Valuing the ocean carbon sink at the country level

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Article

Keywords:

Posted Date: August 11th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3232579/v1

Additional Declarations: There is **NO** Competing Interest.

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Abstract

The ocean carbon sink annually removes about a third of anthropogenic CO_2 emissions, reducing climate change damage and CO_2 abatement costs. While land sinks have been integrated into climate policies, the ocean sink has not—for good reason, since the former stores carbon within the boundaries of a given country, while the latter removes carbon from the atmosphere as global commons. However, the question of the value of the oceanic carbon sink remains, and how it should be attributed when comparing a coastal country with a large exclusive economic zone (EEZ) to a landlocked country. Here, we demonstrate different approaches to valuing the ocean carbon sink, comparing a climate-change-damage-based approach with an abatement-based and market-based approach. We use a high-resolution carbon flux dataset (0.25x0.25 degrees) to estimate the oceanic carbon sinks and sources in coastal areas. We assign a net sink of 1.72 GtC proportional to countries with negative carbon fluxes in their EEZs. In our calculation, the annual value of the global ocean sink ranges from 66 B USD to 1432 B USD.

Main

Since the preindustrial era, the ocean has absorbed roughly 40 percent of anthropogenic fossil fuel and industrial CO_2 emissions (Friedlingstein et al. 2021), reducing the climate change impacts of anthropogenic CO_2 emissions and providing, in addition to many other services, a considerable societal value as a carbon sink. In turn, the questions arise as to what the value of this natural ocean sink is, whether the regional (coastal) variation in the ocean sink should be attributed to the corresponding neighboring countries, and (if at all) how the ocean sink should enter climate policies and national contributions determined under the Paris Agreement (Karstensen et al. 2021). Here, we derive ocean sink data at the country level, accounting for the oceanic sinks in the Exclusive Economic Zones (EEZs) of various countries and compare a climate-change-damage-based approach with an abatement-cost-based approach to valuing the ocean sink. The former utilizes information on the social cost of carbon (SCC), i.e., the marginal damage of an additional ton of CO_2 being released into the atmosphere, and in turn the marginal avoided damage of an additional ton of CO_2 being absorbed by a carbon sink, at the country level. The latter utilizes information on marginal abatement costs at the country level. In a stylized and optimized global climate policy, the two approaches would coincide, since the marginal abatement cost would be equated across countries (either via a global carbon tax or international emissions trading) at the level of the SCC, i.e., the sum of SCCs for all countries. In reality (and in applied work), the two approaches do not, since climate policies are not derived from a global cost-benefit analysis but as part of national priorities and a political bargaining process, with different countries using different instruments to reduce their CO_2 and other greenhouse gas emissions. Hence, applying the two approaches to valuing the ocean sink can produce conflicting outcomes depending on the stringency of the overall climate policy ambition.

Applying the climate-damage-based approach places the valuation of the ocean carbon sink in the natural capital and inclusive wealth (IW) framework (Arrow et al. 2003, Fenichel et al. 2016, Dasgupta 2021, Bastien-Olvera and Moore 2021). Inclusive wealth is defined as the aggregate value of all natural and human-made capital stocks, valued at their shadow prices. Change in (natural) capital stocks assessed with shadow prices provides a basis for sustainability assessment, following a concept of weak sustainability (Rickels et al. 2014). IW assessments (used to measure sustainable development) are applied in the United Nations (UN) Inclusive Wealth Reports (UNU-IHDP UNEP 2012, 2014, Managi and Kumar 2018), while the USA has recently launched a new draft National Strategy to improve its statistical description of economic activity and development by accounting for the wealth contributions of water, air, and other natural assets following the IW approach (The White House 2022). In terms of valuing the ocean carbon sink, applying the shadow value of atmospheric carbon, i.e., the social cost of carbon, allows us to measure the damage avoided, i.e., the social cost of (atmospheric) carbon that would be avoided. Canu et al. (2015) apply this approach to value the carbon sink in the Mediterranean Sea, estimating an annual value between 127 and 1722 M EUR (2011)/year. Such an estimate yields valuable insights into the global contribution to welfare, since all countries benefit from the public good that the ocean carbon sink represents. However, different countries are affected differently by climate change and hence it is assumed that climate change will result in wealth reallocations (Fenichel et al. 2016). Bertram et al. (2021) account for this aspect by applying the country social cost of carbon (CSCC) in their assessment of coastal blue carbon ecosystem sequestration. They show that in particular, countries with relatively large coastal ecosystems but relatively low domestic CSCC provide substantial wealth transfers to the rest of the world. Carbon sequestration in Australia's coastal ecosystems has a global value of about 25 B USD per year, of which almost 23 B USD are received abroad. However, the total amount of annual carbon sequestration attributable to coastal ecosystems (e.g. mangroves etc.) is rather small (Bertram et al. 2021 assume annual sequestration of about 81.21 MtC).[1] Hence the carbon sink wealth contribution of coastal ecosystems is small compared to their total wealth contribution via ecosystem services, the former being estimated to be about 190.7 B USD/year and the latter to be about 31.6 T USD/year (Bertram et al. 2021 and Costanza et al. 2014, respectively). Obviously, the value of the coastal ocean carbon sink is also small compared to the total ocean carbon sink. In this regard, we consider each country's entire EEZ, extending to a maximum of 200 nautical miles (370.4 km) away from the coastline. We discuss different CSCC estimates in our climate-change-damage-based evaluation approach and based on EEZ carbon uptake.

The uncertainty about climate-change impacts on ecosystems, human health and economies was the main reason for defining temperature ceilings as part of the Paris Agreement (keeping the global temperature increase well below 2 °C above pre-industrial levels and ideally limiting it to 1.5 °C). Hence, the aim is to cost-efficiently achieve compliance with the temperature ceiling, while the temperature ceiling determines the marginal abatement cost, i.e., the CO_2 price. The CO_2 price determines the (marginal) value of the (ocean) sink, while the SCC (i.e., the shadow price of the constraint) can be interpreted as the willingness to pay for compliance with such a temperature ceiling (Rogelj et al. 2018, Cross-Chapter Box 5). Accordingly, implemented CO_2 tax levels or observed CO_2 prices on emissions trading markets can be used as information for valuation purposes. However, only a few regions provide this information, and even where CO_2 pricing instruments are in place, like for example in the European Union, they cover only a fraction of the emissions in the region. As such, this

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[1] Note that we report physical amounts in C (i.e., carbon) and economic prices in CO_2, i.e., USD/tCO2. When making reference to value estimates from the literature, we use the unit and currency year as reported in the figure. The monetary quantities in our analysis are presented in 2020 USD at market exchange rates.

price information can be used to point out the value of marginal CO_2 removal if integrated into such a pricing regime but is not in itself sufficient for a global assessment. Hence, economic models are used to derive the information about regional CO_2 prices. Rehdanz et al. (2006) assessed the integration of the ocean anthropogenic carbon sink into a hypothetical carbon market, using model-based estimates for the anthropogenic part of the regional ocean sink provided by Wetzel et al. (2005). Overall, they considered an aggregated ocean sink of anthropogenic carbon of about 0.44 GtC (relative to preindustrial levels), attributed to the individual EEZs of 36 countries. They investigated the potential reduction in abatement costs of including up to 10 percent of their ocean carbon sink within the EEZ for compliance in their reduction targets and emissions trading, showing that a country like Australia would experience a relatively large reduction in abatement costs and even net revenues under international trade if it were allowed to sell ocean sink credits. This indicates that abatement-cost-based pricing information used to value the ocean sink should not be confused with a potential price which would be paid if (part) of the ocean sink were integrated into a CO_2 permit market. The latter would require various additional monitoring and accounting requirements in addition to a discussion on whether the ocean sink is a global common or should be (partially) attributed to countries. However, a partial integration into markets does not necessarily imply double-accounting to compensate for emissions reductions but could also be interpreted as an obligation if the ocean carbon sink weakened. For example, Liu et al. (2023) show that the net uptake of the ocean could decrease since in the simulations a decrease in the physical carbon pump, linked to a decrease in the Meridional Overturning Circulation, could not be compensated for with a simultaneous occurring increase in the biological carbon pump. In addition to a market-based evaluation, we also consider a market integration, the latter under the assumption that countries need to increase their emissions reduction targets to compensate for reduced ocean uptake.

2 Results

Our assessment is based on a unified global ocean partial pressure of carbon dioxide (pCO_2) climatology with 0.25° by 0.25° spatial resolution created by merging an f open-ocean (1° by 1° resolution) and coastal- ocean (0.25° by 0.25° resolution) gridded layer (Landschützer et al. 2020a, b). Further, our assessment is based solely on the surface ocean flux of carbon estimated from the pCO_2 and using the year 2006 as reference (Figure 1). Other sinks, such as burial of particulate carbon in sediments, are not considered (for further details on the calculations see Methods).

