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Key Points:
- Based on the oxygen budget, this study estimated the land and ocean carbon sinks and its response to climate change
- Estimations reveal decadal variability of ocean carbon sink due to combinations of effects of anthropogenic forcing and natural variability
- Future projections indicate the vital role of human activities on changes of ocean and land carbon sink

Supporting Information:
Supporting Information may be found in the online version of this article.

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Estimation of Oceanic and Land Carbon Sinks Based on the Most Recent Oxygen Budget

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Abstract Robust assessments of global carbon uptake are important for understanding Earth's carbon cycle and its response to human impacts. Here, based on the most recent oxygen budget, we presented an alternative estimate of ocean and land carbon sinks over the past few decades and future projections under climate change. For the period from 1990 to 2015, the ocean and land carbon sinks were ~2.16 ± 0.73 and 1.37 ± 0.91 GtC/yr, respectively, which are in good agreement with the results from the Global Carbon Project (GCP). Our estimated temporal evolution of oceanic carbon uptake, however, presents a stronger decadal variation than the quasi-monotonous increase estimated by the GCP. Future projections of carbon sinks show significant discrepancies under different scenarios. At the end of this century, the ocean and land sinks will be 2.96 and 0.75 GtC/yr, respectively, under RCP4.5 (representative concentration pathways), while these values will be much larger under RCP8.5 at ~5.70 and 3.69 GtC/yr, highlighting the vital role of the human-induced influence on the carbon cycle.

Plain Language Summary In the Earth system, the ocean and land work as the carbon reservoirs (i.e., the CO_2 sinks) to absorb CO_2 emissions from human activities, helping to buffer climate change greatly. In this study, the land and ocean sinks are estimated using the most recent oxygen budget. We presented the evolution of the carbon sink in the last few decades as well as its changes under different warming scenarios in the future. Our results reveal the combinations of natural and anthropogenic effects on oceanic carbon sink in the historical period. Furthermore, the vast differences under two warming scenarios indicate the importance of human efforts on emission-reduction.

1. Introduction

The concentration of carbon dioxide (CO_2) in the Earth's atmosphere has increased continuously under the interference of human activities, which is considered to be the main cause of global warming (IPCC, 2013). A study published recently showed that present-day CO_2 (~412 ppm in 2019) exceeds the highest levels that Earth has experienced, at least since the Miocene (Cui et al., 2020), indicating the disruption of the long-established carbon cycle in the Earth system. Under this circumstance, the Paris Agreement was signed to reduce anthropogenic CO_2 emissions, slow the increase in the atmospheric CO_2 concentration and eventually limit global mean surface warming to less than 2°C relative to pre-industrial levels (Knutti et al., 2016; Seneviratne et al., 2016).

The actual atmospheric CO_2 increase is significantly modified by ocean uptake and exchange fluxes with terrestrial ecosystems (Rödenbeck et al., 2003). Previous studies have estimated that the land and ocean have sequestered over 40% of the anthropogenic CO_2 emitted in the last few decades (Friedlingstein et al., 2019; Le Quéré et al., 2018). The net oceanic and terrestrial uptake of atmospheric CO_2, therefore, plays an important role in the modification of the global carbon cycle under ongoing climate change, effectively moderating the impact of anthropogenic CO_2 emissions (Friedlingstein et al., 2006; Wanninkhof et al., 2013). Thus, for a reasonable design of global warming mitigation strategies, one major requirement is to answer how anthropogenic carbon is processed in the climate system, especially the strengths of land and ocean carbon uptake as well as their susceptibility to ongoing climate change (Marotzke et al., 2017; Peters et al., 2017). Future projections of the global climate also require a quantitative understanding of the two sinks to present an accurate assessment of the anthropogenic impacts.

Terrestrial ecosystem models and ocean biochemical models are currently used to estimate land and ocean carbon uptake. However, these results are limited by the lack of spatially explicit observations of carbon changes in vegetation and soils (Arneth et al., 2017) and insufficiency of physical, chemical and biological observations in the ocean (DeVries et al., 2017). Studies also reveal that direct measurement of CO_2 flux may underestimate the uptake due to non-closure of the surface energy balance (Gao et al., 2019, 2020). Under this circumstance, estimates of the global oxygen budget could provide unique insights for quantifying carbon sinks. Atmospheric oxygen is thought to be a mirror of atmospheric carbon dioxide because of the tight coupling between O_2 and CO_2 that occurs during photosynthesis by terrestrial plants and the subsequent respiration, decomposition, and remineralization of organic matter (Battle et al., 2006). In addition to the processes mentioned above, the oxygen and carbon cycle are also influenced by the exchange of O_2 and CO_2 across the air-sea interface (Gruber et al., 2001; Najjar & Keeling, 2000). Based on the close relationship between carbon and oxygen in the global material cycle, we can use the combined long-term trends in atmospheric O_2 and CO_2 concentrations to estimate the global land and ocean carbon sinks (Manning & Keeling, 2006; Tohjima et al., 2019). In addition to the process-based land and ocean models (Chang et al., 2017; Li & Ilyina, 2018), this so-called oxygen-based carbon budget presents an alternative way to quantify the carbon sinks of land and the ocean.

