



DeVries, T., Le Quéré, C., Andrews, O., Berthet, S., Hauck, J., Ilyina, T., Landschützer, P., Lenton, A., Lima, I. D., Nowicki, M., Schwinger, J., & Séférian, R. (2019). Decadal trends in the ocean carbon sink. *Proceedings of the National Academy of Sciences of the United States of America*, 116(24), 11646-11651.
<https://doi.org/10.1073/pnas.19003711116>,
<https://doi.org/10.1073/pnas.19003711116>

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Decadal trends in the ocean carbon sink

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Edited by David M. Karl, University of Hawaii, Honolulu, HI, and approved April 26, 2019 (received for review January 10, 2019)

Measurements show large decadal variability in the rate of CO₂ accumulation in the atmosphere that is not driven by CO₂ 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 CO₂ due to the ocean and the terrestrial biosphere. In this study, we compare three independent methods for estimating oceanic CO₂ uptake and find that the ocean carbon sink could be responsible for up to 40% of the observed decadal variability in atmospheric CO₂ accumulation. Data-based estimates of the ocean carbon sink from pCO₂ mapping methods and decadal ocean inverse models generally agree on the magnitude and sign of decadal variability in the ocean CO₂ sink at both global and regional scales. Simulations with ocean biogeochemical models confirm that climate variability drove the observed decadal trends in ocean CO₂ uptake, but also demonstrate that the sensitivity of ocean CO₂ uptake to climate variability may be too weak in models. Furthermore, all estimates point toward coherent decadal variability in the oceanic and terrestrial CO₂ 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 CO₂ 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 (CO₂) are a major contributor to climate change, accounting for >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 CO₂ accumulates in the atmosphere. The primary driver of atmospheric CO₂ accumulation is anthropogenic emissions from industrial activity and deforestation (2), which has increased by ~60% over the past 30 y (Fig. 1A). CO₂ accumulation in the atmosphere, however, has not always followed the trend in CO₂ emissions. From 1990 to 1999, atmospheric CO₂ accumulated more rapidly than expected from the relatively slow growth in emissions, while in the decade from 2000 to 2009, atmospheric CO₂ accumulation was relatively steady, while emissions rose rapidly (Fig. 1A).

This decadal variability in atmospheric CO₂ accumulation rate is linked to variability in the sources and sinks of CO₂ in the natural environment (5). 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 (6) and can be neglected on recent timescales. Thus, the global carbon budget (3) is primarily a balance between anthropogenic CO₂ emissions from fossil-fuel burning and cement manufacturing (FF) and land-use change

(LUC; i.e., deforestation), and changes in the accumulation of CO₂ in the atmosphere (C_{atm}), ocean (C_{oce}), and land biosphere (C_{land}),

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

Global FF and LUC emissions have an uncertainty of ~10% (3, 7, 8), and atmospheric CO₂ has been measured continuously since 1980 at a global network of stations, with error on the annual average accumulation of < 5% (9). From these observations and Eq. (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 $55 \pm 10\%$ of total carbon emissions over the past 30 y, 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

Significance

The ocean and land absorb anthropogenic CO₂ from industrial fossil-fuel emissions and land-use changes, helping to buffer climate change. Here, we compare decadal variability of ocean CO₂ uptake using three independent methods and find that the ocean could be responsible for as much as 40% of the observed decadal variability of CO₂ 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 CO₂ uptake by the land and ocean is more sensitive to climate variability than currently thought. Models must capture this sensitivity to provide accurate climate predictions.

Author contributions: T.D. and C.L.Q. designed research; T.D., O.A., S.B., J.H., T.I., A.L., I.D.L., J.S., and R.S. performed research; T.D., and M.N. analyzed data; and T.D., C.L.Q., O.A., S.B., J.H., T.I., P.L., A.L., I.D.L., J.S., and R.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: OCIM data are available at <https://tdevries.eri.ucsb.edu/models-and-data-products/>. Timeseries of the SOCOM data following ref. 15 can be obtained from <http://www.bgc-jena.mpg.de/SOCOM/>. Timeseries of the GOBM data are available at <https://doi.org/10.6084/m9.figshare.8091161>.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1900371116/-DCSupplemental.

