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Modern air-sea flux distributions reduce uncertainty in the future ocean carbon sink

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Abstract
The ocean has absorbed about 25% of the carbon emitted by humans to date. To better predict how much climate will change, it is critical to understand how this ocean carbon sink will respond to future emissions. Here, we examine the ocean carbon sink response to low emission (SSP1-1.9, SSP1-2.6), intermediate emission (SSP2-4.5, SSP5-3.4-OS), and high emission (SSP5-8.5) scenarios in CMIP6 Earth System Models and in MAGICC7, a reduced-complexity climate carbon system model. From 2020–2100, the trajectory of the global-mean sink approximately parallels the trajectory of anthropogenic emissions. With increasing cumulative emissions during this century (SSP5-8.5 and SSP2-4.5), the cumulative ocean carbon sink absorbs 20%–30% of cumulative emissions since 2015. In scenarios where emissions decline, the ocean absorbs an increasingly large proportion of emissions (up to 120% of cumulative emissions since 2015). Despite similar responses in all models, there remains substantial quantitative spread in estimates of the cumulative sink through 2100 within each scenario, up to 50 PgC in CMIP6 and 120 PgC in the MAGICC7 ensemble. We demonstrate that for all but SSP1-2.6, approximately half of this future spread can be eliminated if model results are adjusted to agree with modern observation-based estimates. Considering the spatial distribution of air-sea CO_2 fluxes in CMIP6, we find significant zonal-mean divergence from the suite of newly-available observation-based constraints. We conclude that a significant portion of future ocean carbon sink uncertainty is attributable to modern-day errors in the mean state of air-sea CO_2 fluxes, which in turn are associated with model representations of ocean physics and biogeochemistry. Bringing models into agreement with modern observation-based estimates at regional to global scales can substantially reduce uncertainty in future role of the ocean in absorbing anthropogenic CO_2 from the atmosphere and mitigating climate change.

1. Introduction

Since the industrial revolution, emissions due to industrial and land use activities have dramatically increased atmospheric carbon dioxide concentrations. Due to sinks in the ocean and terrestrial biosphere, less than half of these emissions remain in the atmosphere. The ocean has absorbed approximately 25% of anthropogenic emissions both in recent decades and cumulatively since 1750 (Canadell *et al* 2021, Friedlingstein *et al* 2022). This means that as atmospheric CO_2 has increased approximately exponentially, there has also been a comparable increase in the magnitude of ocean carbon sink (Raupach *et al* 2014, Ridge and McKinley 2021). On millenial timescales, the ocean will absorb more than 80% of the total anthropogenic perturbation (Archer *et al* 2009, Cao and Caldeira 2010).

Detailed assessment of the ocean carbon sink's future state have largely focused on CMIP5 earth system model (ESM) projections under the RCP8.5 scenario of steadily increasing emissions through 2100 (Hoffman *et al* 2014, Schwinger *et al* 2014, Randerson *et al* 2015, McKinley *et al* 2016, Wang *et al* 2016, Fassbender *et al* 2017, Goris *et al* 2018). Without significant mitigation, the ocean will remain a strong sink for anthropogenic carbon through 2100, despite modest negative feedbacks due to ocean carbon chemistry and circulation changes. The response is similar in CMIP6 ESMs (Arora *et al* 2020).

Nearly 200 countries have signed the UNFCCC Paris Agreement, indicating a serious intent to rapidly mitigate emissions. These reductions, as well as the changed economics of renewable energy systems, are starting to shift the plausible future emission range away from the highest scenarios (Hausfather and Peters 2020). Aside from climate targets for 2030, many countries also put forward long-term targets—often net-zero CO_2 or net-zero greenhouse gas targets. Given that the ocean will continue to strongly influence the global-mean warming trajectory in the long-term, it is important to assess the future ocean carbon sink under scenarios of mitigation.

Raupach *et al* (2014) discussed the ocean sink in the context of the atmospheric fraction (AF), which is the fraction of annual fossil and land use emissions that remain in the atmosphere. They demonstrated that the near-constant AF of 0.44 from 1959–2013 cannot be explained by underlying mechanisms of the ocean and terrestrial biosphere sinks, but instead is attributable to the approximately exponential atmospheric pCO_2 growth rate. When the atmospheric pCO_2 growth rate slows, AF will be reduced, meaning that less of the emitted carbon will remain in the atmosphere (see figure SPM.7 in IPCC (2021)). For mitigation scenarios, the ratio of cumulative atmospheric load to cumulative emissions, or the cumulative atmospheric fraction (CAF) is preferable (Jones *et al* 2016) because it remains numerically well behaved as emissions approach zero. The CAF is also most directly relevant to climate outcomes that depend on the reservoir of atmospheric CO_2, not its annual fluxes (Matthews *et al* 2020).

The global-mean ocean carbon sink will weaken in absolute magnitude as atmospheric pCO_2 growth rates slow (Cao and Caldeira 2010, Jones *et al* 2016, Zickfeld *et al* 2016, Schwinger and Tjiputra 2018, McKinley *et al* 2020, Canadell *et al* 2021, Ridge and McKinley 2021). Despite a reduced absolute magnitude, as long as the ocean overturning circulation continues to expose waters with additional carbon uptake capacity to the surface, the sink will continue (Zickfeld *et al* 2016). Under mitigation scenarios, CAF estimates for the 21st century should be substantially lower with mitigation than without (Jones *et al* 2016, IPCC 2021). In other words, the ocean will be able to do proportionally more to reduce climate warming as humans increasingly mitigate emissions.

