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Hybrid model estimate of the ocean carbon sink from 1959 to 2022

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Abstract. The ocean takes up around one quarter of anthropogenically emitted carbon and is projected to remain the main carbon sink once global temperatures stabilize. Despite the importance of this carbon sink, estimates of its strength over the last decades remain uncertain, mainly due to too few and unevenly sampled observations and shortcomings in ocean models and their setups. Here, I present a hybrid model estimate of the annually averaged ocean carbon sink from 1959 to 2022 by combining the higher-frequency variability of the annually averaged estimates of the carbon sink from ocean models in hindcast mode and the long-term trends from fully coupled Earth System Models. Ocean models in hindcast mode reproduce the observed climate variability, but their spin-up strategy likely leads to too weak long-term trends, whereas fully coupled Earth System Models simulate their own internal climate variability but better represent long-term trends. By combining these two modelling approaches, I keep the strength of each approach and remove the respective weaknesses. This hybrid model estimate of the ocean carbon sink from 1959 to 2022 is 125±8 Pg C and is similar in magnitude but 70% less uncertain than the best estimate of the Global Carbon Budget.

1 Introduction

The ocean is a major natural sink of anthropogenic carbon (Broecker et al., 1979; Sarmiento et al., 1992) and took up around one quarter of carbon emissions from fossil fuels and land use change over the last decades (Friedlingstein et al., 2023; Terhaar et al., 2022; Müller et al., 2023; DeVries et al., 2023). Moreover, the ocean will continue taking up carbon over the 21st century (Terhaar et al., 2022) and beyond when temperatures are eventually stabilizing (Silvy et al., 2024). Despite the importance of the ocean carbon sink for the global carbon cycle and hence the global climate, large uncertainties exist with respect to the magnitude, variability, and trends of the ocean carbon sink (DeVries et al., 2023; Terhaar et al., 2024; Friedlingstein et al., 2023).

Observation-based annually-resolved estimates of the ocean carbon sink are built on direct observations of the partial pressure of CO_2 (pCO_2) at the ocean surface (Fay et al., 2021). While being built on observations is a strength of these observation-based pCO_2 products, it is also their weakness. As observations are scarce in space and time, they must be extrapolated by methods relying among others on artificial intelligence and machine learning, for example neural networks

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

(Landschützer et al., 2015). However, even these cutting-edge extrapolation methods introduce biases in the strength of the decadal variability (Gloege et al., 2021) and trends (Hauck et al., 2023; Terhaar, 2024). The data scarcity and uneven spacing in the past is impossible to overcome and the question was raised if the different methods of extrapolating these observations have "hit the wall" (Gregor et al., 2019).

An alternative to observation-based pCO_2 products are global ocean biogeochemical models (GOBMs) that are forced with historical atmospheric reanalysis data, atmospheric CO_2, and radiative forcing from other radiative agents. As GOBMs are forced with these historical data, they represent the observed internal climate variability at the ocean surface and hence the high-frequency variability of the annually averaged ocean carbon sink, i.e., inter-annual to sub-decadal variability. However, differences in the simulated carbon sink by GOBMs are caused by differences in the simulated circulation and carbonate chemistry in these models (Terhaar et al., 2024), as well as different ways of setting up these GOBMs, e.g., the lengths of the spin-up or different atmospheric CO_2 during the pre-industrial spin-up (Terhaar et al., 2024). Moreover, using atmospheric forcing from sometime between 1959 and present, the period when atmospheric reanalysis data is provided, for the pre-industrial spin-up leads to a too warm pre-industrial ocean and hence too weak transient warming in GOBMs (Huguenin et al., 2022) and too weak deoxygenation (Takano et al., 2023). This too warm pre-industrial ocean and too weak ocean warming may also influence the ocean carbon sink and its trends through biases in the base state and transient changes in the stratification, solubility, or carbonate chemistry of the ocean. However, the sign and magnitude of that effect remains still unclear.

Another option to estimate the annually resolved ocean carbon sink are fully coupled Earth System Models (ESMs) that are also forced with historical atmospheric CO_2 and radiative forcing from other radiative agents but dynamically simulate their atmosphere. Being dynamically coupled, ESMs do not simulate the phase of the observed internal climate variability and hence not the high-frequency variability of the annually averaged ocean carbon sink. However, ESMs from the most recent phase 6 of the coupled model intercomparison project (CMIP6) are all set up in a common way, having the same atmospheric CO_2 during the pre-industrial spin-up and long enough spin-ups that allow the simulated ocean to reach its own equilibrium (Séférian et al., 2016). Furthermore, their pre-industrial atmospheric and ocean temperatures in ESMs are colder than their respective historical temperatures so that the simulated transient ocean warming aligns with observed ocean warming (Takano et al., 2023). Finally, the simulated global ocean carbon sink could be adjusted for their biases in the simulated ocean circulation and carbonate chemistry with observations (Terhaar et al., 2021, 2022). Thus, ESMs from CMIP6 can be considered to robustly simulate the long-term trends of the ocean carbon sink and the externally-forced decadal variability, which is mostly driven by changes in the atmospheric CO_2 growth rate (Terhaar, 2024; McKinley et al., 2020).