Based on the most recent oxygen budget (Huang et al.,2018) and atmospheric oxygen consumption dataset (Liu et al., 2020), we provide an estimate of net terrestrial and oceanic carbon sinks and the future changes to these sinks under different warming scenarios. Through this work, we expect to present a clear description of the global carbon cycle inferred from the oxygen budget as well as its modifications under anthroponotic forcing.

2. Materials and Methods

2.1. The Calculation of Terrestrial and Oceanic Carbon Sinks

The estimation of carbon sinks based on the oxygen budget is a simple and straightforward approach. The budget equations for atmospheric O_2 and CO_2 can be written as follows (Keeling & Manning, 2014; Tohjima et al., 2019):

$$\Delta CO_2 = F_{\text{fossil}} - S_{\text{ocean}} - S_{\text{land}}, \quad (1)$$

$$\Delta O_2 = -\alpha_F F_{\text{fossil}} + \alpha_B S_{\text{land}} + Z_{\text{ocean}}, \quad (2)$$

where ΔCO_2 and ΔO_2 represent the changes in CO_2 and O_2 in the atmosphere; F_{fossil} is the industrial CO_2 source (mainly from fossil fuel combustion); Z_{ocean} represents the net oceanic oxygen exchange with the atmosphere; α_F and α_B are the averaged O_2:CO_2 molar exchange ratios for fossil fuel burning and land biota, respectively; and S_{land} and S_{ocean} represent the net land carbon sink and ocean carbon sink, respectively. All variables in the equations mentioned above are in the unit of mole, except the dimensionless exchange ratios α_F and α_B.

The most recent oxygen budget proposed by Huang et al. 2018 and atmospheric oxygen consumption datasets (Liu et al., 2020) make it possible to directly estimate the land and ocean carbon sinks with the use of the equations mentioned above. The detailed descriptions of oxygen data used in this study and its validations could be found in Text S1. For the CO_2 data used in calculations, the historical atmospheric CO_2 concentrations and CO_2 emissions could be obtained from the Carbon Dioxide Information Analysis Center (CDIAC, Andres et al., 2016). The future CO_2 concentrations under several emission scenarios used in this study could be found in related studies (Riahi et al., 2011; Thomson et al., 2011).

The ratios α_F and α_B play an important role in the calculations, linking the two equations together. Although the oxidative ratio associated with fossil fuel combustion (α_F) could exhibit temporal variations due to adjustments to global energy sources, there has been only a slight change in α_F (less than 0.03, according to Tohjima et al., 2019) over the last two decades. It is also believed that α_B experienced a decrease of only 0.01 over a period of 100 years, despite the substantial modifications to global vegetation cover by human activities over the past century (Randerson et al., 2006). Therefore, we set the typical values of α_F and α_B as 1.39 and 1.1, respectively, according to Keeling (1988) and Severinghaus (1995)

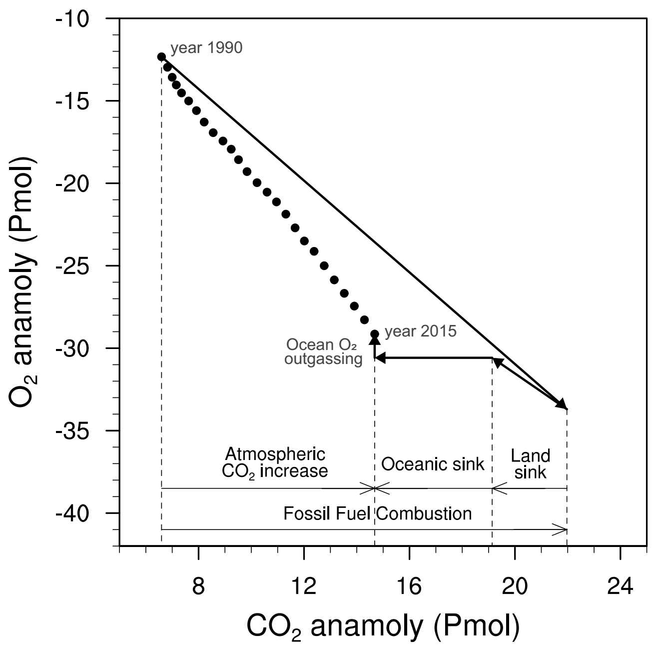

Figure 1. Diagram of the global annual atmospheric O_2 versus CO_2 anomaly. The vectors in this diagram schematically illustrate the contribution of each process related to the changes in O_2 (vertical axis) and CO_2 (horizontal axis) during 1990–2015. The vector associated with fossil fuel is obtained by assuming that 1.39 mol O_2 is consumed for the release of 1 mol CO_2. Land uptake is assumed to occur with a ratio of 1.1 between O_2 and CO_2. The arrow labeled "Ocean O_2 outgassing" indicates the release of O_2 from the ocean to the atmosphere. The unit used here is Pmol (1 Pmol equals 10^{15} mol).