Studies to date have focused on the global-mean ocean carbon sink estimated by reduced complexity models or ESMs. Quantitative uncertainty in the magnitude of the future ocean carbon sink under mitigation scenarios has not received much attention. The global-mean ocean carbon sink is the integrated result of the anthropogenic perturbation superimposed on a background of vigorous natural fluxes (McKinley *et al* 2017, Crisp *et al* 2022). To understand why models differ, local to regional fluxes must be considered since these are the scales on which physical and biogeochemical mechanisms of natural and anthropogenic carbon fluxes occur (McKinley *et al* 2016, Fay and McKinley 2021). For anthropogenic fluxes specifically, advection and water mass transformation at regional scales dominate fluxes into (reemergence) and out of (subduction) the surface mixed layer, which is critical to the movement of anthropogenic carbon to and from the deep ocean (Bopp *et al* 2015, Iudicone *et al* 2016, Toyama *et al* 2017, Ridge and McKinley 2020). Mechanisms of future sink will also occur locally, and thus understanding why ESMs quantitatively differ in their projections requires consideration of the spatial distribution.

Ridge and McKinley (2021) studied the three-dimensional response of the ocean carbon sink to mitigation scenarios in one ESM, the Community Earth System Model Large Ensemble (Kay *et al* 2015). They found that the large-scale spatial distribution of the sink is largely conserved through 2100. The primary change is an increased or decreased amplitude of the sink in high or low emission scenarios. With strong mitigation (1.5 °C scenario), some regions that were previous sinks become sources to the atmosphere as thermocline waters with high anthropogenic carbon content are recirculated to the surface. This study investigates whether these estimates of future flux distributions are consistent across a range of ESMs.

Ocean hindcast models have been critical to the annual global carbon budget (GCB) since its inception (Hauck *et al* 2020, Friedlingstein *et al* 2022). Hindcast models are forced with observed meteorology to estimate the actual evolution of ocean physics and biogeochemistry in recent years. Yet their underlying structures and parameterizations are very similar to the ocean component models in their cousin ESMs. Thus, skill assessments for hindcast models likely provide some information about ESM fidelity. A recent assessment of long-term mean and average seasonal fluxes in the nine hindcast models used in the GCB 2020 (Friedlingstein *et al* 2020) revealed significant regional discrepancies from observation-based estimates (Fay and McKinley 2021).

A robust suite of full global coverage, monthly timescale observation-based products for surface ocean carbon content, from which air-sea CO_2 fluxes can be derived, have only recently become available (Rödenbeck *et al* 2015, Fay *et al* 2021). Though these are based on sparse data, they have high fidelity for the long-term mean and the average seasonal cycle of air-sea CO_2 fluxes (Gloege *et al* 2021). Compared to independent data, modern observation-based products represent surface ocean carbon concentrations much better than hindcast models (Hauck *et al* 2020, Bennington *et al* 2022b). Given this new observational constraint, it is important to assess how the state-of-the-art ESMs from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) suite represent modern-day mean fluxes. Do the CMIP6 ESMs demonstrate similar biases as identified for hindcast models by Fay and McKinley (2021)? What are the implications for uncertainty in projections of the future sink?

To address these issues, we analyze the ocean carbon sink response to emission scenarios with varying degrees of mitigation (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP5-3.4-OS, SSP5-8.5) from CMIP6. We also examine ocean carbon sink estimates from the reduced-complexity climate carbon cycle model, MAGICC7, that was used in the creation of the SSP scenarios (Meinshausen *et al* 2020).

2. Methods

2.1. Emissions Scenarios

We study the ocean carbon sink for 5 Shared Socioeconomic Pathway (SSP) scenarios with low emissions (SSP1-1.9, SSP1-2.6), intermediate emissions (SSP2-4.5, SSP5-3.4-OS), and high emissions (SSP5-8.5) over 2015-2100 (figures 1(a) and S1(a)). For the lower scenarios, atmospheric CO_2 concentrations in 2100 are 393.5 ppm and 445.6 ppm for SSP1-1.9 and SSP1-2.6, respectively. For the intermediate scenarios, concentrations in 2100 are 602.8 ppm and 496.6 ppm for SSP2-4.5 and SSP5-3.4-OS, respectively. And for high emissions (SSP5-8.5), the CO_2 concentration in 2100 is 1135.2 ppm (Meinshausen *et al* 2020).

2.2. CMIP6 Simulations

This study utilizes concentration-driven simulations of ESMs performed as part of the sixth phase of the CMIP6. Monthly average simulated air-sea carbon dioxide fluxes (variable name: fgco2) for the five emission scenarios were obtained from the CMIP6 archive https://esgf-node.llnl.gov/search/cmip6/, (World Climate Research Programme, 2021) (table 1). For analyses, all modeled fluxes were conservatively regridded to a regular 1° latitude by 1° longitude grid using the xesmf module in Python. Simulated fluxes are integrated in space to obtain annual air-sea carbon fluxes for each ensemble member; ensemble means are used in analysis. Ensemble-means are used to damp internal variability. For CNRM, a carbon efflux of 0.78 PgC yr^{-1} that is due to natural inputs from rivers is removed (Séférian *et al* 2019); other ESMs do not include natural river carbon fluxes.