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

As both model estimates will not overcome their respective weaknesses in the near future, I here propose a new hybrid model estimate of the ocean carbon sink combining the inter-annual and sub-decadal variability of the ocean carbon sink from GOBMs and the externally forced decadal variability and long-term evolution of the ocean carbon sink from ESMs. The combined estimate uses the strength and removes the weaknesses of the respective model estimates.

2 Results

2.1 A new hybrid model estimate

The 10 GOBMs from the Global Carbon Budget 2023 simulate a global ocean carbon sink from 1959 to 2022 of various strengths (Friedlingstein et al., 2023) (Fig. 1a, c) but the flux anomaly with respect to the mean simulated carbon sink over the entire period is almost indistinguishable across these GOBMs (Fig. 1b, d). Small common differences in the anomalies exist in 1985 and 1998 for the GOBMs NorESM1-OCv1.2 (Schwinger et al., 2016) and MPIOM-HAMOCC6 (Lacroix et al., 2021b) (Fig. 1b), likely because both use the NCEP reanalysis data (Kanamitsu et al., 2002) to force the simulations and not the JRA55-do (Tsujino et al., 2018) or ERA5 reanalysis datasets (Hersbach et al., 2020) as the other simulations do. Furthermore, the ACCESS (CSIRO) model (Law et al., 2017) simulates slightly weaker anomalies at the beginning of the simulation and stronger anomalies at the end of the simulations resulting in a larger trend of the anomalies over the entire period (Fig. 1b), although the models set-up is not different to the others (Friedlingstein et al., 2023). Nevertheless, the overall strong agreement in simulated anomalies of the global ocean carbon sink across these 10 GOBMs as expressed by the small multi-model standard deviation leads to small uncertainties of the multi-model mean estimate of the high-frequency variability of the simulated global ocean carbon sink by GOBMs (Fig. 1d).

As there small inter-model differences in the simulated high-frequency variability of the global ocean carbon sink by the GOBMs and as it has been shown that ESMs largely agree in the magnitude and long-term trends of the global ocean carbon sink after adjusting for biases in ocean circulation and carbonate chemistry (Terhaar et al., 2022) and that the multi-model mean of ESMs can represent the externally forced decadal trends (Li and Ilyina, 2018; Terhaar, 2024), I here combine both model estimates to create a new hybrid model estimate of the global ocean carbon sink (Fig. 2c, Table A1). The high-frequency variability was here extracted by removing a spline fit (Enting, 1987) from the simulated carbon sink estimate from each GOBM separately (Friedlingstein et al., 2023) (Fig. 2b). The low-frequency variability and long-term trends were calculated by fitting a spline fit (Enting, 1987) to the bias-adjusted simulated carbon sink from each ESM separately (Terhaar et al., 2022) (Fig. 2a). The ESMs were forced with historical forcing until 2014 and with forcing from the Shared Socioeconomic Pathways 1-2.6 (SSP1-2.6) (Riahi et al., 2017) after 2014 as the atmospheric CO_2 under that SSP (Meinshausen et al., 2020) is closest but still slightly above the observed atmospheric CO_2 (Lan et al., 2024). The uncertainty of the hybrid estimate is the combination of the multi-model standard deviation of the high-frequency variability from

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

GOBMs and that of the long-term trends from ESMs, as well as the uncertainty from the spline fit (see Appendix for more details).

