Decadal Trends in the Ocean Carbon Sink

Tim DeVries[a,b,1], Corinne Le Quéré[c], Oliver Andrews[c,d], Sarah Berthet[e], Judith Hauck[f], Tatiana Ilyina[h], Peter Landschützer[h], Andrew Lenton[i,j,k], Ivan D. Lima[l], Michael Nowicki [a,b], Jörg Schwinger[m], and Roland Séférian[e]

[a]Department of Geography, University of California, Santa Barbara, CA, USA; [b]Earth Research Institute, University of California, Santa Barbara, CA, USA; [c]Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK; [d]School of Geographical Sciences, University of Bristol, Bristol, UK; [e]Centre National de Recherche Météorologique, Unite mixte de recherche, Toulouse, France; [f]Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar und Meeresforschung, Germany; [h]Max Planck Institute for Meteorology, Hamburg, Germany; [i]CSIRO Oceans and Atmosphere, Hobart, Australia; [j]Centre for Southern Hemisphere Oceans Research, Hobart, Australia; [k]Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Australia; [l]Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA, USA; [m]NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway

This manuscript was compiled on April 8, 2019

Measurements show large decadal variability in the rate of CO_2 accumulation in the atmosphere that is not driven by CO_2 emissions. The decade of the 1990s experienced enhanced carbon accumulation in the atmosphere relative to emissions, while in the 2000s the atmospheric growth rate slowed even though emissions grew rapidly. These variations are driven by natural sources and sinks of CO_2 due to the ocean and the terrestrial biosphere. In this study we compare three independent methods for estimating oceanic CO_2 uptake, and find that the ocean carbon sink could be responsible for up to 40% of the observed decadal variability in atmospheric CO_2 accumulation. Data-based estimates of the ocean carbon sink from pCO_2 mapping methods and decadal ocean inverse models generally agree on the magnitude and sign of decadal variability in the ocean CO_2 sink at both global and regional scales. Simulations with ocean biogeochemical models confirm that climate variability drove the observed decadal trends in ocean CO_2 uptake, but also demonstrate that the sensitivity of ocean CO_2 uptake to climate variability may be too weak in models. Furthermore, all estimates point toward coherent decadal variability in the oceanic and terrestrial CO_2 sinks, and this variability is not well-matched by current global vegetation models. Reconciling these differences will help to constrain the sensitivity of oceanic and terrestrial CO_2 uptake to climate variability, and lead to improved climate projections and decadal climate predictions.

Carbon dioxide | Ocean carbon sink | Terrestrial carbon sink | Climate variability | Carbon budget

Anthropogenic emissions of carbon dioxide (CO_2) are a major contributor to climate change, accounting for more than 80% of the radiative forcing of anthropogenic greenhouse gases over the past several decades (1). There is therefore a pressing need to understand the factors influencing the rate at which anthropogenic CO_2 accumulates in the atmosphere. The primary driver of atmospheric CO_2 accumulation is anthropogenic emissions from industrial activity and deforestation (2) which has increased by about 60% over the past 30 years (**Fig. 1a**). CO_2 accumulation in the atmosphere, however, has not always followed the trend in CO_2 emissions. From 1990-1999 atmospheric CO_2 accumulated more rapidly than expected from the relatively slow growth in emissions, while in the decade from 2000-2009 atmospheric CO_2 accumulation was relatively steady while emissions rose rapidly (**Fig. 1a**).

This decadal variability in atmospheric CO_2 accumulation rate is linked to variability in the sources and sinks of CO_2 in the natural environment (4). The most important of these natural sources and sinks are terrestrial ecosystems and ocean waters. Other natural sources and sinks such as volcanoes and rock weathering are much smaller and change very slowly (5), and can be neglected on recent timescales. Thus, the global carbon budget (3) is primarily a balance between anthropogenic CO_2 emissions from fossil fuel burning and cement manufacturing (FF) and land-use change (LUC, i.e. deforestation), and changes in the accumulation of CO_2 in the atmosphere (C_{atm}), ocean (C_{oce}) and land biosphere (C_{land}),

$$(\mathrm{FF}+\mathrm{LUC}) - \frac{dC_{atm}}{dt} - \frac{dC_{oce}}{dt} - \frac{dC_{land}}{dt} = 0. \qquad [1]$$

Global FF and LUC emissions have an uncertainty of about 10% (3, 6, 7), and atmospheric CO_2 has been measured continuously since 1980 at a global network of stations, with error on the annual average accumulation of $< 5\%$ (8). From these observations and equation (1), we can infer the accumulation rate of carbon in the combined land and ocean reservoirs (**Fig. 1a**). The total rate of land+ocean carbon accumulation has averaged 55±10% of total carbon emissions over the past 30 years, but has shown significant decadal variability. The 1990s experienced a weakening of the land+ocean carbon sink, while the first decade of the 2000s was characterized by a strengthening land+ocean carbon sink (**Fig. 1b**).

The relative contribution of the land and ocean carbon sinks to this decadal variability cannot be directly measured, due to the heterogeneity of carbon accumulation and large natural carbon reservoirs. For this reason, dynamic global vegetation models (DGVMs) and global ocean biogeochemistry models (GOBMs) are often used to estimate the land and ocean carbon sinks, respectively (3). Methods have also been developed for

Significance Statement

The ocean and land absorb anthropogenic CO_2 from industrial fossil-fuel emissions and land-use changes, helping to buffer climate change. Here we compare decadal variability of ocean CO_2 uptake using three independent methods, and find that the ocean could be responsible for as much as 40% of the observed decadal variability of CO_2 accumulation in the atmosphere. The remaining variability is due to variability in the accumulation of carbon in the terrestrial biosphere. Models capture these variations, but not as strongly as the observations, implying that CO_2 uptake by the land and ocean is more sensitive to climate variability than currently thought. Models must capture this sensitivity in order to provide accurate climate predictions.