when calculating the sinks in the historical period. It should be noted that α_F can significantly change under different warming scenarios when estimating future carbon sinks, which we will discuss in detail in Section 3.2.

The estimate of oceanic O_2 flux now becomes one of the most important contributors to uncertainties in the O_2-based carbon budget (Keeling & Manning, 2014). Early studies of carbon sinks assumed that there was no long-term oceanic effect on the atmosphere, which means that Z_{ocean} is considered zero (Battle et al., 2000; Bender & Battle, 1999). However, there has been increasing evidence that the ocean is warming (Cheng & Zhu, 2018; Li et al., 2019), which contributes to enhanced marine oxygen outgassing and will eventually lead to ocean deoxygenation (Li et al., 2020; Oschlies et al., 2018; Schmidtko et al., 2017). Recent studies have considered this air-sea O_2 flux and made revisions to the O_2-based carbon budget. However, some of these studies were based on a simple relationship between O_2 outgassing and ocean heat content (OHC) (Manning & Keeling, 2006; Tohjima et al., 2019). Ocean biogeochemical climate models are also used to explore the characteristics of the O_2 flux in some studies (Bopp et al., 2002; Plattner et al., 2002); however, a single model may suffer from its own limitations, and system bias exists. In this study, based on the Coupled Model Intercomparison Project phase 5 (CMIP5) simulations (Taylor et al., 2012), we can obtain the air-sea O_2 flux from the ensemble mean of various models (Table S1), providing a better estimate of this term than that obtained by relying on only a simple linear relationship or single model. Detailed comparisons between the air-sea O2 flux from CMIP5 models and the OHC-derived flux could be found in Text S1.

Equations 1 and 2 briefly describe the relationship between oxygen and carbon cycle. Based on the datasets mentioned above, the terrestrial and oceanic carbon sinks (i.e., S_{land} and S_{ocean}) could therefore be calculated by solving the equations.

3. Results

3.1. The Land and Ocean Carbon Sinks in the Historical Period

The global carbon uptake by the ocean and land could be calculated based on budget Equations 1 and 2, which are briefly diagrammed in Figure 1. This figure clearly shows the CO_2 increases (or, conversely, the O_2 decreases) from 1990 to 2015. The related processes are presented as vectors to describe their effects on the oxygen and carbon budgets. For the 25-year period from 1990 to 2015, ~15.4 Pmol CO_2 (equivalent to 184.8 GtC) is released to the atmosphere as a result of fossil fuel combustion, which would lead to a decrease in O_2 of ~21.4 Pmol (684.8 Gt O_2) if no other processes were involved. However, in fact, the CO_2 in the atmosphere increases by only approximately half of this value (~8.1 Pmol). According to the equations (Equations 1 and 2), we can infer that ~2.8 Pmol and 4.5 Pmol CO_2 is absorbed by the land and ocean, respectively. That is, the averaged land and ocean carbon sinks are 1.37 and 2.16 GtC/yr, respectively. Furthermore, the ocean releases ~1.44 Pmol O_2 to the atmosphere in total. Although the value of the outgassing is relatively small compared with other variables, this air-sea O_2 flux is quite important for the revision of our calculations.

To clarify the effect of the air-sea O_2 flux (i.e., Z_{ocean}) on the revision of carbon uptake, we present comparisons of averaged carbon sinks with and without this correction (Figure 2). The estimations by the Global Carbon Project (GCP), which is derived from Global Carbon Budget 2019 (Friedlingstein et al., 2019), are also depicted here as the "standard reference." The land and ocean carbon uptake in our study corresponds well with the results estimated by the GCP, within a difference of ~0.1 GtC/yr. However, if the air-sea

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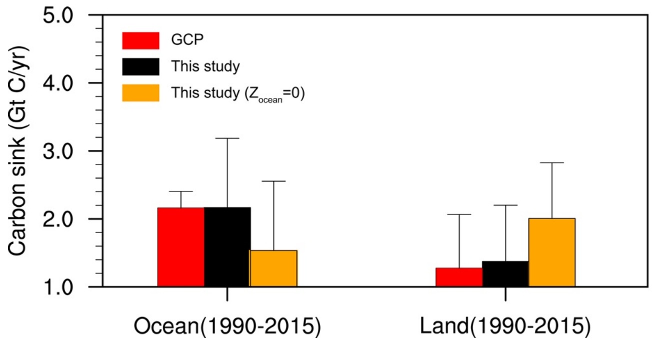

Figure 2. The effect of oceanic O_2 outgassing on the calculation of carbon sinks for a 25-year period from 1990 to 2015. The carbon sinks estimated by the Global Carbon Project, this study and the calculation assuming $Z_{ocean} = 0$ are colored in red, black, and orange, respectively. Note that the error bars here represent the standard deviation of the sinks during the period.

