean + land CO ₂ flux (Gt C yr ⁻¹)		
		18–50°S	50–90°S	Total
Estimates of the ocean fluxes				
T99 (Takahashi et al., 2002)	−1.2	−1.2	−0.6	−1.8
Takahashi et al., 1997	−0.9	−0.9	−0.3	−1.2
Matear and Hirst, 1999	−1.0	−1.0	−0.3	−1.3
Inversion cases				
Control (1980–1997)	−1.0	−1.2	−0.1	−1.3
Control (1980–1991)	−1.2	−1.0	0.0	−1.0
Control (1991–1997)	−0.7	−1.5	−0.3	−1.8
South Africa Test ^b	−0.9	−1.2	−0.3	−1.5
Constrained Southern Ocean ^b	−1.2	−0.2	−0.6	−0.8
Constrained Southern Ocean and Southern Land ^b	−1.2	−0.8	−0.6	−1.4

^aA negative flux denotes uptake of atmospheric CO₂.^b1991–1997.

gradient, by increasing the total annual mean northern hemisphere uptake (land plus and ocean) from 0.9 to 2.4 Gt C yr⁻¹, primarily by increasing the terrestrial biosphere uptake. The inversion also reduces the total southern hemispheric uptake from 1.8 to 1.3 Gt C yr⁻¹ (Table 2).

3.1.1. Southern extratropical (18–90°S) uptake. In the 1980s the southern extratropical uptake was 1.0 Gt C yr⁻¹, while in the 1990s it increases to 1.8 Gt C yr⁻¹ (Table 2). Most of the increase in the southern extratropical uptake between the 1980s and 1990s in the control case is concentrated over South Africa. In fact the region switches from a source to a sink region, increasing its uptake by 0.7 Gt C yr⁻¹. Such a large shift arising from a small continental area of generally low fertility is unlikely. Takahashi et al. (2002) provides a monthly mean global ocean flux distribution for 1995. For consistency, we compare the annual mean fluxes of the T99 ocean flux estimate with the annual mean uptake predicted by the inversion for the period 1991–1997 (Table 2). Note that for all further comparisons between inversion results and the T99 ocean flux estimate we use only inversion results from the 1990s. At a first glance it would appear that the 1.8 Gt C yr⁻¹ southern extratropical (18–90°S) uptake in the 1990s is consistent with the T99 estimate (Table 2). It is important to be careful when interpreting zonal uptake estimates from inversions when they contain regions such as South Africa, which are not well observed, as they tend to produce spurious fluxes.

By reducing the uncertainty on South Africa by a factor of six from the control case (South Africa Test Case, Table 2), two thirds of its uptake is shifted to the tropics such that the total mid-latitude uptake is reduced to 1.2 Gt C yr⁻¹ without changing the local station mismatches. South Africa must be responding to influences outside the southern extratropics. We therefore regard the 1.8 Gt C yr⁻¹ southern extratropical uptake predicted in the control case as an upper-bound value for this region. A total land–ocean uptake larger than the T99 ocean uptake estimate would be difficult to reconcile with the 1990s atmospheric data.

The control case reduces the Southern Ocean uptake south of 50°S relative to the T99 estimate from 0.6 to 0.3 Gt C yr⁻¹ (Table 2). In the mid-latitudes, it produces a substantial uptake on land at the cost of a reduced ocean uptake. The ocean uptake is reduced from 1.2 to 0.7 Gt C yr⁻¹. Although the ocean is generally better constrained than the land regions within the southern mid-latitudes, the difficulty of defining longitudinal structures of sources from atmospheric inversions makes the separation of the land and ocean uptake much less certain than the combined uptake.

3.2. Constrained southern hemisphere cases

To explore the consistency between the spatial distribution of the ocean fluxes and atmospheric inversion estimates we reduce the uncertainty of the T99 oceanic southern extratropical fluxes by a factor of 100 from the control run (Constrained Southern Ocean Case).