TD and CLQ designed the study. TD produced the figures and wrote the manuscript with input from CLQ and PL. OA, SB, JH, TI, AL, IL, JS, RS, and RW performed the global ocean biogeochemistry model simulations and provided input on the manuscript. MN analyzed results from the global ocean biogeochemistry models.

The authors declare no conflict of interest.

[1]To whom correspondence should be addressed. E-mail: tdevriesgeog.ucsb.edu

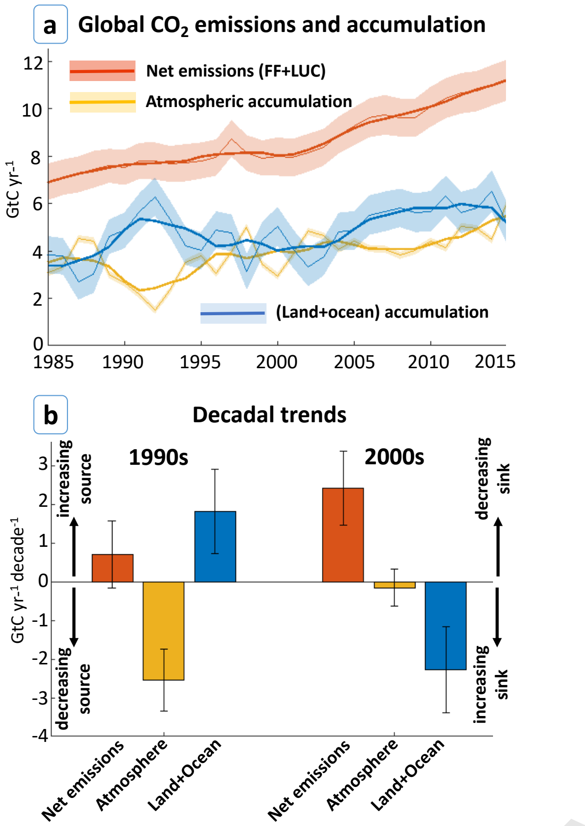

Fig. 1. (a) Global CO_2 emissions from fossil-fuel burning, cement production and land-use change (FF+LUC) (red curve), compared with the measured rate of accumulation of CO_2 in the atmosphere (gold curve), and the inferred rate of change of CO_2 accumulation in the land and ocean (blue curve). Thin lines are annual means and thick lines are 5-year running means. (b) Decadal trends in CO_2 emissions (FF+LUC), and the atmospheric and total land+ocean sinks. For emissions, positive values indicate an increasing source and negative values a decreasing source (left-hand arrows, sign convention as in Eq. (1)). For the atmosphere and land+ocean sinks, positive values indicate a decreasing sink and negative values an increasing sink (right-hand arrows, opposite the sign convention in Eq. (1)). All data from the 2017 Global Carbon Budget (3). Error bars are 1-σ.

estimating CO_2 accumulation in the ocean indirectly from observations using inverse models (9–11), and measurements of the sea-surface partial pressure of CO_2 (pCO_2) (12–14).

While the terrestrial biosphere is the dominant source of interannual variability in the natural CO_2 sinks (4, 15), observations and numerical models have highlighted substantial decadal variability in ocean CO_2 uptake at both regional (16–18) and global scales (19, 20). In particular, recent estimates from several data-based models (21–23) suggest that the decadal variability in the ocean CO_2 sink is larger than currently estimated by global carbon budgets. To assess the robustness of decadal trends in ocean CO_2 uptake, here we compare decadal variability in the ocean carbon sink from three widely-used independent methods: GOBMs participating in the 2017 Global Carbon Budget (3), an ocean circulation inverse model (OCIM) (11, 23), and pCO_2-based flux mapping models from the Surface Ocean pCO_2 Mapping Intercomparison (SOCOM) project (14). We use these methods to deduce the contribution of the ocean carbon sink to the decadal variability of atmospheric carbon accumulation, to examine the mechanisms governing this variability, and to shed light on the decadal variability of the terrestrial CO_2 sink.

Decadal variability of the ocean carbon sink

Estimates of the global ocean carbon sink from the GOBMs, SOCOM products, and the OCIM are in broad agreement regarding the magnitude and temporal evolution of ocean carbon accumulation over the past 30 years (**Fig. 2a**). Estimates of the ocean anthropogenic carbon sink in 2010 from these methods cluster around a mean of $\sim$2.4 GtC yr^{-1} with an uncertainty of $\sim$25% due to differences among the various methods and models (**Fig. 2a**).