O_2 flux was not considered (assuming $Z_{ocean} = 0$), the ocean carbon sink would be underestimated by ~0.6 GtC/yr, while the land carbon uptake would be overestimated. The comparisons reveal the vital importance of oceanic O_2 outgassing for budget calculations. Moreover, the standard deviation of our estimated oceanic carbon sink during the period from 1990 to 2015 is much larger than the results from the GCP, indicating a strong temporal variation signal, which we will discuss in detail later.

We calculate the averaged terrestrial and oceanic carbon uptake for several different periods and compare the results to the results of previous studies. The results are listed in Table 1. The carbon sinks in our study are overall consistent with those in other studies, but slight differences exist between them. In this study, the averaged land carbon uptakes during 1990–2000 and 2000–2010 are 1.31 and 1.26 GtC/yr, respectively, which are relatively larger than those obtained by Keeling and Manning, 2014 (1.22 and 1.05 GtC/yr, respectively). However, our estimations of land carbon uptake (e.g., 1.38 GtC/yr for 2000–2016 and 1.55 GtC/yr for 2003–2016) are slightly smaller than the results from Tohjima et al., 2019 (1.48 and 1.90 GtC/yr, respectively). For ocean carbon uptake, the results in our study are 1.88 GtC/yr (1990–2000) and 2.23 GtC/yr (2000–2010), which are generally less than the estimations from Keeling and Manning, 2014. For a quantified evaluation, the absolute differences between the results from these O_2-based carbon sinks and the process-based GCP are calculated and shown in Table 1. Our results show a relatively small difference compared with the results of other studies, which roughly range from 0.12 to 0.22.

The temporal evolutions of oceanic and terrestrial carbon uptake are presented in Figure 3. Different from the quasi-monotonous increase estimated by the GCP, the oceanic carbon sink in our results shows an overall decreasing trend in the 1990s, while this trend turns to an increase after ~2,000 (Figure 3a). The time series of oceanic carbon uptake is quite similar to that in Landschützer et al. 2016, which is derived from the observed surface partial pressure of CO_2. Both of these results present a shift in ~2,000. We also calculate the linear trend of oceanic carbon uptake for the 10-year period from 2000 to 2010. The rates of increase are

Table 1
Estimates of O_2-Based Carbon Sinks in Different Studies

	Period	Z_{ocean} (Gt yr^{-1})	S_{land}[a] (GtC yr^{-1})	S_{ocean}[a] (GtC yr^{-1})	Differences[b] between GCP
Our results	1990–2000	1.66	1.31(0.84)	1.88(0.72)	0.22
	2000–2010	1.98	1.26(0.93)	2.23(0.75)	0.12
	2000–2016	2.04	1.38(0.98)	2.44(0.76)	0.16
	2003–2016	2.02	1.55(0.95)	2.45(0.73)	0.12
Plattner et al. 2002	1990–2000	2.08	0.70(0.80)	2.40(0.70)	0.91
Keeling et al. 2014	1990–2000	1.41	1.22(0.80)	1.94(0.62)	0.07
	2000–2010	1.41	1.05(0.84)	2.72(0.60)	0.82
Tohjima et al. 2019	2000–2016	1.58	1.48(0.91)	2.55(0.73)	0.31
	2003–2016	1.53	1.90(0.93)	2.35(0.73)	0.45

Abbreviation: GCP, Global Carbon Project.

[a]Estimated uncertainties are shown in parentheses. As suggested by Tohjima et al. (2019), we adopted uncertainties of ±5% for the fossil-fuel-derived CO_2 emission rate and ±0.2 GtC yr^{-1} for the atmospheric CO_2 increasing rate, and the uncertainties of α_B and α_F are ±0.10 and ± 0.04, respectively. The uncertainty of the atmospheric O_2 change is 0.07 Pmol yr^{-1}. In addition, we use the standard deviation between the models to represent the uncertainty of oceanic O_2 outgassing. These uncertainties are propagated to the ocean and land sink uncertainties during calculation. [b]This term is calculated as $\left|S_{land} - S_{land}^{GCP}\right| + \left|S_{ocean} - S_{ocean}^{GCP}\right|$. The S_{ocean}^{GCP} here represents the total land flux in Global Carbon Budget 2019.