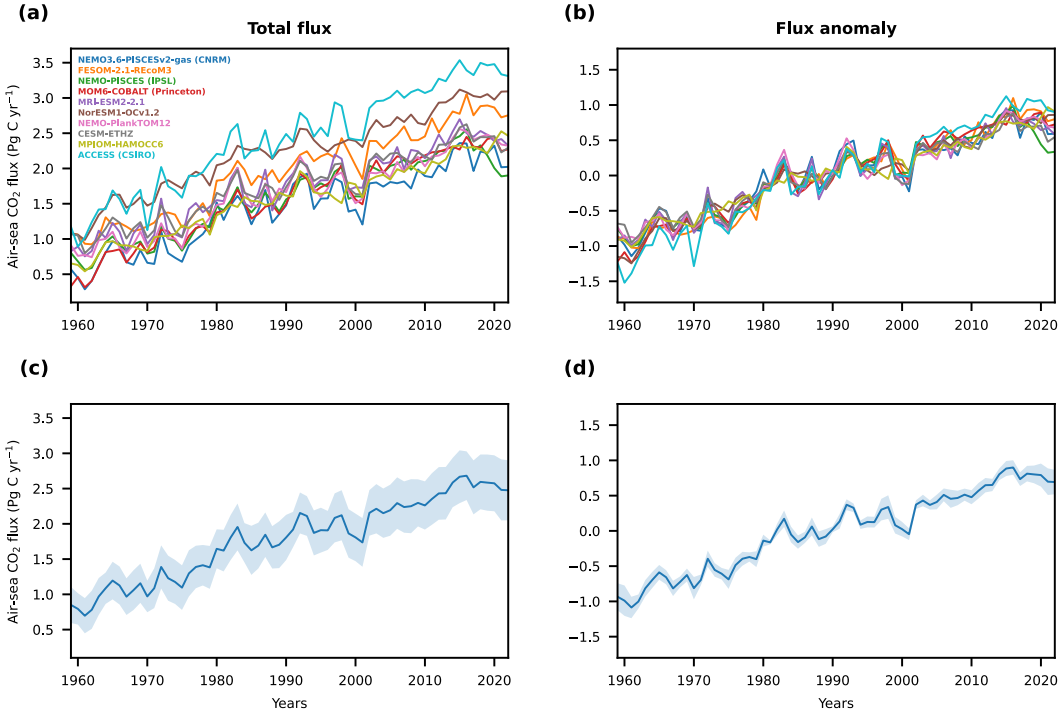


Figure 1: Global ocean carbon sink and its anomaly as simulated by global ocean biogeochemical models. The global ocean carbon sink as defined by the Global Carbon Budget 2023 (Friedlingstein et al., 2023) and **(a)** simulated by 10 global ocean biogeochemical models as well as **(c)** the multi-model mean and standard deviation. In addition, **(b)** the anomaly of the ocean carbon sink for the 10 global ocean biogeochemical models with respect to the mean flux from 1959 to 2022 in the respective GOBM, as well as **(d)** the multi-model mean and standard deviation of that anomaly are shown.

The ocean carbon sink estimated by this hybrid model estimate from 1959 to 2022 is 125±8 Pg C (Fig. 1c, Table A1). It increases from 1.00±0.10 Pg C yr^{-1} in the 1960s to 2.78±0.16 Pg C yr^{-1} in the 2010s. The increase of the ocean carbon sink slows down in the 1990s (decadal trend of 0.10 Pg C yr^{-1} dec^{-1}) and accelerates afterwards (decadal trends of 0.55 and 0.56 Pg C yr^{-1} dec^{-1} in the 2000s and 2010s) as expected from the trends in atmospheric CO_2 and the eruption of Mount Pinatubo in the early 1990s (McKinley et al., 2020; Fay et al., 2023; Terhaar, 2024).

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

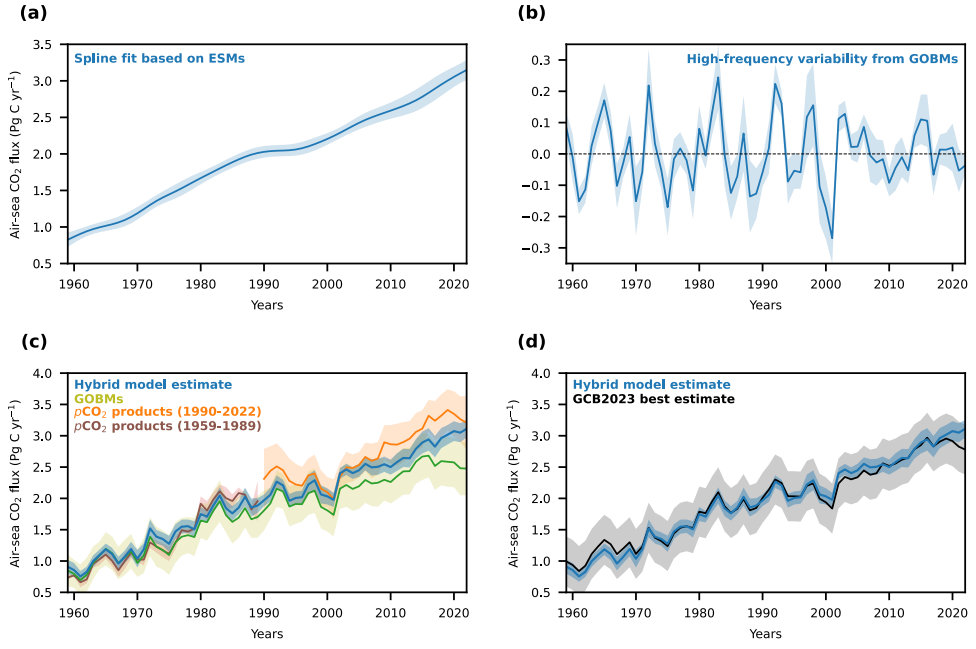


Figure 2: Hybrid model estimate of the ocean carbon sink and its two components. (a) A spline fit to the ocean carbon sink as simulated by ESMs from Earth System Models and adjusted for biases in the ocean circulation and carbonate chemistry (Terhaar et al., 2022) as well as **(b)** the high-frequency variability of the ocean carbon sink anomalies as simulated by GOBMs that was derived after removing a spline fit to the simulated anomalies. The multi-model mean estimates are shown as blue lines and the multi-model standard deviation as blue shading. **(c)** The hybrid estimate is then the sum of the timeseries in **(a)** and **(b)**. The uncertainties of the hybrid model estimates are the combined uncertainties of **(a)** and **(b)** plus the uncertainty from the spline fit (see Appendix for details). In addition, estimates from the GOBMs (olive line and shading for multi-model mean and standard deviation) and the pCO_2 products from the Global Carbon Budget 2023 (Friedlingstein et al., 2023) (orange lines and shading show the multi-product mean and standard deviations over 8 pCO_2 products from 1990 to 2022, brown lines show the shading for multi-product mean and standard deviation over 2 pCO_2 products from 1959 to 2021) are shown for comparison in **(c)** and the best estimate from the Global Carbon Budget 2023 (black line and shading for multi-model mean and uncertainty as reported in the Global Carbon Budget 2023) in **(d)**.

