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Trends and regional distributions of land and ocean carbon sinks

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Abstract

We show here a new estimate of the variability and long-term trends in the net land carbon sink from 1960 onwards calculated from the difference between fossil fuel emissions, the observed atmospheric growth rate, and the ocean uptake obtained by recent ocean model simulations forced with reanalysis wind stress and heat and water fluxes. The net land carbon sink appears to have increased by −0.88 (−0.77 to −1.04) Pg C yr^{-1} after ∼1988/1989 from a relatively constant mean of −0.27 Pg C yr^{-1} before then to −1.15 Pg C yr^{-1} thereafter (the sign convention is negative out of the atmosphere). This result is significant at the 1% critical level. The increase in net land uptake is partially compensated by a reduction in the expected oceanic uptake, which we estimate from model simulations as about 0.35 (0.26 to 0.49) Pg C yr^{-1}. This implies that the atmospheric growth rate must have decreased by about −0.53 (−0.51 to −0.55) Pg C yr^{-1} (equivalent to −0.25 ppm yr^{-1}) below what would have been projected if the ocean uptake had continued to grow at the rate expected from a constant climate model and if the net land uptake had continued at its pre-1988/1989 level. A regional synthesis and assessment of the land carbon sources and sinks over the post 1988/1989 period reveals broad agreement that the northern hemisphere land is a major sink of atmospheric CO_2, but there remain major discrepancies with regard to the sign and magnitude of the net flux to and from tropical land.

1 Introduction

Between 1960 and 2007, increases in atmospheric CO_2 concentration can account for 56% of the cumulative fossil fuel and cement emissions of 257 Pg C (Boden et al., 2009), and ocean models can account for ∼33% (cf. Sabine et al., 2004). The remaining ∼11% are generally assumed to have been taken up by the terrestrial biosphere, with various sink mechanisms presumed to exceed the sources due to land use changes such as tropical deforestation. Estimates of these numbers have remained remarkably consistent over time (e.g., Broecker et al., 1979) although our confidence in them, particularly in estimates of the oceanic uptake (cf. Gruber et al., 2009) has greatly improved. By contrast, one of the enduring problems in carbon cycle research continues to be pinning down the components that make up the net terrestrial biosphere contribution to the carbon budget, namely the land carbon sources and the putative land carbon sinks, and to determine their causes and develop the ability to predict how they will behave in the future.

This study was originally motivated by two specific results from recent literature that raised some questions in our minds regarding some of the conceptions that we had formed about the atmospheric CO_2 growth rate and land carbon sink. The first is the analysis by Canadell et al. (2007), who concluded from their estimate of the increase in the airborne fraction of CO_2 emissions that the atmospheric CO_2 growth rate was accelerating (cf. Le Quéré et al., 2009), implying that the efficiency of the CO_2 sinks in the land and ocean have been declining over time. However, we were uneasy about their use of the airborne fraction to evaluate trends in the carbon sink efficiencies for three reasons:

1. Canadell et al. (2007) calculated the airborne efficiency as AF=AGR/(FF+LU) where AGR is the atmospheric growth rate in Pg C yr^{-1}, and the denominator is the sum of fossil fuel emissions, FF, which are reasonably well known, and the land use source, LU, which is not (e.g., Houghton, 2003; Grainger, 2008), potentially leading to substantial biases in the trend analysis.

2. We were concerned about the difficulties inherent in the analysis of ratios such as the airborne fraction where the denominator is increasing by a large amount over time. Such an increase in the denominator will inevitably cause any variability in the absolute value of the numerator to appear to be smaller and smaller over time. For example, a ±3 Pg C yr^{-1} interannual variability in the land carbon sink such as is observed would translate into ±1.15 variability in the airborne fraction when the emissions are 2.6 Pg C yr^{-1}, as the fossil fuel emissions were in 1960, but only

±0.34 when the emissions are 8.7 Pg C yr^{-1}, as the fossil fuel emissions were in 2008. This problem of the gradual suppression of the variability can also lead to biases in the representation of the mean and trends of the airborne fraction or the corresponding land and ocean uptake fractions.

3. Finally, the use of the airborne fraction as a diagnostic of the status of the global carbon cycle carries with it an implicit assumption that a system with constant efficiency carbon sinks will be one where the airborne fraction remains constant over time (cf. Canadell et al., 2007). For this to be true, the carbon sinks, which determine how much of the CO_2 emitted into the atmosphere actually stays there, must be directly proportional to the sources, which is only likely to be true under certain circumstances. An additional problem is that the airborne fraction depends not only on the behavior of the carbon sinks, but also on the behavior of the fossil fuel and land use sources. We were particularly concerned about the impact of the rapid reduction from 4% to 1.0% per year in the growth rate of fossil fuel emissions that occurred between the period 1960–1978 versus 1979–1999, and the near constancy of the land use emissions over the entire period since 1960 (see below), both of which would likely influence the airborne fraction without any changes in the "efficiency" of the carbon sinks.

In this paper, we examine instead the actual magnitude of the atmospheric CO_2 growth rate, oceanic uptake, and estimated net land carbon flux. Our analysis leads us to conclude that the oceanic uptake does indeed appear to have become somewhat less efficient, in agreement with earlier studies (cf., Le Quéré et al., 2007); but that there has been an even larger offsetting increase in the net land carbon sink with the consequence that in the last 20 years the atmospheric CO_2 growth rate has been marginally slower than might have been expected.

The second result that motivated this study was the finding by Phillips et al. (1998), Chave et al. (2008), Phillips et al. (2009), and Lewis et al. (2009) based on regular forest censuses that there appears to be a very large contemporary terrestrial carbon sink in mature tropical forests, large enough indeed to approximately balance the estimated tropical deforestation source. While the net zero flux in the tropical land regions implied by these results is within the range of uncertainty of many atmospheric inversion studies (cf. Denman et al., 2007; and further discussion below), such inverse studies also obtain estimates of the air-sea flux that are inconsistent with our best knowledge of the ocean carbon cycle (cf. Gruber et al., 2009). Jacobson et al. (2007a, b) were able to reconcile the atmospheric constraints with the oceanic observations in a joint atmosphere-ocean inverse. However, when they did this, they found a large net carbon loss to the atmosphere in tropical land regions that was approximately equal to the deforestation source. This implied that there was no significant CO_2 tropical carbon sink outside the areas impacted by deforestation, contrary to the results from in situ measurements.

In this study, we revisit the regional carbon flux estimates, examining both "bottom-up" estimates of land carbon fluxes, that is those based on ecosystem measurements and process-based models, and "top-down" estimates, that is those based on carbon budgets and atmospheric and joint atmosphere-ocean inverse studies. We find that neither the atmosphere only inverse studies nor the joint atmosphere-ocean inverse studies are fully consistent with the bottom up estimates of both the land and ocean carbon fluxes.

In the next section, we summarize the global carbon budget for the period between 1960 and 2007, considering first the best-known components of the carbon cycle, which are the atmospheric CO_2 growth rate and fossil fuel emissions. We then show five model-based estimates of the next best-known component of the carbon budget, oceanic uptake, and finally estimate the net land carbon sink by subtracting the atmospheric CO_2 growth rate and estimated oceanic uptake from the fossil fuel emissions. The primary new elements in our analysis are our use of several model-based estimates of the time-varying uptake of CO_2 by the ocean (cf. Le Quéré et al., 2009), and the use of these to estimate the behavior of the land carbon sink over time.

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2 Global carbon budget, 1960 to 2007

See Appendix A for a description of the data sources and analysis methods used in preparing the figures and tables presented in this section. By convention, a sink of CO_2 is reported as negative (removing CO_2 from the atmosphere) and a source as positive (adding CO_2 to the atmosphere).