2.3. MAGICC7

MAGICC7 is a reduced-complexity climate carbon system model (section S1.1) calibrated to emulate CMIP5 ESMs (Meinshausen *et al* 2011, 2020) and for the results shown here, the range of CMIP6 ESMs used for IPCC AR6 WG1 assessments (see Cross-Chapter Box 7.1 in IPCC AR6 WG1 (Forster *et al* 2021)). MAGICC7 simulates the land and global-mean ocean carbon sinks that occur in response to emissions. It was used to develop atmospheric carbon dioxide concentrations for the SSP scenarios (Meinshausen *et al* 2020), which were then input to the concentration-driven CMIP6 runs that we analyze here. For the comparison between the CMIP6 ensemble and MAGICC7, the probabilistic version of MAGICC7 has been calibrated to comprehensively reflect climate system response uncertainties (Forster *et al* 2021). Our comparisons are a consistency check between the ocean sink estimates from MAGICC7 and the ocean sink estimates resulting from the state-of-the-art CMIP6 suite driven with the atmospheric concentrations derived from MAGICC7.

2.4. Observation-based products

For the years 2010–2019, we compare the CMIP6 models to the currently-available ensemble of observation based products (table 2). These products are produced using machine learning and other statistical methods to extrapolate sparse pCO_2 observations to global coverage. All products estimate monthly fluxes for the 1980s to the 2020s, while two of the newest products start in 1959 (Rödenbeck *et al* 2022, Bennington *et al* 2022b). A suite of wind speed products is then used to estimate CO_2 flux (Fay *et al* 2021). These products have been shown to offer robust estimates of long-term mean CO_2 fluxes from global to regional scales (Fay and McKinley 2021, Gloege *et al* 2022, Bennington *et al* 2022b).

Observation-based products provide an estimate of the total air-sea CO_2 flux, the sum of the anthropogenic fluxes and outgassing due to the import of natural carbon from rivers (Crisp *et al* 2022). Since CMIP6 and MAGICC7 models estimate only anthropogenic fluxes, we remove the natural efflux due to rivers in each latitude band, based on the spatial distribution from Lacroix *et al* (2020) and the global total flux of +0.65 PgC yr^{-1} (Regnier *et al* 2022) (positive to the atmosphere).

2.5. Ratio of cumulative sink to cumulative emissions (CSF_{ocean})

The AF is the fraction of annual fossil and land use emissions that remain in the atmosphere

Table 1. Earth System Models used, references, number of ensemble members for each SSP scenario and color in figure 3.

Earth System Model	Reference	SSP1 1.9	SSP1 2.6	SSP2 4.5	SSP5 3.4	SSP5 8.5	Color in figure 3
ACCESS-ESM1-5	Ziehn *et al* (2020)	—	9	30	—	10	purple
CanESM5	Swart *et al* (2019)	6	—	—	—	—	orange
CNRM-ESM2-1	Boucher *et al* (2020)	5	5	10	5	5	red
IPSL-CM6A-LR	Boucher *et al* (2020)	6	6	11	2	6	blue
MIROC-ES2L	Hajima *et al* (2020)	5	3	—	—	—	pink
MPI-ESM1-2-LR	Mauritsen *et al* (2019)	—	10	10	—	10	light blue
UKESM1-0-LL	Sellar *et al* (2019)	5	16	16	5	6	green

Table 2. Observation-based products used in this study.

	Reference
CMEMS-FFNN	Denvil-Sommer *et al* (2019)
CSIR-ML6	Gregor *et al* (2019)
JENA-MLS	Rödenbeck *et al* (2022)
JMA-MLR	Iida *et al* (2021)
LDEO-HPD	Gloege *et al* (2022), Bennington *et al* (2022b)
MPI-SOMFFN	Landschützer *et al* (2020)
NIES-FNN	Zeng *et al* (2015)
pCO_2-Residual	Bennington *et al* (2022a)

(Raupach *et al* 2014). The CAF is the ratio of cumulative atmospheric load to cumulative emissions (Jones *et al* 2016). Here, we evaluate the role of the ocean sink in setting the CAF. Thus, we define a cumulative sink fraction as the ratio of cumulative land and ocean sinks to cumulative emissions (CSF = CSF_{land} + CSF_{ocean}; and CSF = 1-CAF). In this study, the ocean component (CSF_{ocean}) is the ratio of the cumulative ocean sink since 2015 to cumulative emissions since 2015.

3. Results

As emissions accumulate through 2100 (figure 1(a), S1), the cumulative ocean sink (figure 1(b)) follows a similar trajectory. With higher emissions, the ocean accumulates more carbon, and with lesser emissions, less carbon is absorbed by the ocean. However, the ratio of cumulative sink to cumulative emissions (CSF_{ocean}) has the opposite response (IPCC (2021)). With accelerating emissions (SSP5-8.5 and SSP2-4.5), the ocean accumulates between 17% and 33% of the cumulative emissions after 2015. If emission rates decline, the ocean takes up a greater portion of emitted carbon, between 39% and 112% under SSP5-3.4-OS, SSP1-2.6 and SSP1-1.9 (figure 1(c), table 3).