2.2 Comparison to previous estimates of the global ocean carbon sink

The new hybrid model estimate of the global ocean carbon sink differs from previous estimates by pCO_2 products and GOBMs in terms of magnitude, trend, and variability. The ocean carbon sink in the hybrid model estimate is 10% (11 Pg C) larger than the estimate from GOBMs for the period from 1959 to 2022 (Fig. A1a). The absolute difference between both estimates has some variability over time but remains on average the same until 2014. After 2014, the hybrid estimate becomes steadily larger until and the difference rises from 0.24 Pg C yr^{-1} (8%) averaged from 2005 to 2014 to 0.65 Pg C yr^{-1} (26%) in 2022 (Fig. A1a). The difference before 2014 is likely due to a bias in the GOBMs in their simulated circulation and carbonate chemistry (Terhaar et al., 2024) that also exists in ESMs but was corrected for (Terhaar et al., 2022). After 2014, the increasing difference may either be explained by slightly different trajectories of atmospheric CO_2 in ESMs under SSP1-

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

2.6 and the historical atmospheric CO_2. Based on a previously identified relationship between changes in the trend of atmospheric CO_2 and trends in the ocean carbon sink (Terhaar, 2024), the trend in the ocean carbon sink in the ESMs from 2013 to 2022 is likely around 0.2 Pg C yr^{-1} dec^{-1} too large. The difference in the atmospheric CO_2 trajectory thus explains around half of the difference of both estimates after 2014. The other half might be due to biased transient warming caused by the spin-up strategy (Takano et al., 2023; Huguenin et al., 2022) and hence a bias in the evolution of the ocean carbon sink. However, to quantify such an effect, simulations with GOBMs following the spin-up strategy by Huguenin et al. (2022) would have to be performed.

Compared to pCO_2 products, the hybrid estimate of the global ocean carbon sink is only 3% (1 Pg C) larger for the period from 1959 and 1989 than the two pCO_2 products that provide estimates before 1990 and is 8% (7 Pg C) smaller than all 8 pCO_2 products on average for the period from 1990 to 2022 (Fig. A1b). The difference in the early 1990s and after 2000 might be due to overly strong decadal variability that has been shown to exist at least in one pCO_2 product (Gloege et al., 2021). This explanation is further supported by two further studies, one that showed that extrapolating unevenly spaced observations in space and time lead to overly strong trends in the estimates of the ocean carbon sink by pCO_2 products (Hauck et al., 2023) and one that used ESMs to show that the trends in pCO_2 products lies outside of what can be expected based on changes in the atmospheric CO2 growth rate and climate variability (Terhaar, 2024). After 2019, the difference between the hybrid model estimate and the pCO_2 products decreases again, likely because of the above discussed difference in observed atmospheric CO_2 and the prescribed atmospheric CO_2 in ESMs after 2014 following SSP1-2.6.

The hybrid estimate is almost identical to the best estimate of the ocean carbon sink provided by the Global Carbon Budget 2023 (Fig. 2d), which represents the average of the estimate by GOBMs and the pCO_2 products. The hybrid estimate thus corroborates this best estimate by the Global Carbon Budget 2023. However, instead of simply averaging two independent estimates, the hybrid model estimate uses the best available knowledge to remove the weaknesses of each model estimate and to only keep the strengths. As the hybrid model estimate explains the differences, its uncertainty is around 70% smaller than that of the best estimate of the Global Carbon Budget 2023.

3 Conclusion

Overall, the hybrid model estimate of the global ocean carbon sink combines two so far mostly separated model classes and successfully manages to account for the shortcomings in the different global ocean carbon sink estimates, i.e., the low bias in GOBMs due to the spin-up and the representation of the ocean circulation and carbonate chemistry and the bias towards too large decadal variability and trends in the pCO_2 products. The same method could also be applied to derive hybrid model estimates of regional and monthly-resolved estimates of the ocean carbon sink.

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

Although this hybrid estimate provides an improvement to existing estimates of both model classes, GOBMs (Friedlingstein et al., 2023; DeVries et al., 2023) and ESMs (Terhaar et al., 2022), it still has shortcomings. One shortcoming is the forcing of ESMs with SSPs after 2014 that leads to slightly too high carbon sink estimates from 2015 to 2022. This shortcoming could be overcome if ESMs were run with observed atmospheric CO_2 after the historical forcing from CMIP6 ends in 2014. Another shortcoming is that all ESMs start in 1850 and are spun-up with atmospheric CO_2, which leads of an underestimation of the ocean carbon sink (Bronselaer et al., 2017) of around 0.05-0.10 Pg C yr^{-1} for ESMs for the period from 1959 to 2022 (Terhaar et al., 2024). This underestimation could be removed if ESMs were to start before the industrial revolution and the associated increase in atmospheric CO_2.