2.1 Fossil fuel emissions

Figure 1a shows the fossil fuel and cement production emissions estimates that we use for our carbon budget (Boden et al., 2009; updated through 2008 by Marland, personal communication). Fossil fuel burning increased at a rate of 4.0% per year for two decades between 1960 and 1979, before dropping to 1.0% per year for the next two decades. The growth rate surged to 3.8% per year over the past six years from 2002 to the end of the data set in 2008 (cf. Raupach et al., 2007), but is expected to level off or decrease in 2009 because of the economic recession (Le Quéré et al., 2009). The uncertainty of the fossil fuel emissions is considered to be about 5%. Of particular concern for our trend analysis are systematic errors, such as the recent reduction in the liquid fuel emission estimates starting in 1977 (Boden et al., 2009). However, this particular revision turned out to be too small to impact our results in a significant manner.

2.2 Atmospheric CO_2 increase

Model simulations and comparisons between observations at various locations around the world show that the annual growth rate of atmospheric CO_2 measured at Mauna Loa is representative of the growth rate of the atmosphere as a whole. The longest nearly continuous record of this concentration is that of Keeling et al. (2001). Figure 1a shows the deseasonalized monthly rate of increase of atmospheric CO_2 from that data set through 2008. Given the major influence of fossil fuel emissions on the atmosphere, one would expect the atmospheric CO_2 growth rate to increase in conjunction with the increase in fossil fuel emissions, as it does. However, the growth rate of atmospheric CO_2 has been exceedingly variable (Fig. 1a). This variability is highly correlated with the El Niño/Southern Oscillation, which is the globally dominant mode of climate variability. Analysis of atmospheric transport models and observations suggests that the variability results primarily from terrestrial processes (Peylin et al., 2005; Baker et al., 2006), with the greater part attributed to the tropics, split evenly between Asia and the combined Africa/South America land region (Baker et al., 2006). In general, the land biosphere loses carbon to the atmosphere during warm climate El Niño events and increases carbon uptake during cold climate La Niña and volcanic eruption events, particularly during and after the Mt. Pinatubo eruption of June 1991 (Peylin et al., 2005; Jones and Cox, 2001; Roderick et al., 2001; Gu et al., 2003). The ocean usually has an opposite impact on the observed atmospheric CO_2 growth rate due to the suppression of Equatorial CO_2 outgassing during El Niño resulting from reduced upwelling of carbon, with the opposite occurring during La Niña events (Feely et al., 2006), but this effect is much smaller than the land effect.

2.3 Oceanic CO_2 uptake

A recent set of ocean carbon cycle models has been developed with the goal of simulating the time-varying nature of ocean circulation over the last few decades by forcing with wind and heat and water fluxes from reanalysis of observed meteorological fields (Wetzel et al., 2005; Le Quéré et al., 2007; Lovenduski et al., 2008; Rodgers et al., 2008). These simulations suggest that starting in the mid-1980's there was a leveling off of oceanic CO_2 uptake (Fig. 1b). This came as something of a surprise, since previous ocean modeling work with both steady-state ocean models and coupled climate models forced with the observed CO_2 predicted that ocean uptake should have increased over this time period. In the case of one of the ocean model studies, that of Le Quéré et al. (2007), they have performed a simulation in a model with climatological-mean wind and heat and water flux forcing and increasing CO_2 (Le Quéré, personal

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communication). Comparison of the reanalysis forced model with the climatological-mean forced model shows a reduction in the oceanic sink of 0.06 Pg C yr^{-1} between 1960 and 1988, and 0.31 Pg C yr^{-1} between 1989 and 2007 (recall that the sign convention for a sink is negative, such that a positive change means a smaller sink). The flattening of the carbon uptake after 1988/1989 due to climate change thus represents a drop of 0.25 Pg C yr^{-1} in the ocean carbon sink in the post-1988/1989 period relative to the pre-1988/1989 period.

In the absence of constant climatological-mean simulations for the other models, an alternative way to estimate how much we would have expected the oceanic uptake to increase if climate had remained constant is to use the results of a ten-model ocean inversion designed to estimate surface carbon fluxes consistent with ocean interior data from the global ocean carbon survey of the 1990s (Mikaloff-Fletcher et al., 2006). As the models underlying the inversion were forced with a climatic average of seasonally varying winds and heat and water fluxes, the estimated surface carbon fluxes reflect a climatological-mean uptake and vary only in response to the increase in atmospheric CO_2. The 1989–2007 mean sink estimated by the ocean inversion shown in Fig. 1b and Table 1 is higher by -0.95 ± 0.08 (p-value<0.00001) than the mean sink between 1960 and 1988. By contrast, as Fig. 2 and Table 1 show, the average increase in the oceanic sink by the models that are subject to time-varying forcing is only −0.51 (−0.44 to −0.57) Pg C yr^{-1} (p-value<0.00001 for each model). The difference between these ocean results show that, on average, the time-varying ocean models take up 0.35 (0.26 to 0.49) Pg C yr^{-1} less CO_2 after 1988/1989 than they would have if ocean circulation and biogeochemistry had remained constant. As noted above, the one model group that actually did the appropriate climatological-mean calculation with their model, Le Quéré et al. (2007), obtained a reduction of only 0.25 Pg C yr^{-1} with reanalysis forcing versus our estimate of 0.49 ± 0.07 Pg C yr^{-1} for their model when compared to the Mikaloff-Fletcher et al. (2006) simulation. However, until additional results are available from other models it is difficult to know if our estimate obtained by comparison with Mikaloff-Fletcher et al. is indeed too high, as the Le Quéré et al. result would suggest.

As regards the location and mechanisms of the reduced oceanic CO_2 uptake simulated by the models, a large portion of it occurs in the Southern Ocean, where an intensification of winds leads to increased upwelling of waters rich in pre-anthropogenic dissolved inorganic carbon (DIC) that is then released to the atmosphere as CO_2 (Wetzel et al., 2005; Le Quéré et al., 2007; Lovenduski et al., 2007, 2008). The enhanced upwelling also accelerates the uptake of anthropogenic CO_2, but this effect is smaller (Lovenduski et al., 2008). Taken together, these changes in wind forcing reduce the Southern Ocean net sink for atmospheric CO_2. Climate model simulations are able to reproduce a similar intensification of the winds resulting from a combination of increased greenhouse gases and stratospheric ozone depletion (cf. Thompson and Solomon, 2002; Chen and Held, 2007; Lenton et al., 2009). Ongoing studies are analyzing the trends in ocean model regions outside the Southern Ocean as well as the sensitivity of ocean models to forcing with other reanalysis products.

Time series observations of air-sea CO_2 fluxes are extremely limited, but there is evidence from 23 years of observations in the Equatorial Pacific of an increase in the outgassing flux of 0.09 ± 0.16 Pg C yr^{-1} after the Pacific Decadal Oscillation regime shift of 1997–98 (Feely et al., 2006). There is also evidence of a decline of 0.24 ± 0.1 Pg C yr^{-1} in CO_2 uptake in the North Atlantic between 20° N and 65° N sometime during the period between 1994/1995 and 2002–2005 (Schuster and Watson, 2007). By contrast, in the North Pacific, the observed rate of increase of surface ocean pCO_2 over a 35 year period lags the atmospheric growth rate slightly (though the difference in growth rates is not statistically significant), and in the Bering Sea and periphery of the Sea of Okhotsk, the surface ocean pCO_2 has actually decreased over time (Takahashi et al., 2006), suggesting that in this region the uptake may have increased over time. By contrast with some of these findings, observations from the Hawaii Ocean Time series (HOT) and Bermuda-Atlantic Time series (BATS) stations show little evidence of a long-term trend in the air-sea gradient of CO_2 (e.g., Gruber et al., 2002; Bates, 2007; Keeling et al., 2004; Dore et al., 2009). The observational analyses and model results suggest that the decline in oceanic uptake if it stands up to continued investigation, is likely a complex global scale phenomenon that alters the current distribution of oceanic sources and sinks, and that it involves changes in both the “natural” carbon cycle that existed before the Anthropocene as well as to the rate of uptake of the anthropogenic perturbation per se.