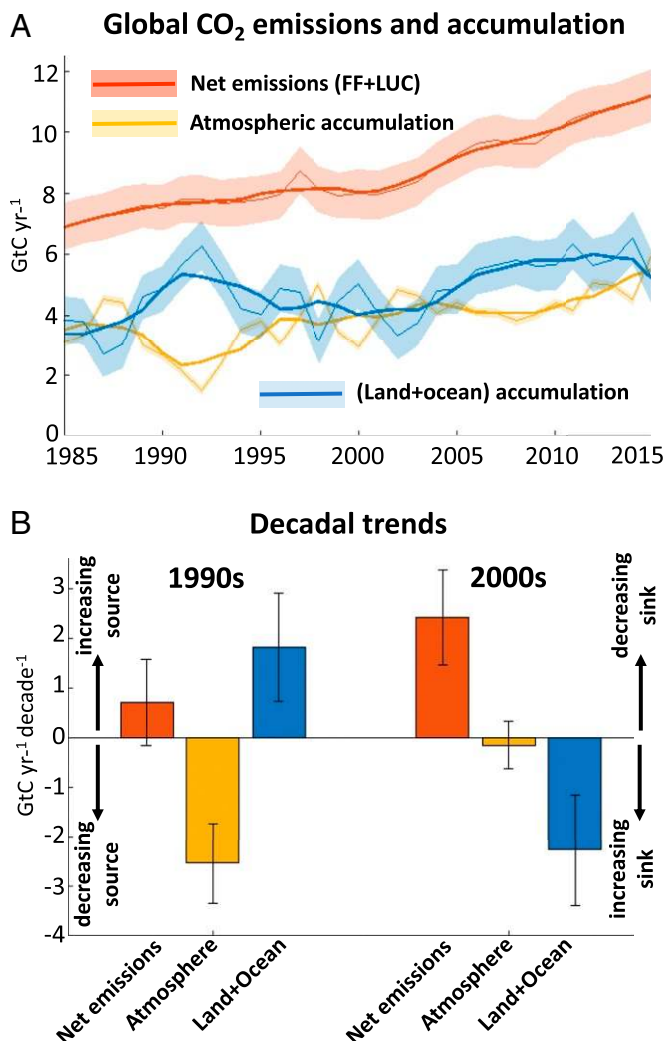


Fig. 1. (A) Global CO₂ emissions from fossil-fuel-burning, cement production, and land-use change (FF+LUC) (red curve), compared with the measured rate of accumulation of CO₂ in the atmosphere (gold curve) and the inferred rate of change of CO₂ accumulation in the land and ocean (blue curve). Thin lines are annual means, and thick lines are 5-y running means. (B) Decadal trends in CO₂ 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 are from the 2017 Global Carbon Budget (3, 4). Error bars are 1- σ .

(GOBMs) are often used to estimate the land and ocean carbon sinks, respectively (3). Methods have also been developed for estimating CO₂ accumulation in the ocean indirectly from observations using inverse models (10–12) and measurements of the sea-surface partial pressure of CO₂ (pCO₂) (13–15).

While the terrestrial biosphere is the dominant source of interannual variability in the natural CO₂ sinks (5, 16), observations and numerical models have highlighted substantial decadal variability in ocean CO₂ uptake at both regional (17–19) and global scales (20, 21). In particular, recent estimates from several data-based models (22–24) suggest that the decadal variability in the ocean CO₂ sink is larger than currently estimated by global carbon budgets. To assess the robustness of decadal trends in ocean CO₂ uptake, here, we compare decadal variabil-

ity 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) (12, 24), and pCO₂-based flux mapping models from the Surface Ocean pCO₂ Mapping Intercomparison (SOCOM) project (15). 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 CO₂ 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 y (Fig. 24). Estimates of the ocean anthropogenic carbon sink in 2010 from these methods cluster around a mean of $\sim 2.4 \text{ GtC}\cdot\text{y}^{-1}$ with an uncertainty of $\sim 25\%$ due to differences among the various methods and models (Fig. 24).