The need for a hybrid model estimate of the global ocean carbon arose due to shortcomings in both model classes. As ESMs will always simulate an internal climate variability in a different phase than the observed one, this estimate remains a necessary fix until GOBMs are set up so that they can overcome their current weaknesses. To overcome current weaknesses, I recommend testing if an improved spin-up strategy that accounts for the difference in atmospheric and surface ocean temperatures as well as radiation between the pre-industrial times and the mid 20th century, for example as proposed by Huguenin et al. (2022), may explain differences in the trends of the ocean carbon sink between GOBMs and ESMs. Furthermore, previous suggestions provided by Terhaar et al. (2024), such as a long enough spin-up and an early starting date and an associated atmospheric CO_2 during the spin-up, will likely also improve the carbon sink estimates by GOBMs. Once GOBMs are set-up in a common way, emergent constraints could also be used in GOBMs to correct for biases in the ocean circulation and carbonate chemistry as it was done for ESMs regionally and globally (Goris et al., 2018; Terhaar et al., 2021, 2022, 2020; Bourgeois et al., 2022; Vaittinada Ayar et al., 2022). Until then, the here provided hybrid model estimate of the global ocean annually averaged carbon sink circumvents these shortcomings in GOBMs at present with the help of ESMs and thus provides a robust estimate of the global ocean carbon from 1959 to 2022.

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

4 Appendix

4.1 Estimates of the ocean carbon sink

Estimates of the ocean carbon sink, defined as the change in the globally integrated air-sea CO_2 flux since pre-industrial times due to increasing CO_2 and climate change, from pCO_2 products, GOBMs, and ESMs was used. Estimates of the global ocean carbon sink were directly taken for 8 pCO_2 products (Table A2) and 10 GOBMs (Table A3) from the Global Carbon Budget 2023 (Friedlingstein et al., 2023) (https://doi.org/10.18160/gcp-2023). In addition, the best estimate from the Global Carbon Budget 2023 was also directly taken from https://doi.org/10.18160/gcp-2023. For ESMs, estimates of the ocean carbon sink were calculated for 14 ESMs under historical forcing until 2014 and SSP1-2.6 from 2015 to 2022 following Terhaar et al. (2022) (Table A4).

The carbon sink estimates from ESMs were adjusted for biases in each model's circulation and carbonate chemistry as described by Terhaar et al (2022). The same predictors as in Terhaar et al (2022) were used. For the target variable, however, I here did not use the ocean carbon sink estimates from 1997 to 2014 but the ocean carbon sink from 1959 to 2022, the period for which this new hybrid model estimate provides annual ocean carbon sink estimates. To calculate the adjustment factors, I here used SSP5-8.5 after 2014 for which 3 more ESMs provide output (Table A4) as the higher number of ESMs makes the fit between predictors and target variables more robust (r^2 decreases from 0.82 to 0.63 when only using the 14 ESMs that provide output for SSP1-2.6).

4.2 Separating high-frequency variability and long-term trends

The high-frequency variability and long-term trends of the annually averaged global carbon sink in ESMs and GOBMs were separated by fitting a spline following Enting (1987) to the respective ocean carbon sink estimate. The fit itself represents the long-term trends and decadal variability and the residual, the difference between the original time series and the spline fit, is the defined as the high-frequency variability. I here used an openly available python implementation of this spline fitting method (https://github.com/friedrichs-repo/enting_spline) with a cut-off period of 15 years. The cut-off period describes the period where 50% of the signal is attenuated by the spline. 15 years was chosen so guarantee that all sub-decadal variability is removed from the original timeseries.

To test the sensitivity to the choice, a hybrid model estimate was also calculated using an 11-year running mean instead of an spline using Enting (1987) with a cut-off period of 15 years. The hybrid model estimate using the 11-year running mean is almost indistinguishable from the estimate using Enting (1987) with a cut-off period of 15 years but differs at the start of the

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

end of the timeseries (Fig. A2). The running mean flattens of at the ends of timeseries with strong trends because neither the smaller values before the beginning of the timeseries nor the potentially larger values after the end of the timeseries are included. Thus, I here decided to rely on the spline fit from Enting (1987).

The spline fit itself also comes with uncertainties due to the choice of the cutoff period. Here, I calculated the hybrid model estimate using cutoff periods from 10 to 20 years (Fig. A3). The resulting hybrid model estimate is insensitive to the choice of the cutoff period. This insensitivity shows that it is essential that the inter-annual variability is taken from the GOBMs and the long-term trends from the ESMs. The variability in between, however, can be taken from either GOBMs or ESMs as the decadal variability and trends of the ocean carbon sink are mainly driven by the change in the trends in atmospheric CO_2, i.e., the growth rate of atmospheric CO_2 (McKinley et al., 2017, 2020; Fay et al., 2023; Terhaar, 2024), and other external forcing such as volcanoes (McKinley et al., 2020; Fay et al., 2023; Frölicher et al., 2013), which are prescribed in GOBMs and ESMs (until 2014) based on observations.