2.4 Net terrestrial sources and sinks

Figure 1c shows our top-down estimate of the annual net fluxes of CO_2 between the atmosphere and the land biosphere calculated by taking the difference between fossil fuel emissions and the annual atmospheric growth rate and oceanic uptake. Since these land fluxes are computed by difference, it is important to have in mind that they also reflect errors in the component sources and sinks that go into the calculation. Three estimates are shown based on the ocean models from Fig. 1b. The estimate using the Mikaloff Fletcher et al. (2006) results represents the expected behavior of the net land flux if the ocean circulation had remained constant over time, while the other two estimates represent an upper (Le Quéré et al., 2007) and lower (Wetzel et al., 2005) limit of the inferred increase in net land fluxes if the ocean-atmosphere CO_2 fluxes change in response to time-varying ocean circulation and biogeochemistry.

The predominant signal in the inferred net land flux of Fig. 1c is the very large interannual variability. A comparison of Fig. 1a, b, and c, shows that most of this interannual variability carries over from the atmospheric growth rate, i.e. much of it is associated with ENSO variability. In addition, it has been shown that cooler than normal episodes associated with explosive volcanic eruptions, such as the Pinatubo eruption in 1991 tend to lead to a negative net land flux, i.e. enhance the net uptake by the land.

Despite the magnitude of the variability, it is possible to note a tendency for the net land fluxes to be more negative after 1988/1989 than before, reflecting a stronger sink. We show in Fig. 3 the cumulative land uptake estimated from 1960 onwards. Cumulative distribution plots such as this are a useful way of low-pass filtering observations, provided one has in mind that the smoothing is progressively greater as one goes from the early part of the record when the cumulative flux is small, to the latter part of the record where it becomes much larger. In a diagram such as this, a line with a constant slope implies a constant land flux. If the land carbon sink were increasing with time, as might be expected if the land uptake were due to CO_2 fertilization, the cumulative land inventory would be concave upwards, unless the fertilization effect became saturated. In any case, this view of the data suggests that the land flux varied about a relatively constant mean before 1988/1989, and that it varied about a higher mean after 1988/1989. The climate impact of the Pinatubo eruption led to a large increase in the land carbon inventory between 1991 and 1993, after which the cumulative land carbon inventory settled back again, but continued to increase at a faster pace (steeper slope) than before 1988/1989. In other words, not only does the CO_2 uptake of the Pinatubo era appear to have been retained by the land, but it also appears that the land shifted to a higher overall uptake rate than before, possibly beginning before the Pinatubo eruption.

The net land sink estimated using the four time-varying ocean models of Fig. 1b increases by an average of −0.88 (−0.77 to −1.04) Pg C yr^{-1} (p-value=0.00 to 0.01) from −0.27 (0.04 to −0.54) Pg C yr^{-1} before the 1988/1989 bend in the cumulative uptake to −1.15 (−0.90 to −1.36) thereafter (see Table 2). Without the years of maximum Pinatubo impact in 1991–93, the increase is −0.72 (−0.56 to −0.92) Pg C yr^{-1} (p-value=0.00 to 0.05). Arguably, the Pinatubo anomaly should be included in the post 1988/1989 analysis since in a neutral land biosphere, one might have expected the land to release most of the excess carbon taken up during the Pinatubo period back to the atmosphere in reasonably short order, as suggested by the terrestrial response to the El Niño driven variability. An increase in the net land carbon sink such as we observe had been noted previously for the 1990s relative to the 1980s (Schimel et al., 2001). However, our analysis suggests that there may have been a much greater persistence in time of this signal, including that the major Pinatubo anomaly of 1991 to 1993 can account for only −0.17 (−0.12 to −0.21) Pg C yr^{-1} of the −0.88 Pg C yr^{-1} increase in our long-term averages.

How consistent is this ocean model-based partitioning between the land and ocean with other, independent constraints, such as those based on measurements of carbon-13 in the ocean and atmosphere or of the atmospheric O_2/N_2 ratio (e.g., Battle et al., 2000; Bender et al., 2005; Manning and Keeling, 2006)? Given the uncertainties in our knowledge of carbon isotope fractionations and the small magnitude of the change in the net land carbon sink relative to the interannual variability, it is unlikely that the signal resulting from such a change in the land carbon sink could be detected in carbon isotope measurements. The O_2/N_2 tracer is more promising, but measurements were not initiated until after the change in the net land carbon sink occurred and the uncertainties in the land uptake estimates based on this tracer are very large. Our post-1988/1989 net land uptake estimate of −1.15 (−0.90 to −1.36) Pg C yr^{-1} is consistent within uncertainty, though at the upper limit of the atmospheric oxygen based estimate of −0.51±0.74 Pg C yr^{-1} for the period of 1993 to 2003 by Manning and Keeling (2006). A possible implication of our result is that Manning and Keeling may have overestimated the magnitude of the correction for the outgassing of oxygen due to warming of the ocean. Without this degassing, their estimate of the land carbon sink would be −0.99 Pg C yr^{-1}.

We emphasize that our estimate of the net land uptake is calculated as the difference between fossil fuel emissions, the atmospheric growth rate, and the oceanic uptake. The requirement for an increase in the net land carbon sink of −0.88 Pg C yr^{-1} after ~1988/1989 arises from the fact that the atmosphere and ocean in combination are taking up a smaller portion of the fossil fuel emissions than they were prior to 1988/1989, which means that the land must account for more. Our analyses of the time series in Fig. 1 together with the pre-1988/1989, post-1988/1989 averages shown in Fig. 2 and Tables 1 and 2, suggest that the oceanic carbon uptake lagged the growth that would have been expected if ocean circulation and biogeochemistry had remained constant. Summing our estimated reduction in oceanic uptake of 0.35 (0.26 to 0.49) Pg C yr^{-1} that we calculate after 1988/1989 to the increase in land uptake of −0.88 (−0.77 to −1.04) Pg C yr^{-1} gives an estimated reduction in the atmospheric growth rate of −0.53 (−0.51 to −0.55) Pg C yr^{-1}. The uncertainties in these estimates are large. However, if they hold up to further scrutiny, the implications for the land carbon sink are dramatic given that they represent more than a quadrupling of the net land carbon sink and a 50% increase in the absolute magnitude of the total annual land carbon sink since 1960 (see discussion in Sect. 5). The implied reduction in atmospheric growth rate would be a challenge to detect, because it is relatively small compared to the observed growth rate and its interannual variability.

3 Bottom-up estimates of the spatial distribution of carbon fluxes after ~1990

We turn now to a discussion of bottom-up estimates of the land carbon source and sink components to examine their consistency with the top-down estimates of the net carbon flux, and see what clues the bottom-up estimates may offer as to the cause of the acceleration in the net terrestrial uptake and its spatial distribution (see gray area in Fig. 2). The main terrestrial source of CO_2 to the atmosphere is tropical land use change (mainly deforestation), which has variously been estimated as either ~1.1±0.3 Pg C yr^{-1} based on analyses of satellite observations (Achard et al., 2004, 2002; DeFries et al., 2002) for the 1980s and 1990s, or ~2.2±0.6 Pg C yr^{-1} from "bookkeeping" methods based on FAO expert opinion and official governmental estimates from the 1990s (Houghton, 2003; cf., Food and Agriculture Organization, 2001; Fearnside, 2000). (Bookkeeping methods track the amount of carbon released to the atmosphere from clearing and decay of plant material, plus the amount of carbon accumulated as vegetation grows back.) However, recently, Houghton (2007) revised his bookkeeping estimates down to ~1.5±0.8 Pg C yr^{-1} for the period between 1960 and 2006. This includes an estimate of non-tropical land use change, but the non-tropical component is <4% after 1988/1989. The reduction in uptake is due primarily to revised FAO tropical land use change estimates (R. Houghton, personal communication; note, however, that the reliability of FAO inventories is unclear, Grainger, 2008). In addition, there are some new estimates by Shevliakova et al. (2009) that combine the bookkeeping and satellite methods, giving estimates that are as low as 1.1 Pg C yr^{-1}

over this time interval. In what follows, we will use for our estimate of the tropical land use change source the median of these new estimates, 1.3 Pg C yr^{-1} with a nominal uncertainty of ±0.8 Pg C yr^{-1}.