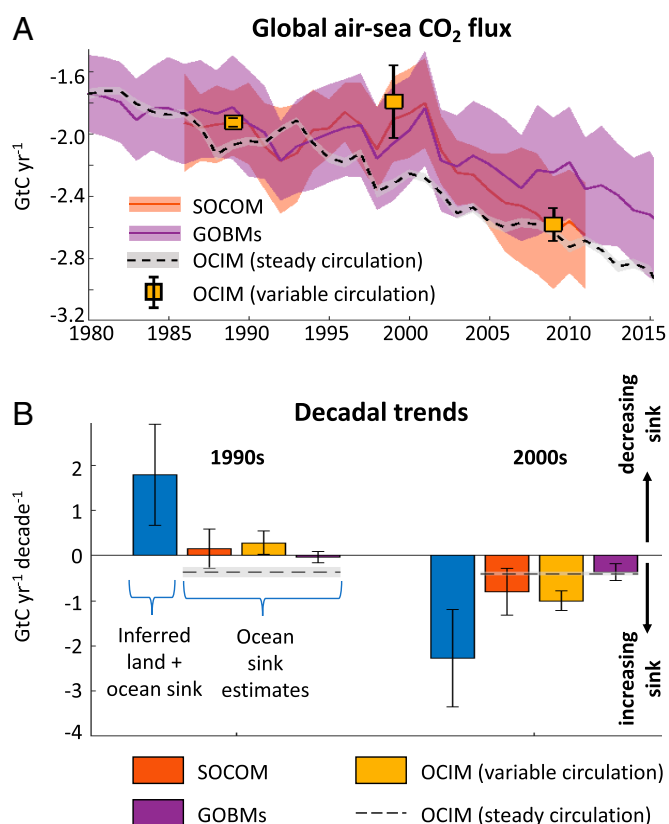


Fig. 2. (A) Estimates of the ocean carbon sink from a subset of models participating in the SOCOM project (15), a subset of GOBMs participating in the 2017 Global Carbon Budget (3) and an OCIM with (24) and without (12) decadal variability in ocean circulation. Thick lines are the ensemble mean from each method, with shading representing one SD uncertainty. For the OCIM with variable circulation, the mean value at the end of each decade (1989, 1999, and 2009) is shown, with error bars representing one SD. For the OCIM with constant circulation, error bars are the ensemble range. SOCOM results have been adjusted for out-gassing of riverine CO_2 (*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).

the high latitudes, the SOCUM-based estimates place more of the weakening in the 1990s CO₂ 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. 3 *B–D*). In the low latitudes, the SOCUM and OCIM models agree that the Pacific and Indian Oceans were a weakening sink in the 1990s (Fig. 3*F*), while the OCIM simulates a weaker-trending Atlantic Ocean sink than most of the SOCUM products (Fig. 3*E*). The strengthening of the ocean CO₂ sink in the 2000s is consistent across regions in both the SOCUM and OCIM models.

Decadal trends in the GOBM-simulated oceanic CO₂ uptake are not as variable as those diagnosed by the SOCUM products or the variable-circulation OCIM. For example, in the Southern Ocean, the observation-based methods infer large decadal variations in the ocean CO₂ 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. 3*B*). 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. 3*F*).

Climate-Driven Trends in Ocean Carbon Uptake

To separate the impacts of CO₂- and climate-forced variability on ocean CO₂ uptake in the GOBMs, we performed additional model simulations in which the climate forcing was held constant and in which the atmospheric CO₂ concentration was held constant (*Materials and Methods*). Based on these simulations, we isolated the decadal trends of oceanic CO₂ uptake due to atmospheric CO₂ increase and due to climate variability (Fig. 4). These simulations reveal that trends in ocean

CO₂ uptake in the 1990s and 2000s are nearly indistinguishable for the CO₂-only forcing case (both between decades and among models) and that decadal variability in the CO₂ sink is driven exclusively by climate variability. Eight of nine of the GOBMs predict that climate variability drove a weakening of the global ocean CO₂ sink in the 1990s, and five of nine predict that climate variability drove a strengthening trend in the 2000s (Fig. 4*A*).

The regions with the strongest climate-driven decadal variability in the GOBMs are the Southern Ocean (Fig. 4*B*) and the low-latitude Pacific and Indian Oceans (Fig. 4*F*). 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 CO₂ uptake in the 1990s and increasing CO₂ 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 CO₂ sink in the 2000s compared with 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 CO₂ 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 (24, 27). These trends could be due to modes of internal variability in the climate system (22) or to external forcing [e.g., the eruption of Mount Pinatubo in 1991 (28, 29)], which can alter the states of internal climate modes (30), and thus the global winds. External drivers could be amplified by atmospheric (31) or oceanic (32) teleconnections to enhance decadal variability in ocean circulation.

Although the GOBMs display a consistent response to climate forcing, their climate-driven variability of ocean CO₂ uptake appears to be too weak compared with the data-based methods. Indeed, the GOBMs that perform best compared with the most accurate pCO₂-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 counteracts circulation-driven CO₂ 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 CO₂ uptake, while the opposite is true of models with weak variability in biological carbon export. Thus, the compensation between circulation-driven and biologically driven CO₂ 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 CO₂ uptake is poorly known and should be a priority for future study.