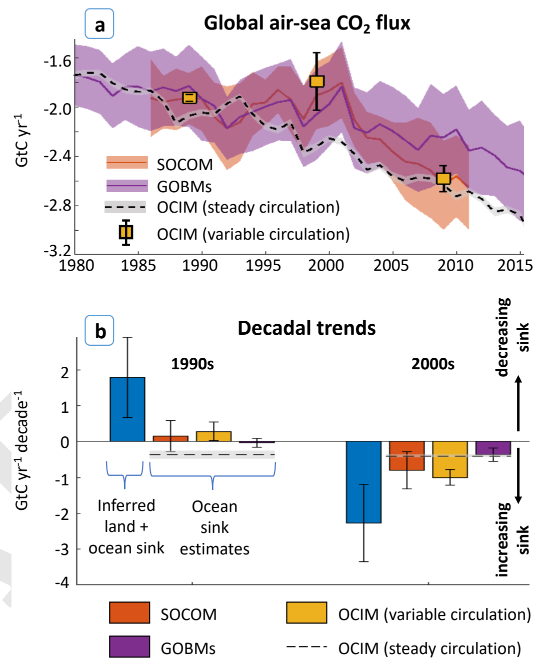

Fig. 2. (a) Estimates of the ocean carbon sink from a subset of models participating in the Surface Ocean pCO_2 Mapping (SOCOM) project (14), a subset of Global Ocean Biogeochemical Models (GOBMs) participating in the 2017 Global Carbon Budget (3) and an ocean circulation inverse model (OCIM) with (23) and without (11) decadal variability in ocean circulation. Thick lines are the ensemble mean from each method, with shading representing one standard deviation uncertainty. For the OCIM with variable circulation the mean value at the end of each decade (1989, 1999, 2009) is shown, with error bars representing one standard deviation. For the OCIM with constant circulation, error bars are the ensemble range. SOCOM results have been adjusted for outgassing of riverine CO_2 (see Materials and Methods). (b) Decadal trends in the net (land+ocean) carbon sink (blue bar, same as in Fig. 1), and four estimates of decadal trends in the ocean carbon sink from SOCOM models (red bar), GOBMs (purple bar), and OCIM with decadal variability in ocean circulation (gold bar) and without any variability in ocean circulation (dashed line).

A closer look at the decadal trends in ocean CO_2 uptake reveals that the various methods of estimating the oceanic CO_2 sink differ in the magnitude of their decadal variability (**Fig. 2b**). The OCIM with steady circulation simulates CO_2 uptake by an ocean with no variability in circulation or biology (11), and therefore the decadal trends are very similar for both the 1990s and the 2000s, with global ocean CO_2 accumulation accelerating at $\sim$0.4 Gt C yr^{-1} decade $^{-1}$. All of the other methods display significantly more decadal variability, strongly suggesting decadal trends in ocean circulation and/or biology over this time period (**Fig. 2b**).

Decadal trends in ocean CO_2 uptake are strongest in the observation-based models. In the 1990s, SOCOM products (14) and the OCIM with decadally-varying circulation (23)

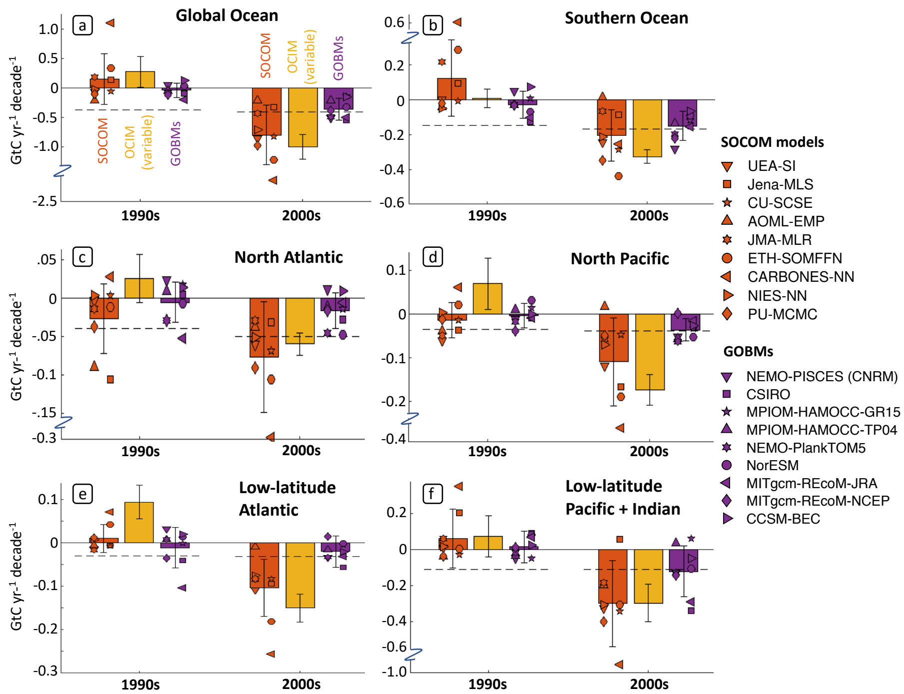

Fig. 3. Decadal trends in ocean carbon uptake for the global ocean (a) and for different ocean regions (b-f) as defined by the biomes of (24) (see SI Appendix for biome definitions, and definitions of the models used here). The global ocean in (a) is the sum of the regions in (b-f) and does not include coastal regions and marginal seas. Trends and color-coding as in Fig. 2(b), with symbols representing individual models. Positive trends represent a weakening oceanic CO_2 sink, and negative trends a strengthening oceanic CO_2 sink.

diagnose a weakening trend of 0.15±0.43 Gt C yr^{-1} decade $^{-1}$ and 0.28±0.26 Gt C yr^{-1} decade $^{-1}$, respectively, which in turn accounts for 8% $(-10-83\%)$ and 16% $(1-77\%)$ of the observed 1.8±1.1 Gt C yr^{-1} decade $^{-1}$ weakening of the net (land+ocean) carbon sink. In the 2000s, the SOCOM products estimate a strengthening of the ocean carbon sink by 0.80±0.51 Gt C yr^{-1} decade $^{-1}$ that is consistent with the 1.0±0.2 Gt C yr^{-1} decade $^{-1}$ strengthening inferred by the OCIM with variable circulation. These trends account for 35% $(9-109\%)$ and 43% $(24-100\%)$, respectively, of the observed 2.3±1.1 Gt C yr^{-1} decade $^{-1}$ strengthening trend of the total (land+ocean) carbon sink in the 2000s. Based on the average trends in the observation-based models over the 1990s and the first decade of the 2000s, the ocean is responsible for ∼10-40% of the observed decadal variability in the natural carbon sinks.