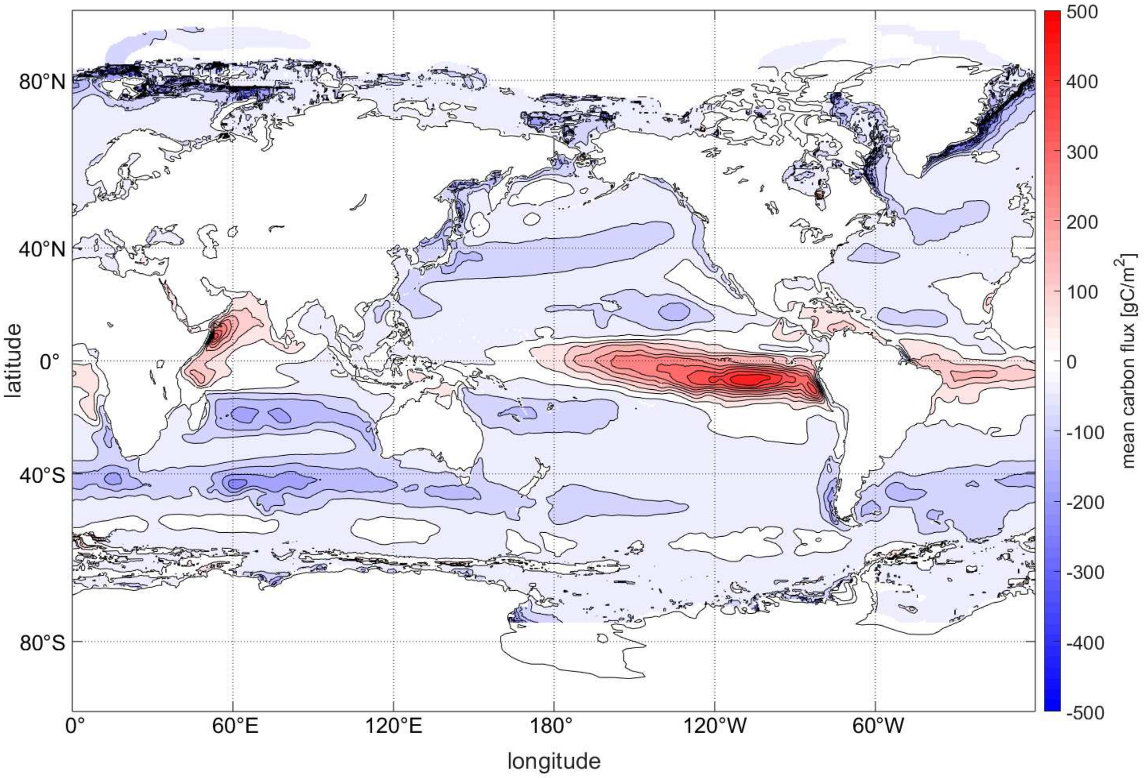

Figure 1: Geographical distribution of the surface ocean carbon flux (g C m^{-2}y^{-1}) data estimated from the Landschützer et al. (2020a) pCO2 data and referenced to the year 2006 atmospheric carbon concentration.

Overall, we resolve the ocean using 568 grid cells with even (0.25°) latitudinal and longitudinal spacing; thus, the area of each cell is latitude dependent. The high seas cover 213 million km^2 in 26 cells. The remaining 542 grid cells are assigned to 236 territories. Of these 236 territories, 225 are assigned to countries comprised by 147 mainland entries, 11 islands and exclaves (e.g. the Azores and Alaska, respectively), and 67 oversea territories (e.g. Greenland), while 11 territories (e.g. Antarctica) were not assigned to any country. The ocean flux data at the territory level is shown in Figure 2a and for Europe in particular in Figure 2b.

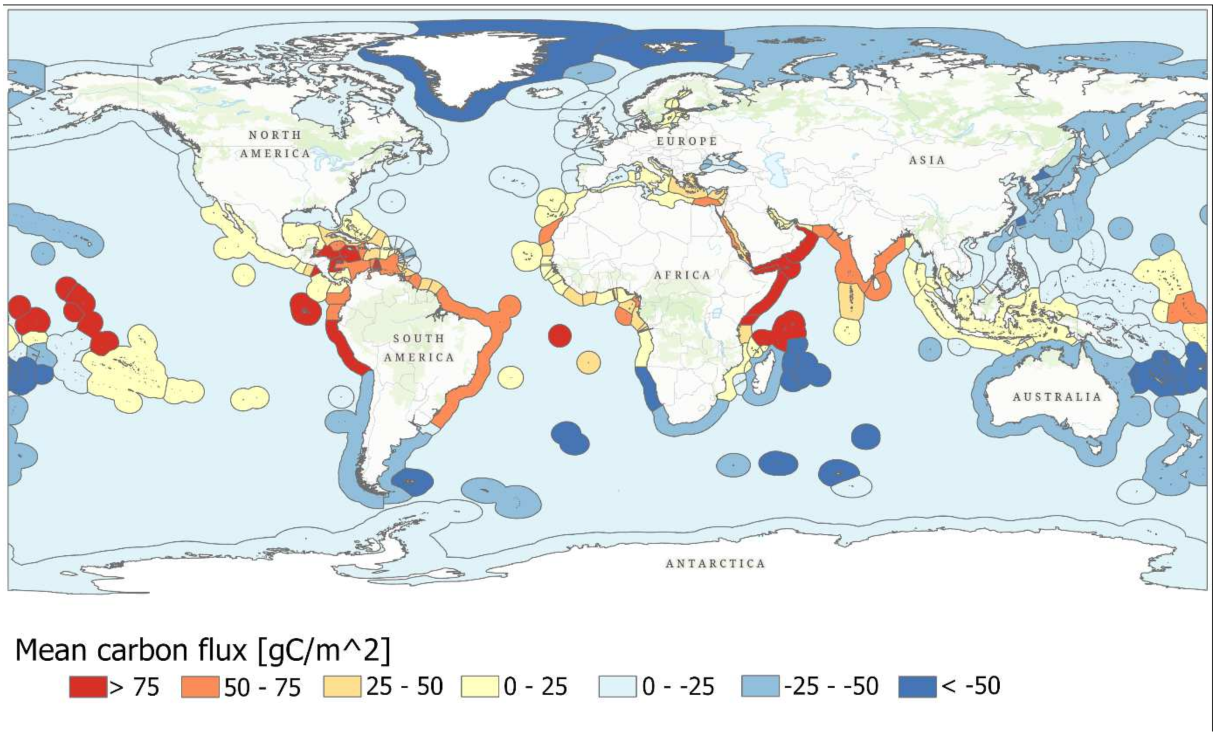

Figure 2a: Mean EEZ ocean carbon flux (sink and source, g C $m^{-2}y^{-1}$) for all countries estimated from the Landschützer et al. (2020a) pCO2 data and referenced to the year 2006 atmospheric carbon concentration.