4.3 Uncertainty estimates

The uncertainties of the hybrid model estimate of the ocean carbon sink are a combination of the multi-model standard deviation of the high-frequency estimates from the GOBMs and the long-term trends from the ESMs, as well as the uncertainty from the choice of the cutoff period that was used to calculate the spline (Table A1). The uncertainty of the cutoff period was calculated as the standard deviation of all 11 estimates with cutoff periods from 10 to 20 years (Fig. A3). The different uncertainties are added using error propagation, i.e., by calculating the square root of the sums of the squares of each uncertainty. The difference in the atmospheric CO_2 in the ESMs under SSP1-2.6 after 2014 was not explicitly added as an uncertainty but discussed as a caveat in the manuscript. All uncertainties are given as 1-σ.

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

240

Table A1: Annually averaged best estimates and uncertainties (1-σ) of the global ocean carbon sink by the hybrid model estimate. All units are in Pg C yr^{-1}.

Year	Best estimate	Uncertainty from GOBMs	Uncertainty from ESMs	Uncertainty from cutoff period	Combined uncertainty
1959	0.91	0.05	0.10	0.01	0.11
1960	0.85	0.08	0.08	0.01	0.11
1961	0.75	0.04	0.07	0.02	0.09
1962	0.83	0.04	0.07	0.02	0.08
1963	1.00	0.06	0.07	0.01	0.09
1964	1.09	0.05	0.07	0.01	0.09
1965	1.19	0.06	0.07	0.02	0.09
1966	1.11	0.06	0.07	0.02	0.10
1967	0.96	0.07	0.08	0.02	0.11
1968	1.07	0.05	0.09	0.02	0.10
1969	1.19	0.07	0.09	0.01	0.12
1970	1.04	0.11	0.09	0.00	0.14
1971	1.19	0.05	0.08	0.00	0.10
1972	1.52	0.12	0.08	0.01	0.14
1973	1.39	0.07	0.08	0.02	0.11
1974	1.35	0.06	0.08	0.02	0.11
1975	1.27	0.09	0.09	0.02	0.13
1976	1.47	0.06	0.10	0.02	0.12
1977	1.55	0.05	0.10	0.01	0.11
1978	1.56	0.05	0.10	0.00	0.11
1979	1.51	0.09	0.09	0.00	0.13
1980	1.75	0.07	0.08	0.01	0.11
1981	1.71	0.04	0.08	0.02	0.09
1982	1.89	0.07	0.07	0.03	0.11
1983	2.05	0.10	0.07	0.03	0.13
1984	1.84	0.10	0.08	0.01	0.13
1985	1.76	0.09	0.08	0.00	0.12
1986	1.85	0.07	0.08	0.02	0.11
1987	2.03	0.12	0.08	0.03	0.15
1988	1.85	0.12	0.08	0.03	0.14
1989	1.89	0.08	0.08	0.03	0.12
1990	1.97	0.05	0.08	0.02	0.09
1991	2.06	0.08	0.08	0.00	0.11
1992	2.27	0.06	0.08	0.01	0.10
1993	2.21	0.04	0.08	0.02	0.09
1994	1.96	0.07	0.08	0.03	0.11

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

1995	2.01	0.06	0.08	0.02	0.10
1996	2.02	0.05	0.09	0.02	0.10
1997	2.22	0.13	0.09	0.01	0.16
1998	2.29	0.13	0.09	0.00	0.16
1999	2.06	0.12	0.08	0.01	0.14
2000	2.03	0.10	0.08	0.02	0.13
2001	1.98	0.08	0.08	0.02	0.11
2002	2.40	0.04	0.08	0.01	0.09
2003	2.46	0.04	0.08	0.01	0.09
2004	2.40	0.04	0.08	0.01	0.09
2005	2.45	0.05	0.09	0.00	0.10
2006	2.55	0.04	0.10	0.01	0.10
2007	2.50	0.08	0.10	0.01	0.13
2008	2.50	0.07	0.10	0.01	0.13
2009	2.55	0.06	0.11	0.01	0.12
2010	2.50	0.04	0.11	0.01	0.12
2011	2.58	0.07	0.12	0.01	0.14
2012	2.65	0.06	0.13	0.01	0.15
2013	2.64	0.04	0.14	0.02	0.15
2014	2.79	0.04	0.15	0.03	0.16
2015	2.89	0.08	0.15	0.03	0.18
2016	2.94	0.08	0.16	0.02	0.18
2017	2.83	0.07	0.16	0.01	0.17
2018	2.96	0.05	0.15	0.00	0.16
2019	3.02	0.05	0.15	0.01	0.16
2020	3.07	0.08	0.14	0.01	0.16
2021	3.05	0.07	0.13	0.02	0.15
2022	3.11	0.03	0.14	0.02	0.14

Table A2: Observation-based pCO_2 products from the Global Carbon Budget 2023 (Friedlingstein et al., 2023).