For each scenario, there are significant differences between the maximum and minimum predictions (figure 1(b)), with a spread of 30–50 PgC in the cumulative uptake by 2100 ocean sink in CMIP6 models (table 4) and range of 120 PgC in the MAGICC7 ensemble (table 5). In all scenarios except SSP1-2.6 for both CMIP6 and MAGICC7, this spread can be reduced by 43% to 66% if all models estimates are adjusted to have the same sink magnitude in 2020 (3 PgC yr^{-1}, Friedlingstein *et al* (2022)) (figures 1(d), S1, S2; tables 3 and 4). This adjustment is accomplished by adding to all years the difference from 3 PgC yr^{-1} in 2020 for that CMIP6 or MAGICC7 model. Consistent with ESMs tending to underestimate the modern day sink (Hoffman *et al* 2014), uptake estimates here are increased in most cases. The reduced spread occurs because maximum uptake estimates are increased less than minimum estimates (tables 4 and 5). For SSP1-2.6 in CMIP6, the maximum and minimum are increased by about the same amount.

With this adjustment, the spread in ratios of sink to emissions (CSF_{ocean}) for CMIP6 is also reduced by 57% or more in all scenarios except SSP1-2.6 (figure 1(e); table 3). For SSP1-2.6 in CMIP6, there is a bimodal distribution of the projected cumulative sink and CSF_{ocean} after the adjustment of the 2020 sink (figures 1(d) and (e)). This substantial reduction in spread, from homogenizing the present-day sink estimates, indicates that under most scenarios, half or more of future uncertainty is attributable to modern mean-state errors.

Newly available observation-based products offer the best-available constraint for mean air-sea CO_2 fluxes at basin to global scales (Gloege *et al* 2022, Bennington *et al* 2022b). To better understand the performance of the CMIP6 models suite, we compare them to the currently-available suite of products (table 2) for the 2010s (2010–2019). For this period, the large scale pattern of air-sea flux in the CMIP6 models is broadly comparable to the products (figure 2, left; S3). Outgassing occurs across much of the equatorial band, while uptake is greatest in the high northern latitudes and around 40° S.

Looking to the future, we choose one model as an example of the CMIP6 suite, IPSL-CM6A-LR, to visualize expected air-sea flux changes. Changes in other models are similar (maps not shown, zonal means are compared in figure 3). If emissions continue on a very high emission trajectory (SSP5-8.5), the ocean will take up more carbon in the 2050s than in the 2010s (figure 2, right). By the 2090s, across