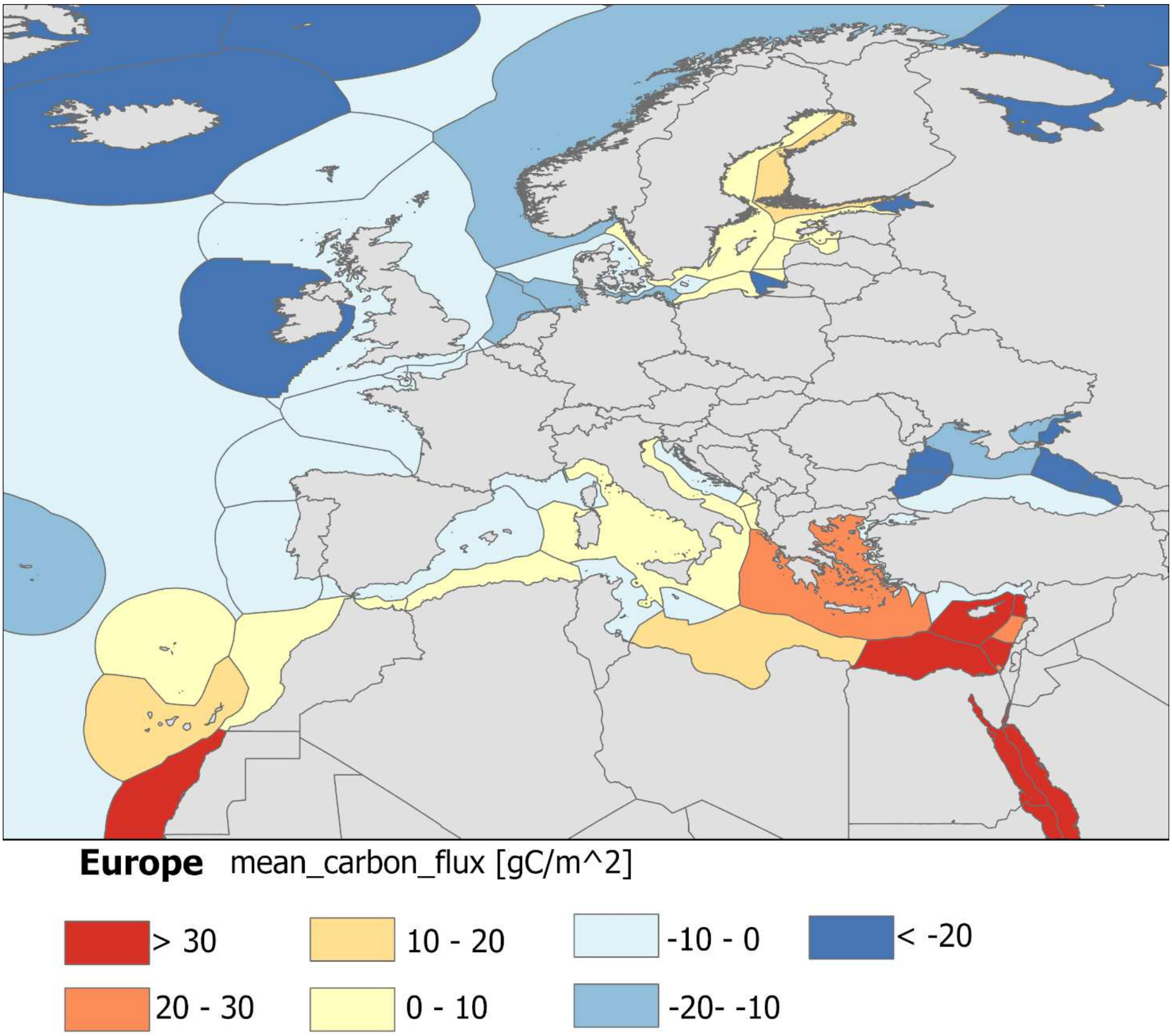

Figure 2b: Mean EEZ ocean carbon flux (sink and source, g C m^{-2}y^{-1}) for Europe estimated from the Landschützer et al. (2020a) pCO2 data and referenced to the year 2006 atmospheric carbon concentration.

The total net carbon sink from our dataset estimated from the Landschützer et al. (2020) pCO$_2$ data is 1.63 Gt Cy^{-1} (Std 0.03) in reference to the year 2006 atmospheric carbon concentration. We combine this ocean and coastal carbon uptake with carbon uptake in coastal blue carbon ecosystems, mangroves, saltmarshes and seagrass meadows, obtained from Bertram et al. (2021), which yields a net ocean carbon sink of 1.72 GtC y^{-1} (Std 0.03). Note that the gross ocean carbon uptake is 4.73GtCy^{-1} (Std 0.03), which is offset by sources (loss of ocean carbon) from outgassing amounting to 3.02 GtC y^{-1} (Std 0.03) (Figures 1 and 2). Hence, there are several countries with a net carbon source in their EEZs. Figure 3 shows the ten countries with the largest carbon sources in their EEZs, and the ten countries with the largest carbon sinks in their EEZs, differentiating between the carbon flux within national borders and oversea territories, also including EU29 (i.e., including Iceland and Norway). The reason for considering EU29 is that the 27 European Union (EU) countries and those of the European Economic Area (here, Iceland and Norway; we did not include Liechtenstein) have a common climate policy and in turn an aggregate emissions reduction target in the UNFCCC context. Accordingly, we consider the aggregated EU countries but report individual EU country data where appropriate. Figure 3 shows that Denmark benefits from its oversea carbon sink around Greenland, while other European countries like Norway and France benefit from the carbon sinks in their oversea territories. Overall, oversea territories result in a net carbon sink of 0.95 GtC y^{-1} for their sovereign countries, with the EU27 benefitting from the largest amount, 0.88 GtC y^{-1}.

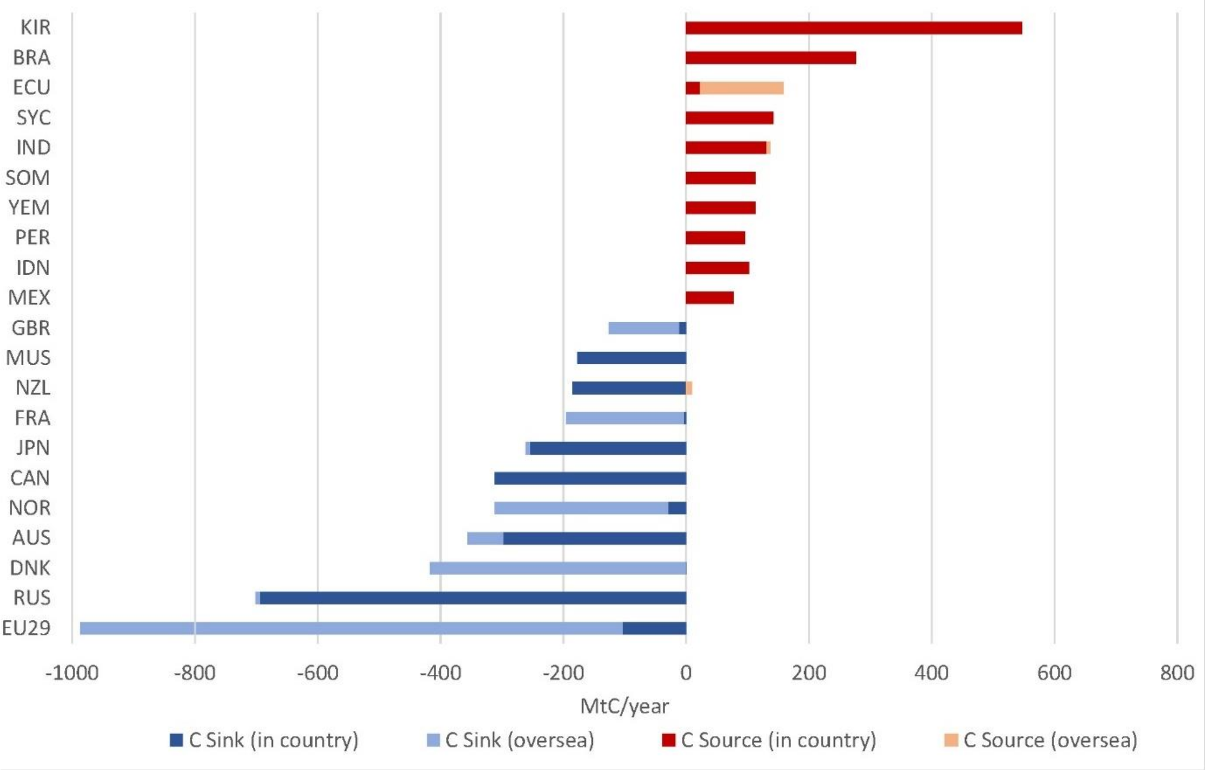

Figure 3: Top 10 countries in terms of ocean carbon sources (outgassing, in red) and ocean carbon sinks (uptake, in blue), respectively. The ocean carbon sources and sinks related to any oversea territories are also shown (KIR: Kiribati, BRA: Brazil, ECU: Ecuador, SYC: Seychelles, IND: India, SOM: Somalia, YEM: Yemen, PER: Peru, IDN: Indonesia, MEX: Mexico, GBR: UK and Northern Ireland, MUS: Mauritius, NZL: New Zealand, FRA: France, JPN: Japan, CAN: Canada, NOR: Norway, AUS: Australia, DNK: Denmark, RUS: Russian Federation, EU29: EU27+Norway and Iceland).

The highest carbon source (outgassing) is estimated for Kiribati (KIR) (Figure 3), an island nation in the tropical Pacific Ocean, with approximately 726 km^2 land area and a 3,550,000-km^2 EEZ located in the

Pacific upwelling area. Almost all of Kiribati's waters are considered to be carbon sources (based on the surface pCO_2 field estimate used here) and would contribute a negative value, i.e., a global cost if the country were held responsible for its ocean carbon sources.