***p*CO2 product**	**Time period in GCB 2023**	**References**
CMEMS-LSCE-FFNNv2	1990-2022	(Chau et al., 2022)
JMA-MLR	1990-2022	(Iida et al., 2021)
LDEO-HPD	1959-2022	(Gloege et al., 2022; Bennington et al., 2022)
MPI-SOMFFN	1990-2022	(Landschützer et al., 2016)
NIES-ML3	1990-2022	(Zeng et al., 2022)
OS-ETHZ-GRaCER	1990-2022	(Gregor and Gruber, 2021)
Jena-MLS	1959-2022	(Rödenbeck et al., 2014, 2022)
UPEx-Watson	1990-2022	(Watson et al., 2020)

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

Table A3: Global ocean biogeochemical models from the Global Carbon Budget 2023 (Friedlingstein et al., 2023).

Model name	References
NEMO3.6-PISCESv2-gas (CNRM)	(Berthet et al., 2019; Séférian et al., 2019)
FESOM-2.1-REcoM2	(Gürses et al., 2023)
NEMO-PISCES (IPSL)	(Aumont et al., 2015)
MOM6-COBALT (Princeton)	(Liao et al., 2020)
MRI-ESM2-2	(Nakano et al., 2011; Urakawa et al., 2020)
MICOM-HAMOCC (NorESM-OCv1.2)	(Schwinger et al., 2016)
NEMO-PlankTOM12	(Wright et al., 2021)
CESM-ETHZ	(Doney et al., 2009)
MPIOM-HAMOCC6	(Lacroix et al., 2021a)
ACCESS (CSIRO)	(Law et al., 2017)

Table A4: List of Earth System Models that were used in this study.

Model name	Available SSPs	References
ACCESS-ESM1-5	SSP1-2.6 / SSP5-8.5	(Ziehn et al., 2020)
CanESM5	SSP1-2.6 / SSP5-8.5	(Swart et al., 2019; Christian et al., 2022)
CanESM5-CanOE	SSP1-2.6 / SSP5-8.5	(Swart et al., 2019; Christian et al., 2022)
CESM2	SSP1-2.6 / SSP5-8.5	(Danabasoglu et al., 2020)
CESM2-WACCM	SSP1-2.6 / SSP5-8.5	(Danabasoglu et al., 2020)
CMCC-ESM2	SSP1-2.6 / SSP5-8.5	(Lovato et al., 2022)
EC-Earth3-CC	SSP5-8.5	(Döscher et al., 2022)
GFDL-CM4	SSP5-8.5	(Held et al., 2019)
GFDL-ESM4	SSP1-2.6 / SSP5-8.5	(Dunne et al., 2020; Stock et al., 2020)
IPSL-CM6A-LR	SSP1-2.6 / SSP5-8.5	(Boucher et al., 2020)
MIROC-ES2L	SSP1-2.6 / SSP5-8.5	(Hajima et al., 2020)
MPI-ESM1-2-HR	SSP1-2.6 / SSP5-8.5	(Gutjahr et al., 2019)
MPI-ESM1-2-LR	SSP1-2.6 / SSP5-8.5	(Mauritsen et al., 2019)
MRI-ESM2-0	SSP5-8.5	(Yukimoto et al., 2019)
NorESM2-LM	SSP1-2.6 / SSP5-8.5	(Tjiputra et al., 2020; Seland et al., 2020)
NorESM2-MM	SSP1-2.6 / SSP5-8.5	(Tjiputra et al., 2020; Seland et al., 2020)
UKESM1-0-LL	SSP1-2.6 / SSP5-8.5	(Sellar et al., 2020)