The GOBMs also simulate weaker-than-expected ocean CO_2 uptake during the 1990s followed by a strengthening trend during the 2000s, but the magnitude of decadal variability is smaller than that estimated by SOCOM and the variable-circulation OCIM. For example, in the 2000s the growth rate of oceanic CO_2 uptake in the GOBMs was slightly less than simulated by the OCIM with constant circulation and biology, while the other methods estimate that oceanic uptake was accelerating roughly twice as fast as it would with constant circulation and biology (**Fig. 2b**). According to average trends in the GOBMs over 1990s and the first decade of the 2000s, the ocean is responsible for ∼0-20% of the decadal variability in the natural carbon sinks, which is about half of the variability estimated by the observation-based approaches.

Despite the overall agreement among the methods on the sign of the decadal variability in the ocean CO_2 sink, there is substantial spread in the magnitude of the decadal trends both across models within a particular method, and across oceanographic regions (**Fig. 3**). With respect to the global ocean CO_2 uptake, the SOCOM products range from a trend of -0.21 to 1.11 GtC yr^{-1} $decade^{-1}$ in the 1990s, to -0.21 to -2.13 GtC yr^{-1} $decade^{-1}$ in the 2000s. Almost all (eight out of nine) of the SOCOM products show a more rapidly strengthening CO_2 sink in the 2000s compared to the 1990s. Different GOBMs also exhibit substantially different decadal variability, although all of the GOBMs simulate a strengthening of the ocean CO_2 sink in the 2000s relative to the 1990s (**Fig. 3a**).

To examine regional patterns of decadal variability in the ocean CO_2 sink, we integrated the air-sea CO_2 fluxes within different regions based on biomes defined by ref. (24) (see SI Appendix). The model-average trends across different methods (SOCOM, GOBMs, and OCIM), and in different oceanographic regions, display a remarkable pattern: in every region every method (on average) predicts that the oceanic CO_2 uptake increased faster in the 2000s than in the 1990s (**Fig. 3b-f**). The best agreement at regional scales across methods is found between the SOCOM products and the OCIM with variable circulation. In all regions these methods infer an oceanic CO_2 sink that strengthened much faster in the 2000s than in the 1990s. In the high latitudes, the SOCOM-based estimates place more of the weakening in the 1990s CO_2 sink in the Southern Ocean, while the OCIM-based estimates suggest that more of the weakening occurred in the North Atlantic and North Pacific (**Fig. 3b-d**). In the low-latitudes, the SOCOM and OCIM models agree that the Pacific and Indian Oceans were a weakening sink in the 1990s (**Fig. 3f**), while the OCIM simulates a weaker-trending Atlantic Ocean sink than most of the SOCOM products (**Fig. 3e**). The strengthening of the ocean CO_2 sink in the 2000s is consistent across regions in both the SOCOM and OCIM models.

Decadal trends in the GOBM-simulated oceanic CO_2 uptake are not as variable as those diagnosed by the SOCOM products or the variable-circulation OCIM. For example, in the Southern Ocean the observation-based methods infer large decadal variations in the ocean CO_2 sink, but the GOBMs simulate only a slight strengthening trend from the 1990s to the 2000s, with the exception of the NEMO-PISCES (CNRM) model which simulates a large strengthening (**Fig. 3b**). The same is true in the low-latitude Pacific and Indian, which has the largest decadal variability next to the Southern Ocean in the observation-based estimates, but displays weak decadal variability in the GOBMs (**Fig. 3f**).

Climate-driven trends in ocean carbon uptake

To separate the impacts of CO_2-forced and climate-forced variability on ocean CO_2 uptake in the GOBMs, we performed additional model simulations in which the climate forcing was held constant, and in which the atmospheric CO_2 concentration was held constant (see Materials and Methods). Based on these simulations we isolated the decadal trends of oceanic CO_2 uptake due to atmospheric CO_2 increase and due to climate variability (**Fig. 4**). These simulations reveal that trends in ocean CO_2 uptake in the 1990s and 2000s are nearly indistinguishable for the CO_2-only forcing case (both between decades and among models), and that decadal variability in the CO_2 sink is driven exclusively by climate variability. Eight out of nine of the GOBMs predict that climate variability drove a weakening of the global ocean CO_2 sink in the 1990s, and five out of nine predict that climate variability drove a strengthening trend in the 2000s (**Fig. 4a**).

The regions with the strongest climate-driven decadal variability in the GOBMs are the Southern Ocean (**Fig 4b**) and the low-latitude Pacific and Indian Oceans (**Fig 4f**). Within these regions, however, the different models diverge substantially. In the Southern Ocean the NEMO-PISCES (CNRM) model displays the largest climate-driven decadal variability, with decreasing CO_2 uptake in the 1990s and increasing CO_2 uptake in the 2000s, consistent with the observation-based estimates. But some models display the opposite trend, such as the CSIRO model which simulates a weakening Southern Ocean CO_2 sink in the 2000s compared to the 1990s. In the low-latitude Pacific and Indian Oceans it is the CSIRO model that displays the strongest climate-driven variability, in a direction consistent with the observation-based estimates.