Not all outgassing regions are assigned to countries (Figure 1) and hence open ocean outgassing (which amounts in net terms to 78.81 MtC/year in our dataset) would remain unassigned in a purely country-based assessment. Hence, we assume that any valuation of the ocean carbon sink would acknowledge the global commons character of the ocean sink in that only the net carbon sink would be considered. Accordingly, we attribute the net carbon sink of 1.72 Gt C proportionally to countries with negative ocean carbon flux in their EEZs. More precisely, countries with a negative EEZ ocean carbon flux (including oversea territories) are assigned a fraction of the total net sink value, while those with a positive EEZ carbon flux (like Kiribati) are assigned no share (i.e., they are assessed as if they had no EEZ carbon sink). Under these criteria, a total of 63 countries with a net sink are also considered in our economic valuation (the full list is provided in Table ST1, including countries with a positive ocean flux, i.e., outgassing, which are not assigned an ocean sink). It is also of interest to compare for the ten countries, including the aggregated value for EU countries (EU29), with the largest ocean sink (Figure 4) the relation to their net emissions, i.e., the gross fossil fuel and industrial emissions (Friedlingstein et al. 2021) after deducting the attributed ocean sink. We find that, despite their large attributed ocean sinks, regions like the EU29, Russia and Japan remain net carbon emitters. In contrast, countries with large (attributed) ocean sinks but low carbon emissions like Denmark or New Zealand are, in net terms, would be net sink countries.

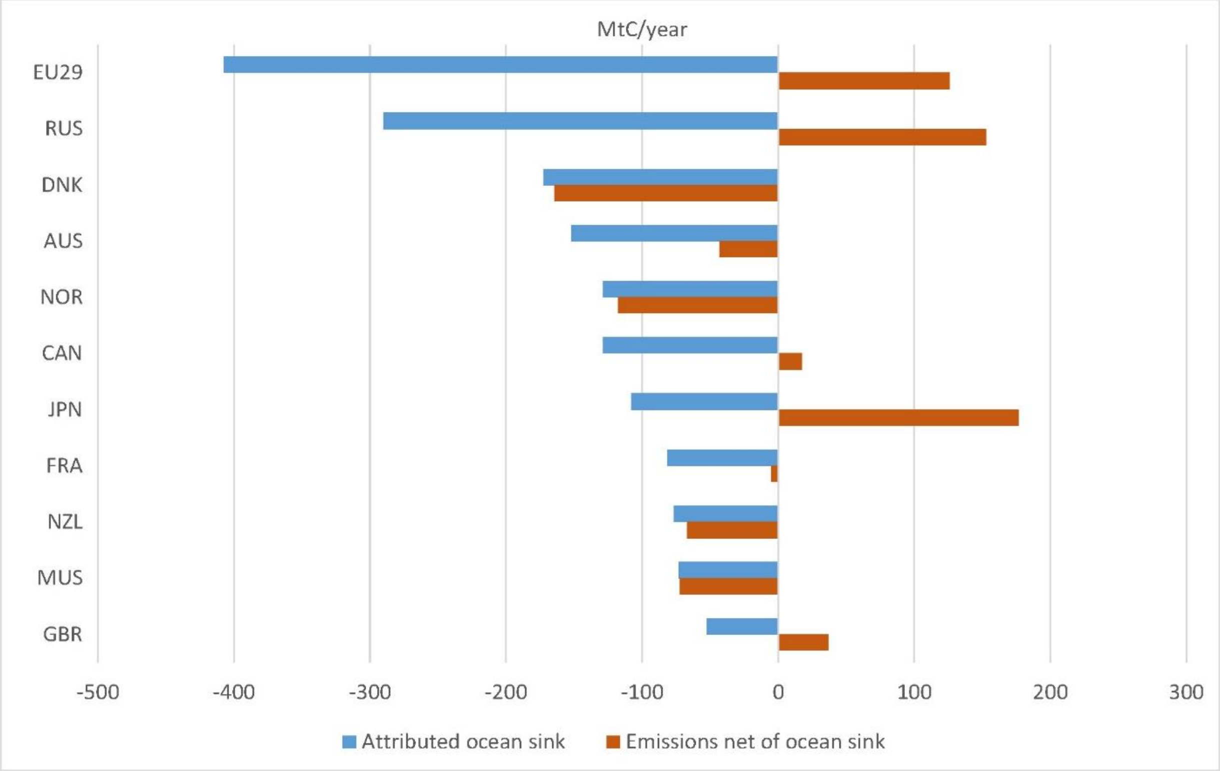

Figure 4: Top 10 countries and the EU29 in terms of attributed ocean sinks, displaying the fossil fuel and industrial emissions obtained from Friedlingstein et al. (2021) net of the attributed ocean sinks (EU29: EU27+Norway and Iceland, RUS: Russian Federation, DNK: Denmark, AUS: Australia, NOR: Norway, CAN: Canada, JPN: Japan, FRA: France, NZL: New Zealand, MUS: Mauritius, GBR: UK and Northern Ireland).

Based on this (or any other ocean sink data), valuation can be obtained by multiplication with price data. Figure 5 shows the price data considered in this study for the ten countries with the highest carbon emissions in the fossil and industrial sector. For the climate-damage-based approach, we consider two different estimates, one obtained from Ricke et al. (2018, 2019) and using the climate change impact estimate of Dell, Jones, and Olken (2012), henceforth abbreviated as DJO, and one obtained from Tol (2019). We have not aggregated the two estimates, since they rely on different assumptions about the impacts of climate change on GDP (Tol 2019) vs. GDP growth (DJO, see Methods and Discussions). For the abatement-cost-based approach, we obtain marginal abatement cost curves (MACCs) estimates using the Dynamic Applied Regional Trade (DART) model (see section 3) and consider the unconditional (low) and conditional (high) emissions reduction targets as announced by countries in their national determined contributions (NDCs) as part of the UNFCCC process (see Methods).

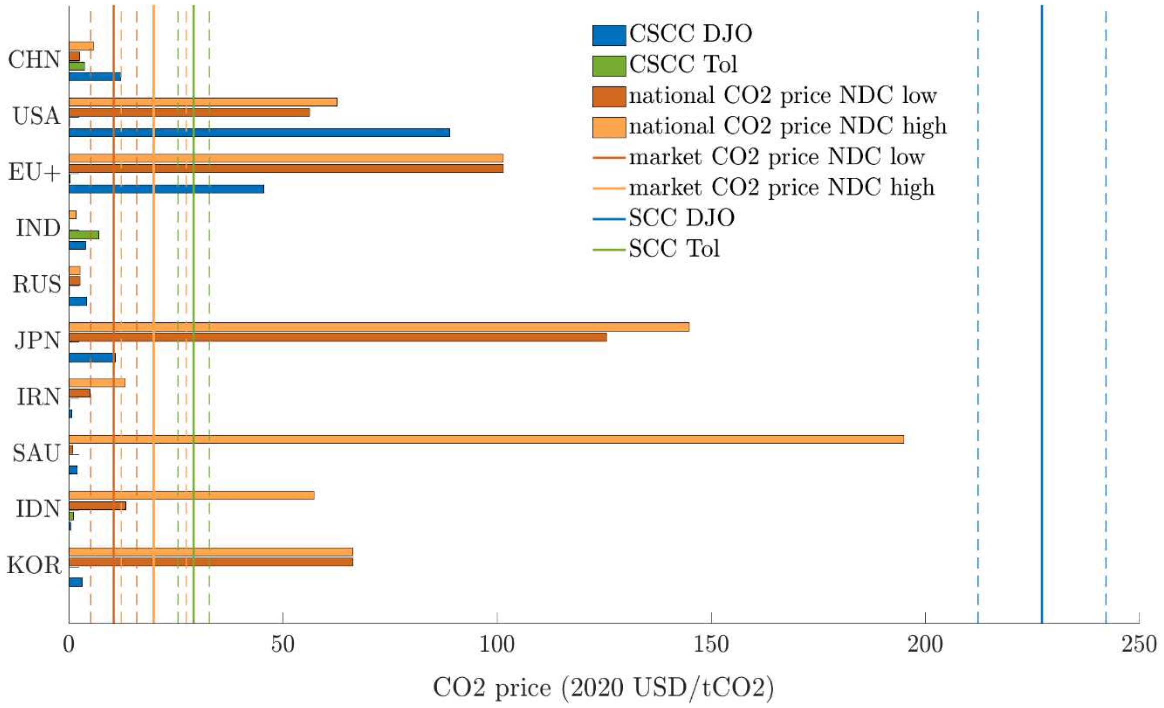

Figure 5: CO_2 prices at the national and global level. The national CO_2 prices show the country social cost of carbon (CSCC) for the climate change impact estimate provided by Dell et al. (2012) (DJO) and for the climate change impact estimate provided by Tol (2019), together with the national CO_2 prices (marginal abatement costs) for emissions reductions as defined in the national determined contributions (NDCs) with either low or high ambition. The global CO_2 prices show the sum of the CSCCs, i.e., the social cost of carbon, again for both impact functions and the global CO_2 prices obtained under full emissions trading.