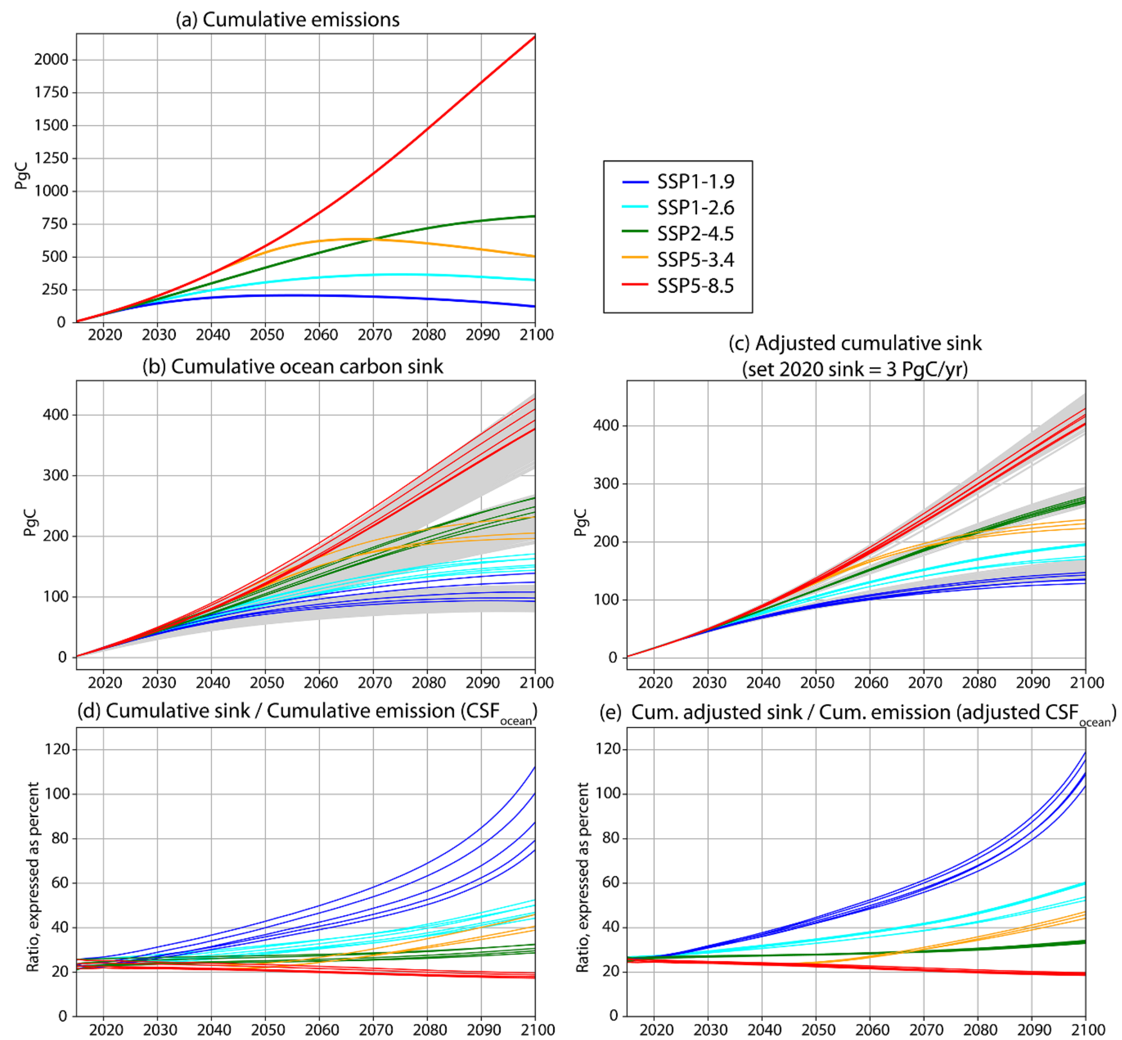

Figure 1. Cumulative CO_2 emissions and ocean sink 2015–2100 for CMIP6 (color) and MAGICC7.0 (gray). (a) Cumulative emissions from 2015, (b) Cumulative ocean carbon sink, (c) Adjusted ocean sink, with 2020 sink set to 3 PgC yr^{-1}, (d) CSF_{ocean} unadjusted, expressed as percent (e) CSF_{ocean} adjusted, expressed as percent. Emission and sink rates are shown in figure S1. For clarity, MAGICC7.0 for SSP5-3.4 and SSP1-2.6 are shown in figure S2. Adjustment for each model ensemble is accomplished by adding to all years the difference from 3 PgC yr^{-1} in 2020.

Table 3. 2100 Ocean Carbon Ratio (Sink/Emissions). CMIP6 Ensemble Means. Adjustment for each model ensemble is accomplished by adding to all years the difference from 3 PgC yr^{-1} in 2020.

CMIP6 Ratio	SSP1 1.9	SSP1 2.6	SSP2 4.5	SSP5 3.4	SSP5 8.5
Unadjusted Max	1.12	0.52	0.33	0.46	0.20
Unadjusted Min	0.75	0.44	0.29	0.39	0.17
spread	0.37	0.08	0.04	0.07	0.03
Adjusted Max	1.19	0.61	0.34	0.47	0.20
Adjusted Min	1.04	0.52	0.33	0.44	0.19
spread	0.15	0.09	0.01	0.03	0.01

the oceans south of 30° N, this pattern of greater uptake intensifies. However, there is reduced uptake compared to the 2010s north of 30° N. With intermediate emissions (SSP2-4.5) carbon uptake increases in the Southern Ocean and declines in the North Atlantic and North Pacific by the 2050s. By 2090, there is substantially reduced uptake almost everywhere, except the high latitude Southern Ocean. Under the lowest emission scenario (SSP1-1.9) by the 2050s, carbon uptake declines compared to the 2010s except in the high latitude Southern Ocean. By the 2090s, uptake further declines everywhere. In summary, change in the ocean carbon sink under future scenarios is rather spatially homogeneous, except in the Southern Ocean where the carbon uptake generally persists, and in the North Atlantic and

Table 4. 2100 Ocean Carbon Sink Spread Across CMIP6 Ensemble Means. Adjustment for each model ensemble is accomplished by adding to all years the difference from 3 PgC yr^{-1} in 2020. Spread is the maximum minus minimum at 2100.

CMIP6 Models	SSP1 1.9	SSP1 2.6	SSP2 4.5	SSP5 3.4	SSP5 8.5
Unadjusted Max (PgC)	139	171	264	232	428
Unadjusted Min (PgC)	93	144	233	196	377
spread (PgC)	46	27	31	35	51
Adjusted Max (PgC)	147	197	278	238	431
Adjusted Min (PgC)	128	170	267	223	403
spread (PgC)	19	27	11	15	27
Change of Spread (PgC)	−27	0	−20	−20	−24
Change of Spread (%)	−59%	0%	−66%	−58%	−46%

Table 5. 2100 Ocean Carbon Sink Spread Across MAGICC7.0 Ensemble Members. Adjustment for each model ensemble is accomplished by adding to all years the difference from 3 PgC yr^{-1} in 2020. Spread is the maximum minus minimum at 2100.

MAGICC7.0	SSP1 1.9	SSP1 2.6	SSP2 4.5	SSP5 3.4	SSP5 8.5
Unadjusted Max (PgC)	170	119	268	232	435
Unadjusted Min (PgC)	115	76	189	159	314
spread (PgC)	55	43	79	73	121
Adjusted Max (PgC)	211	169	294	262	456
Adjusted Min (PgC)	182	135	261	227	387
spread (PgC)	29	34	33	35	69
Change of Spread (PgC)	−26	−9	−46	−38	−52
Change of Spread (%)	−47%	−21%	−58%	−52%	−43%