Bottom up estimates of land carbon sinks are only available for the post-1988/1989 period. The most complete inventory of land carbon sinks is for North America for circa 2003 (Pacala et al., 2007). This shows a net carbon sink of −0.5±0.3 Pg C yr^{-1} with ~60% from the forest sector due to increases in the mean age of forest stands because of relaxed rates of harvest, agricultural abandonment, and fire suppression. The remaining sink is due to other human activities such as construction of dams, the practices of the forest products and waste disposal industries, and accumulation of carbon in wood products and landfills, reservoirs, pasture lands and wetlands. Research is mixed on the role that fertilization by nitrogen or CO_2 plays in the North American carbon sink (Pacala et al., 2007). Inventories from Eurasia are less complete, but by augmenting the estimates for the temperate and boreal Eurasian forest sector (−0.3±0.1; Goodale et al., 2002) with the non-forest sector implied by the North American inventory, we arrive at an estimate of −1.0±0.5 Pg C yr^{-1} for the combined north temperate and boreal zones. Both this estimate and its uncertainty must be viewed as tentative. Although estimates from eddy-covariance studies have provided useful local confirmation of the inventory methods (Barford et al., 2001; Pacala et al., 2007), they cannot be used yet to determine average fluxes over large regions (though see Jung et al., 2009). This is because the network of such sites is too small to average accurately over heterogeneity in the physical environment and terrestrial land use, and there continue to be concerns of bias due to the inability to retrieve fluxes during periods of stratification, which occur primarily at night when ecosystems are a net source of CO_2.

Carbon inventory measurements in mature tropical forests are far less extensive than temperate inventory estimates. Measurements of a 60 000-tree network across Amazonia indicates that primary forest gained carbon during the 1990's at an average rate of −0.8±0.3 Pg C yr^{-1} (Phillips et al., 2009). Using similar data from fewer but much larger plots from Southeast Asia (6 plots) and Africa (2 plots) (Chave et al., 2008) and the same reasoning as in the Amazonian study by Phillip et al. (1998) to extrapolate these studies spatially, we obtain a total tropical mature forest sink estimate of -1.4 ± 0.8 Pg C yr^{-1}. This number is consistent with the just published study of Lewis et al. (2009) which reports results from 79 plots of ~1 ha area in Africa, which were combined with growth trends estimated from South American and Asian tropical plots, to obtain a pantropical sink estimate in old-growth forests of -1.3 Pg C yr^{-1} (confidence interval=-0.8 to -1.6) over the last decades. Whether or not these measurements are sufficiently broad in scope to be representative is being hotly debated in the literature, as is the mechanism (e.g., Malhi et al., 2008). Some have suggested that the changes are due to growth stimulation in response to a changing environment including elevated CO_2, changes in temperature and precipitation, modified insolation or diffuse radiation; while others have argued that it is rather a response to a changing disturbance regime or possibly recovery from a large scale mega-disturbance event or even simply a measurement artifact.

Summing up our bottom-up estimates of the north temperate and boreal terrestrial carbon sinks together with our estimate of the tropical sink, we arrive at a global terrestrial carbon sink estimate of -2.4 ± 0.9 Pg C yr^{-1} for the post-1988/1989 period. Given our tropical land use source estimate of 1.3 ± 0.8 Pg C yr^{-1}, we obtain a total bottom up net land sink estimate of approximately -1.1 ± 1.2 Pg C yr^{-1}. This is in very good agreement with our top-down post-1988/1989 net land sink estimate of -1.15 (-0.90 to -1.36) Pg C yr^{-1} (Table 2 and Fig. 2). We note that while the top-down estimate of Fig. 1c shows that interannual variability of the net land carbon sink is very large (±3 Pg C yr^{-1}), the measurements underlying the bottom-up estimates mostly span a long period of time so that the appropriate top-down estimate to compare them with is the long-term average, as we have done.

4 Top-down estimates of the spatial distribution of carbon fluxes

The bottom up estimates of the land carbon sinks and land-use change sources that we have discussed provide also a first view of the regional distribution of carbon sources and sinks, with an estimated net sink of $-1.0\pm0.5\,\mathrm{Pg\,C\,yr^{-1}}$ in the temperate and boreal northern hemisphere and a tiny net sink of $-0.1\pm1.1\,\mathrm{Pg\,C\,yr^{-1}}$ in the tropics (uptake of $-1.4\pm0.8\,\mathrm{Pg\,C\,yr^{-1}}$ minus land use source of $1.3\pm0.8\,\mathrm{Pg\,C\,yr^{-1}}$). Another method to estimate the regional distribution of carbon sources and sinks is the top-down atmospheric inversion method, where a set of regionally resolved ocean-atmosphere and land-atmosphere carbon fluxes are adjusted to be optimally consistent with the observed atmospheric CO_2 distribution. One of the most prominent of such studies is the Transcom-3 inversion intercomparison, which used average data for the period between 1992 and 1996 (Gurney et al., 2004; cf. Denman et al., 2007). While this period includes the tail end of the Pinatubo anomaly, the average net land carbon sink over the period is similar to that over the entire period from 1988/1989 to 2007 (cf. Fig. 1c). The Transcom-3 inversions obtained a net source of carbon in the tropical and southern hemisphere land and a large net sink for carbon in the northern hemisphere land (orange bars in Fig. 4).

The uncertainties in the Transcom-3 atmospheric inverse land uptake estimates and the bottom up land uptake estimates overlap, but there is a rather large offset of $\sim1\,\mathrm{Pg\,C\,yr^{-1}}$ between them, with the atmospheric inverse showing a large tropical source where the bottom up estimates show a near zero flux, and the atmospheric inverse showing a much larger sink in the extratropics than the bottom up estimates. Furthermore, there is a large discrepancy between the air-sea flux estimates obtained by the Transcom-3 atmospheric inversions and independent air-sea flux estimates obtained both by air-sea pCO_2 difference measurements combined with a gas exchange model (blue bars in Fig. 4; Takahashi et al., 2009), and by ocean inverse estimates (light green bars; Gruber et al., 2009). The disagreement is particularly striking in the tropical ocean, where the Transcom-3 atmospheric inverse models tend to underestimate

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the degassing flux relative to the ocean observation based estimates; in the southern hemisphere temperate latitudes, where atmospheric inverse models tend to underestimate the uptake relative to the observation based estimates; and in the Southern Ocean, where the atmospheric inverse models tend to overestimate the oceanic sink relative to the observation based estimates (cf. Gruber et al., 2009).

The use of ocean interior constraints on air-sea fluxes in a joint atmosphere-ocean inversion ensures that the solution obtained is consistent with the air-sea flux estimates (Jacobson et al., 2007b). However, the land carbon flux solution obtained in this way (light green bar in the upper part of Fig. 4) differs from the terrestrial bottom up estimates by almost 2 Pg C yr^{-1}, with the joint inverse giving a much larger source in the tropics and southern hemisphere, and a much larger sink in the northern extra tropics than the bottom-up estimates. These are large differences, but unfortunately the uncertainties on the terrestrial flux estimates are so large that the difference is statistically significant at the one standard deviation level only for the northern hemisphere extratropics.

An important source of error in atmospheric inversions is the uncertainty in atmospheric transport, which needs to be specified from an atmospheric transport model in order to determine how atmospheric CO_2 changes at a particular location in response to fluxes at the surface. The uncertainty in this transport is difficult to quantify and is usually assessed by model intercomparison, as in the Transcom-3 study. In a recent study that made use of new vertical CO_2 profiles in the atmosphere (Stephens et al., 2007), only three of the Transcom-3 atmospheric transport models were found to be consistent with the annual mean observed vertical gradients of CO_2 in the annual mean (though this was due to a cancellation of errors in the seasonal profiles). However, while this subset of models did change the land fluxes somewhat, in fact bringing them into better agreement with the bottom-up land flux estimates, they compare poorly with the ocean-based flux estimates (Fig. 4). Using these three atmospheric transport models in the joint inverse gives results shown in the dark green bars in Fig. 4 that are similar to the full Transcom-3 model suite for air-sea fluxes, with slight changes on land

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tending to give fluxes that are in slightly better agreement with the bottom up estimates.