There are substantial differences between the two climate change impact estimates: 227.28 USD/tCO2 (Std 14.95) based on DJO, and 29.17 USD/tCO2 (Std 3.69) based on Tol (2019) (Figure 5). However, even for the rather large DJO-CSCC estimates, in 6 out of the 10 countries shown in Figure 2, the marginal abatement cost exceeds the country-specific marginal damage, indicating higher-than-optimal abatement efforts for the country in isolation. For these countries, the NDCs include some concern for climate damage that occurs outside their borders. Unfortunately, this does not hold true for China, the USA, India, or Russia, which in total contribute 59 percent of the projected emissions for 2030. Overall, in 109 countries (of the 146 used in the abatement-based approach), the national CO_2 prices – marginal abatement costs for the given NDCs under high ambition – exceed the DJO-CSCC estimate, and in 5 countries, they even exceed the DJO estimate of the global SCC. For the lower Tol (2019)-CSCC estimates, in 112 countries, the national CO_2 prices exceed the CSCC estimate, and in 34 countries, they even exceed the Tol estimate of the global SCC. At the same time, even for the rather small Tol (2019)-CSCC estimates, not every country's marginal abatement cost exceeds its country-specific marginal damage. This especially applies to India (for both NDC ambition levels) and to China (for the low NDC ambition level); see Figure 5. Overall, the national carbon price (= marginal abatement cost) falls short of the country-specific social cost of carbon in 63 and 59 countries under low NDC ambition levels, and in 37 and 34 countries under high NDC ambition levels, for the DJO and Tol (2019) CSCC estimates, respectively. These countries would experience an economic gain by increasing their emissions reductions ambitions, and thus should spend more on abatement efforts for purely selfish reasons.

Furthermore, Figure 5 indicates the efficiency gains from emissions trading. With full emissions trading, the average (emissions-weighted) CO_2 price falls from 28.09 USD/tCO_2 (Std 18.22) to a market price of 10.51 USD/tCO_2 (Std 5.40) and from 42.39 USD/tCO_2 (Std 20.79) to 19.85 USD/tCO_2 (Std 7.60) for low and high ambition levels in the NDCs, respectively. So, even under high ambition levels in the abatement levels, the market price falls short of the rather low Tol-SCC estimate of 29.17 USD/tCO2 (Std 9.70), indicating that under full emissions trading, the emissions reduction levels should be increased even under cost-benefit consideration. The full list of CO_2 price data can be found in Table ST2.

The CO_2 price data allows us to derive proportional value estimates for the ocean sink. The value of the annual global ocean sink of 1.72 GtC (Std 0.03) ranges from 66.21 B USD/year (Std 33.96) to 1433 B USD/year (Std 97.45) for the abatement-cost-based assessment approach (assuming full emissions trading and low ambition levels in the NDCs) and for the climate-change-damage-based assessment approach (assuming the climate change impacts estimate by DJO). Under the abatement-cost-based assessment approach, the value of the largest attributed ocean sink, that of the EU29 (including their oversea carbon sinks) of 0.41GtC, ranges from 15.70 B USD/year (Std 8.04) to 151.50 B USD/year (Std 53.78) under full emissions trading and no emissions trading, respectively. Under the climate-change-damage based assessment, the corresponding value range from 43.53 B USD/year (Std 5.53) to 339.22 B USD/year (Std 23.08) for the climate change impact estimates by Tol (2019) and DJO, respectively.

Following Bertram et al. (2021), the combination of CSCC and SCC allows us to derive information about wealth distribution. While applying the (global) SCC yields insights into the global wealth contribution, only a fraction of this contribution accrues domestically and is measured by the domestic CSCC. The remaining contribution generates wealth abroad and is measured by the SCC minus the domestic CSCC. However, at the same time, the ocean sinks outside national borders (and EEZs) also contribute to reducing climate change impacts domestically and are measured by the domestic CSCC. Netting these two wealth flows allows us to determine whether countries are net donors or net recipients of ocean wealth. Figure 6 shows the top 10 donors and top 10 recipients of ocean carbon wealth based on the DJO climate impact estimate, while also displaying the corresponding information for the Tol (2019) climate impact estimate, which clearly suggests a different ranking.

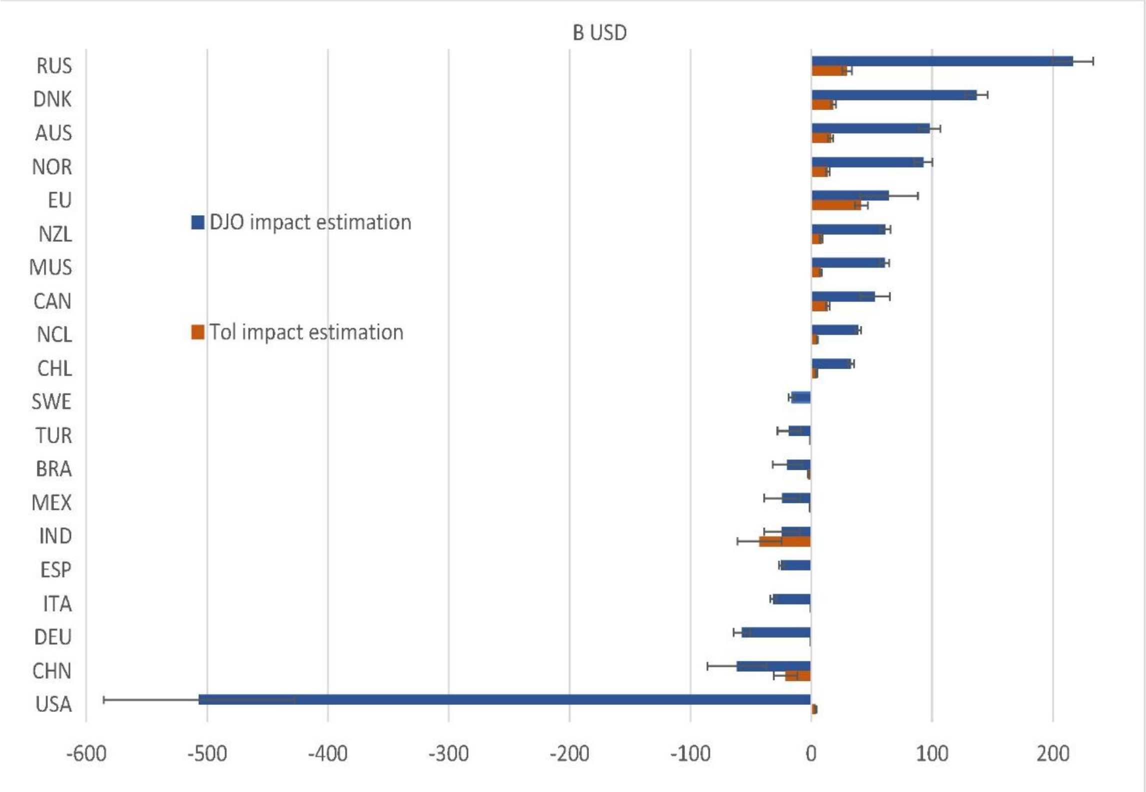

Figure 6: Ocean-based wealth transfer. Positive values indicate countries (or regions) where the outbound wealth flux exceeds the inbound wealth flux (and vice versa for negative values). The selection of countries represents, according to the DJO climate impact estimate, the top 10 donors and top 10 recipients of ocean carbon wealth. The figure also displays the corresponding values based on the Tol climate impact estimate, which clearly do not reflect the same ranking.

The CSCC estimates differ not only in total levels but also for individual countries (Figure 6). This can be highlighted by two examples. First, according to the DJO estimate, the USA has a rather high CSCC of 88.96 USD/tCO_2 (Std 13.26), which represents roughly 44 percent of the DJO global SCC estimate. Hence, while it has an attributed domestic ocean sink of 171.01 MtCO_2/year (Std 0.27), i.e., almost 3 percent of the total attributed ocean carbon sink, about 44 percent of the corresponding total ocean carbon wealth is accrued at home. In turn, the ocean sinks outside the USA result in high ocean carbon wealth inflow, since they are also multiplied by the USA's high CSCC. In contrast, according to the Tol (2019) estimate, the USA's CSCC is only 0.19 USD/tCO_2 (Std 0.1), less than one percent of the Tol (2019) global SCC estimate. Accordingly, the valuation of the domestic US ocean carbon sink results in a higher outbound contribution than the inflow of the foreign ocean carbon sink. The other example is

India. According to the DJO estimate, the CSCC is 3.98 USD/tCO_2 (Std 2.42), i.e., about 2 percent of the global SCC, while according to the Tol (2019) estimate, the CSCC is 6.97 USD/tCO_2 (Std 2.98), i.e., about 24 percent of the global SCC. Hence, the valuation of the carbon sink inflow is higher, and in turn according to Tol (2019), India receives more ocean carbon wealth than it does according to Dell et al. (2012). The complete wealth analysis, considering both climate impact estimates (DJO and Tol, 2019); the ocean carbon sink only; and the fossil fuel and industrial emissions net of ocean sink can be found in the supplementary tables ST3 to ST6.