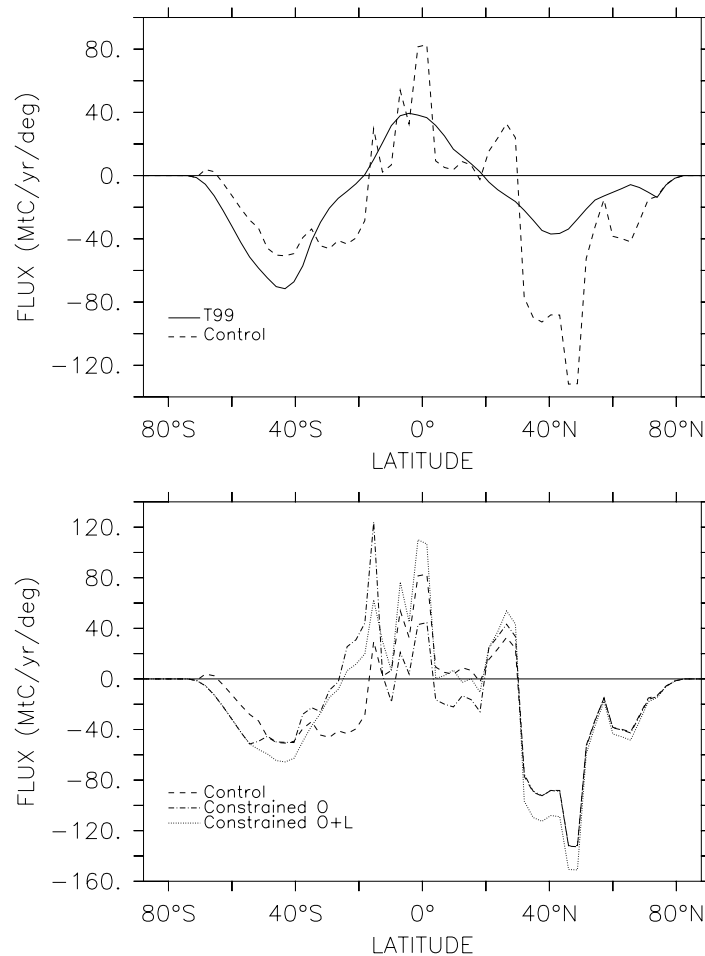


Fig. 4. The zonal annual mean (1991–1997) CO₂ uptake (Mt C yr deg⁻¹) for: (a) the T99 ocean flux estimate in Takahashi et al. (2002) used as the initial ocean flux estimate in the control inversion, and the predicted combined land and ocean (total) uptake of the control inversion, and (b) the predicted total uptake of the control, constrained southern extratropical ocean (Constrained O) and constrained southern extratropical ocean and land (Constrained O + L) inversion cases. A negative flux denotes uptake of atmospheric CO₂ by the either the land or ocean.

This forces an increased ocean uptake in the high latitudes of the southern hemisphere and moves the uptake in the mid-latitude southern hemisphere from the land to the ocean.

In the inversion, the atmospheric observations are matched by introducing a large land source of 1.5 Gt C yr⁻¹ over the southern mid-latitudes (18–50°S) and by reducing the total southern extratropical uptake to 0.8 Gt C yr⁻¹ (Table 2; Constrained O, Fig. 4b). This reduction is produced by an unrealistic (1.7 Gt C yr⁻¹) source concentrated over temperate South America. South America like South Africa is a region poorly

constrained by atmospheric station measurements and consequently has the freedom in the inversion to produce spurious fluxes.

To limit the size of these fluxes we reduced the uncertainty on the southern hemisphere land regions by a factor of four from the control case (Constrained Southern Ocean and Land case). In this inversion, the northern hemisphere terrestrial uptake increases by 0.7 Gt C yr⁻¹ relative to the constrained Southern Ocean inversion, and the uptake in the tropics is reduced. Extra uptake in the northern hemisphere satisfies the interhemispheric gradient, while fluxes in the

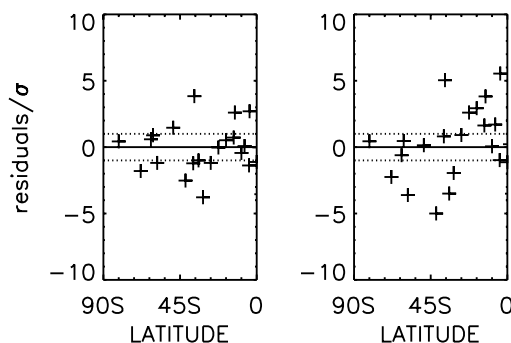


Fig. 5. Normalised residuals for all southern hemisphere atmospheric CO₂ measuring stations from (a) the control inversion and (b) the constrained southern ocean and land inversion (Constrained O + L).

tropics are reduced to satisfy the atmospheric growth rate (Constrained O + L, Fig. 4b).

Figure 5a shows the normalised mismatches to observations at all southern hemisphere stations for the control case. In our control case the average station mismatch for all stations within the high latitudes is zero, indicating that the inversion succeeds in satisfying the large-scale atmospheric station constraint. Forcing a larger southern extratropical uptake introduces large systematic biases to the southern hemisphere stations (Fig. 5b). The negative bias in the high latitudes indicates that the stations require less local uptake. The mid-latitude stations become positively biased, indicating that they require more local uptake.