Solving the inconsistencies between the bottom-up and top-down estimates of the regional distribution of land sources and sinks for atmospheric CO_2 has to comprise all four of the following: (1) improved bottom up land carbon flux estimates including particularly carbon inventory measurements with improved measurements of soil carbon inventory; (2) incorporating the new oceanic constraints into atmospheric analyses and exploring the extent to which it is possible to fit both these and the bottom up land flux estimates simultaneously; (3) improved atmospheric transport models; and (4) improved atmospheric observational constraints, of which vertical profiles and the possibility of obtaining atmospheric CO_2 data from satellite observations are significant developments.

5 Discussion and conclusions

We have examined the atmospheric growth rate (AGR), oceanic uptake (S_{OC}), and net land carbon sink (NS_L), the sum of which is required to equal the fossil fuel emissions (i.e., $FF=AGR+S_{OC}+NS_L$). Observational and model based estimates enable us to determine three of these four variables with reasonable confidence, namely AGR, S_{OC}, and FF, from which we are able to estimate the fourth, NS_L. As regards the ocean carbon sink, our comparison of the ocean uptake in four models with reanalysis climate forcing versus models with constant climate forcing led to the conclusion that oceanic uptake may have slowed relative to expectation, in agreement with previous studies that were based on single models only (Canadell et al., 2007; Le Quéré et al., 2007; Lovenduski et al., 2007; cf. Le Quéré et al., 2009).

As regards the net land carbon sink NS_L, our analysis shows that it appears to have been small between 1960 until ~1988/1989 (Figs. 1c and 3), with the longer-term record shown in Fig. 5 suggesting that it may have been at or near zero (the cumulative flux was nearly constant) from as early as ~1930. The net land carbon sink appears to have increased after 1988/1989. The nature of the increase is extremely difficult to detect given the short time scale of the record, the huge variability of the net land uptake estimate, and the differences between the land uptake estimates obtained with the different ocean models. Thus it is difficult for us to say whether the increase represents an abrupt shift to a higher uptake or a more gradual increase.

What might have caused the net land carbon sink to increase after 1988/1989? The net land carbon sink NS_L, is equal to the difference between the land sink S_L and the land use source LU, i.e., $NS_L = S_L - LU$. Thus, an increase in NS_L could have been caused either by an increase in the land sink S_L or a decrease in the land use LU or some combination of these. Up to now we have avoided separating the time history of the net land carbon sink into its components because of the low confidence level in the land use estimates. However, as Fig. 6a shows, the land use source LU as presented in Houghton (2007) and Canadell et al. (2007) has, if anything, increased slightly in time, which implies that the increase in the net land carbon sink NS_L must be due primarily to an increase in the land carbon sink S_L (Figs. 5b, c and 6a, b).

What can observations and/or models tell us about the nature of the terrestrial carbon sink S_L and the causes of its changes? The bottom-up carbon sink estimates of the land-atmosphere carbon fluxes for the post-1988/1989 period support the results obtained by our top down estimate. A next step would be to determine if such changes can be observed in land models that are forced with land use changes and reanalysis climate; and to determine if there are bottom-up observations that can tell us what was different prior to 1988/1989 and where and how the transition to a higher land uptake occurred. Candidates for what could be responsible for such an increase in the net land carbon sink include:

1. An error in the calculation of net land use due to an underestimate of pre-1988/1989 fossil fuel emissions or an overestimate of post 1988/1989 fossil fuel emissions or an error in the ocean carbon sink. The recent revisions to the fossil fuel estimates that we use in our calculations lowered the fossil fuel emissions by ~0.2 Pg C yr^{-1} after 2004 and ~0.1 Pg C yr^{-1} after 1993, which reduced our estimate of the increase in the land flux. Furthermore, the leveling off of the oceanic

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carbon sink that we showed in Fig. 1b is estimated directly from ocean model simulations forced with reanalyzed meteorological observations, and supported by a modest number of observations. In addition to continued long-term observations of the ocean carbon system and a more in-depth analysis of the ocean models, additional model studies are needed to examine the extent to which eddy transfer in the ocean may in fact cancel some of the effects of increased wind-driven Ekman divergence in the Southern Ocean (cf. Hallberg and Gnanadesikan, 2006; Boning et al., 2008). It is currently an area of active research to determine whether the mesoscale parameterization used in the global models represented in Fig. 1b is adequate to represent the effect of eddy transfers found in higher resolution models. An additional issue with the ocean model simulations is whether the atmospheric forcing fields themselves represent skillfully decadal variations in the state of the atmosphere. If for example the post-1988/1989 leveling of ocean uptake were shown to be wrong, this would reduce our estimate of the change in the land carbon sink from −0.88 to −0.64 Pg C yr^{-1} with p=0.02.

2. A decrease in land use emissions, which is not supported by existing publications, as we have shown in Fig. 6.

3. A change in the total land carbon sink due to (a) a fertilization effect such as the cumulative impact of CO_2 fertilization (cf. Schimel et al., 2004); (b) growth stimulation by climate variability such as the Atlantic Multidecadal Oscillation shift in 1996 and/or the Pacific Decadal Oscillation shift in 1998, both of which come at an opportune time following the June 1991 Pinatubo eruption (c) climate change such as the impact of the increased incidence of droughts after the mid-1980s (Trenberth et al., 2007; Buermann et al., 2007), (d) changes in solar irradiance reaching the Earth's surface, which began to increase about 20 years ago after undergoing a long period of dimming due to the impact of aerosols (Romanou et al., 2007); or (e) an increase in the growing season length due to global warming.

We note that the net land carbon uptake shown in Fig. 1c and the land carbon uptake shown in Fig. 6a are highly variable in time. With such a short record, it is difficult to know if the increase in the land uptake is due to a change in the baseline behavior, or if it may in fact be related to changes in the variability resulting from known nonlinearities in the response of the hydrological cycle to ENSO variability in conjunction with nonlinearities in the terrestrial carbon response to variations in hydrological or other climate forcing.

We conclude that the net land carbon sink appears to have increased relative to expectation, and the oceanic sink has reduced relative to expectation. The difference between these two is small and uncertain, but the increase in the land uptake is larger than the reduction in the ocean uptake, implying that the atmospheric growth rate decreased over time with respect to its "expected" behavior. Our conclusions thus differ significantly from those of Canadell et al. (2007), who concluded that the land and ocean carbon sinks were decreasing in efficiency because the airborne fraction was increasing over time. Our analysis suggests that fundamental changes in the carbon cycle may be underway in both the oceans and terrestrial biosphere that pose important challenges to our mechanistic understanding of controls on carbon flux variability and trends.