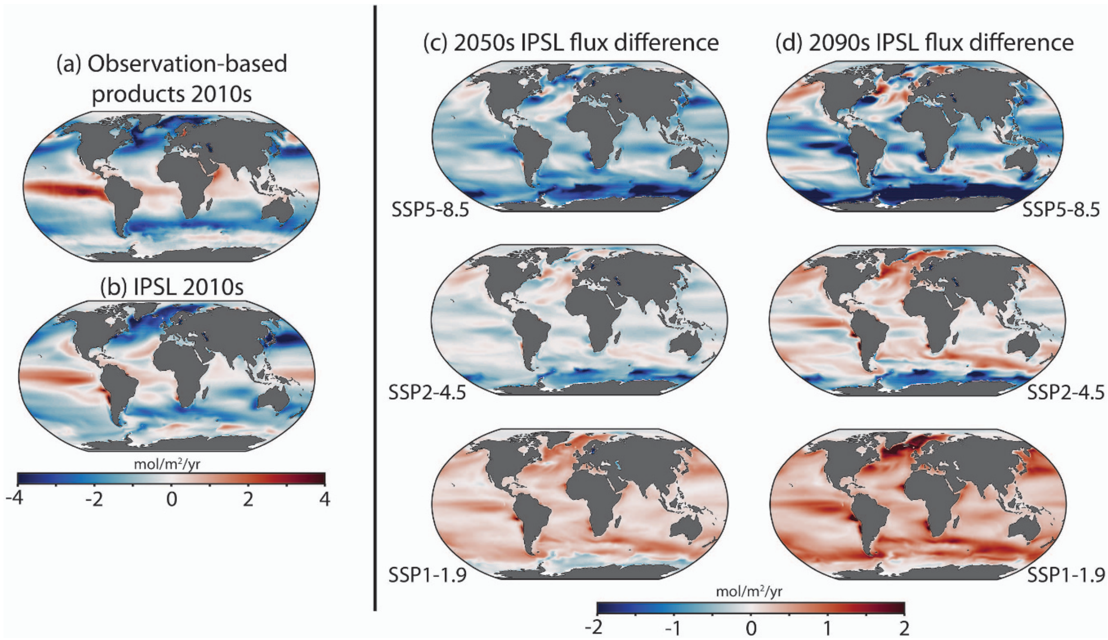

Figure 2. Mapped air-sea CO_2 fluxes, present and future difference. (a) Mean flux from 8 observation-based products (table 2) for the 2010s (2010–2019), (b) IPSL-CM6A-LR for 2010s, (c) flux change from the 2010s to the 2050s in IPSL under SSP1-1.9, SSP2-4.5 and SSP5-8.5, (d) as (c) for change to the 2090s. Means for other models in the 2010s are compared to the observation-based products in figure S3.

North Pacific where slowing uptake occurs under all scenarios.

Considering air-sea fluxes in zonal average allows for comparison of the CMIP6 suite to the modern spatial distribution (figure 3, left), as well as the future change predicted by each ESMs (figure 3, right). At latitudes north of 55° S, the CMIP6 ESMs capture the basic features of the observed flux distribution. However, the magnitude of modeled fluxes frequently lies outside the 2σ spread of the eight observation-based products. In the high latitude Southern Ocean, the observation-based products indicate a slight sink for