The abatement-cost-based assessment approach does not allow such an analysis of the transfer of wealth, as it assigns countries quantitative emissions reduction targets. However, the approach does allow us to analyze the effects of integrating the ocean carbon sink into national or even global emissions trading. In contrast to Rehdanz et al. (2006), we consider the possibility that the weakening of the ocean sink may result in additional emissions reductions to compensate for it. To demonstrate such a possibility, we simply assume that countries with carbon uptake in their EEZs would have to increase their emissions reductions by 5 percent of their national ocean sinks. This would roughly compensate for the 12 percent weakening of the global ocean sink. For those countries with the largest attributed sinks (and for which price data is available), Figure 7 shows the percentage increase in CO_2 prices under high emissions reduction ambitions. Note that for the USA, the increase in CO_2 prices is only 0.60 (Std 0.38) percent, since its attributed ocean sink (-44.83 MtC (Std 0.10)) and hence the corresponding increase in its reduction target by 5 percent (2.24 MtC) is small relative to the BAU emissions (1378.23 MtC, Std 144.68) and the reduction target.

This is very different from Mauritius, which has a large sink relative to its BAU emissions and hence its reduction target, as a result of which its carbon prices increase more than fivefold. Overall, the increase in the average (emissions-weighted) carbon price is 3.41 percent (Std 2.99). Note that the reduction target only increases for those countries with attributed ocean sinks, while for the remaining countries the national carbon price remains unchanged. Emissions trading again dampens the price increase, since now the increase in the reduction target is part of overall emissions trading and in turn the increase is only 1.91 percent (Std 1.26).

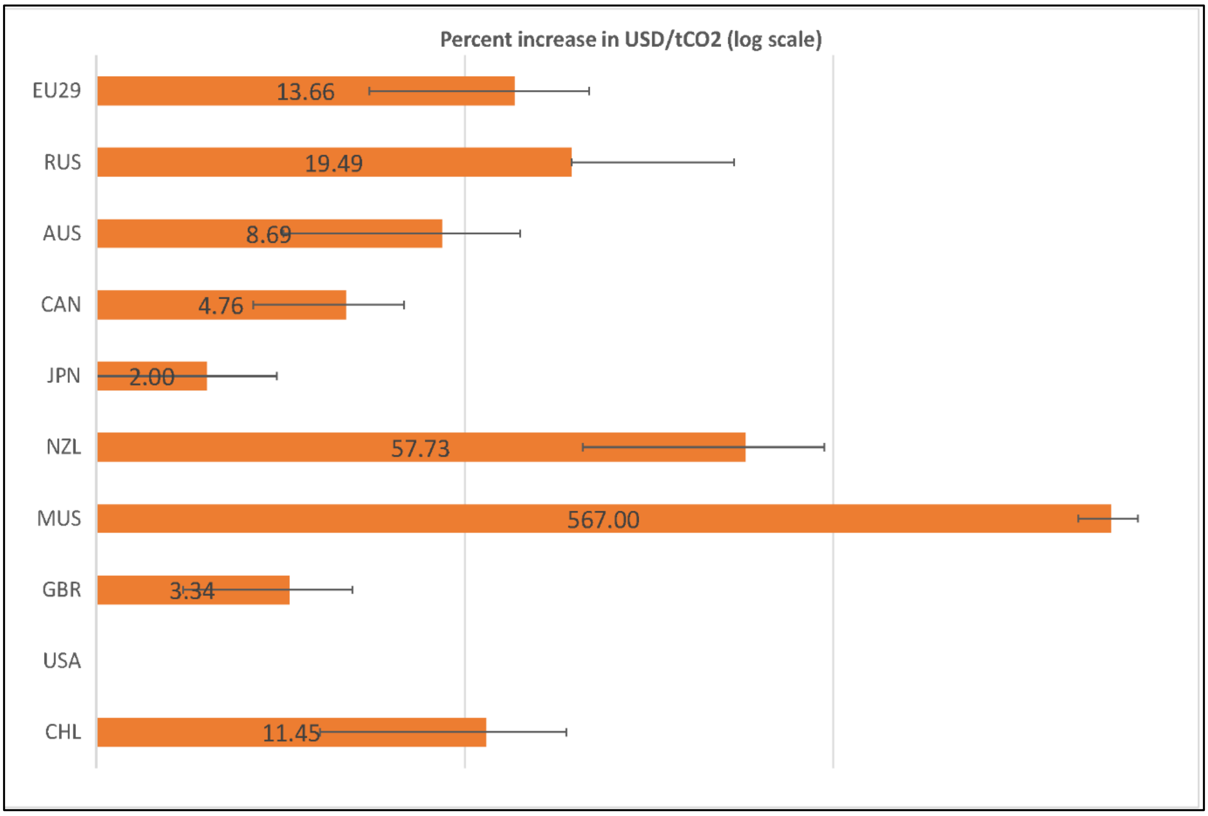

Figure 7: Implications of a weakening ocean sink. The figure shows the price increase due to higher emissions reductions to compensate for a weakening ocean sink by about 12 percent for the NDCs with a high emissions reduction ambition. The figure shows the 10 regions and countries with the largest attributed sink. The abbreviations are EU29: European Union plus Norway and Iceland, RUS: Russia, AUS: Australia, CAN: Canada, JPN: Japan, NZL: New Zealand, MUS: Mauritius, GBR: Great Britain, USA: United States of America, and CHL: Chile.

While in this calculation the increase in the emissions reduction targets is supposed to compensate for the weakening ocean sink (i.e., the climate damage would remain unchanged), it also reveals the main difference between the two approaches. In the abatement-cost-based assessment, moving from high to low emissions reduction ambitions implies lowering the global reduction target from 29.45 to 16.00 percent (relative to business as usual in 2030), and in turn the emissions-weighted national CO_2 prices drop from 42.40 USD/tCO_2 (Std 20.79) to 28.09 USD/tCO_2 (Std 18.22) and the global carbon price under full emissions trading drops from 19.85 USD/tCO_2 (Std 7.60) to 10.51 USD/tCO_2 (Std 5.39). However, lower emissions reductions imply higher marginal damage and in turn, the CO_2 prices increase under a climate-change-damage-based approach. Considering the DJO estimates, the global SCC increases from 227.28 USD/tCO_2 (Std 14.94) to 240.19 USD/tCO_2 (Std 15.98) if the emissions increase from RCP60 to RCP85. Hence, under the climate-change-damage-based approach, the highest valuations are derived for the ocean sink under high emissions scenarios (i.e., low emissions abatement efforts), while just the opposite is true for the abatement-cost-based approach, where the highest valuation is obtained under low emissions scenarios (i.e., high emission abatement efforts). As already discussed, these two opposing cost components can both be used to determine the optimal climate policy in a cost-benefit framework, but in applied valuation work, climate policy is not derived under a comprehensive cost-benefit analysis. Hence, increasing emissions reduction efforts beyond the levels proposed in the NDCs such that they align with the Paris temperature targets lowers the value of the ocean sink under a climate-change-damage-based approach.

3 Discussion and Conclusions

Based on a recent pCO_2 dataset that depicts the surface ocean at comparatively high spatial resolution (0.25° by 0.25°, Landschützer et al., 2020a,b), we estimate the ocean carbon flux following standard procedures (e.g. see Fay et al. 2021) and with reference to the atmospheric CO_2 concentration in 2006. While our carbon flux estimate is not expected to numerically compare with previously published global carbon fluxes based on coarser resolution data (e.g. 1°; GCP, Friedlingstein et al. 2021), the focus is on using a flux dataset with high spatial resolution to evaluate the carbon sinks in individual nations' EEZs. The regional uptake pattern of our dataset resembles previously published global maps (e.g. Fay et al. 2021); however, individual data points may be substantially different and may impact local uptake in EEZs and limit the generalization of our valuation. Our dataset is referenced to only one year (2006) and that excludes investigating the impact of temporal variability of pCO_2 fluxes over an EEZ region (or globally). Our focus here is on the feasibility of evaluating the regional ocean carbon sink.