Appendix A

Data sources and methods

(1) *Fossil fuel emissions*: Annual fossil fuel emissions from 1750 through 2006 are from Boden et al., 2009 supplemented by Marland, personal communication, who provided slightly updated 2006 emissions and estimates of the 2007 and 2008 emissions. These annual data were used directly in the analysis shown in Tables 1 and 2 as well as Figs. 2 and 5. The monthly data shown in Fig. 1a and used in producing Figs. 3 and 6 were interpolated from the annual data using the mass conserving method of Rasmussen

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(1991). We calculate the long-term average annual growth rate of emissions over a time interval from $t=0$ to $t=T$ following the annual mortality concept used in the ecological literature (Sheil et al., 1995). The algebraic formulation for the long-term average annual growth rate approach is

$$\mathrm{FF}(T) = \mathrm{FF}(0) \cdot (1 + \text{growth rate})^T$$

where FF is fossil fuel emissions for a given year t. Inverting the above equation gives the growth rate as

$$\text{growth rate} = \left(\frac{\mathrm{FF}(T)}{\mathrm{FF}(0)}\right)^{\frac{1}{T}} - 1$$

(2) *Atmospheric growth rate*: The monthly atmospheric CO_2 data are obtained from the filled data set given in column 9 of http://scrippsco2.ucsd.edu/data/in_situ_co2/monthly_mlo.csv (Keeling et al., 2001). The annual growth rate of CO_2 in Pg C shown in Fig. 1a is calculated month by month for time t in months using the equation

$$\frac{d\mathrm{CO}_2}{dt} = \gamma \cdot [p\mathrm{CO}_2(t+6) - p\mathrm{CO}_2(t-6)]$$

$$\gamma = 2.1276 \frac{\mathrm{PgC}}{\mathrm{ppm}}$$

where pCO_2 is the atmospheric partial pressure of CO_2 in ppm. The growth rate is then smoothed with a 3-months boxcar filter to remove short time scale variability. The conversion factor γ is calculated as follows: atmospheric carbon dioxide is reported as the dry air molar mixing ratio in ppm units per year. This is converted to Pg C of CO_2 in the atmosphere using the relationships:

$$N_{\mathrm{air}} = \frac{m_{\mathrm{atm}}}{\mu_{\mathrm{air}}}$$

$$\mu_{\mathrm{air}} = 0.0289644 + 0.012011 \cdot \left(\chi_{\mathrm{CO}_2} - 0.0004\right)$$

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$$N_{CO_2} = \chi_{CO_2} \cdot N_{air}$$
$$m_{CO_2} = \mu_C \cdot N_{CO_2}$$

where N_{air} is the number of moles in the atmosphere, m_{atm} is the total dry mass of the atmosphere for which we use the estimate of $5.1352 \pm 0.0003 \times 10^{18}$ kg from Trenberth and Smith (2005), μ_{air} is the molar mass of air in kg mol^{-1} for which we use the relationship given by Khélifa et al. (2007) χ_{CO_2}, is the dry air molar mixing ratio of carbon dioxide obtained by measurements, and μ_C=12 g mol^{-1} is the molar mass of carbon. The conversion factor we obtain is 2.12760 Pg C per ppm of dry air in January 1960, decreasing to 2.12754 by December of 2008. We thus use a conversion factor γ of 2.1276 Pg C per ppm of dry air.

The annual atmospheric CO_2 growth rate used in Tables 1 and 2 and Figs. 2 and 5 is calculated by taking the difference between the December and January mean at the end of the year minus the December and January mean at the start of the year multiplied by the conversion factor γ.

(3) *Ocean uptake*: The Le Quéré et al. (2007), Lovenduski et al. (2008), Rodgers et al. (2008) and Wetzel et al. (2005) monthly uptake results are from "hindcast" simulations using the 6-hourly NCEP-1 Kalnay et al. (1996) reanalysis winds, and freshwater and heat fluxes as described in each of the papers. All models include seasonality. Annual means used in the Tables 1 and 2 and Fig. 2 calculations are obtained by taking the average of the monthly results. The monthly ocean uptake results shown in Fig. 1b and used for the net land uptakes in Fig. 1c have been deseasonalized and smoothed with a 3 month boxcar filter using the same approach as with the atmospheric growth rate.

The Mikaloff Fletcher et al. (2006) ocean uptake is estimated using their equation

$$S_{OC} = -2.15 \cdot \frac{pCO_2 - 277.9514}{359.6619 - 277.9514}$$

where pCO_2 is the atmospheric CO_2 in ppm of dry air. The annual oceanic uptake is calculated using the annual average atmospheric Mauna Loa pCO_2, and the monthly

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uptake is estimated using the deseasonalized and smoothed monthly Mauna Loa atmospheric pCO_2 data.

Only the Le Quéré et al. (2007) model has been run out to the full length of time of our analysis in 2007. The Wetzel et al. (2005) and Rodgers et al. (2008) simulations were run out to 2003, and the Lovenduski et al. (2008) simulation was run out to 2004. Because the oceanic uptake is relatively flat after 1990, the post-1988/1989 ocean uptake averages given in Table 1 are relatively insensitive to the averaging interval used. We present the average of all models until the most recent full year of each simulation, which varies from 2003 to 2007.

None of the ocean or net land uptake calculations shown in this paper include the weathering and river flux contribution of $\sim$0.45 Pg C yr^{-1}, which should be subtracted from the net land uptake (thereby increasing the land uptake) and added to the ocean uptake (thereby decreasing the ocean uptake) for comparison with observations (cf. Jacobson et al., 2007a).

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Table 1. Mean of ocean uptakes in the ocean models in Fig. 1b for the periods 1960–1988 and 1989–2007 and the difference Δ=1989–2007 minus 1960–1988. Also shown is $\Delta_{\mathrm{Model\,X-Reference}}$=1989–2007 average minus 1960–1988 average of the year-by-year difference between each model (Model X) minus the reference constant climate model of Mikaloff-Fletcher et al. (2006). The mean ocean uptakes are calculated using the annual mean ocean uptake to remove the autocorrelation.

	1960–1988	1989–2007	Δ	p^b	$\Delta^c_{\mathrm{Model\,X-Reference}}$	p^b
Reference ocean model[a]	−1.41	−2.36	−0.95±0.08	0.00**		
Le Quéré et al. (2007)	−1.77	−2.20	−0.44±0.07	0.00**	0.49±0.07	0.00**
Lovenduski et al. (2008)	−1.28	−1.80	−0.51±0.10	0.00**	0.34±0.09	0.00**
Rodgers et al. (2008)	−1.60	−2.16	−0.57±0.07	0.00**	0.26±0.05	0.00**
Wetzel et al. (2005)	−1.19	−1.70	−0.51±0.08	0.00**	0.32±0.08	0.00**
MEAN	−1.46	−1.97	−0.51	–	0.35	–

[a] Reference ocean model is the ocean uptake and net land uptake calculated using the constant climate ocean inverse model result of Mikaloff-Fletcher et al. (2006).

[b] p is the p-value. The null hypothesis that the 1960–1988 mean is equal to the 1989–2007 mean is tested against the alternative that the 1960–1988 mean is smaller than the 1989–2007 mean using a t-test. The p-value is the probability, under the null hypothesis, of observing a value at least as extreme as the observed test statistic. The smaller the p-value, the more significant the test is.

[c] $\Delta_{\mathrm{Model\,X-Reference}}$ differs slightly from $\Delta_{\mathrm{Model\,X}}-\Delta_{\mathrm{Reference}}$ for the Lovenduski et al. (2008), Rodgers et al. (2008) and Wetzel et al. (2005) simulations because $\Delta_{\mathrm{Model\,X-Reference}}$ is calculated only over the period covered by the Model X simulations (2003 for Wetzel et al. and Rodgers et al.; 2004 for Lovenduski et al.; see Appendix A).

**Significant at 1% critical level (or 99% confidence level).

Table 2. The mean of land uptakes for the periods 1960–1988 and 1989–2007 and the difference Δ=1989–2007 minus 1960–1988 using each of the ocean models shown in Fig. 1b. The land uptake numbers are calculated from the annual means to remove the autocorrelation.

	1960–1988	1989–2007	Δ	p^b
Reference ocean model[a]	−0.32	−0.96	−0.64±0.30	0.02*
Le Quéré et al. (2007)	0.04	−1.01	−1.04±0.31	0.00**
Lovenduski et al. (2008)	−0.45	−1.34	−0.89±0.32	0.00**
Rodgers et al. (2008)	−0.13	−0.90	−0.77±0.32	0.01**
Wetzel et al. (2005)	−0.54	−1.36	−0.83±0.34	0.01**
MEAN	−0.27	−1.15	−0.88	

[a] Reference ocean model is the ocean uptake and net land uptake calculated using the constant climate ocean inverse model result of Mikaloff-Fletcher et al. (2006).
[b] p is the p-value. The null hypothesis that the 1960–1988 mean is equal to the 1989–2007 mean is tested against the alternative that the 1960–1988 mean is smaller than the 1989–2007 mean using a t-test. The p-value is the probability, under the null hypothesis, of observing a value at least as extreme as the observed test statistic. The smaller the p-value, the more significant the test is.
* Significant at 5% critical level (or 95% confidence level).
** Significant at 1% critical level (or 99% confidence level).