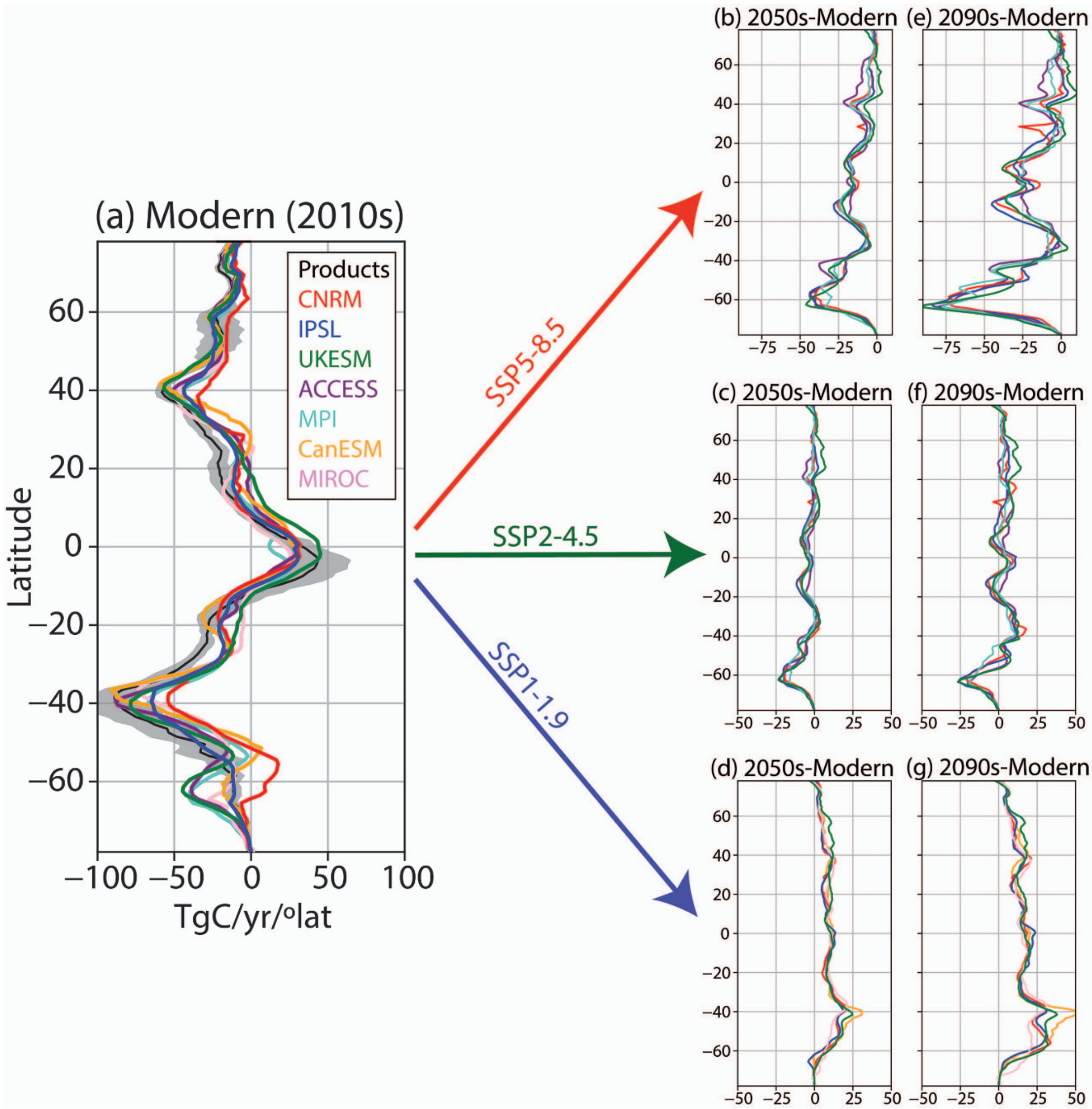

Figure 3. Zonal mean fluxes. (a) Fluxes in 2010s for 7 CMIP6 model ensemble means (colors) compared to observation-based products (black) with 2σ spread (gray), (b) change to 2050s under SSP5-8.5 (note shifted zero line), (c) change to 2050s under SSP2-4.5, (d) change to 2050s under SSP1-1.9, (e) as (b) for 2090s, (f) as (c) for 2090s, (e) as (d) for 2090s. The *x*-axis has the same absolute scale on all panels to allow direct comparison of magnitudes.

2010–2019, but the ESMs simulate from a large sink to a modest source.

In the future under both high, intermediate and low scenarios, the CMIP6 models all suggest a very similar response relative to their modern flux distribution. Under SSP5-8.5, the sink grows at all latitudes, with the strongest increase in the Southern Ocean. Under SSP2-4.5, most latitudes have a modest increase by 2050 and then a decline through 2090, while the Southern Ocean sink grows. Under SSP1-1.9, the sink reduces at all latitudes, with enhanced magnitude of reduction between 40° S and 60° S. The key point here is that despite the significant spread across the CMIP6 models for the 2010s (figure 3, left), there is strong agreement with respect to the magnitude of future sink change (figure 3, right). This finding applies to all five scenarios considered here. In other words, as for the global mean (figure 1), the modern state of the CMIP6 ESMs holds a significant portion of the uncertainty with respect to the magnitude of the future ocean sink across emission scenarios.

4. Discussion

The future ocean carbon sink will grow if emissions grown and decline if emissions decline. Yet, there remains substantial disagreement as to the magnitude of the projected ocean carbon sink within each scenario for both the CMIP6 ESM suite and the MAGICC7 ensemble (figure 1). Significant reduction in the spread of the future global-mean cumulative ocean sink can be achieved by adjusting the models to capture modern best-estimates (figure 1). Under most scenarios, 50% or more of uncertainty in the magnitude of the ocean carbon sink at 2100 can be eliminated (table 4 and 5). This indicates a strong connection between present-day and future mean-state biases. Under SSP1-2.6 in CMIP6, this adjustment leads to a tightening of projections into a bimodal distribution, but no reduction in total spread.

Global mean results from CMIP6 to MAGICC7 are in substantial agreement (figure 1), aside from the larger spread across the MAGICC7 ensemble. Homogenizing the global-mean sink to the same 2020 value also substantially reduces the future spread of MAGICC7 projections and increases the agreement with CMIP6 (figures 1(b) and (c); S1(b) and (c)). This provides another line of evidence that present-day bias is a major contributor to our future uncertainty. One notable difference between CMIP6 and MAGICC7 is that in the very high emission scenario (SSP5-8.5), the CMIP6 models suggest a slightly earlier weakening of the ocean carbon sinks around the 2080s, whereas MAGICC7 ensemble members tend to plateau at this time (figure S1). This difference may be due to reduction in the ocean overturning circulation that occurs in CMIP6 at this time (Liu *et al* 2022). While MAGICC7 does parametrize changes in the ocean's overturning circulation, these changes do not directly affect the ocean's carbon cycle response.

As noted in previous analyses (Jones *et al* 2016, IPCC 2021), the percentage of future emissions that will be stored in the ocean is strongly dependent on the emissions trajectory (figure 1(d)). We show the uncertainty in estimates of CSF_{ocean} can also be substantially reduced by addressing discrepancies in estimates of present-day fluxes (figure 1(e)). Under SSP1-1.9 by 2100, cumulative emissions since 2015 and until the point of the net-zero emissions are around 209 PgC until 2055 and are then reduced again to 124 PgC by the end of the century due to net CO_2 removals (i.e. negative emissions) after 2055. With our proposed adjustment to the modern best-estimate, we would predict that all net cumulative emissions by 2100 would go into the ocean (128–147 PgC). Without adjustment, the predicted uptake has a much broader range (93 to 139 PgC) that would leave up to 12% of cumulative emissions in the atmosphere (figures 1(b) and (c); table 4). The difference in these predictions illustrates the value of reducing prediction uncertainty.