We obtain (C)SCC values using an empirical approach provided by Ricke et al. (2018, 2019) and an integrated-assessment model-based approach provided by Tol (2019). The approach put forward by Ricke et al. includes two different climate change impact functions, of which in particular the climate change impact estimate provided by Burke et al. (2015) has been the subject of criticism. Burke et al. (2015) assume that temperature increase has a permanent influence on the growth rates of gross domestic product (GDP). In combination with a non-linear impact function, their approach results in very high SCC estimates but also, in some regions, considerably higher GDP from climate change (Tol 2019). Since the impact of temperature increase on GDP growth rates is persistent in this approach, regions like Canada and Russia steadily gain from climate change and begin dominating climate change losers towards 2100 (Rickels et al. 2020). The persistent impact of temperature increase on GDP growth rates was not confirmed in follow-up studies conducted by Kalkuhl and Wenz (2020), Newell et al. (2022) or Tol (2022). However, these studies provide estimates for the global SCC only. The CSCC estimates obtained by Tol are not affected by such conceptual issues; however, his estimate results in considerably lower SCC estimates than those recently suggested by the literature: his estimates add up to 29.17 USD/tCO_2 (Std 3.67). In contrast, Kalkuhl and Wenz (2020) find an empirically derived estimated range for the SCC (in the year 2030) from 92 to 181 USD/tCO_2, the former obtained under a cross-section estimate, the latter under a population-based panel estimate. Similarly, Rennert et al. (2022) derive a model-based estimate for the SCC of 185 USD/tCO_2 (44–413 USD/tCO_2, 5%–95% range). Hence, we include in our assessment the estimates of Ricke et al. (2018, 2019), while restricting it to the climate change impact function provided by Dell et al. (2012), which results in an average SCC of 227.28 USD/tCO_2 (Std 14.95). We do not aggregate the two SCC estimates, since they rely on very different assumptions, but instead provide the estimates separately, highlighting the unresolved uncertainties in terms of quantifying the impacts of climate change.

A previous meta-study provided by Böhringer et al. (2021) finds a range for the emissions-weighted global average CO_2 price from 12.66 USD/tCO_2 to 42.86 USD/tCO_2 for implementing the NDCs in 2030. The emissions-weighted global average CO_2 prices in our study are 28.09 USD/tCO_2 (Std 18.22) and 42.39 USD/tCO_2 (Std 20.79) for low and high emissions reduction ambition levels as defined in the NDCs. Note that our estimates involve substantial uncertainty, as we assume a larger variation in future business-as-usual GDP and CO_2 emissions than the studies underlying the comparison in Böhringer et al. (2021). Despite the relatively good fit with other studies, it should be acknowledged that such CGE models aggregate several countries to regions and consider only some (economically) large countries like China, the USA, Germany and India separately, while many small countries (in particular developing countries in Africa, Asia and Latin America) are aggregated. The DART model underlying our estimate provides results for 21 regions, which we break down to the country level, assuming that within a given region, a country with low emissions efficiency (i.e., a high emissions-to-GDP ratio) has lower abatement costs than countries which already have a higher emissions efficiency. However, for large DART regions like Africa, this seems to be a strong assumption and hence our results for economically small countries, many of which have comparatively large attributed ocean sinks, should be considered with caution.

Generally speaking, in light of the global commons character of the ocean carbon sink, it would seem more sensible to apply the climate-change-damage-based assessment approach to derive information about ocean carbon wealth in an inclusive wealth framework. However, at the same time, the various possible components of climate change impacts result in considerable uncertainty in damage-based approaches and thus a large range of value estimates. In contrast, abatement-cost-based approaches, despite the uncertainty about innovations in emission abatement technologies, appear to yield a narrower range if applied to the valuation of the ocean sink. However, assigning property rights with implications for improving carbon uptake might be restricted to coastal blue carbon ecosystems, since the common pool open ocean carbon sink does not appear to benefit from direct management

(Rickels et al. 2016). Moreover, the redistribution of the anthropogenic carbon by ocean transport processes is creating a different picture of the total amount of ocean storage of anthropogenic carbon (e.g. Gruber et al. 2019) and so does resolving the surface pCO2 field using improved observation-based techniques (e.g. Olivier et al. 2022). Consequently, the inclusion of the ocean carbon sink in countries' climate policies might be restricted to these coastal blue carbon ecosystems. On the other hand, the overuse of the open-access atmospheric carbon reservoir also translates into an overuse of the ocean carbon reservoir. An abatement-cost-based approach could be used to assess the implications of assigning responsibilities for maintaining the ocean carbon sink.

Acknowledgements

WR and JK acknowledges funding from the EU Horizon 2020 project Eurosea (862626). SP and ST acknowledge funding from RETAKE. FM acknowledges funding from Test-ArtUp.

Competing interests

The authors declare that they have no conflicts of interest.

Methods

Estimating and attributing ocean uptake

We used a combined open-ocean and coastal-ocean pCO_2 mapped monthly climatology with an overall spatial resolution of 0.25° by 0.25° (Landschützer et al., 2020a,b). This pCO_2 dataset has a monthly resolution and presents a mean field for the entire period 1998 to 2015, which we scaled to a flux considering the atmospheric CO_2 concentration for 2006 (centered in the underlying data period). For the carbon flux calculations, we used ERA5 sea-level atmospheric pressure, sea-surface temperature and salinity fields (Hersbach et al. 2023), and the NOAA multiple satellites blended 0.25° Sea Wind product (Saha and Huai-Min 2022). To calculate the total annual carbon flux in the EEZ of each country, we first multiplied the grid of annual carbon flux rate per m^2 by the area of the respective grid cell to obtain the total annual carbon flux for each grid cell. Second, we overlaid the EEZ boundaries (version 11, territories) layer from the Flanders Marine Institute (2020) with the total annual carbon flux (Figure 1) to calculate the sum and standard deviation of the annual carbon flux of each EEZ territory. Due to the relatively coarse resolution of the flux grid (0.25° by 0.25°) and the shape and areal extent of the individual EEZs, in total 12 EEZs did not overlap with any grid cell of the annual carbon flux dataset, namely the Alhucemas Islands, Bosnia and Herzegovina, Ceuta, Chafarinas Islands, Doumeira Islands, Gibraltar, Jordan, Melilla, Peñón de Vélez de la Gomera, Perejil Island, Sint-Maarten, and Slovenia. Thus, total carbon fluxes were not calculated for these countries. For each country and the assignment of oversea areas can be found in supplementary material M1_data.

Climate-change-damage-based assessment approach

Following Canu et al. (2015) and Bertram et al. (2021), we applied the inclusive wealth approach and calculated the total ocean carbon wealth contribution of the ocean carbon sink in the EEZ of each country *i* as

$$W_{i,total} = OCS_i * SCC \; with \; SCC = \textstyle\sum_i CSCC_i, \qquad \text{(Meq1)}$$

where *OSC$_I$* indicates the ocean carbon sink in the EEZ (measured in tCO$_2$/year) and *SCC* is the (global) social cost of carbon, which is the sum of CSCC$_i$, i.e., the country social cost of carbon. Using CSCC allowed us to distinguish between domestic, outbound and inbound ocean carbon wealth contributions. The domestic ocean carbon wealth contribution is:

$$W_{i,domestic} = OCS_i * CSCC_i \,, \qquad \text{(Meq2)}$$

the outbound ocean carbon wealth contribution is:

$$W_{i,out} = OCS_i * \left(\textstyle\sum_{j \neq i} CSCC_j\right), \qquad \text{(Meq3)}$$

and the inbound ocean carbon wealth contribution for country *i* is:

$$W_{i,in} = \left(\textstyle\sum_{j \neq i} OCS_j\right) * CSCC_i. \qquad \text{(Meq4)}$$

Net carbon wealth redistribution is defined as the difference between outbound and inbound ocean carbon wealth contributions.