Although the magnitude of the total (ocean and land) southern extratropical uptake from the control inversion agrees with the T99 estimate, the ocean uptake is inconsistent. The spatial distribution of the T99 estimate cannot be prescribed in the inversion without producing unrealistic land sources or systematic biases in the southern hemisphere observing stations. The large southern hemisphere uptake as given by Takahashi et al. (2002) cannot be reconciled with the atmospheric data, without reallocating the fluxes between the mid- and high latitudes.

The station bias shown in Fig. 5b also allows us to assess the contribution of possible systematic observational errors. For the constrained fluxes to be consistent with the atmospheric observations requires a systematic overestimate of the interhemispheric gradient of 0.5 ppm. Given the relative uniformity of the southern hemisphere atmospheric CO₂ concentrations, and estimates of measurement precision and possible bias (for example, flask storage effects in the annually supplied

and retrieved flasks at Antarctic sites) such a large error (0.5 ppm) is unlikely.

3.3. Sensitivity studies

Atmospheric inversions use data taken at discrete measuring sites. These measurements can be effected by local source features. If local sources are very different from large-scale averages these effects can be misleading. To test the sensitivity of the atmospheric inversion to the initial estimates of the ocean fluxes we perform two additional inversions using ocean flux estimates from Takahashi et al. (1997) and the ocean carbon cycle model from Matear and Hirst (1999). These ocean flux estimates have different geographical patterns from the T99 estimate used in the control case, and a range of Southern Hemisphere ocean uptakes (Table 2). Despite differences between the initial zonal uptakes of up to 0.3 Gt C yr⁻¹ (Table 2) the range in the uptakes predicted by the inversions is much lower. The predicted uptakes in the mid-latitudes and high latitudes lie in the range 1.65 ± 0.1 and 0.25 ± 0.05 Gt C yr⁻¹, respectively (Table 3). The predicted southern hemisphere uptake is not sensitive to either the local

Table 3. The range of annual mean zonal CO₂ uptakes obtained by the inversion for a series of cases where either the initial estimate of the ocean fluxes is changed or successive southern hemisphere atmospheric stations are removed from the network

Zonal CO ₂ uptake (Gt C yr ⁻¹)	Sensitivity studies	
	Initial ocean flux ^a	Station network ^b
18–50°S	-1.65 ± 0.1	-1.4 ± 0.3
50–90°S	-0.25 ± 0.05	-0.2 ± 0.2
Total	-1.9 ± 0.1	-1.65 ± 0.15

^aThe initial ocean uptake estimates used in the inversions are the ocean flux estimates from Takahashi et al. (1997), T99 in Takahashi et al. (2002) and Matear and Hirst (1999).

^bThe range in the fluxes comes from the following cases. In the control inversion the high latitudes (south of 50°S) contain six stations: South Pole (spo), Palmer Station (psa), Macquarie Island (mqa), Syowa Station (syo), Mawson Station (maa) and Halley Bay (hba). The inversion cases are generated by removing the following stations from the high latitude network; (i) all stations except psa, (ii) all stations except spo, (iii) all stations, (iv) spo, (v) hba and psa. Two cases are included where the following stations from the mid-latitude (18–50°S) network are removed; (vi) all stations and (vii) Cape Grim. We also include the control case.

geographical pattern or the magnitude of the initial ocean flux estimates.

Despite the inclusion of more data in the T99 ocean flux estimate the inconsistency with the atmosphere inversion has increased. The ocean fluxes from both Takahashi et al. (1997) and Matear and Hirst (1999) agree better with the inversion estimates, particularly in the high-latitude Southern Ocean, where both estimate a 0.3 Gt C yr^{-1} CO_2 uptake, identical to our inversion estimate.

The choice of stations in a latitudinal band could also potentially influence the zonal CO_2 uptake. We ran a series of inversion cases in which we removed successive southern hemisphere stations from the network. Although the range in the extratropical southern hemisphere uptakes predicted by this suite of inversions is only ± 0.15 (Table 3), the range in the zonal uptake estimates is greater (i.e. ± 0.3 in the mid-latitudes and ± 0.2 in the high latitudes). The choice of southern hemisphere stations redistributes the uptake between the mid and high latitudes. Although the atmospheric inversion robustly determines the total southern hemisphere uptake the inversion has more difficulty allocating the uptake between the mid- and high latitudes.