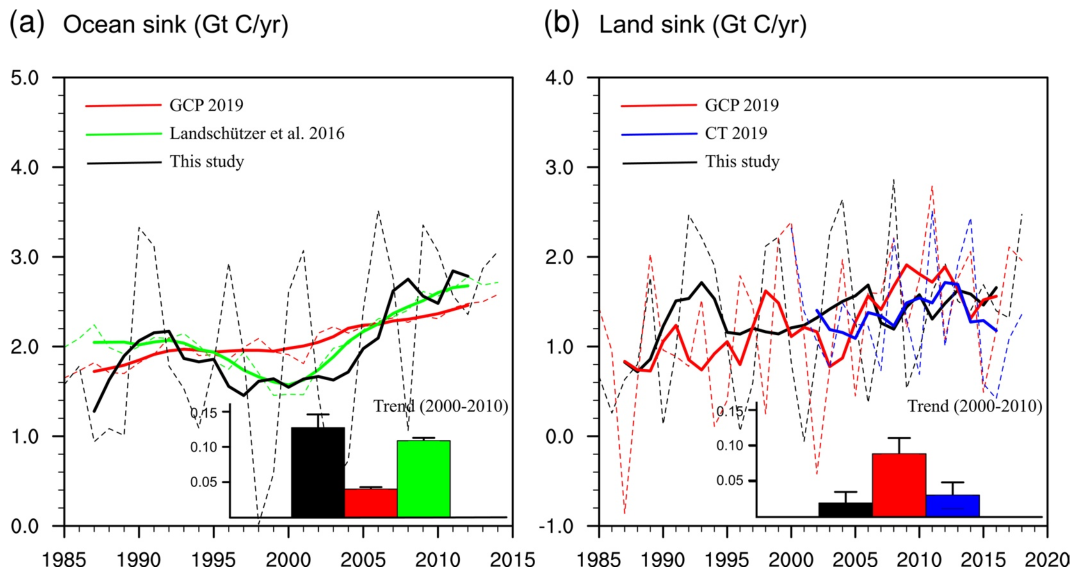

Figure 3. Estimated time series of ocean (a) and land (b) carbon sinks in the historical period. The thin dashed lines and thick solid lines represent the annual and 5-year running averaged sinks, respectively. The linear trend of the sink for the 10-year period from 2000 to 2010 is shown as the bar chart in the lower right of each panel. The error bars represent the uncertainties of the trend. The results of this study are colored in black. The results derived from the Global Carbon Project, Landschützer et al. 2016, and Carbon Tracker (CT 2019) are colored in red, green, and blue, respectively.

~0.12 GtC yr^{-2} for this study and 0.11 GtC yr^{-2} for Landschützer et al. 2016, while the GCP shows a much smaller rate of ~0.04 GtC yr^{-2} during this period.

For further explorations, the ensemble empirical mode decomposition (EEMD) method is used in this study (See Text S2 for details), which can decompose data into several different components with intrinsic timescales (Ji et al., 2014; Huang et al., 2017; Wang et al., 2014). Based on this method, we can split the evolution of oceanic carbon uptake into decadal variability (DV) and the long-term trend (Figure 4). The long-term upward trend (red line in Figure 4) is primarily related to increases in anthropogenic CO_2 emissions, while