Overall, climate variability drove a weakening of oceanic CO_2 uptake in the 1990s and a strengthening in the 2000s across multiple models and geographic regions. The geographical consistency of these trends suggests that this is a response to a global climatic pattern, likely large-scale changes in wind-driven ocean circulation (23, 25). These trends could be due to modes of internal variability in the climate system (21), or to external forcing (e.g. the eruption of Mount Pinatubo in 1991 (26, 27)) which can alter the states of internal climate modes (28), and thus the global winds. External drivers could be amplified by atmospheric (29) or oceanic (30) teleconnections to enhance decadal variability in ocean circulation.

Although the GOBMs display a consistent response to climate forcing, their climate-driven variability of ocean CO_2 uptake appears to be too weak when compared to the data-based methods. Indeed, the GOBMs that perform best when compared to the most accurate pCO_2-based flux reconstructions, are also the models that exhibit the largest decadal variability at the regional scale (SI Appendix **Figs. S1 and S2**). The weak climate-forced variability of GOBMs might stem from either a weak ocean circulation response to atmospheric forcing, or to changes in biologically-driven carbon uptake that counteract circulation-driven CO_2 uptake. To examine the latter possibility, we examined decadal trends in the biologically-driven export of carbon below the surface ocean in the climate-forced GOBMs (SI Appendix **Fig. S3**). Models with strong decadal variability in biological carbon export generally have weak decadal variability in climate-forced CO_2 uptake, while the opposite is true of models with weak variability in biological carbon export. Thus the compensation between circulation-driven and biologically-driven CO_2 uptake is one factor that reduces the sensitivity of the GOBMs to climate variability. The relative roles of biology and physics for determining decadal variability in ocean CO_2 uptake is poorly known, and should be a priority for future study.

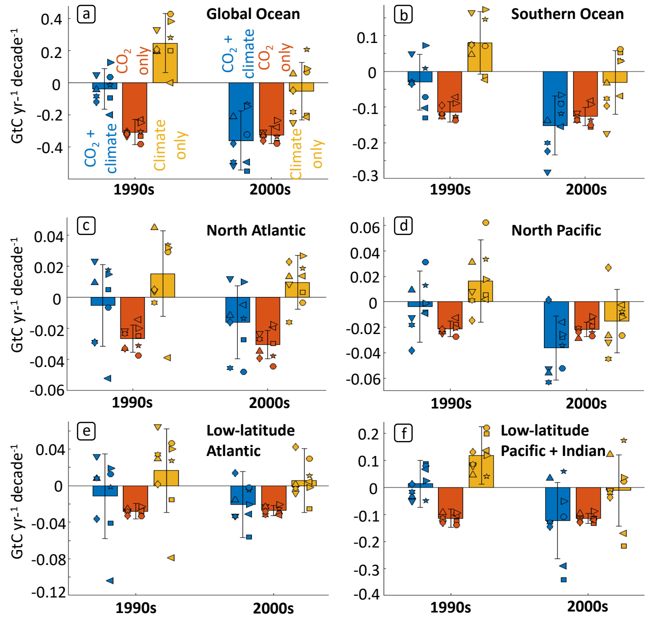

Fig. 4. Decadal trends in ocean carbon uptake simulated by GOBMs for the regions in Fig. 3. Shown separately are the trends due to both CO_2 and climate variability (blue bar; same as purple bar in Fig. 3), trends due to CO_2 variability only (red bar), and trends due to climate variability only (gold bar). Error bars are one standard deviation of the model ensemble mean. Symbols represent results from individual models as defined in Fig. 3.

Discussion and conclusions

The agreement among the various methods of determining ocean CO_2 uptake demonstrates a broad consensus in the magnitude of the ocean carbon sink over the past several decades, and in the timing of the decadal variability (**Fig. 2**). This agreement is especially encouraging considering that the three methods considered here are entirely independent. The observation-based methods (SOCOM and OCIM) predict greater decadal variability of the ocean CO_2 sink than ocean biogeochemistry models, and suggest that roughly 10-40% of the decadal variability in the natural CO_2 sinks can be attributed to the ocean. Ocean biogeochemistry models simulate less decadal variability of the ocean CO_2 sink, which could partly explain why current global carbon budgets (which rely mainly on GOBMs to estimate the oceanic CO_2 sink) have a declining budget imbalance in the 1990s, followed by an increasing imbalance in the 2000s (3). A muted variability of GOBMs compared to observations has also been observed for oxygen (31), suggesting it is not unique to the carbon cycle.

These results also have important implications for decadal trends in the other major natural sink of anthropogenic CO_2, the terrestrial biosphere. The decadal trends in the ocean CO_2 sink from the three methods considered here (SOCOM, OCIM, and GOBMs), can be compared to the total land+ocean CO_2 sink (**Fig. 1b**), to deduce the decadal trends in the terrestrial CO_2 sink (see Materials and Methods). The decadal trends in the terrestrial CO_2 sink so calculated demonstrate that the terrestrial biosphere was a decreasing sink of CO_2 in the 1990s, and an increasing sink of CO_2 in the first decade of the 2000s (the residual land sink in **Fig. 5**).