Discussion and Conclusions

The agreement among the various methods of determining ocean CO₂ 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 (SOCUM and OCIM) predict greater decadal variability of the ocean CO₂ sink than ocean biogeochemistry

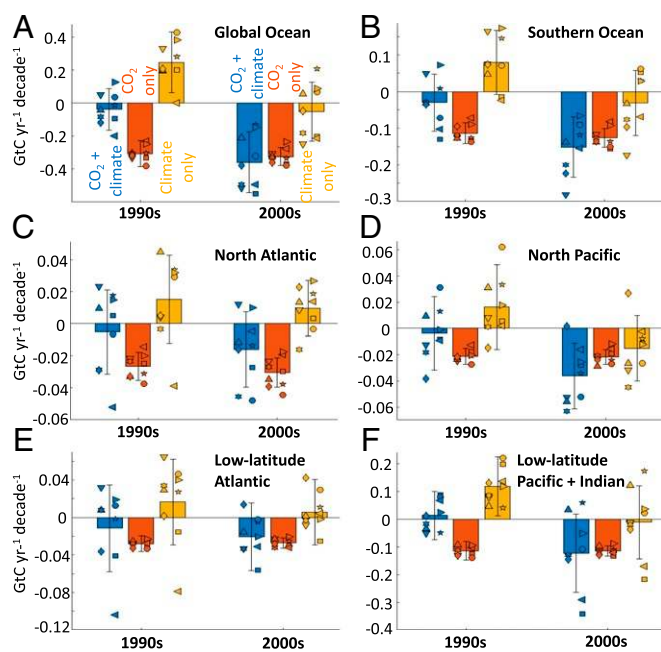


Fig. 4. Decadal trends in ocean carbon uptake simulated by GOBMs for the regions in Fig. 3. (A) Global ocean. (B) Southern Ocean. (C) North Atlantic. (D) North Pacific. (E) Low-latitude Atlantic. (F) Low-latitude Pacific + Indian. Shown separately are the trends due to both CO₂ and climate variability (blue bar; same as purple bar in Fig. 3), trends due to CO₂ variability only (red bar), and trends due to climate variability only (gold bar). Error bars are one SD of the model ensemble mean. Symbols represent results from individual models as defined in Fig. 3.

models and suggest that $\sim 10\text{--}40\%$ 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 with observations has also been observed for oxygen (33), suggesting that 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 with the total land+ocean CO_2 sink (Fig. 1B) to deduce the decadal trends in the terrestrial CO_2 sink (*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).

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 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

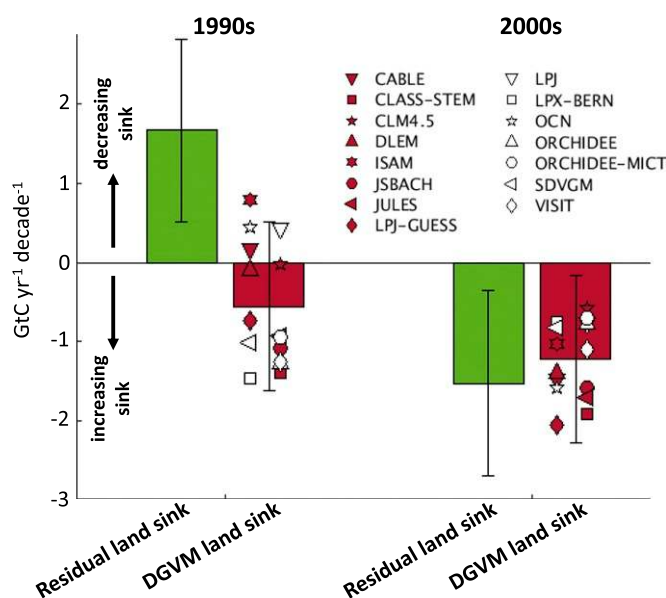


Fig. 5. Trends in the terrestrial CO_2 sink calculated as a residual from the global carbon budget (Eq. 1) using the estimates of the ocean CO_2 sink from three methods considered here (GOBMs, SOCOM, and OCIM with variable circulation) and from the DGVMs participating in the 2017 Global Carbon Budget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

of the oceanic CO_2 sink, this is unlikely to be a source of bias. Errors in fossil-fuel CO_2 emissions (34) and LUC emissions (35) 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 (36) and the strong El Niño event of 1998 (16).

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 (37). As the community moves toward decadal climate prediction (38, 39), 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 (*SI Appendix*), leading to improved constraints on the magnitude and variability of the ocean CO_2 sink and reducing imbalances in global carbon budgets (37). 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

p CO_2 -Based Flux Mapping Products. The SOCOM products are based on historical observations of surface-ocean p CO_2 compiled in the Surface Ocean CO_2 Atlas (SOCAT) (40) and the Lamont-Doherty Earth Observatory (41) datasets. The SOCOM models use various interpolation schemes to fill in the gaps in the data records to create continuous maps of p CO_2 at monthly resolution, from which air-sea fluxes are calculated (15). See *SI Appendix* for additional information.