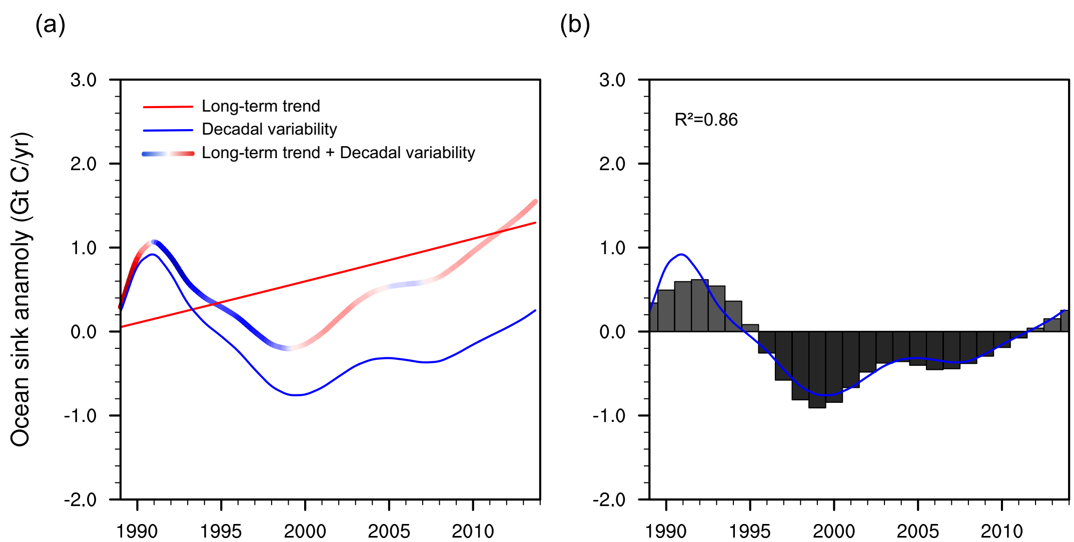

Figure 4. The ensemble empirical mode decomposition decomposed oceanic carbon uptake (a) and its regression using classic oceanic modes (b). The components for the long-term trend, decadal variability (DV), and the trend plus DV are colored in red, blue, and blue-red, respectively. The bar in Figure 4b represents the regression using the DV in the oceanic internal climate modes.

the decadal oscillation (blue line in Figure 4) is thought to be induced mainly by internal climate variability. To examine the modulated effect of the oceanic modes on the carbon sink, we apply stepwise multiple linear regression analysis here. The regression-based approximation of the DV using the multivariate ENSO index (MEI), Arctic Oscillation (AO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) index can explain 86% of its variance (Figure 4b), demonstrating the domination of these internal oceanic climate modes on the DV in oceanic carbon uptake. This DV enhances or suppresses the long-term trend, eventually resulting in a decline in oceanic carbon uptake in the 1990s and an accelerated carbon uptake after 2,000, as shown in Figure 4a.

In addition to the ocean, our results reveal an enhancement of terrestrial carbon uptake after 2,000, which has also been reported by previous studies (Piao et al., 2018; Keenan et al., 2016). The calculations suggest that the averaged land carbon sinks increase from 1.26 (2000–2010) to 1.55 GtC/yr (2003–2016), as presented in Table 1. The linear regression also shows that there is a positive trend of ~0.02 GtC yr^{-2} for the 10-year period from 2000 to 2010, although the rate is relatively smaller than 0.03 GtC yr^{-2}, as obtained by