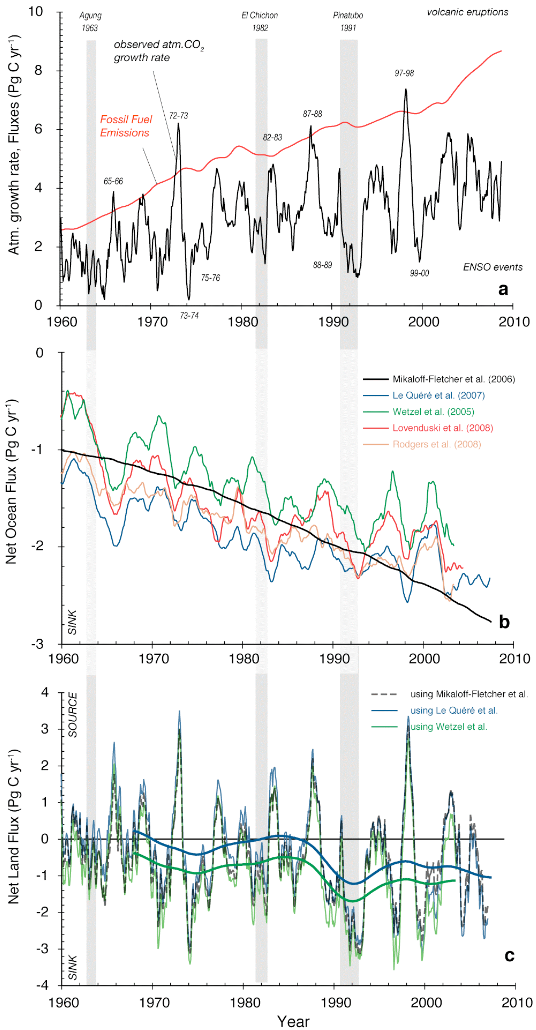

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Fig. 1. Monthly deseasonalized carbon fluxes in $Pg\,C\,yr^{-1}$. **(a)** Fossil fuel emissions and annual atmospheric growth rate calculated with Mauna Loa data (see Appendix A for data sources and methods). Major volcanic eruptions and ENSO events are identified by their dates. **(b)** Net atmosphere-ocean fluxes of CO_2 as simulated by ocean models. The solid black line labeled Mikaloff-Fletcher et al. (2006) represents the expected temporal evolution of the ocean uptake if there is no change in ocean circulation and transport. By construction, this goes through our best data and model based estimates of ocean CO_2 uptake of $\sim 2.2 \pm 0.2\,Pg\,C\,yr^{-1}$ for the 1990s and early 2000s (cf. Gruber et al., 2009). The Le Quéré et al. (2007), Lovenduski et al. (2008), Rodgers et al. (2008) and Wetzel et al. (2005) results are from ocean "hindcast" simulations, where an ocean carbon cycle model is forced with re-analyzed variations of wind, and freshwater and heat fluxes over the last few decades. The Le Quéré et al., Rodgers et al., and the Lovenduski et al. simulations all overlap the Mikaloff-Fletcher et al. result during the 1990s. The Wetzel et al. ocean carbon sink estimate is somewhat on the low side, though its behavior in time, which is the aspect of these models that we emphasize in the discussion, is similar to that of the others. **(c)** Net atmosphere-land fluxes of CO_2 estimated by subtracting three model estimates of the ocean sink from panel (b) and the atmospheric CO_2 growth rate from panel (a) from the fossil fuel emissions shown in panel (a). The smooth lines are from a Butterworth filter with a five year smoothing time scale.

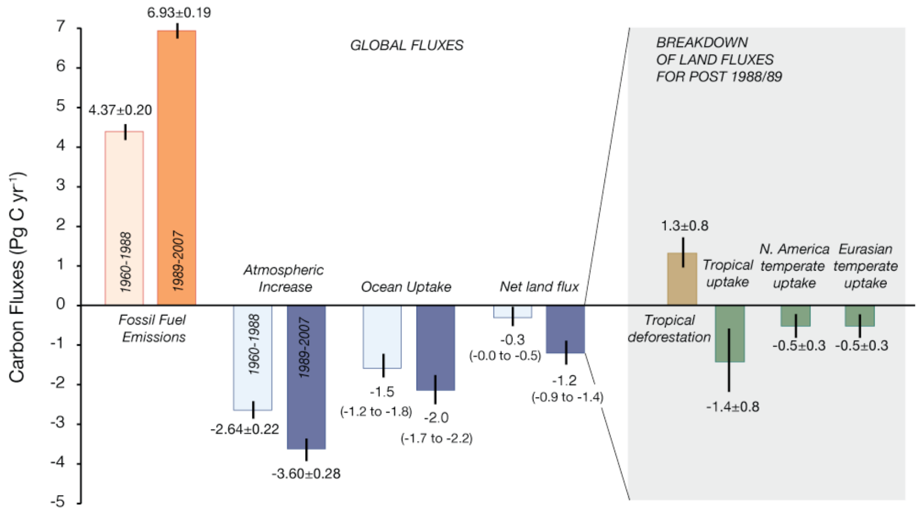

Fig. 2. Global flux estimates for 1960 to 1988 and 1989 to 2007 obtained by averaging the fluxes shown in Fig. 1 and Table 1. The shaded region on the right summarizes the post-1988/1989 bottom up land source and sink components discussed in the text.

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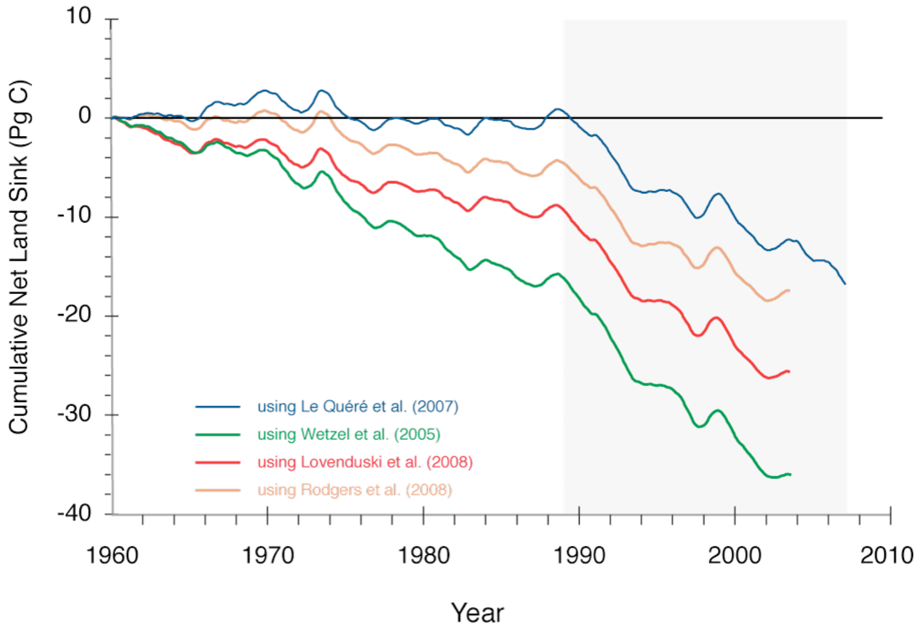

Fig. 3. Cumulative net land uptake starting from 1960 calculated from the results in Fig. 1c.