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

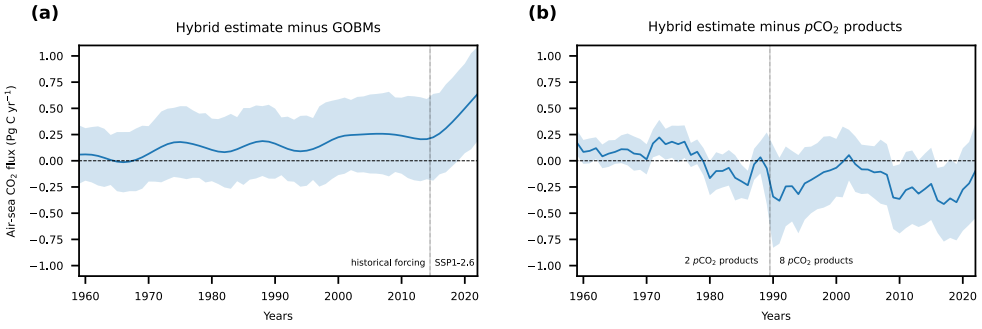
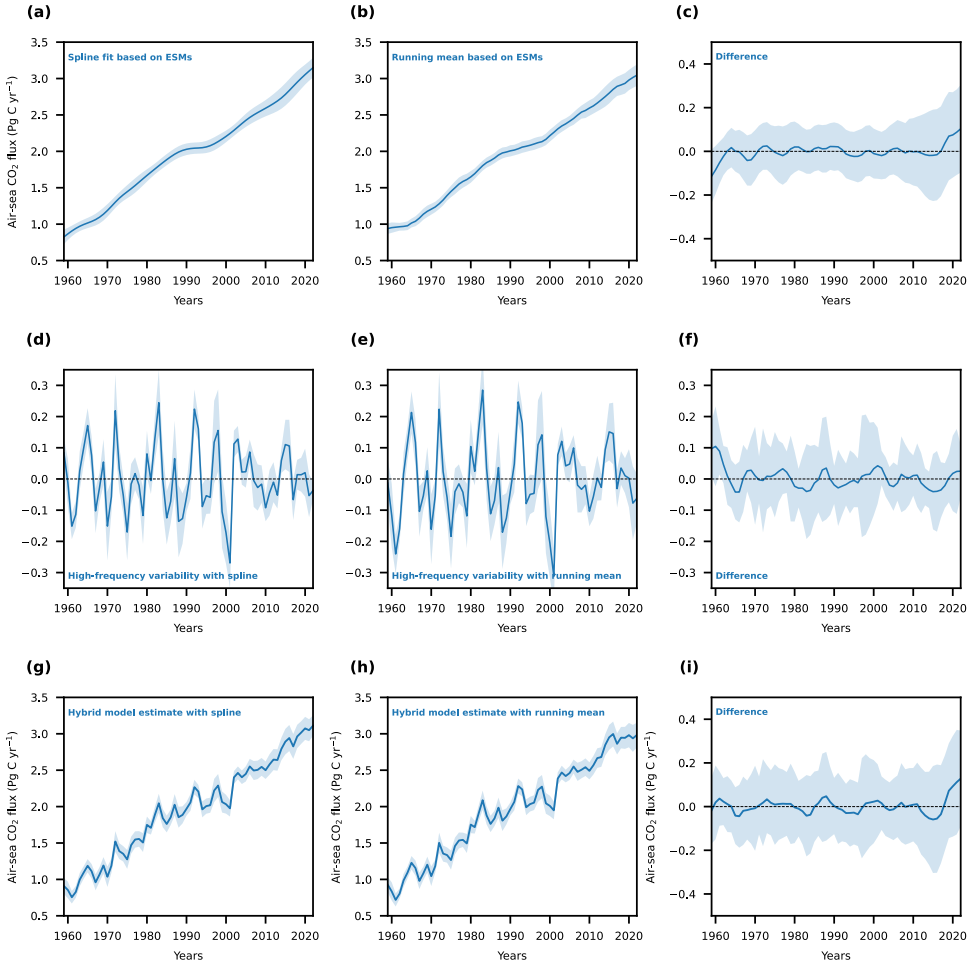


Figure A1: Difference in estimates of the global ocean carbon sink between the new hybrid estimate and estimates from GOBMs and pCO_2 products. Difference between the hybrid estimate of the global ocean carbon sink and the estimates **(a)** from GOBMs and **(b)** pCO_2 products from the Global Carbon Budget 2023 (Friedlingstein et al., 2023). The blue lines indicate the mean difference and the uncertainties show the combined uncertainties from the two respective estimates.

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024



265 **Figure A2: Difference in estimates of the global ocean carbon sink between the new hybrid estimate and estimates from GOBMs and pCO_2 products.** Difference between the hybrid estimate of the global ocean carbon sink and the estimates **(a)** from GOBMs and **(b)** pCO_2 products from the Global Carbon Budget 2023 (Friedlingstein et al., 2023). The blue lines indicate the mean difference and the uncertainties show the combined uncertainties from the two respective estimates.

270

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

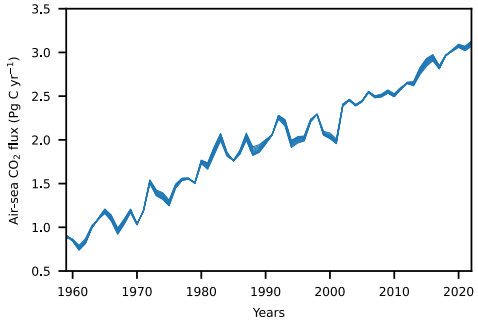


Figure A3: The global ocean carbon sink estimate by the hybrid model estimate using different cutoff periods. Each of the 11 lines here represents the global ocean carbon sink estimate by the hybrid model estimate using cutoff periods from 10 to 20 years.

275

https://doi.org/10.5194/egusphere-2024-2171
Preprint. Discussion started: 24 July 2024

Data availability

The Earth system model output used in this study is available via the Earth System Grid Federation (https://esgf-node.ipsl.upmc.fr/projects/esgf-ipsl/, last access: 1 June 2022). The data from the Global Carbon Budget 2023 is available here (https://doi.org/10.18160/gcp-2023). The best estimate and uncertainties of the annually averaged estimate of the global carbon sink provided as estimated by the here presented hybrid model estimate are presented in table A1. If hybrid model estimate is too long for tables in other studies, please reference it as GOBM-ESM estimate.

Competing interests

The author has declared that he has no competing interests.

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https://doi.org/10.5194/egusphere-2024-2171
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