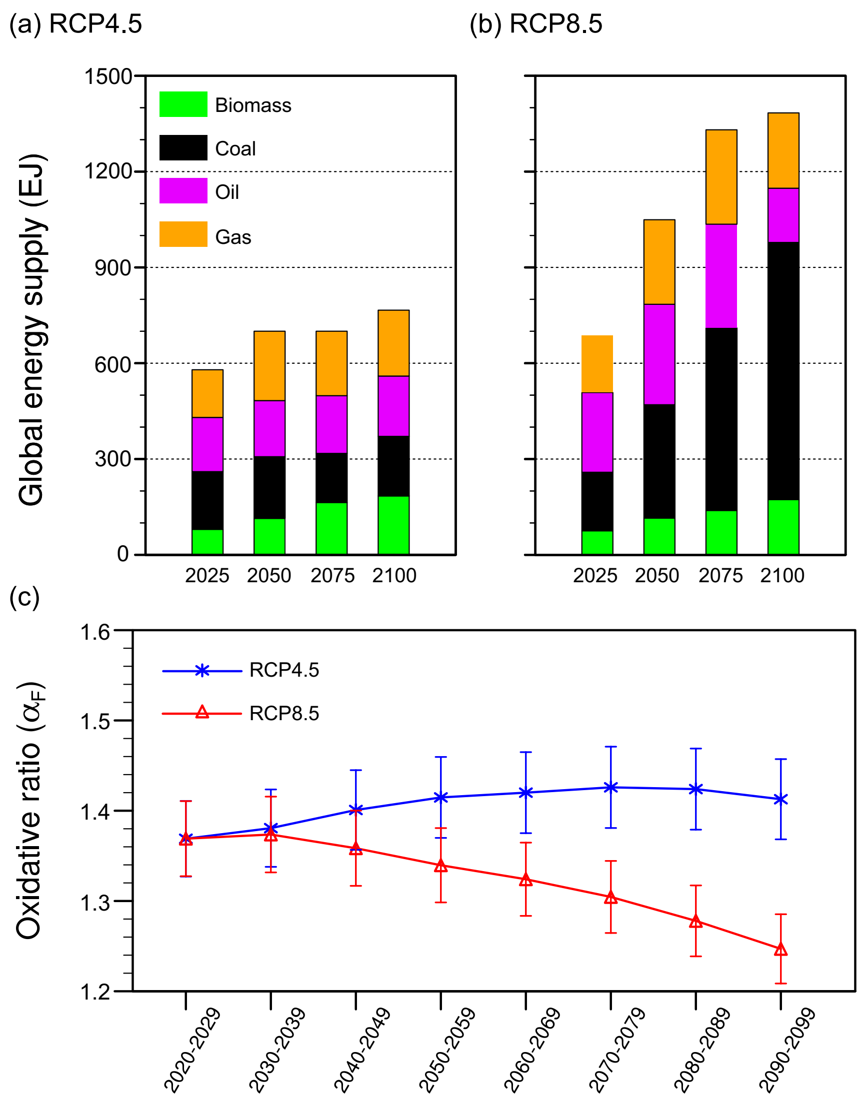

Figure 5. Changes in global energy supply under two scenarios ((a) RCP4.5, (b) RCP8.5), and (c) the related oxidative ratio. The different types of energy sources are colored green (biomass), black (coal), purple (oil), and orange (gas) and were derived from Riahi et al. 2011 to Thomson et al. 2011. The blue line with asterisks and red line with triangles represent the oxidative ratios (α_F) under RCP4.5 and RCP8.5, respectively. Error bars represent the total uncertainty of α_F due to its uncertainty in each fuel type. RCP, representative concentration pathways.

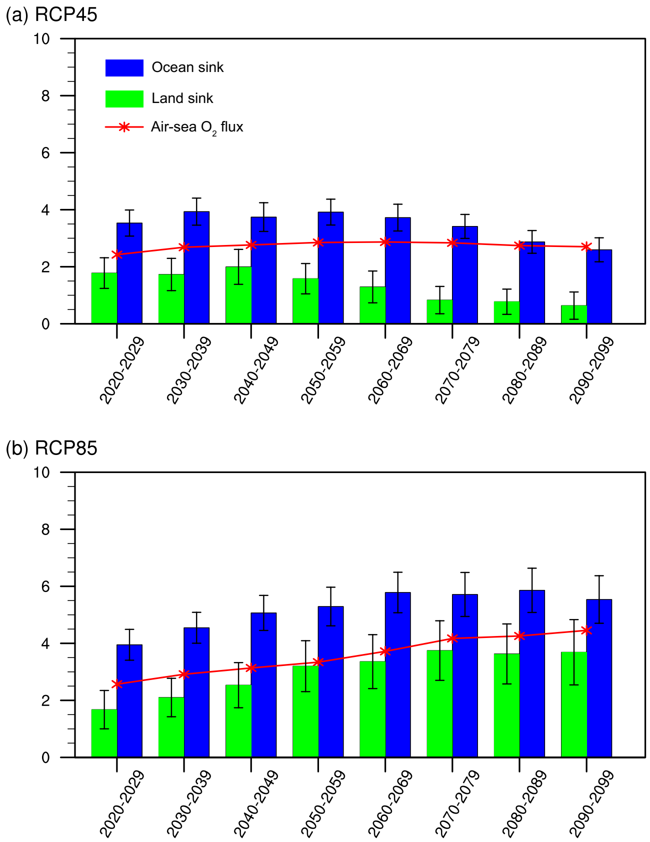

Figure 6. Future projections of the ocean and land carbon uptake under two scenarios ((a) RCP4.5, (b) RCP8.5). The ocean and land sinks are colored in blue and green, respectively. The changes in air-sea O_2 flux are depicted here as the red line with asterisks. Error bars represent the uncertainties of the carbon sinks. RCP, representative concentration pathways.

the Carbon Tracker 2019 (Jacobson et al., 2020), and 0.09 GtC yr^{-2}, as obtained by the GCP. Although there is currently still discussion about the detailed mechanisms behind the increased land carbon uptake, it is generally believed that this increase occurs as a consequence of the combined influences of increased atmospheric carbon dioxide, climate variability and changes in land use (Ciais et al., 2019; Piao, Wang, Wang, et al., 2020; Yue et al., 2020).

3.2. Future Carbon Sinks Under Climate Change

The increasing atmospheric CO_2 concentration caused by the higher demand for fossil fuel consumption, enhanced oceanic oxygen outgassing under global warming, and other related processes will continuously change the carbon and oxygen cycle. Here, we estimate the future carbon sinks under two different warming scenarios, RCP4.5 and RCP8.5 (representative concentration pathways [RCPs]), to explore the role of anthropogenic forcing in the modification of carbon sinks.

Future changes in the oxidative ratio (α_F) should be first considered due to its high sensitivity to the structure of global energy consumption. The high-emission scenario RCP8.5 describes a very different energy consumption strategy than the relatively low-emission scenario RCP4.5 (Figures 5a and 5b). Therefore, according to the change in the proportions of different types of fossil fuels (e.g., coal, oil, and natural gas), the evolution of α_F could be approximately estimated (See Text S3 for the details). As presented in Figures 5c and 5a slight increase in α_F can be found under RCP4.5, while a significant decrease in α_F occurs under RCP8.5, which is attributable to the growing dependence on coal with a relatively low α_F. By the end of the 21st century, ~58% of the global energy would be supplied by coal combustion in RCP8.5. In RCP4.5, the contribution of coal would gradually decrease, and biomass and natural gas sources would be popularized. Since the α_F of biomass is close to that of coal, the variations in their proportions would not significantly change the influence on the long-term trend of global α_F.