For CMIP6, there are substantial regional biases against modern observation-based data products. Zonal-mean fluxes from CMIP6 frequently lie outside the 2σ spread of the observation-based products (figure 3), a finding is consistent with recent regional assessment of related ocean hindcast models (Fay and McKinley 2021). While this finding is clear, the drivers of modeled mean-state biases are difficult to pinpoint. Air-sea CO_2 fluxes are the local emergent property of modeled representations of ocean circulation and biogeochemistry (Crisp *et al* 2022). Many studies have compared the mean, seasonal and interannual variability in air-sea CO_2 fluxes across models and to data-based estimates (Schuster *et al* 2013, McKinley *et al* 2017, Mongwe *et al* 2018, Gruber *et al* 2019, Hauck *et al* 2020, Fay and McKinley 2021, Fu *et al* 2022). These studies have identified biases and concluded that there is a need to improve model representations of ocean circulation, ecosystems, and terrestrial carbon fluxes into the ocean. However, a single dominant driver of model biases has not been identified. In-depth analysis of individual models will be required to identify the required development steps.

Spatial patterns of air-sea CO_2 exchange do not change substantially through the 21st century (figure 2), which is consistent with previous analysis of the CESM Large Ensemble (Ridge and McKinley 2021). While emissions increase, model regions of influx increase and regions of efflux decrease in magnitude (figure 2). There is some disagreement across models as to change in the northern middle to high latitudes under SSP5-8.5 (figure 3). Prior studies suggest modeled physical processes that could cause some of this spread. In the previous version of CESM under high emissions (RCP8.5), the future North Atlantic experiences large freshwater fluxes that increasingly limit carbon uptake (Ridge 2020, Ridge and McKinley 2020). Differential responses of the Atlantic Meridional Overturning Circulation and deep southward transport of anthropogenic carbon may also contribute to these differences (Yool *et al* 2021, Liu *et al* 2022).

We demonstrate clear links between the future and the modern mean state of the ocean carbon sink in CMIP6 models and MAGICC7, and the future and the modern zonal distribution of the sink in CMIP6. This finding is consistent with Terhaar *et al* (2022) who propose to constrain CMIP6 ocean sink estimates using three observational constraints related to the modern mean ocean circulation and carbon chemistry. Previous analyses of CMIP5 models under high emission scenarios also pointed to the forward propagation of modern mean state errors (Hoffman *et al* 2014, Wang *et al* 2016). Future model development work can use newly-available observation-based products (table 2) as a target for regional mean fluxes in the modern era. This approach should lead to substantial reductions in uncertainty of future projections of the ocean carbon sink.

We propose that, in order to substantially reduce uncertainty in the future ocean carbon sink under a range of plausible emission scenarios, regional mean air-sea CO_2 fluxes from the newly-available suite of observation-based products should be used as a target for ocean biogeochemical model development. At the same time, it is important to emphasize the substantial uncertainty that remains in observation-based estimates. This is true if the global mean ocean carbon sink is quantified for a single year or for a decade: 3.0 ± 0.4 PgC yr^{-1} (1σ) for 2020 (Friedlingstein *et al* 2022); 2.5 ± 0.6 PgC yr^{-1} (1σ) for 2010–2019 (Friedlingstein *et al* 2020; figure 5.12 of Canadell *et al* 2021). Uncertainties at regional scales are even larger proportions of the mean (figure 3, left). The sparsity of ocean carbon observations drives much of the uncertainty in observation-based estimates (Bushinsky *et al* 2019, Gloege *et al* 2021). At the same time as models are improved toward the observational constraints that are now available, tighter observational constraints should be developed. Observations can also provide the basis for a post-simulation correction (Gloege *et al* 2022, Bennington *et al* 2022b). Improving both observation-based estimates and models will better constrain the global carbon cycle, which in turn will better support the climate policymaking process (Peters *et al* 2017).

5. Conclusion

The future ocean carbon sink will grow in absolute magnitude as future carbon emissions grow, and decline in magnitude as emissions decline. However, the proportion of future cumulative emissions that get absorbed by the ocean will be much greater if mitigation occurs. As emissions decline, the proportion of cumulative emissions absorbed by the ocean could be as high as 120%. But as long as emissions continue to rise, the ocean will accumulate only 20%–30%.

While there is consensus across models as to these qualitative behaviors of the future ocean sink, significant quantitative uncertainties remain across all emission scenarios. These uncertainties can be substantially reduced by refining ocean models and the ocean components of ESMs to better represent the modern flux distribution that observation-based products can now constrain. Going forward, improving modeled representations of the modern ocean carbon sink offers a tractable path forward to improving ocean and global carbon cycle projections, and thus the trajectory of future climate change.

Data availability statement

The data used here are from the CMIP6 simulations performed by various modeling groups and publicly available from the CMIP6 archive: https://esgf-node.llnl.gov/search/cmip6/, WCRP (2021), last access: 20 July 2021. The carbon emissions scenarios within this article were obtained from the SSP database hosted by the IIASA Energy Program at https://tntcat.iiasa.ac.at/SspDb. MAGICC7 is available for download at https://magicc.org/download/magicc7 with the data used in this study being available at the following URL/DOI: 10.5281/zenodo.7679402.

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