3.4. Seasonality

The comparison of the seasonal variability of the CO_2 fluxes in the Southern Ocean between the T99 ocean flux estimate and the fluxes predicted by the in-

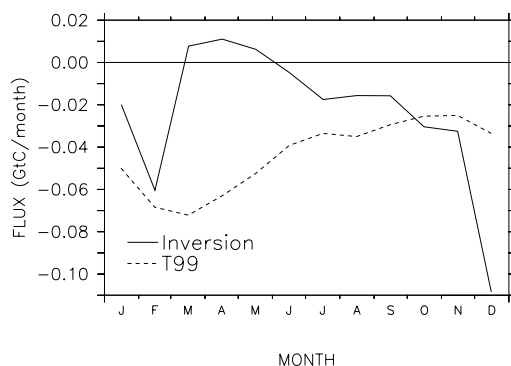


Fig. 6. Seasonal oceanic CO_2 fluxes (Gt C month^{-1}) for the Southern Ocean south of 50°S . The solid line represents the monthly mean fluxes predicted by the inversion for the period 1991–1997. The dashed line represents the T99 ocean flux estimate in Takahashi et al. (2002).

version (Fig. 6) suggests a possible explanation for the higher ocean uptake estimates from ocean observations (Fig. 1). In the Southern Ocean (south of 50°S), the control inversion predicts a source to the atmosphere in autumn, while for the T99 estimate the ocean is an uptake region throughout the year. Observational evidence supporting a seasonal Southern Ocean source is mounting as more data are acquired (Bousquet et al., 2000; N. Metzl, personal communication; B. Tilbrook, personal communication). The winter observations from the south Indian Ocean (N. Metzl, LBCM/IPSL, personal communication) indicated that the Southern Ocean is a source during winter. Although the new winter observations are only from the Indian Ocean, extrapolating these new observations with a seasonal mixed-layer model produces an estimate that reduces the annual uptake in the Southern Ocean from 0.5 to 0.1 Gt C yr^{-1} (Fig. 1). This demonstrates how under-sampling of the Southern Ocean in winter may cause Takahashi et al. (2002) to overestimate the Southern Ocean CO_2 uptake because it contains few winter measurements.

4. Summary

Our atmospheric inversion study predicts a total (land and ocean) southern hemisphere CO_2 uptake of $1.65\text{--}1.90 \text{ Gt C yr}^{-1}$ for the 1990s (1991–1997) from sensitivity studies that varied both the initial ocean flux distribution and the atmospheric stations used in the inversion. The magnitudes and spatial flux distributions predicted by the inversion in the southern extratropical oceans are inconsistent with the T99 estimate for two reasons. Firstly, although the 1.8 Gt C yr^{-1} total (ocean and land) southern hemisphere uptake from the control inversion is the same magnitude as the T99 estimate, the consistency is only achieved by shifting southern extratropical ocean uptake to the land. Constraining the ocean fluxes to the T99 values results in either unrealistic southern hemisphere land sources or unrealistic mismatches between observed and predicted atmospheric CO_2 concentrations at southern hemisphere observing stations. Secondly, the inversion redistributes the uptake between the mid- and high latitudes. There is a persistent reduction in the high-latitude Southern Ocean ($50^\circ\text{S}\text{--}90^\circ\text{S}$) uptake, which is also one of the most robust findings from Gurney et al. (2002). Our results suggest that the T99 estimate for the Southern Ocean uptake south of 50°S is too large. Contrary to the T99 flux estimate, our inversion

results suggest the high-latitude Southern Ocean is a source of CO₂ to the atmosphere in the autumn–winter period. There is mounting observational evidence indicating that the high-latitude Southern Ocean is an atmospheric source during the autumn–winter period (Metzl et al., 2001; B. Tilbrook, personal communication). The recognized undersampling of the Southern Ocean in the T99 winter ocean flux estimate can produce flux estimates that are biased by summer observations and cause an overestimate of the high-latitude Southern Ocean CO₂ uptake.

The re-analysis of the T99 flux estimates including the latest winter data could potentially reconcile atmospheric inversion estimates with ocean-based estimates of the Southern Ocean CO₂ uptake. However, to increase our confidence in both ocean- and atmosphere-based estimates other approaches must also be pursued. One should (i) explore the impact of additional stations and/or improved measurement frequency and precision in southern hemisphere regions which are poorly constrained, (ii) divide the South-

ern Ocean into oceanographically sensible regions in the inversion, (iii) apply adjoint methods which allow much greater resolution of the land and ocean regions, (iv) combine the ocean inversion approach of Gloor et al. (2002) with atmospheric inversions, (v) improve regional ocean flux and uncertainty estimates and (vi) develop effective ways of integrating sporadic cruise data into the inversions.

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