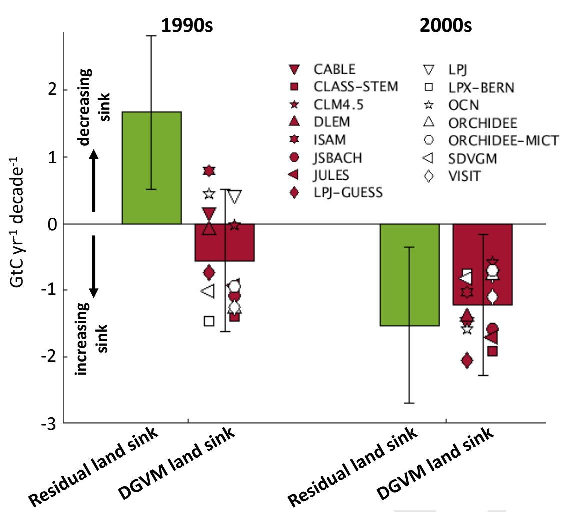

Fig. 5. Trends in the terrestrial CO_2 sink calculated as a residual from the global carbon budget (Equation 1) using the estimates of the ocean CO_2 sink from three methods considered here (GOBMs, SOCOM, and OCIM with variable circulation), and from the dynamic global vegetation models (DGVMs) participating in the 2017 Global Carbon Budget (3). See SI Appendix for definitions of DGVMs used here.

These decadal trends are in the same direction as those of the oceanic CO_2 sink, but even larger in magnitude, and can place important constraints on the dynamic global vegetation models (DGVMs) that are used to estimate the terrestrial CO_2 sink in the Global Carbon Budget (3). The DGVMs are in good agreement with the residual land sink regarding the strengthening of the terrestrial CO_2 sink in the 2000s, indicating consistency between the emissions data, the ocean CO_2 sink estimates, and the predictions of DGVMs during this period (**Fig. 5**). But during the 1990s, the DGVMs show less consistency, with one group of DGVMs simulating a neutral to weakening CO_2 sink (in agreement with the residual land sink), and another group simulating a strengthening CO_2 sink.

Differences between the residual land sink and the DGVM land sink during the 1990s could be due to biases in the ocean CO_2 sink estimates, in the CO_2 emissions, or in the DGVMs. Given the agreement between the three independent estimates of the oceanic CO_2 sink, this is unlikely to be a source of bias. Errors in fossil-fuel CO_2 emissions (32) and LUC emissions (33) could be larger than reported, and partly responsible for some of the discrepancy. The remaining discrepancies can be attributed to biases in the DGVMs, and as such could indicate a greater climate sensitivity of the terrestrial CO_2 sink than currently thought. In particular, the model discrepancies in the 1990s trends could partly reflect the different degrees to which the DGVMs are sensitive to the eruption of Mt. Pinatubo in 1991 (34) and the strong El Niño event of 1998 (15).

The findings of this study imply that both oceanic and terrestrial carbon cycle models underestimate decadal variability in CO_2 uptake, which hinders the ability of these models to predict climate change on decadal timescales, and likely contributes to decadal imbalances in current global carbon budgets (35). As the community moves towards decadal climate prediction (36, 37), it will be important to correctly resolve the climate sensitivity of oceanic and terrestrial carbon uptake. Continued development of observation-based methods for tracking ocean CO_2 uptake should alleviate their remaining structural errors (see SI Appendix), leading to improved constraints on the magnitude and variability of the ocean CO_2 sink, and reducing imbalances in global carbon budgets (35). This in turn will facilitate calibration of ocean biogeochemical models and terrestrial dynamic vegetation models, leading to improved climate projections and decadal predictions.

Materials and Methods

pCO_2-based flux mapping products. The surface ocean pCO_2 mapping (SOCOM) products are based on historical observations of surface-ocean pCO_2 compiled in the Surface Ocean CO_2 Atlas (SOCAT) (38) and the Lamont-Doherty Earth Observatory (39) datasets. The SOCOM models employ various interpolation schemes to fill in the gaps in the data records to create continuous maps of pCO_2 at monthly resolution, from which air-sea fluxes are calculated (14). See SI Appendix for additional information.

Inverse models. We used two versions of the ocean circulation inverse model (OCIM). The first diagnoses the uptake of anthropogenic CO_2 in the absence of any changes to ocean circulation, solubility, or biology (11). Uncertainties are derived from the 10 different versions of the model described in ref. (11). The second version of the OCIM diagnoses the decadal-mean ocean CO_2 sink given decadal variations in ocean circulation along with mean state biology (23). Uncertainties are derived from 160 different versions of the model described in ref. (23). See SI Appendix for additional information.

Global ocean biogeochemistry models (GOBMs). We used a subset of the global ocean biogeochemistry models (GOBMs) used in the 2017 Global Carbon Budget (GCB17) (3): NEMO-PISCES (CNRM), CSIRO, NorESM, MPIOM-HAMOCC, NEMO-PlankTOM5, MITgcm-REcoM2, and CCSM-BEC. Each model performed three simulations: Simulation A uses reanalysis climate forcing and observed atmospheric CO_2 concentrations 1959-2017. Simulation B uses constant climate forcing and atmospheric CO_2. Simulation C uses constant climate forcing and observed atmospheric CO_2 concentrations 1959-2017. In Figure 4, "CO_2+climate" is from simulation A, "CO_2 only" is from simulation C− simulation B, and "climate only" is from simulation A − simulation C. Models differ in their spin-up procedure and climate forcing, as detailed in the SI Appendix and **Table S1**.

Accounting for riverine carbon. The OCIM and GOBMs do not account for a de-gassing of 0.45-0.78 GtC yr^{-1} (40, 41) of riverine CO_2, but the SOCOM products do. In order to make the CO_2 fluxes comparable across all methods, we have added a flux of 0.6 GtC yr^{-1} to the globally-integrated SOCOM CO_2 sink in Fig. 2.