Figure 6 shows the modifications of the ocean and land carbon uptake in the future under different warming scenarios. Compared with the historical period, the land carbon sink has an apparent upward trend in the first half of the 21st century under both the RCP4.5 and RCP8.5 scenarios. However, the projection shows that discrepancy arises after the 2050s. The land carbon sink reaches its peak and then decreases in RCP4.5, while it continues to increase in RCP8.5. According to our calculation, the land carbon sink finally turns to 0.75 and 3.69 GtC/yr at the end of the century under the RCP4.5 and RCP8.5 scenarios, respectively. The characteristics of the ocean carbon sink under the two scenarios are similar to those of the land sink. Under the RCP4.5 scenario, the ocean sink reaches its peak (~4.25 GtC/yr) in the 2050s and decreases to 2.96 GtC/yr at the end of the century. However, in RCP8.5, the ocean sink increases during almost the whole century and finally reaches ~5.70 GtC/yr. This difference in the carbon sink between RCP4.5 and RCP8.5 can be mainly attributed to the disparities of emission pathways in the two scenarios. The CO_2 emissions caused by human-induced activities in RCP8.5 are much larger than those in RCP4.5 (Figures 5a and 5b), which would directly lead to a fast increase in atmospheric CO_2 concentration. Another factor leading to this difference is the changes in air-sea O_2 flux under the two scenarios (red lines in Figure 6). Furthermore, the responses of O_2 flux to climate change differ between RCP4.5 and RCP8.5, which changes the O_2 budget and eventually influences the carbon sink. To make it clear, the contribution of each factor in Equations 1 and 2 to the carbon uptake are presented in Figure S4, from which we can see a much more variability of carbon uptake related with fossil fuel combustion and atmospheric oxygen combustion in RCP8.5 than it in RCP4.5. The discrepancies under different emission scenarios clearly reveal the vital role of human activities in the modifications of carbon sinks under climate change.

4. Conclusions

The shift in carbon cycle reflects human impacts on Earth's environments. Variations of terrestrial carbon uptake are tightly associated with groundwater changes (Missik et al., 2019), vegetation greenness (Piao, Wang, Park, et al., 2020) and global urban expansion (Chen et al., 2020; Liu et al., 2019). The ocean heat-carbon coupling found in Bronselaer and Zanna 2020 reveals the importance of ocean carbon uptake on the understanding of ocean circulation and heat uptake changes (Chen & Tung, 2014, 2016). It therefore leads to an urgency for the scientific community to focus on quantifying the variability in the carbon cycle, especially the variability in land and ocean carbon sinks (Peters et al., 2017).

In this study, we presented an alternative estimate of carbon sinks based on the oxygen budget, which exhibits an overall good agreement with the GCP but has stronger DV. Our study also discussed the human-induced impact on the carbon cycle. It is foreseeable that the influences of human-related activities on the global carbon sink will continue to increase in the future. However, as shown in our study, the future magnitude of carbon uptake could vary markedly in different RCP scenarios, suggesting the tremendous influences of anthropogenic forcing on modifications to the carbon cycle.

The estimations in this study provide a valuable complement for studies of global carbon sinks under climate change. However, our results are based on the relationships between oxygen and the carbon cycle, which are simplified into the two equations (Equations 1 and 2). An imbalance exists in the oxygen budget (Huang et al., 2018), there are systematic errors in the parametrization of oxidative ratios (Liu et al., 2020), and uncertainties occur when estimating CO_2 emissions. All of these factors contribute to a relatively large uncertainty (0.6–1.0 GtC/yr) when this method is used to estimate carbon sinks. Thus, to further understand carbon uptake and the relationships between oxygen and the carbon cycle, a better characterization of these critical processes is required for future studies.

Data Availability Statement

The air-sea O_2 flux in CMIP5 can be downloaded at https://esgf-node.llnl.gov/search/esgf-llnl/. The access of oxygen budget and atmospheric oxygen consumption data set can be obtained from Huang et al. 2018 and Liu et al, 2020, respectively. The historical atmospheric CO_2 concentrations and CO_2 emissions could be obtained from the CDIAC (https://cdiac.ess-dive.lbl.gov/). The data of projected emission pathways are available at RCP Database (http://www.iiasa.ac.at/web-apps/tnt/RcpDb). The MEI, AO, PDO, and AMO index can be downloaded in the KNMI Climate Explorer (https://climexp.knmi.nl/start.cgi).

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