We obtained estimates from the literature for the CSCC from Ricke et al. (2018, 2019) and Tol (2019). Ricke et al. (2018, 2019) use two different climate-damage functions, one provided by Burke et al. (2015) and one provided by Dell et al. (2012). In terms of Ricke et al. (2018, 2019), we used only those CSCC estimates based on the damage impact function put forward by Dell et al. (2012), which yielded a smaller (negative) impact for rich countries that appears more consistent with the literature, has a linear specification for the change in temperature, and does not have a U-shaped impact projection towards 2100 for global impacts. The estimation strategy put forward by Ricke et al. (2018, 2019) also includes all SSPs and considers three RCPs: RCP45, RCP60 and RCP85. From these scenarios, we used the one obtained for RCP60, as here the emissions were comparable to the baseline emissions in Tol (2019) and considered the scenarios with a pure rate of time preference of 1 percent and a marginal elasticity of utility of 1.5. The estimates in Ricke et al. (2018, 2019) are presented in USD PPP (2005); hence we converted these two market exchange values and used the GDP deflator (both obtained from the World Bank) to obtain estimates in 2020 USD. Based on this approach, we obtained an average SCC of 227.28 USD/tCO2 (Std 14.95) (across the different SSPs and climate change uncertainty estimates provided in Ricke et al. (2019)). Tol (2019) provides estimates for the impact of climate change on the level of economic activity for different impact functions. We used the estimates obtained from the Tol impact function for the different SSPs and a pure rate of time preference of 1 percent and income elasticity of impacts of -1.68. The estimates are provided by Tol (2019) in 2010 USD at market exchange rates. We used the USD GDP deflator to convert the estimates into 2020 USD (to make them comparable with our abatement cost estimates). This allowed us to obtain an average SCC (across the five SSPs) of 29.17 USD/tCO2 (Std 3.67). For each country, the CSCC estimates can be found in supplementary material M2_data.

Abatement-cost-based assessment approach

We used the Dynamic Applied Regional Trade (DART) model to estimate marginal abatement cost curves, providing information on the abatement-cost-based CO_2 price for a given emissions reduction level. DART is a global and recursive dynamic computable general equilibrium (CGE) model (Klepper et al. 2003, Winkler et al. 2021). The advantage of using a global CGE model lies in its ability to capture not just the direct domestic multiplier effects of a carbon price but also indirect implications via changes in international energy prices and trade flows (Klepper and Peterson 2006). Given that economic structures vary across regions, marginal abatement costs differ widely across regions and therefore need to be calculated individually. We calibrated the DART model to the GTAP10 database (Aguiar et al. 2019) with 2014 as the base year and the baseline dynamics calibrated to the GDP data from IEA (2020) and updated to include renewable energy data from the IEA (2022). With this updated model, MACC curves for the year 2030 were generated separately for each model region by varying the emissions reduction target of said region between 0% reduction relative to 2014 levels theoretically up to 100% relative to baseline in increments of 5% while assuming that the rest of the regions fulfilled their national determined contribution (NDC) targets as specified in Böhringer et al. (2021).

Based on this approach, for each region *i,* we created cubic abatement cost curves, $AC_i(E_i)$, which imply quadratic marginal abatement cost curves, and $MAC_i(E_i)$ to the modelled values where E_i

represents the actual 2030 emissions in the reduction scenario. Let $E_{i,BAU}$ denote the 2030 emissions in the business-as-usual (BAU) scenario without climate policy and $Y_{i,BAU}$ GDP in 2030, then

$$AC_i(\mathrm{E}_i) = \alpha_i * (1 - \frac{E_i}{E_{i,BAU}})^3 Y_{i,BAU} E_{i,BAU} \tag{Meq5}$$

$$MAC_i(\mathrm{E}_i) = \frac{\mathrm{dAC_i(E_i)}}{\mathrm{-dE_i}} = \alpha_i * 3 * (1 - \frac{E_i}{E_{i,BAU}})^2 Y_{i,BAU} \tag{Meq6}$$

Note that the marginal abatement costs (MAC) are defined by the derivate with respect to minus E_i since they measure how the abatement cost increase if abatement is increased, i.e. emissions are reduced.

The abatement cost parameters were determined by solving the following minimization problem

$$\min_{\alpha_i} \sum \left(P_{CO_2^{DART}} - (3\alpha_i\, R_i^2 Y_{i,BAU}) \right)^2. \tag{Meq7}$$

Thus, the cost parameters α_i were calibrated by minimizing the sum of the difference between the CO_2 price $P_{CO_2^{DART}}$ and the CO_2 price following from the condition (Meq6). To obtain country-specific abatement cost functions for the DART regions with more than one country, we used the approach proposed by Tol (2005) and assumed a 10-percent spread in relative costs between the country with the highest carbon intensity (CO_2/GDP) and the country with the lowest carbon intensity for a 10-percent reduction. For each country, the resulting parameters can be found in supplementary material M3_Data.

To quantify abatement costs, we drew on the latest information on the Nationally Determined Contributions (NDCs) from CLIMATE RESOURCE, who provide an NDC database covering each country's initial NDC and the development of its climate policy over time (Meinshausen et al. 2022). The dataset includes all NDC updates submitted up to November 2nd, 2022. The NDCs vary in their commitment levels depending on the emissions reductions of other countries. We extracted the updated covered GHG data for low and high ambition targets, respectively. Hot air was included; emissions from the LULUCF sector were not. For both high and low ambitions, the target emissions from 2030 and 2020 were set in ratio. The low emissions-reduction ambitions imply a reduction of 16.00 percent relative to business as usual in 2030, while the high emissions-reduction ambitions imply a reduction of 29.45 percent.

Furthermore, information on business-as-usual GDP, $Y_{i,BAU}$ and 2030 business-as-usual CO_2 emissions, $E_{i,BAU}$ was obtained from the DART model and we considered the projections for all SSPs in the baseline (marker) specification (Riahi et al. 2017, i.e., SSP1: van Vuuren et al. 2017, SSP2: Fricko et al.

2017, SSP3: Fujimori et al. 2017, Calvin et al. 2017, and SSP5: Kriegler et al. 2017) together with the OECD GDP growth projections (Dellink et al. 2017). Hence, we considered a total of six scenarios for future GDP and emissions. We transformed this data into values relative to the base year in the specific scenario and used data on GDP from the World Bank (World Bank 2022) and on CO_2 emissions from the Global Carbon Project (Friedlingstein et al. 2021) in 2020 as the common base year values. For each scenario, we calculated the marginal abatement cost for the low and high emissions-reduction targets.

The MACCs also allowed us to derive a market solution, i.e., countries trade emissions reductions. Accordingly, we used the MACCs in the following model framework. The countries, i, face an exogenously set emissions cap A_i (provided by the NDCs). Without emissions reductions, business-as-usual emissions are realized, $E_{i,BAU}$. The total amount of emissions by each country, E_i, is non-negative and no country can abate more than it emits,

$$0 \leq E_i \leq E_{i,\mathrm{BAU}}. \qquad \text{(Meq 8)}$$

We allowed for a market on tradable emissions reduction permits, where the permit price is represented by π and the number of permits each country purchases or sells by T_i. In order to fulfill the emissions target, every country can reduce its baseline emissions and trade permits on the market. Thus, the difference between emissions and the number of permits must not exceed the emissions cap,

$$E_i - T_i \leq A_i. \qquad \text{(Meq9)}$$

The total cost of achieving a given target A_i is determined by the sum of abatement and permit trading costs (or trading benefits if a country is a net seller of permits, $T_i < 0$). Therefore, each country solves the following optimization problem,

$$\min_{R_i,\mathrm{T}_i} C_i = AC_i(R_i) + \pi\, T_i, \qquad \text{(Meq10)}$$

subject to equations (Meq9). Solving the static optimization problem, assuming an interior solution, yields the well-known efficiency rule that for all countries, the marginal cost of abatement equals the permit price,

$$AC'(\mathrm{E}_i^*) = \pi. \qquad \text{(Meq11)}$$

The market allocates the permits efficiently. Condition (Meq11) shows that the optimal rate of emissions reduction can be expressed as a function of the carbon credit price, $\mathrm{E}_i^*(\pi)$. The optimal permit price can be determined using the overall compliance condition,

$$\sum_{\mathrm{i}}^{\mathrm{n}} \mathrm{E}_{\mathrm{i}}^*(\pi^*) = \sum_{\mathrm{i}}^{\mathrm{n}} \mathrm{A}_{\mathrm{i}}, \qquad \text{(Meq12)}$$

which states that the sum of all countries' net emissions equals the sum of all countries' emissions caps. With the functional form defined in (Meq5), the solution for the permit price is

$$\pi = \left(\frac{\sum_{i=1}^{n} \mathrm{E}_{i,\mathrm{BAU}} - \sum_{i=1}^{n} A_i}{\sum_{i=1}^{n} \mathrm{E}_{i,\mathrm{BAU}} \sqrt{(3\alpha_i Y_i)^{-1}}}\right)^2 \qquad \text{(Meq13)}$$

which then determines via (Meq11) the country-specific emissions levels and trading positions. The inclusion of the ocean sink (i.e., a compensation for a weakening ocean sink) is achieved by reducing each country's A_{i} accordingly.

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