Calculating decadal trends. Air-sea CO_2 fluxes from the SOCOM products, the GOBMs, and the steady-circulation OCIM were annually-averaged, then used to compute the linear trend in ocean CO_2 uptake for the 1990s (1990-1999) and the first decade of the 2000s (2000-2009). Uncertainties on the decadal trends for each method include ensemble uncertainty, as well as an uncertainty of ±1 year for the beginning and ending years of the trend calculations (i.e. $1990 \pm 1 - 1999 \pm 1$ and $2000 \pm 1 - 2009 \pm 1$). For the OCIM-variable, decadal trends were calculated as the average air-sea flux within a given decade minus the average air-sea flux in the preceding decade. This method minimizes the effects of discontinuities in the air-sea CO_2 flux introduced by abrupt changes in the ocean circulation at the demarcations of different decades (1990 and 2000), and gives trends similar to those using the final year of each decade (i.e. 2009-1999) to calculate trends. For regional decadal trends in Figs. 3 and 4, we integrated the air-sea CO_2 fluxes over distinct oceanographic regions based on the time-mean open-ocean biomes defined by ref. (24). In order to avoid differences in the model domains near the coast, the global ocean CO_2 uptake in all figures is the summation over all of the individual regions, and thus ignores a small contribution from coastal regions as well as the polar ice-covered regions. See SI Appendix for more information.

Calculation of decadal trends in the terrestrial CO_2 sink. To calculate decadal trends in the terrestrial CO_2 sink, we first calculated decadal trends in the ocean carbon sink using all of the methods considered here that resolve decadal variability in the ocean CO_2 sink (SOCOM, GOBMs, and OCIM-variable, as displayed in **Fig. 2b**). We then subtracted these ocean-only trends from the trend in the total (land+ocean) CO_2 sink (**Fig. 1b**) to obtain the trends in the "residual land sink" (**Fig. 5**). Reported uncertainties include uncertainty in the CO_2 emissions, uncertainty in the atmospheric CO_2 concentration, uncertainty in the ocean CO_2 sink (treating all methods of estimating the ocean CO_2 sink as equally probable), and uncertainty due to varying the beginning and ending years for the trend calculation by ±1 year. Trends in the terrestrial CO_2 sink in the DGVMs are calculated in exactly the same way as those for the GOBMs, varying the starting and ending points of the trend calculation for each DGVM by $\pm$ 1 year. See SI Appendix for a full list of the DGVMs used here.

Data availability. OCIM data are available from the lead author and at https://tdevries.eri.ucsb.edu/models-and-data-products/. Timeseries of the SOCOM data following ref. (14) can be obtained from http://www.bgc-jena.mpg.de/SOCOM/. Timeseries of the GOBM data are available at (url to follow upon acceptance).

ACKNOWLEDGMENTS. We thank Rebecca Wright and Erik Buitenhuis at University of East Anglia, Norwich, for providing updated runs from the NEMO-PlankTOM5 model. TD acknowledges support from NSF grant OCE-1658392. CL thanks the UK Natural Environment Research Council for funding to the SONATA project (no. NE/P021417/1). PL was supported by the Max Planck Society for the Advancement of Science. JH was supported under Helmholtz Young Investigator Group Marine Carbon and Ecosystem Feedbacks in the Earth System (MarESys), grant number VH-NG-1301. SB and RS thank the H2020 project CRESCENDO "Coordinated Research in Earth Systems and Climate: Experiments, kNowledge, Dissemination and Outreach" which received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 641816. The Surface Ocean CO_2 Atlas (SOCAT) is an international effort, endorsed by the International Ocean Carbon Coordination Project (IOCCP), the Surface Ocean-Lower Atmosphere Study (SOLAS) and the Integrated Marine Biosphere Research (IMBeR) program, to deliver a uniformly quality-controlled surface ocean CO_2 database. The many researchers and funding agencies responsible for the collection of data and quality control are thanked for their contributions to SOCAT.