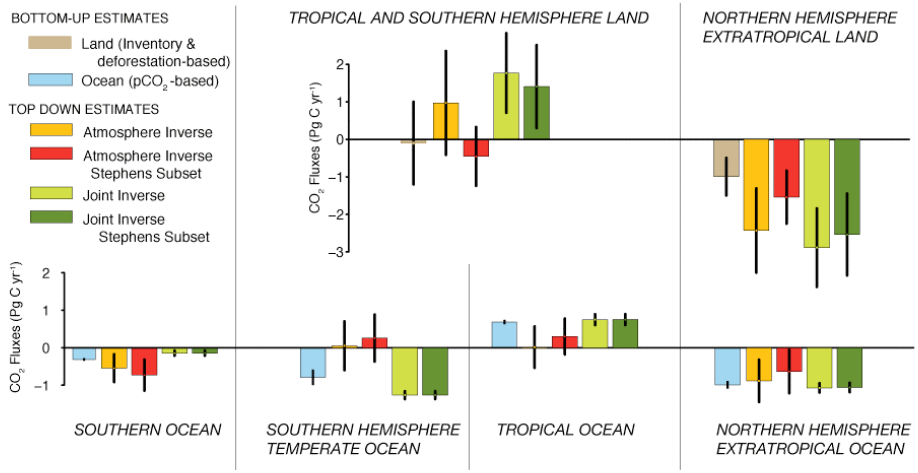

Fig. 4. Regional flux estimates for the land and ocean. The bottom-up land inventory estimates are as described in the text and shown in Fig. 2. The ocean pCO_2 based estimates are from Takahashi et al. (2009), the atmosphere inverse results are from the Transcom-3 study of Gurney et al. (2004), the "Atmosphere Inverse Stephens Subset" is from a new atmospheric inverse calculation we did as part of this study using a subset of three of the Transcom-3 atmospheric transport models that provide a better fit to certain criteria based on observed vertical profiles of CO_2 in the atmosphere (Stephens et al., 2007), the joint inverse is from Jacobson et al. (2007a), and the "Joint Inverse Stephens Subset" is from a new calculation we did using the Stephens subset of Transcom-3 models. Note that the oceanic data constrain the air-sea flux so strongly that the results of ocean-only inverse studies (e.g., Gruber et al., 2009), i.e., those that do not include the atmospheric constraint used in the joint inverse, give virtually the same answer as the joint inverse. The latitude boundaries used to calculate the ocean uptake are 44° S, 18° S and 18° N.

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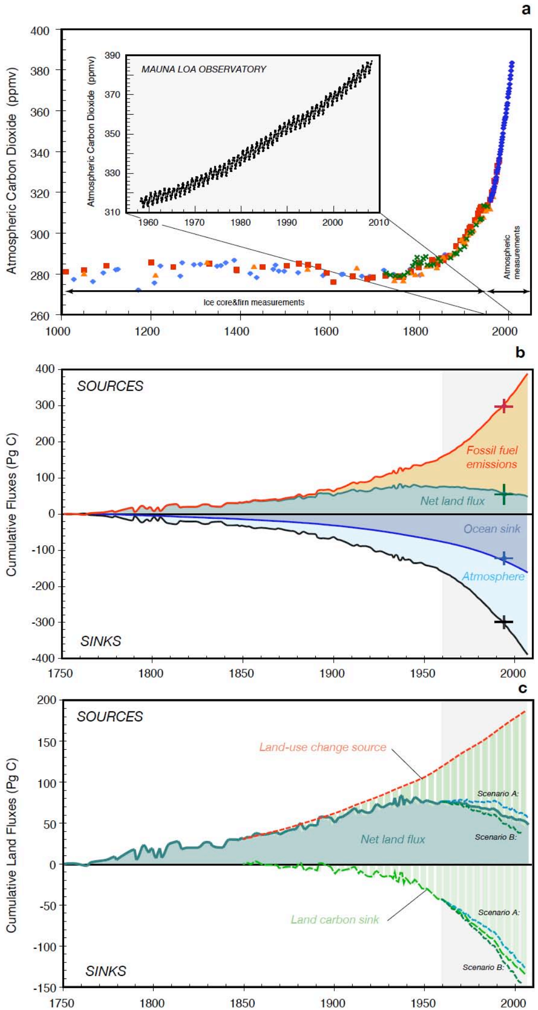

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Fig. 5. Atmospheric CO_2 and the cumulative carbon budget starting from 1750. Sources for data are as described in Appendix A with additional sources given in the caption. **(a)** Atmospheric CO_2 variations over the last 1000 years. The data until 1958 stem from a series of Antarctic ice cores (Barnola, 1999), while the data from 1958 onward are from the Mauna Loa Observatory in Hawaii. The inset shows the monthly Mauna Loa measurements, whereas the main plot depicts the annual means. **(b)** Cumulative carbon fluxes from 1750 onwards of the main sources and sinks of the global carbon cycle including fossil fuel emissions, the atmospheric CO_2 increase, ocean uptake, and net land flux. The atmospheric increase is calculated from a spline fit to the ice core and Mauna Loa CO_2 data from (a), the ocean uptake is based on the ocean inversion of Mikaloff-Fletcher et al. (2006) scaled to the respective year assuming a linear relationship between ocean uptake and atmospheric CO_2 (see Appendix A) and the net land flux is computed by the difference Net land flux=fossil fuel emissions−atmospheric CO_2 increase−ocean uptake. The symbols are estimates from Sabine et al. (2004) for the period from 1800 to 1994 summed to the 1790 to 1810 average of our estimates. **(c)** The cumulative net land flux from panel (b) (solid blue line) plus two additional scenarios for the net land flux based on the oceanic uptake estimates of Le Quéré et al. (2007; Scenario A) and Wetzel et al. (2005; Scenario B) which represent upper and lower limits of the ocean uptake estimates from Fig. 1b, respectively. Also shown in the figure is the cumulative land use source of Houghton (2007) for the period 1850 to 2005, which is summed in this figure to the 1850 net land flux. The total area under this curve including the cross-hatched blue area and the solid light blue area is our best estimate of the total land use change sources of CO_2 to the atmosphere. The solid blue area is that portion of the source that can be accounted for by the carbon budget in panel (b). The cross-hatched area thus must be balanced by the additional sinks shown in the lower part of this diagram.

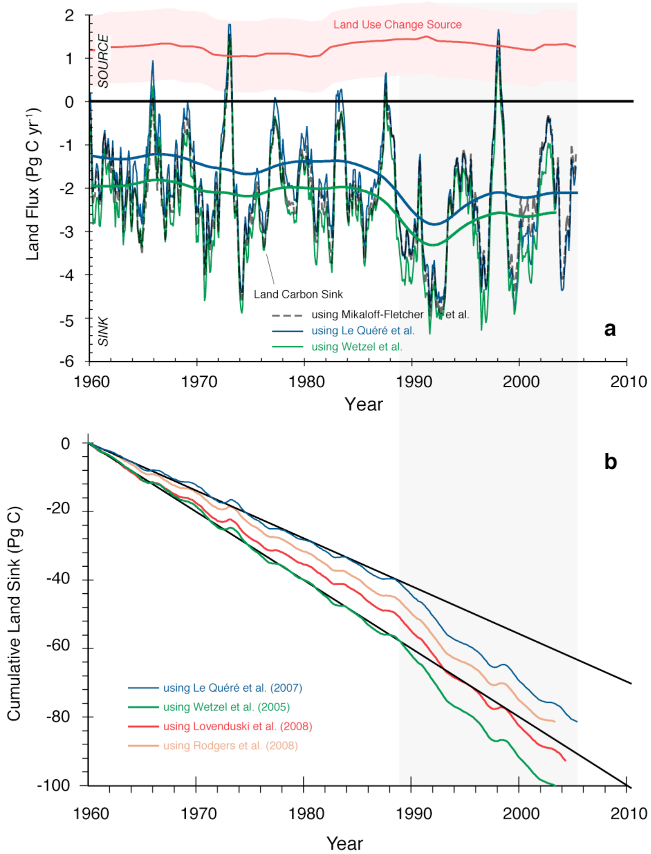

Fig. 6. The **(a)** annual and **(b)** cumulative land carbon sink calculated as in Fig. 5 and shown from 1960 onwards. The annual land carbon sink also shows smoothed lines filtered with a 5 year Butterworth filter. The straight lines in (b) are drawn in by hand to provide a guide to the eye showing that the slope increases after 1988/1989.

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