Inverse Models. We use two versions of the OCIM. The first diagnoses the uptake of anthropogenic CO_2 in the absence of any changes to ocean circulation, solubility, or biology (12). Uncertainties are derived from the 10 different versions of the model described in ref. 12. 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 (24). Uncertainties are derived from 160 different versions of the model described in ref. 24. See *SI Appendix* for additional information.

GOBMs. We use a subset of the GOBMs used in the 2017 Global Carbon Budget (3): NEMO-PISCES (CNRM), CSIRO, NorESM, MPIOM-HAMOC, NEMO-PlankTOM5, MITgcm-RECO2, and CCSM-BEC. Each model performs three simulations: Simulation A uses reanalysis climate forcing and observed atmospheric CO_2 concentrations from 1959–2017. Simulation B uses constant climate forcing and observed atmospheric CO_2 concentrations from 1959–2017. In Fig. 4, “ CO_2 +climate” is from simulation A, “ CO_2 only” is from simulation B, and “climate only” is from simulation C. Models differ in their spin-up procedure and climate forcing, as detailed in *SI Appendix* and *SI Appendix*, Table S1.

Accounting for Riverine Carbon. The OCIM and GOBMs do not account for a degassing of $0.45\text{--}0.78\text{ GtC}\cdot\text{y}^{-1}$ (42, 43) of riverine CO_2 , but the SOCOM products do. To make the CO_2 fluxes comparable across all methods, we add a flux of $0.6\text{ GtC}\cdot\text{y}^{-1}$ 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 are 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 $\pm 1\text{ y}$ for the beginning and ending years of the trend calculations (i.e., 1990 ± 1 to 1999 ± 1 and 2000 ± 1 to 2009 ± 1). For the variable-circulation OCIM, decadal trends are 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 CO₂ 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 integrate the air-sea CO₂ fluxes over distinct oceanographic regions based on the time-mean open-ocean biomes defined by ref. 25. To avoid differences in the model domains near the coast, the global ocean CO₂ uptake in all figures is the summation over all of the individual open-ocean 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 CO₂ Sink. To calculate decadal trends in the terrestrial CO₂ sink, we first calculate decadal trends in the ocean carbon sink using all of the methods considered here that resolve decadal variability in the ocean CO₂ sink (SOCOM, GOBMs, and OCIM-variable, as displayed in Fig. 2B). We then subtract these ocean-only trends from the trend in the total (land+ocean) CO₂ sink (Fig. 1B) to obtain the trends in the “residual land sink” (Fig. 5). Reported uncertainties include uncertainty in the CO₂ emissions, uncertainty in the atmospheric CO₂ concentration, uncertainty in the ocean CO₂ sink (treating all methods of estimating the ocean CO₂ sink as equally probable), and uncertainty due to varying the beginning and ending years for the trend calculation by ± 1 y. Trends in the terrestrial CO₂ 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 ± 1 y. See *SI Appendix* for a full list of the DGVMs used here.

Data Availability.

OCIM data are available at <https://tdevries.eri.ucsb.edu/models-and-data-products/>. Timeseries of the SOCOM data following ref. 15 can be obtained from <http://www.bgc-jena.mpg.de/SOCOM/>. Timeseries of the GOBM data are available at <https://doi.org/10.6084/m9.figshare.8091161>.

ACKNOWLEDGMENTS. We thank Rebecca Wright and Erik Buitenhuis at University of East Anglia, Norwich, for providing updated runs from the NEMO-PlankTOM5 model. T.D. was supported by NSF Grant OCE-1658392. C.L.Q. thanks the UK Natural Environment Research Council for supporting the SONATA Project (Grant NE/P021417/1). P.L. was supported by the Max Planck Society for the Advancement of Science. J.H. was supported under Helmholtz Young Investigator Group Marine Carbon and Ecosystem Feedbacks in the Earth System (MarESys) Grant VH-NG-1301. S.B. and R.S. were supported by 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 No 641816. SOCAT is an international effort, endorsed by the International Ocean Carbon Coordination Project, the Surface Ocean-Lower Atmosphere Study, and the Integrated Marine Biosphere Research program, to deliver a uniformly quality-controlled surface ocean CO₂ database. The many researchers and funding agencies responsible for the collection of data and quality control are thanked for their contributions to SOCAT.

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