1. Myhre G, et al. (2013) *Anthropogenic and Natural Radiative Forcing*, eds. Stocker T, et al. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA), p. 659–740.
2. Ciais P, et al. (2013) *Carbon and Other Biogeochemical Cycles*, eds. Stocker T, et al. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA), p. 465–570.
3. Le Quéré C, et al. (2018) Global carbon budget 2017. *Earth System Science Data* 10(1):405–448.
4. Keenan TF, et al. (2016) Recent pause in the growth rate of atmospheric co 2 due to enhanced terrestrial carbon uptake. *Nature communications* 7:13428.
5. Burton MR, Sawyer GM, Granieri D (2013) Deep carbon emissions from volcanoes. *Reviews in Mineralogy and Geochemistry* 75(1):323–354.
6. Andres RJ, Boden TA, Higdon D (2014) A new evaluation of the uncertainty associated with cdiac estimates of fossil fuel carbon dioxide emission. *Tellus B: Chemical and Physical Meteorology* 66(1):23616.
7. Ballantyne A, et al. (2015) Audit of the global carbon budget: estimate errors and their impact on uptake uncertainty. *Biogeosciences (Online)* 12(8).
8. Conway TJ, et al. (1994) Evidence for interannual variability of the carbon cycle from the national oceanic and atmospheric administration/climate monitoring and diagnostics laboratory global air sampling network. *Journal of Geophysical Research: Atmospheres* 99(D11):22831–22855.
9. Gruber N, et al. (2009) Oceanic sources, sinks, and transport of atmospheric co2. *Global Biogeochemical Cycles* 23(1).
10. Khatiwala S, Primeau F, Hall T (2009) Reconstruction of the history of anthropogenic co_2 concentrations in the ocean. *Nature* 462(7271):346.
11. DeVries T (2014) The oceanic anthropogenic co2 sink: Storage, air-sea fluxes, and transports over the industrial era. *Global Biogeochemical Cycles* 28(7):631–647.
12. Takahashi T, et al. (2009) Climatological mean and decadal change in surface ocean pco2, and net sea–air co2 flux over the global oceans. *Deep Sea Research Part II: Topical Studies in Oceanography* 56(8-10):554–577.
13. Landschützer P, Gruber N, Bakker D, Schuster U (2014) Recent variability of the global ocean carbon sink. *Global Biogeochemical Cycles* 28(9):927–949.
14. Rödenbeck C, et al. (2015) Data-based estimates of the ocean carbon sink variability–first results of the surface ocean pco2 mapping intercomparison (socom). *Biogeosciences* 12:7251–7278.
15. Kim JS, Kug JS, Yoon JH, Jeong SJ (2016) Increased atmospheric co2 growth rate during el niño driven by reduced terrestrial productivity in the cmip5 esms. *Journal of Climate* 29(24):8783–8805.
16. Takahashi T, Sutherland SC, Feely RA, Cosca CE (2003) Decadal variation of the surface water pco2 in the western and central equatorial pacific. *Science* 302(5646):852–856.
17. Landschützer P, et al. (2015) The reinvigoration of the southern ocean carbon sink. *Science* 349(6253):1221–1224.
18. Breeden ML, McKinley GA (2016) Climate impacts on multidecadal pco 2 variability in the north atlantic: 1948–2009. *Biogeosciences* 13(11):3387–3396.
19. Fay A, McKinley G (2013) Global trends in surface ocean pco2 from in situ data. *Global Biogeochemical Cycles* 27(2):541–557.
20. Séférian R, Berthet S, Chevallier M (2018) Assessing the decadal predictability of land and ocean carbon uptake. *Geophysical Research Letters* 45(5):2455–2466.
21. Landschuetzer P, Gruber N, Bakker DC (2016) Decadal variations and trends of the global ocean carbon sink. *Global Biogeochemical Cycles* 30(10):1396–1417.
22. Landschützer P, Ilyina T, Lovenduski NS (2019) Detecting Regional Modes of Variability in Observation-Based Surface Ocean pCO_2. *Geophysical Research Letters*.
23. DeVries T, Holzer M, Primeau F (2017) Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. *Nature* 542(7640):215.
24. Fay A, McKinley G (2014) Global open-ocean biomes: mean and temporal variability. *Earth System Science Data* 6(2):273–284.
25. Le Quéré C, Takahashi T, Buitenhuis ET, Rödenbeck C, Sutherland SC (2010) Impact of climate change and variability on the global oceanic sink of co2. *Global Biogeochemical Cycles* 24(4).
26. Frölicher T, Joos F, Raible C (2011) Sensitivity of atmospheric co2 and climate to explosive volcanic eruptions. *Biogeosciences* 8(8):2317–2339.
27. Raupach MR, et al. (2014) The declining uptake rate of atmospheric co 2 by land and ocean sinks. *Biogeosciences* 11(13):3453–3475.
28. Stevenson S, et al. (2018) Climate variability, volcanic forcing, and last millennium hydroclimate extremes. *Journal of Climate* 31(11):4309–4327.
29. McGregor S, Stuecker MF, Kajtar JB, England MH, Collins M (2018) Model tropical atlantic biases underpin diminished pacific decadal variability. *Nature Climate Change* p. 1.
30. Peterson RG, White WB (1998) Slow oceanic teleconnections linking the antarctic circumpolar wave with the tropical el niño-southern oscillation. *Journal of Geophysical Research: Oceans* 103(C11):24573–24583.
31. Andrews O, Bindoff N, Halloran P, Ilyina T, Le Quéré C (2013) Detecting an external influence on recent changes in oceanic oxygen using an optimal fingerprinting method. *Biogeosciences* 10:1799–1813.
32. Saeki T, Patra P (2017) Implications of overestimated anthropogenic co_2 emissions on east asian and global land co_2 flux inversion. *Geoscience Letters* 4(9).
33. Le Quéré C, et al. (2009) Trends in the sources and sinks of carbon dioxide. *Nature geoscience* 2(12):831.
34. Frölicher TL, Joos F, Raible CC, Sarmiento JL (2013) Atmospheric co2 response to volcanic eruptions: The role of enso, season, and variability. *Global Biogeochemical Cycles* 27(1):239–251.
35. Quéré CL, et al. (2018) Global carbon budget 2018. *Earth System Science Data* 10(4):2141–2194.
36. Boer GJ, et al. (2016) The decadal climate prediction project (dcpp) contribution to cmip6. *Geoscientific Model Development* 9:3751–3777.
37. Yeager S, et al. (2018) Predicting near-term changes in the earth system: A large ensemble of initialized decadal prediction simulations using the community earth system model. *Bulletin of the American Meteorological Society* pp. 1867–1886.
38. Bakker DCE, et al. (2016) A multi-decade record of high-quality $f co_2$ data in version 3 of the surface ocean co_2 atlas (socat). *Earth System Science Data* 8(2):383–413.
39. Takahashi T, Sutherland SC, Kozyr A (2014) Global ocean surface water partial pressure of

co2 database: Measurements performed during 1957?2013 (version 2013).

40. Jacobson AR, Mikaloff Fletcher SE, Gruber N, Sarmiento JL, Gloor M (2007) A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide: 1. methods and global-scale fluxes. *Global Biogeochemical Cycles* 21(1).

41. Resplandy L, et al. (2018) Revision of global carbon fluxes based on a reassessment of oceanic and riverine carbon transport. *Nature Geoscience* 11(7):504.